Performance of Photovoltaic Systems Recorded by Open Solar Performance and Reliability Clearinghouse (oSPARC)

Andy Walker, Jal Desai, and Donna Heimiller

National Renewable Energy Laboratory

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Abstract

This article analyzes data, including system production, co-incident insolation, and ambient temperature, from 2,200 photovoltaic systems collected through the Open Solar Performance and Reliability Clearinghouse (oSPARC, 2018) to analyze how actual performance compares with expectations. The systems range in size from 2 kW-1,200 kW, with an average size of 229 kW, and were activated in oSPARC between March 13, 2007, and Dec. 16, 2016. The data is analyzed according to three standard definitions of Performance Ratio based on 1) Standard Test Conditions (STC); 2) PVUSA Test Conditions (PTC); and 3) PTC adjusted for measured temperature, system age, and balance-of-system efficiency. We introduce a fourth definition by lumping two unknows (Performance Ratio and Balance-of-System Efficiency) into one measured performance indicator. Results indicate that—after correcting for measured insolation, de-rating for temperature, and correcting for balance-of-system efficiency and degradation as a result of system age—the performance ratio of this particular sample of 2,200 systems averages 91.7% of the expected annual production. Being normalized for environmental conditions, this ratio would ideally be 100%, suggesting that as much as 8.3% of lost production could be recovered through optimal operations and maintenance. Also because the method already normalizes for measured sunlight and temperature, no correlation was found between performance and land use type (urban, agricultural, etc.), but one parameter for which correlation was found is air quality, with performance of systems notably lower in areas where particulate matter causes additional soiling.

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1 Introduction

The Open Solar Performance and Reliability Clearinghouse (oSPARC) system, accessible through the Asset Performance Suite at apsuite.sunspec.org and also posted at http://osparc.sunspec.org/ (oSPARC, 2018), incorporates a cloud-based computing service platform and standardized communications protocols to log and analyze performance data from participating solar PV power plants. oSPARC provides real, measured data on performance and reliability by receiving and aggregating performance statistics pertaining to yield, availability, and reliability. Information from the oSPARC database informs solar and financial industry personnel about actual PV system performance. Solar photovoltaic (PV) project developers also benefit by understanding how the information generated by solar power plants is used in investment risk assessment scenarios. Additional information about oSPARC is available at www.sunspec.org/osparc/.

The SunSpec Alliance oSPARC Implementer's Guide describes the following details for users: plant information profile, plant meta data, time series data, plant availability and status, oSPARC web service, oSPARC user query, oSPARC output report, and anonymization for vendors and plant participants. Report data are anonymized to respect the confidentiality of participants. oSPARC leverages SunSpec Alliance specifications and the "SunSpec Alliance Best Practices in Solar Performance Monitoring" guidelines, which are available at sunspec.org.

2 Background

The paper “Weather-Corrected Performance Ratio” (Dierauf et al. 2012) describes 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 the paper “Performance ratio revisited: is PR > 90% realistic?” (Reich et al. 2012a), the authors report performance ratio (based on Standard Test Conditions, called PR_{STC} in this paper) of 100 systems in Germany between 70% and 90% for the year 2010, with a median 84%, and 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), the authors have presented the data of performance ratio for the past 30 years and how it has evolved over the years, as low as 50% in the 1980s to 90% and more currently due to improvements in components and reduction in shading. In the book chapter “Introduction to Photovoltaic System Performance” (Pearsall 2017), the author covers the basics of the PV system performance and 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.

This effort to collect performance data was initiated after a PV O&M Working Group convened by the US DOE Solar Technology Office recommended standards, actuarial performance data, best practices, and O&M cost estimating model as research priorities. Sunspec Alliance was selected in a Funding Opportunity Announcement to create and host the open System Performance and Reliability Clearinghouse. This report examines data collected under that effort.

3 Nomenclature

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

Rd = 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)

degr = an age degradation factor that is 1.0 initially but degrades at the rate Rd (per year) to represent the cumulative lost production over a multi-year analysis period

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. This parameter is entered as the user defines the plant in oSPARC.

E = energy, in units of kWh

G = Irradiance, incident flux of radiant power per unit area, units of $W \cdot m^2$

G_{ref} = Reference value of Irradiance, equal to 1000 W/m^2

G_{POA} = Plane of Array (POA) Irradiance, the sum of direct, diffuse, and ground-reflected irradiance incident upon an inclined surface parallel to the plane of the modules in the PV array, also known as POA irradiance 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_{STC} = Performance Ratio based on Standard Test Conditions

PR_{PTC} = Performance Ratio based on PV USA Test Conditions

$PR_{adjusted}$ = Performance Ratio based on PV USA Test Conditions, but adjusted for balance of system efficiency (η_{BOS}), degradation due to age, and de-rate due to temperature

STC = Standard test conditions, reference values of in-plane irradiance (1,000 W/m^2), PV cell junction temperature (25°C), and the reference spectral irradiance defined in IEC 60904-3

$T_{ambient}$ = ambient temperature (°C), averaged over the duration of the time interval t_2-t_1

4 PV Power Plant User Input Description

Performance Ratio may be thought of as "actual production" divided by "expected production," making the calculation of expected production as important to this ratio as the measured energy production is. Users of the oSPARC database must enter sufficient data to perform this calculation, including: Direct Current (DC) rating according to standard test conditions (STC), temperature coefficient, and balance-of-system efficiency. The user must also specify the orientation (tilt angle, azimuth angle, and tracking if any) of the PV Array so that Plane-of-Array insolation may be ascertained. The age of the PV power plant is inferred by the date of activation in oSPARC. With this system description, it is possible to calculate the Performance Ratio.

4.1 Plant STC and PTC Ratings

The minimum system size of the systems in this study was 2 kW and the maximum size was 1,200 kW, with an average size of 229 kW (STC rating).

Table 1. Size of PV Systems in Sample, Based on Standard Test Condition (STC) and PV USA Test Condition (PTC)

	Rated Power (STC)	Rated Power (PTC)
Minimum	2.1	1.7
Average	229	199
Standard Deviation of Average	266	232
Maximum	1,186	1,019

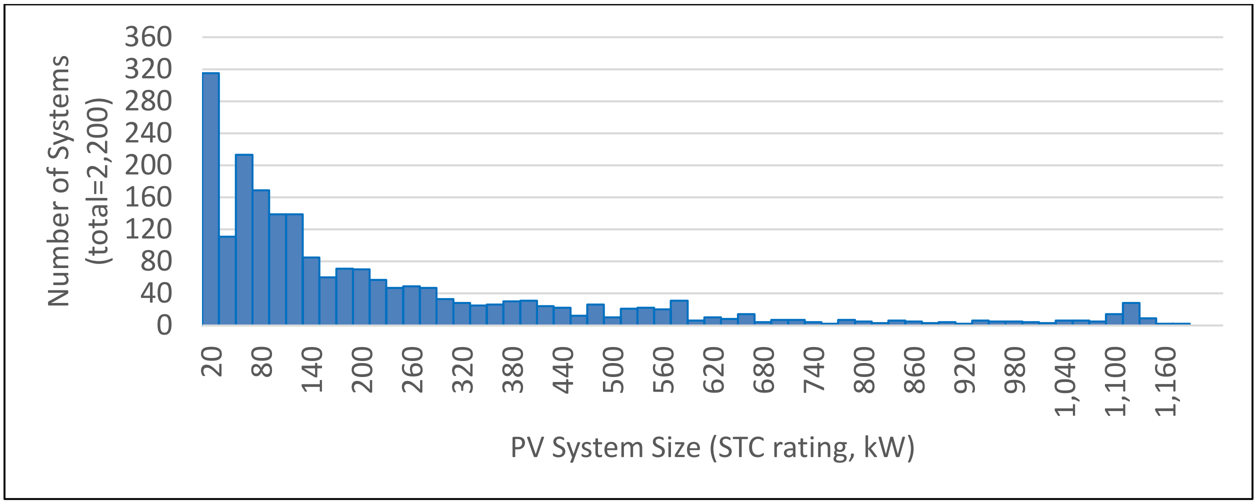

Figure 1. Size of PV systems in sample, based on Standard Test Condition (STC)

4.2 Balance of System Efficiency

The Balance of System Efficiency (η_{BOS}) is entered into oSPARC by the user as part of the PV Power Plant Description. In the oSPARC data schema, a factor for shading losses (equal or less than 1.0) is included in balance-of-system efficiency and is entered by the user. This user-entered shading factor is responsible for much of the variation in the value for η_{BOS} for each system.

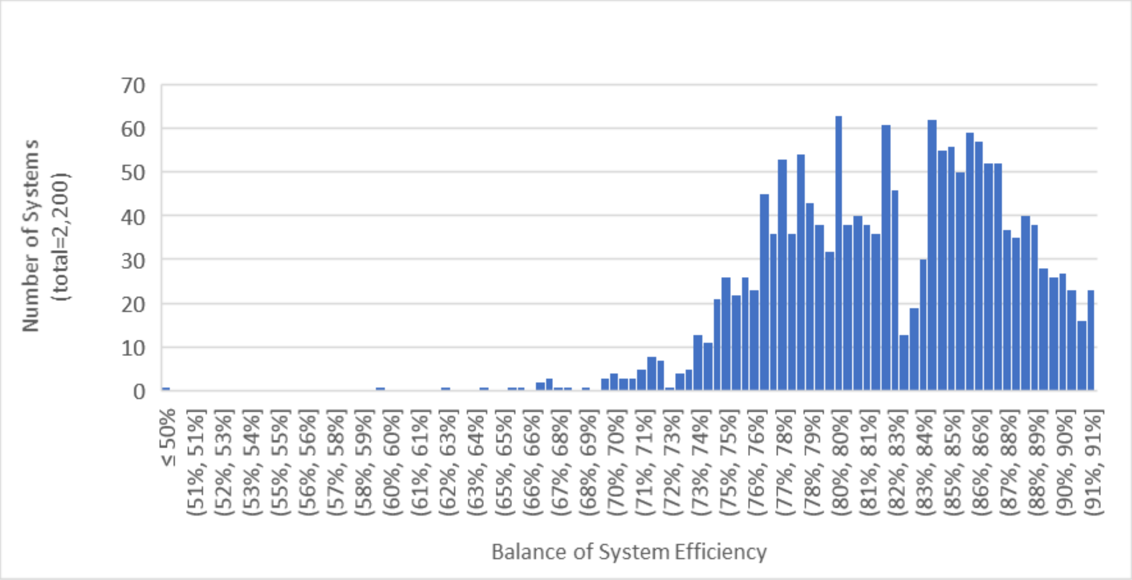

Figure 2. Histogram of Balance of System Efficiency values entered by users into oSPARC database as part of plant description

Table 2. Balance of System Efficiency as Input into oSPARC by Users: Minimum, Average, Maximum, and Standard Deviation

	Balance of System Efficiency
Minimum η_{BOS}	48.0%
Average η_{BOS}	82.2%
Standard Deviation of η_{BOS}	5.1%
Maximum η_{BOS}	91.3%

4.3 Temperature Coefficient

The temperature coefficient of each system is calculated based on the difference between the STC rating and the PTC (PV USA Test Condition) rating of each system as entered by users into oSPARC as part of the description of each plant. The difference in the ratings is because of temperature change on module output. STC holds the PV cell at a temperature of 25° C, whereas PTC holds the air temperature around the module at 20 °C and allows the cell to rise to an operating temperature. the calculation of the temperature coefficient requires an assumption of Nominal Operating Cell Temperature, which we assume to be 47 °C, a typical value.

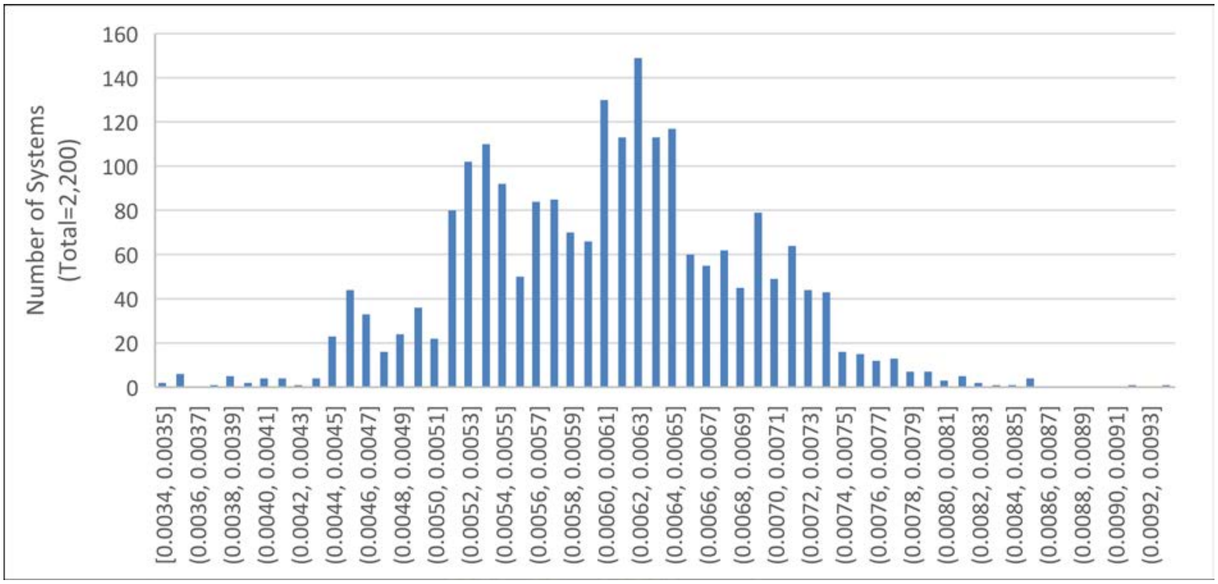

Figure 3. Histogram distribution of power temperature coefficient based on the difference between STC and PTC ratings (units are fraction energy loss per degree Celsius above 25 C)

4.4 Degradation with Age of System

PV system degradation rate, R_d, is often assumed to be 0.6% to 1% per year to unavoidable degradation in the performance of the PV cells themselves (Kurtz et al. 2016). Here we adopt the value 0.6%/year as an assumption on which to normalize performance ratio with system age.

Performance Ratio is calculated over some period of time, the effects of the degradation rate are integrated over multiple years. This integrated effect is the "degr" factor in the equation for adjusted Performance Ratio.

$$degr = \frac{1}{Age}\int_{t1}^{t2}(1-R_d)^t dt = \frac{1}{Age}\left[\frac{(1-R_d)^{Age}}{\ln{(1-R_d)}} - \frac{1}{\ln(1-Rd)}\right] \qquad \text{Equation 1}$$

Where Age = $t_2 - t_1$ in the case where t_2 is the present time. For example, a degradation rate of Rd=0.01 (1%/year) and a time period of 10 years over which Performance Ratio is calculated would result in a degradation factor of degr=0.95. This factor, degr, is calculated based on the age of each system and used in the normalization of PR_{adjusted}, Adjusted Performance Ratio.

A degradation rate is also estimated from the data set by calculating the Performance Ratio adjusted for balance of system efficiency and temperature, and then performing a linear regression analysis to determine what degradation rate best matches the entire data set. In this data set, we observe very little degradation, averaging 0.07%/year. We conclude however, based on the low coefficient of regression between PR and age of R-squared=9E-05, that this data set does not demonstrate a statistically significant reduction in performance based on data within this first 10 years of system age.

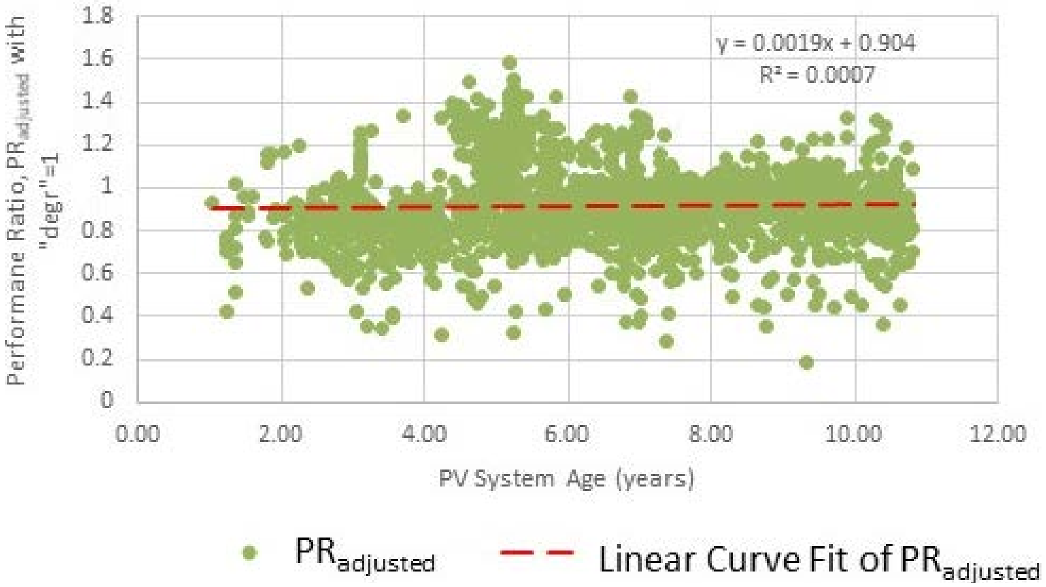

Figure 4. Performance Ratio of older systems is not significantly less than that of new systems in the data set considered here.

5 Coincident Climate Data

5.1 Insolation in Plane of Array

Insolation, also known as irradiation, is the time integral of irradiance. Access to Plane-of-Array (POA) Insolation and temperature data for each site is a feature of the oSPARC platform, in partnership with Clean Power Research which is the original source of the climate data. Each irradiation quantity H corresponding to an irradiance quantity G is calculated by integrating (or summing) the irradiance:

$$H_{POA} = \int_{t=t1}^{t=t2} G_{POA}\, dt \qquad \text{Equation 2}$$

H_{POA} divided by the number of days in the sample duration gives the average daily insolation on the plane of the array, $H_{POA,daily}$. Since H_{POA} varies with the time period that a PV system has been connected to oSPARC (as well as tilt and azimuth from the PV Power Plant Description), $H_{POA,daily}$ is presented in the following figure and table.

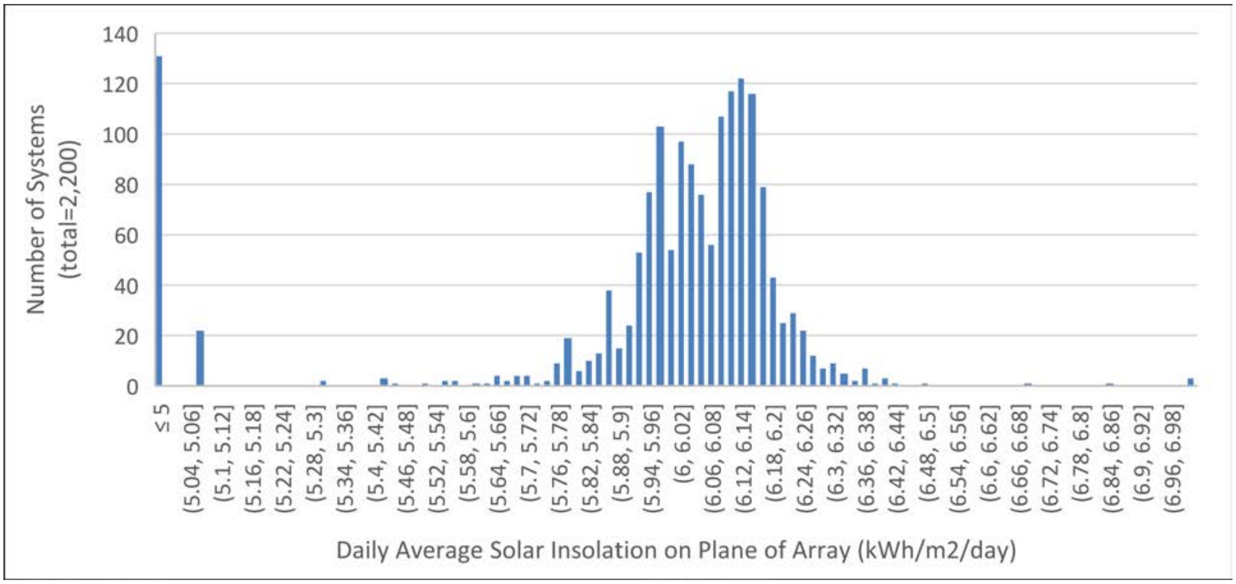

Figure 5. Histogram of $H_{POA,daily}$, daily average solar insolation for each PV System (total=2,200)

Table 3. Average and Standard Deviation of Average Daily Insolation in Plane of Array for all PV Systems (total=2,200)

Average of $H_{POA,daily}$ Average (kWh/m^2/day)	StdDev of $H_{POA,daily}$ Average (kWh/m^2/day)
6.06	1.57

Because the PV system arrays are all in different locations and different orientations (tilt and azimuth angles), this average value of $H_{POA,daily}$ is not used in the calculations to come, rather the solar resource specific to a system location and duration of time (t1 to t2) must be used to calculate the Performance Ratio of each system. The solar resource data is combined with the system description to calculate the reference yield.

5.2 Coincident Temperature

Temperature data are used for the normalization of adjusted Performance Ratio and are associated with each system location over the time period t_1 to t_2. The temperature correction in the calculation of the adjusted performance ratio, $PR_{adjusted}$, improves the R-squared of a linear regression. The R-squared is 0.0007 for Performance Ratio based on Standard Test Conditions and 0.0230 when adjusted for temperature. But both values show that the dependence of Performance Ratio with averaged ambient temperature within the range of 7°C to 19°C measured here is not a strong dependence.

Table 4. Summary of Average Temperatures (°C) at Each Location Provided by the oSPARC Platform

	Average Ambient Temperature (°C) over reporting period
Minimum Avg. Temp (°C)	7.6
Average Temp (°C)	14.2
St Dev of Avg. (°C)	1.6
Maximum Avg. Temp (°C)	19.5

6 Annual Energy Delivery

6.1 AC Energy Production

The AC energy production over the performance period of each system is given by:

$$E_{out} = \int_{t=t1}^{t=t2} P_{out} dt \qquad \text{Equation 3}$$

Where t_1 is the time of the beginning of the performance period when the system was set up in the oSPARC database and t_2 is the end of the period when the data is reported. AC energy production thus varies with system size, solar resource, and duration of the time period that oSPARC has been collecting data from a site. This AC Energy Production is the primary performance parameter recorded by the oSPARC database for each system.

7 Calculation of Performance Ratio

IEC 61724-1:2017 (webstore.iec.ch/publication/33622, accessed 12/6/2018) outlines methods for PV system monitoring, analysis, and performance metrics. Standard IEC 61724 describes alternative definitions of "Performance Ratio," which are based on PV array ratings, and "Performance Indices," which are based on comparison to model results. The performance ratio (PR) is the quotient of the system's final yield to its reference yield. The definition of "reference yield" should be specified explicitly and depends on the power rating used in its definition, because it may or may not normalize for the overall effect of losses on the system output due to array temperature and system component inefficiencies or failures, including balance of system components.

7.1 Reference Yield Based on Standard Test Conditions (STC)

The array DC power rating, P_{STC}, is the total rated DC power output of all installed PV modules at the power rating reference condition, assumed in the standard to be standard test conditions (STCs) or concentrator standard test conditions (CSTCs). P_{STC} is given in units of kW and is added up as the sum of individual PV module rating data from PV module manufacturer datasheets or module labels. In the oSPARC database, the STC rating is entered by a user as the plant description is created. The PR referenced to Standard Test Conditions is given by Equation 4.

$$PR_{STC} = \frac{E_{out} G_{ref}}{P_{STC} H_{POA}} \quad \text{Equation 4}$$

Where G_{ref} = reference value of insolation associated with the STC rating, equal to 1000 W/m^2.

7.2 Reference Yield Based on PV USA Test Conditions (PTC)

Here we consider the PV USA Test Condition (PTC) rating as the reference condition. P_{PTC} is also given in units of kW. STC stipulates a 25°C PV cell temperature, whereas PTC stipulates 20°C air temperature, and the PV cell temperature is allowed to vary, and it is often higher, resulting in a lower PV cell efficiency) than under STC conditions. oSPARC data includes the PTC rating entered by the user for each of the PV power plants, and so we are also able to examine a Performance Ratio based on PTC rating in Equation 5.

$$PR_{PTC} = \frac{E_{out} G_{ref}}{P_{PTC} H_{POA}} \quad \text{Equation 5}$$

7.3 Reference Yield Adjusted for Balance of System Efficiency, Degradation Due to Age, and Temperature

The PTC rating assumes a constant 20°C ambient temperature. In this third version of PR we apply a correction factor, δ, based on average temperature at a location, which enables a comparison of PR across different climates by considering that power production can be expected to be lower at ambient temperature greater than 20°C. Another known source of inefficiency that we can adjust for is the age of the installation and resulting degradation in efficiency, degr. Finally, we can normalize PR with the Balance of System Efficiency (η_{BOS})

entered by the user. The measured power delivered by the inverter (kW) is divided by a calculation based on environmental conditions, degradation, and η_{BOS} by Equation 6.

$$PR_{adusted} = \frac{E_{out}G_{ref}}{P_{PTC}H_{POA}\{\eta_{BOS} * degr * \left(1 - \delta(T_{ambient} - 20°C)\right)\}} \qquad \text{Equation 6}$$

The derivation of this equation involves the concept of Nominal Operating Cell Temperature (NOCT), a constant that cancels out of the equation, but the resulting equation is easy to explain: P_{PTC} accounts for the fact that the array is operating at some elevation in temperature above a 20°C surrounding air temperature, so expected energy delivery is adjusted down if the ambient temperature is greater than 20°C and up if the ambient temperature averages less than 20°C, in the proportion determined by the temperature coefficient.

7.4 Performance Ratio and Balance-of-System Efficiency Combined.

There has long been some confusion regarding what should be assumed in balance of system efficiency and what should be measured in performance ratio. For example, as shown in Table 5 below, default values for PVWatts software include losses in the definition of η_{BOS} that are performance issues rather than system descriptors, such as soiling. Shading and Snow could be considered performance issues or could be treated as environmental parameters in the same way that insolation and temperature affect the expected performance (the denominator of the Performance Ratio).

Table 5. Default values for balance-of-system efficiency factors from the popular PVWatts software [https://pvwatts.nrel.gov/pvwatts.php] show some parameters which cannot be separated from measured performance ratio.

Balance of System Efficency Factor	**Default Value**	**Performance or System Issue?**
Soiling (%):	2%	Performance
Shading (%):	3%	Performance
Snow (%):	0%	Performance
Mismatch (%):	2%	System
Wiring (%):	2%	System & Performance
Connections (%):	0.50%	System & Performance
Light-Induced Degradation (%):	1.50%	System
Nameplate Rating (%): \	1%	System
Age (%):	0%	System
Availability (%):	3%	Performance
Inverter Loss	4%	System
Total Effective ηBOS	**82.5%**	

We propose a fourth version of PR that is similar to the third definition except it is **not** normalized with the Balance of System Efficiency (η_{BOS}), which is entered by the user. By doing this, standard of deviation is reduced as we are negating the impact on PR of the highly variable η_{BOS} entered by the user. So, in Equation 7, we are combining two unknowns into one figure-of-merit and solving for the product of (PR * η_{BOS}).

$$(PR_{adusted} * \eta_{BOS}) = \frac{E_{out}G_{ref}}{P_{PTC}H_{POA}\{degr * (1 - \delta(T_{ambient} - 20°\mathrm{C}))\}} \qquad \text{Equation 7}$$

A histogram comparing the Performance Ratio of these four definitions of Reference Yield is provided in the following Figure 6, and the four values are listed out in Table 6.

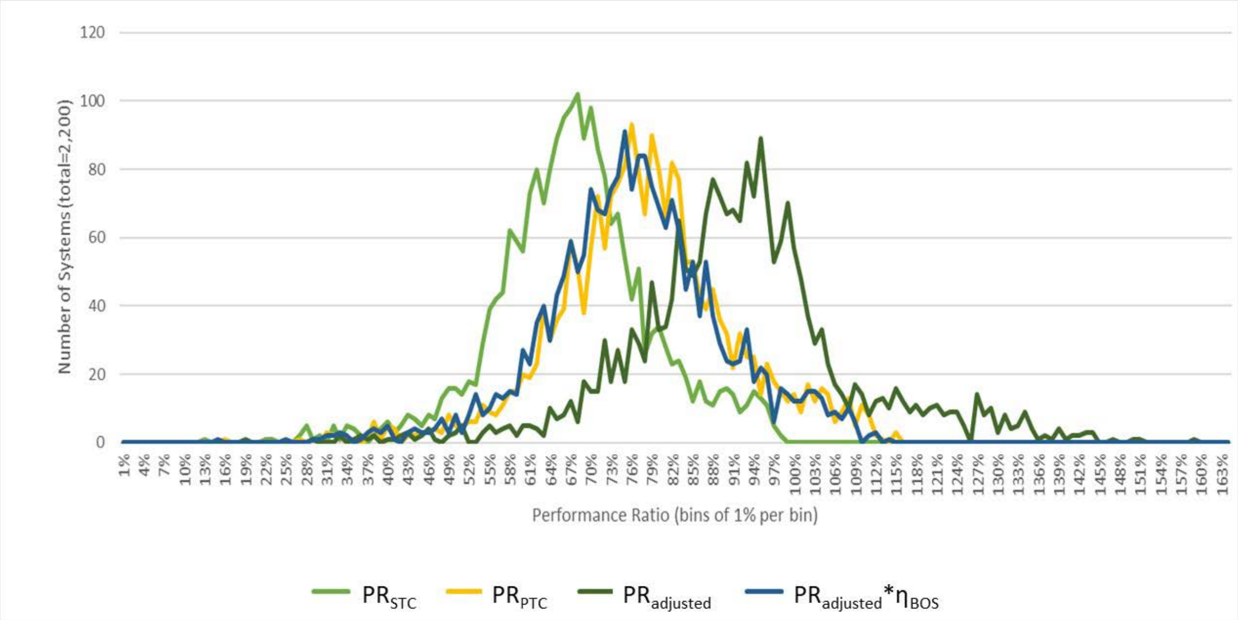

Figure 6. Histogram comparing four definitions of Performance Ratio: 1) PR_{STC} based on Standard Test Conditions 2) PR_{PTC} based on PV USA Test Conditions); 3) $PR_{adusted}$ based on PTC rating and also adjusted for balance-of-system efficiency, degradation due to age, and de-rate based on temperature; and 4) the product of $PR_{adusted}$ and balance of system efficiency ($PR_{adusted} * \eta_{BOS}$) .

Table 6. Comparison of Minimum Values, Average Values and Standard Deviation, and Maximum Values of four Definitions of Performance Ratio: 1. PR_{STC} Based on Standard Test Conditions; 2. PR_{PTC} Based on PV USA Test Conditions; 3. $PR_{adjusted}$ based on PTC Rating Adjusted for Balance-of-System Efficiency, Degradation Due to Age, and De-Rate Based on temperature; and 4. the product of $PR_{adjusted}$* η_{BOS} .

	1. PR_{STC} (Standard Test Condition)	**2. PR_{PTC} (PV USA Test Condition)**	**3. $PR_{adjusted}$ (adjusted for temperature, age and η_{BOS})**	**4. $PR_{adjusted}$* η_{BOS}**
Average	67.0%	77.3%	91.7%	76.0%
Standard Deviation of Avg.	11.5%	13.3%	16.4%	13.1%
Minimum	12.9%	15.3%	18.6%	14.5%
Maximum	97.4%	114.6%	158.8%	113.5%

8 Correlation with Environmental Parameters

The location of these 2,200 PV systems is shown in Figure 7, which also shows land cover type. All sites are in California.

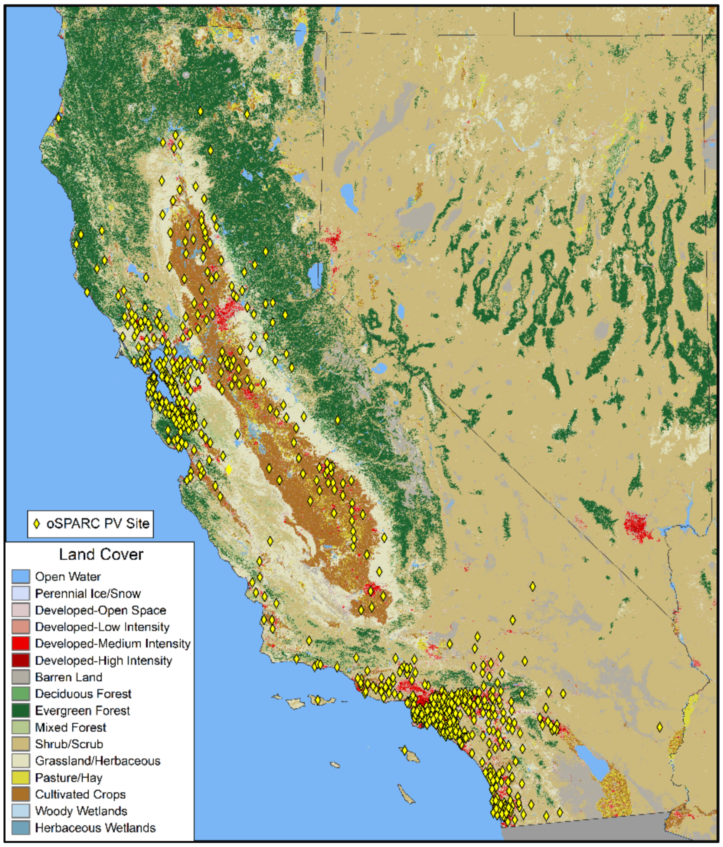

Figure 7. PV power plant locations, all in California, on a map of land cover type

8.1 Site Characteristics

Physical site characteristics were extracted for each site using the centroid of the postal zip code entered by the user into oSPARC. For each location NREL accessed geospatial data sets consisting of 30 m resolution, which is a higher spatial resolution relative to the locational accuracy of the zip code centroid; so extracted values may not truly represent site conditions depending on the diversity of conditions within the zip code area. Sources of geospatial data include: surface elevation (m) (USGS 2002), slope derived from the surface elevation data (%), and 2011 land cover classification (USGS 2014).

8.2 Climate Variables

Climate variables from WorldClim Version 2 (Fick and Hijmans 2017) were extracted for each site, also using the centroid of the reported zip code. The data set represents average monthly climate data for precipitation (mm), wind speed (m/s), and water vapor pressure (kPa) with a nominal spatial resolution of 1 km^2. Precipitation, wind speed, and water vapor pressure values were created using a weighted distribution of the monthly values corresponding to a standard 365-day year.

8.3 Air Quality and Aerosols

Variables related to air quality were extracted for analysis. This includes presence within EPA-designated nonattainment areas for particulates (EPA 2018), proximity to recent fires (2010-2016) (MTBS 2018), and proximity to the ocean. Distance was calculated from the centroid of the site's reported zip code to the edge of the closest fire boundary and to the nearest ocean edge.

8.4 8.4 Correlation

Based on the GIS and oSPARC data, we tried to find out if there was any correlation between these seven parameters and the adjusted performance ratio ($PR_{adjusted}$). We used Tableau software to create the graphs of Figures 8 and 9 and Table 6 below.

Environmental conditions certainly affect PV output, but all the forms of PR adjust for the most important environmental condition, which is sunlight, and "Weather Adjusted Performance Ratio" adjusts the PR value for measured temperature as well. Perhaps because many of the differences in environmental effects manifest as differences in sunlight or temperature (for example an urban rooftop might be warmer than one in a rural location), correlation with the environmental conditions listed in the following table show very low R^2 values and are not a source of actionable information regarding reported PR values.

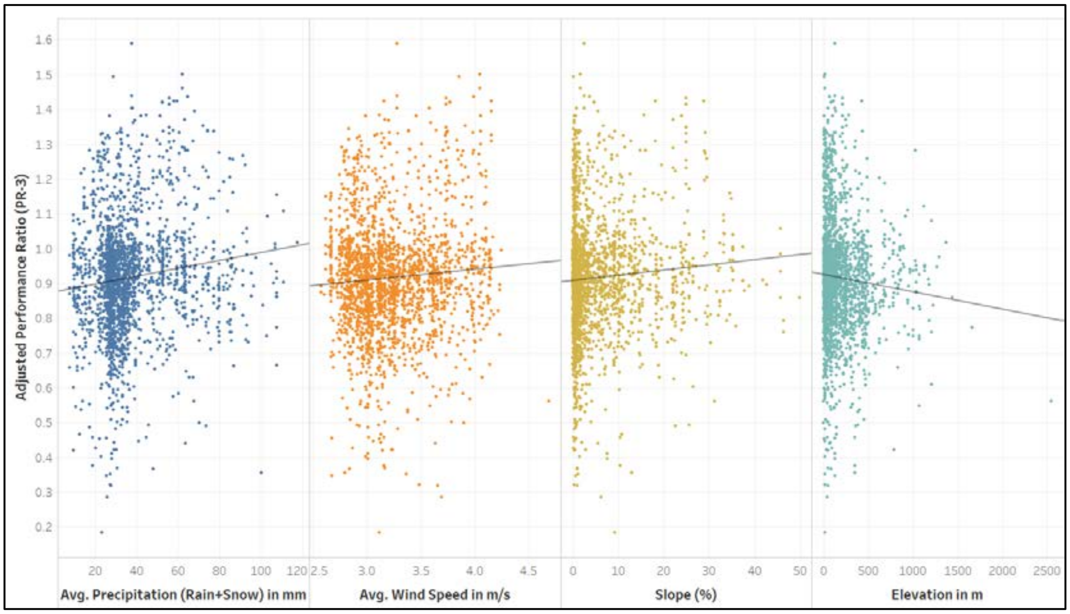

Figure 8. Correlation of parameters with Performance Ratio ($PR_{adjusted}$) to precipitation, wind speed, ground slope, and elevation

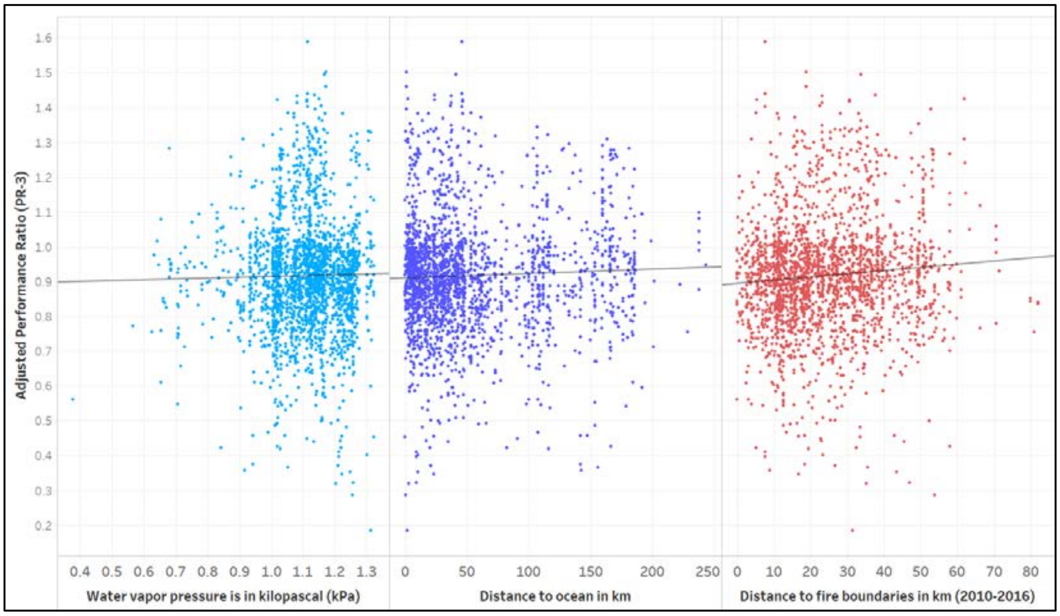

Figure 9. Correlation of parameters with Performance Ratio ($PR_{adjuste}$) to water vapor pressure, distance to ocean, and distance to fire boundaries

Table 7. Summary of the Linear Trend Line Model of Seven Parameters with Performance Ratio ($PR_{adjusted}$)

Parameters		Slope	Intercept	Equation	R- Squared	p -value
Adjusted Performance Ratio (PR-3)	Average Precipitation (Rain+Snow) in mm	0.0011	0.8750	0.0011*Average Precipitation (Rain+Snow) in mm + 0.8750	0.0149	<0.0001
Adjusted Performance Ratio (PR-3)	Average Wind Speed in m/s	0.0312	0.8159	0.0312*Average Wind Speed in m/s + 0.8159	0.0049	0.0010
Adjusted Performance Ratio (PR-3)	Slope (%)	0.0015	0.9085	0.0015*Slope (%) + 0.9085	0.0052	0.0008
Adjusted Performance Ratio (PR-3)	Elevation in m	-0.0005	0.9256	(-)0.0005*Elevation in m + 0.9256	0.0046	0.0016
Adjusted Performance Ratio (PR-3)	Water vapor pressure in kilopascal (kPa)	0.0233	0.8909	0.0233*Water vapor pressure in kilopascal (kPa) + 0.8909	0.0003	0.4332
Adjusted Performance Ratio (PR-3)	Distance to ocean in km	0.0001	0.9101	0.0001*Distance to ocean in km + 0.9101	0.0016	0.0661
Adjusted Performance Ratio (PR-3)	Distance to fire boundaries in km	0.0009	0.8947	0.0009*Distance to fire boundaries in km + 0.8947	0.0064	0.0002

Table 8. Average of Adjusted Performance Ratio ($PR_{adjusted}$) for Areas with Poor Air Quality (PM-10 Nonattainment area) and Good Air Quality (PM-10 Attainment Areas)

	Average Adjusted Performance Ratio ($PR_{adjusted}$)
PM 10 Attainment Areas	0.959
PM 10 Nonattainment Areas	0.869

As Table 7 shows, the R-squared value is low for all seven parameters. Based on that, it can be inferred that there is no correlation of these parameters with the performance ratio ($PR_{adjusted}$) of PV systems for the given set of data. Correlation is shown to be very weak. For some environmental parameters this is to be expected, such as precipitation, water vapor, proximity to wildfires, and elevation, because the use of measured solar resource data for each site factors out this dependence. Much of the dependence on land-use type (dense urban development versus cropland, for example) is reduced by normalizing for temperature. Proximity to the ocean also did not show a perceptible dependence, despite likely soiling by bird populations near the coast, salt air, corrosion, or other factors. An exception is air-quality nonattainment areas, where the measured performance of plants is consistently lower, as shown in Table 8, likely due to particulate matter (PM10), such as diesel soot, exacerbating soiling rate.

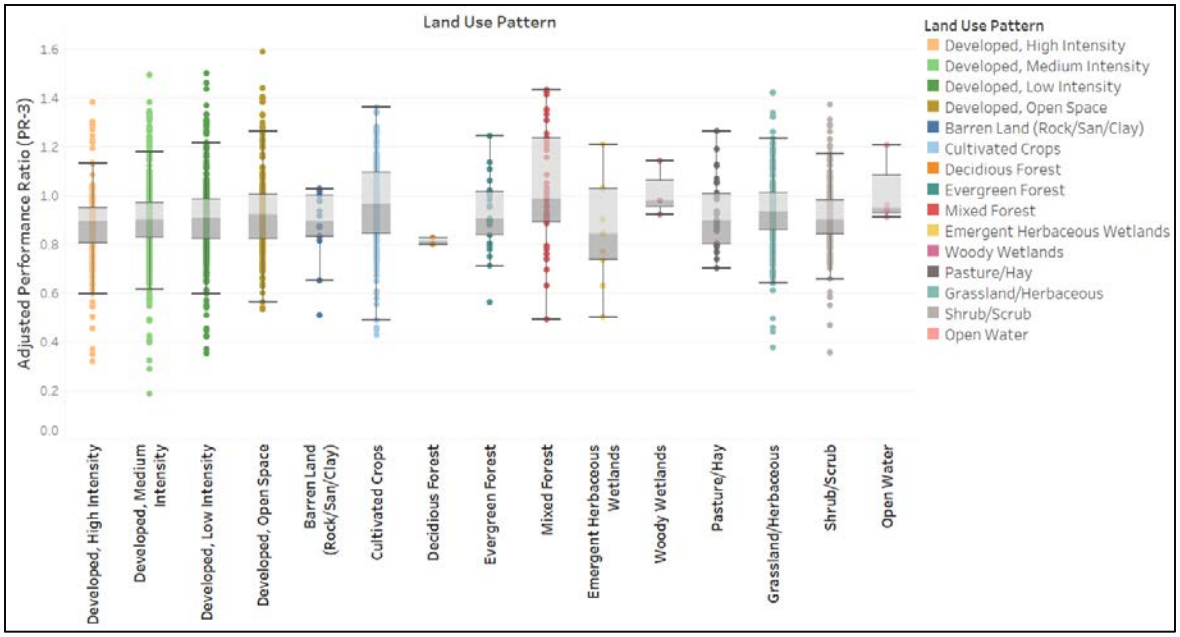

Figure 10. Variation of Performance Ratio ($PR_{adjusted,}$) according to land use type

Table 9. Summary of the Linear Trend Line Model of Seven Parameters with Performance Ratio ($PR_{adjusted}$)

Land Use Pattern	Average Performance Ratio ($PR_{adjusted}$)	Median Performance Ratio ($PR_{adjusted}$)
Developed, High Intensity	0.876	0.894
Developed, Medium Intensity	0.902	0.9
Developed, Low Intensity	0.908	0.908
Developed, Open Space	0.928	0.921
Barren Land (Rock/Sand/Clay)	0.876	0.894
Cultivated Crops	0.962	0.964
Deciduous Forest	0.813	0.813
Evergreen Forest	0.923	0.903
Mixed Forest	1.029	0.985
Emergent Herbaceous Wetlands	0.849	0.842
Woody Wetlands	1.015	0.98
Pasture/Hay	0.923	0.898
Grassland/Herbaceous	0.933	0.936
Shrub/Scrub	0.911	0.901
Open Water	1.003	0.948

As expected, from the above table, average and median performance ratio ($PR_{adjusted}$) decreases from low intensity to high intensity developed land use type. Open space, forest, cropland, wetlands, grassland, and open water have slightly higher PR values that more developed (urban) land use types. The cause of this is not identified but soiling, shading by surrounding buildings, and higher temperatures in urban areas are contributing factors.

9 Conclusions

Production data from a population of 2,200 systems in California as recorded by the oSPARC performance database is presented in terms of Performance Ratio. A comparison of four calculations of Performance Ratio is presented with Reference Yield based on STC (PR_{STC}), based on PTC (PR_{PTC}), based on PTC normalized for temperature, age, and balance-of-system efficiency ($PR_{adjusted}$), and based on PTC normalized for temperature and age multiplied by balance-of-system efficiency ($PR_{adjusted} * \eta_{BOS}$). The range of values in the value of $PR_{adjusted}$, the weather-adjusted Performance Ratio, is greater than the other two with a standard deviation of 16.8%, due to the range of parameters such as balance-of-system efficiency entered by the users of the database. The average value of $PR_{adjusted}$ is 91.7%, after correcting for balance of system efficiency, age, and temperature, which indicates that there is potential to recover about 8.3% of underperformance through optimal operation and maintenance.

All four methods of defining PR are valid if interpreted consistently. By adjusting for actual site temperature, $PR_{adjusted}$ allows a comparison of systems of different ages operating in different temperature climates, and in contrast PR_{STC} and PR_{PTC} would not be accurate for such a comparison. The ideal value of $PR_{adjusted}$ would be 1.0 making it easy to interpret the value, whereas values generated by the other methods must be interpreted in terms of other factors such as η_{BOS}. If η_{BOS} is precisely known, then $PR_{adjusted}$ definition would be apt and if it is unknown then considering the product ($PR_{adjusted} * \eta_{BOS}$) would be advantageous to combine the two otherwise unknown values into one measured parameter.

Correlation with environmental parameters other than sunlight and temperature is shown to be very weak, partly because the dependence on some environmental parameters (precipitation, water vapor, elevation, and proximity to wildfires) is removed by normalizing for measured solar resource and dependence on other parameters (land use type) is removed by normalizing for temperature. Of seven environmental parameters examined, none had a significant correlation with performance after the energy delivery was normalized for measured sunlight and temperature, except for air-quality nonattainment areas, where the measured performance of plants was perceptibly lower, likely due to particulate matter (PM10), such as diesel soot, exacerbating soiling rate.

An important conclusion of this work is that the details of the expected energy performance (the denominator) , such as the user-entered value of η_{BOS}, are just as important as measured performance (the numerator) in the calculation of the numerical value for performance ratio. The oSPARC data results in the highest values of $PR_{adjusted}$ where the users of the databased entered a low factor of (eg 0.6) for expected shading loss, and in reality the shading losses were not that bad.

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