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Standard Test Method for
Reporting Photovoltaic Non-Concentrator System Performance[1]

This standard is issued under the fixed designation E2848; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

~~ᵋ¹ NOTE—Annex A1, Eq A1.5 was corrected editorially in September 2012.~~

1. Scope

1.1 This test method provides measurement and analysis procedures for determining the capacity of a specific photovoltaic system built in a particular place and in operation under natural sunlight.

1.2 This test method is used for the following purposes:

1.2.1 acceptance testing of newly installed photovoltaic systems,

1.2.2 reporting of dc or ac system performance, and

1.2.3 monitoring of photovoltaic system performance.

1.3 This test method should not be used for:

1.3.1 testing of individual photovoltaic modules for comparison to nameplate power ratings,

1.3.2 testing of individual photovoltaic modules or systems for comparison to other photovoltaic modules or systems,

1.3.3 testing of photovoltaic systems for the purpose of comparing the performance of photovoltaic systems located in different places.

1.4 In this test method, photovoltaic system power is reported with respect to a set of reporting conditions (RC) including: solar irradiance in the plane of the modules, ambient temperature, and wind speed (see Section 6). Measurements under a variety of reporting conditions are allowed to facilitate testing and comparison of results.

1.5 This test method assumes that the solar cell temperature is directly influenced by ambient temperature and wind speed; if not the regression results may be less meaningful.

1.6 The capacity measured according to this test method should not be used to make representations about the energy generation capabilities of the system.

1.7 This test method is not applicable to concentrator photovoltaic systems; as an alternative, Test Method E2527 should be considered for such systems.

1.8 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D6176 Practice for Measuring Surface Atmospheric Temperature with Electrical Resistance Temperature Sensors

E772 Terminology of Solar Energy Conversion

E824 Test Method for Transfer of Calibration From Reference to Field Radiometers

E927 Specification for Solar Simulation for Photovoltaic Testing

E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight

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E973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell

E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells

E1040 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells

E1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum

E1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells

E2527 Test Method for Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Systems Under Natural Sunlight

G138 Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

G183 Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers

2.2 *IEEE Standards:*

IEEE 1526-2003 Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems

IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems

2.3 *International Standards Organization Standards:*

ISO/IEC Guide 98-1:2009 Uncertainty of measurement—Part 1: Introduction to the expression of uncertainty in measurement

ISO/IEC Guide 98-3:2008 Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

2.4 *World Meteorological Organization (WMO) Standard:*

WMO-No. 8 Guide to Meteorological Instruments and Methods of Observation, Seventh Ed., 2008

3. Terminology

3.1 *Definitions*—Definitions of terms used in this test method may be found in Terminology E772, IEEE 1547-2003, and ISO/IEC Guide 98-1:2009 and ISO/IEC Guide 98-3:2008.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *averaging interval, n*—the time interval over which data ~~is~~are averaged to obtain one data point. The performance test ~~is performed using~~ uses these averaged data.

3.2.2 *data collection period, n*—the period of time defined by the user of this test method during which system output power, irradiance, ambient temperature, and wind speed are measured and recorded for the purposes of a single regression analysis.

3.2.3 *plane-of-array irradiance, POA, n*—see *solar irradiance, hemispherical* in Tables G173.

3.2.4 *reporting conditions, RC, n*—an agreed-upon set of conditions including the plane-of-array irradiance, ambient temperature, and wind speed conditions to which photovoltaic system performance are reported. The reporting conditions must also state the type of radiometer used to measure the plane-of-array irradiance. In the case where this test method is to be used for acceptance testing of a photovoltaic system or reporting of photovoltaic system performance for contractual purposes, ~~RC~~ RC, or the method that will be used to derive the RC, shall be stated in the contract or agreed upon in writing by the parties to the acceptance testing and reporting prior to the start of the test.

3.2.5 *sampling interval, n*—the elapsed time between scans of the sensors used to measure power, irradiance, ambient temperature and wind speed. Individual data points used for the performance test are averages of the values recorded in these scans. There are multiple sampling intervals in each averaging interval.

3.2.6 *utility grid, n*—see **electric power system** in IEEE 1547-2003.

3.3 *Symbols:* The following symbols and units are used in this test method:

3.3.1 α—reference cell I_{SC} temperature coefficient, $°C^{-1}$

3.3.2 a_1, a_2, a_3, a_4—linear regression coefficients, arbitrary

3.3.3 a, b, c, d—spectral mismatch factor calibration constants, arbitrary

3.3.4 C—reference cell calibration constant, Am^2W^{-1}

3.3.5 C_o—reference cell calibration constant at SRC, Am^2W^{-1}

3.3.6 E—plane-of-array irradiance, W/m^2

3.3.7 E_o ~~RC rating irradiance (plane-of-array),~~irradiance at SRC, plane-of-array, W/m^2

3.3.8 ~~$P=E_o(\lambda)$—photovoltaic system power, ac or~~ reference spectral irradiance distribution, Wm^{-2} ~~dc,~~nm^{-1} ~~W~~

3.3.9 E_{RC}—RC rating irradiance, plane-of-array, W/m^2

3.3.10 ~~P~~E_{oRC}~~=~~(λ)—~~photovoltaic system power~~spectral irradiance distribution at RC, ~~ac~~ Wm^{-2} or nm^{-1} ~~dc, W~~

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3.3.11 ~~T~~$E_{a\overline{T}}$~~(λ)—ambient temperature, °C~~spectral irradiance distribution, test light source, Wm^{-2} nm^{-1}

3.3.12 ~~T~~F~~—~~$_o$~~RC rating temperature, °C~~fractional error in short-circuit current, dimensionless

3.3.13 ~~v~~I_{SC}~~—wind speed, m/s~~short-circuit current, A

3.3.14 ~~v~~M~~—~~$_o$~~RC rating wind speed, m/s~~spectral mismatch factor, dimensionless

3.3.15 p—p-value, ~~a~~ dimensionless quantity used to determine the significance of an individual regression coefficient to the overall rating result

3.3.16 P—photovoltaic system power, ac or dc, W

3.3.17 P_{RC}—photovoltaic system power at RC, ac or dc, W

3.3.18 RC—reporting conditions

3.3.19 $R_R(λ)$—reference cell spectral responsivity, A/W

3.3.20 $R_T(λ)$—test device spectral responsivity, A/W

3.3.21 SRC—standard reporting conditions

3.3.22 SE—standard error, W

3.3.23 T_a—ambient temperature, °C

3.3.24 T_{RC}—RC rating temperature, °C

3.3.25 U_{95}—expanded uncertainty with a 95 % coverage probability of photovoltaic system power at RC, W

3.3.26 λ—wavelength, nm

3.3.27 v—wind speed, m/s

3.3.28 v_{RC}—RC rating wind speed, m/s

4. Summary of Test Method

4.1 Photovoltaic system power, solar irradiance, ambient temperature, and wind speed data are collected over a defined period of time using a data acquisition system.

4.2 Multiple linear regression is then used to fit the collected data to the performance equation (Eq 1) and thereby calculate the regression coefficients a_1, a_2, a_3, and a_4.

$$P = E(a_1 + a_2 E + a_3 T_a + a_4 v) \tag{1}$$

$$P = E(a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot v) \tag{1}$$

4.3 Substitution of the RC values E_o, T_o, and v_o into Eq 1 then gives the ac or dc power at the ~~Reporting Conditions.~~reporting conditions.

$$P_o = E_o(a_1 + a_2 E_o + a_3 T_o + a_4 v_o) \tag{2}$$

$$P_{RC} = E_{RC}(a_1 + a_2 \cdot E_{RC} + a_3 \cdot T_{RC} + a_4 \cdot v_{RC}) \tag{2}$$

4.4 The collected input data and the performance at the reporting conditions are then reported.

5. Significance and Use

5.1 Because there are a number of choices in this test method that depend on different applications and system configurations, it is the responsibility of the user of this test method to specify the details and protocol of an individual system power measurement prior to the beginning of a measurement.

5.2 Unlike device-level measurements that report performance at a fixed device temperature of 25°C, such as Test Methods E1036, this test method uses regression to a reference ambient air temperature.

5.2.1 System power values calculated using this test method are therefore much more indicative of the power a system actually produces compared with reporting performance at a relatively cold device temperature such as 25°C.

5.2.2 Using ambient temperature reduces the complexity of the data acquisition and analysis by avoiding the issues associated with defining and measuring the device temperature of an entire photovoltaic system.

5.2.3 The user of this test method must select the time period over which system data are collected, and the averaging interval for the data collection within the constraints of 8.3.

5.2.4 It is assumed that the system performance does not degrade or change during the data collection time period. This assumption influences the selection of the data collection period because system performance can have seasonal variations.

5.3 The irradiance shall be measured in the plane of the modules under test. If multiple planes exist (particularly in the case of rolling terrain), then the plane or planes in which irradiance measurement will occur must be reported with the test results. In the case where this test method is to be used for acceptance testing of a photovoltaic system or reporting of photovoltaic system

performance for contractual purposes, the plane or planes in which irradiance measurement will occur must be agreed upon by the parties to the test prior to the start of the test.

Note 1—In general, the irradiance measurement should occur in the plane in which the majority of modules are oriented. Placing the measurement device in a plane with a larger tilt than the majority will cause apparent under-performance in the winter and over-performance in the summer.

5.3.1 The linear regression results will be most reliable when the measured irradiance, ambient temperature, and wind speed data during the data collection period are distributed around the reporting conditions. When this is not the case, the reported power will be an extrapolation to the reporting conditions.

5.4 Accumulation of dirt (soiling) on the photovoltaic modules can have a significant impact on the system rating. The user of this test may want to eliminate or quantify the level of soiling on the modules prior to conducting the test.

5.5 Repeated regression calculations on the same system to the same RC and using the same type of irradiance measurement device over successive data collection periods can be used to monitor performance changes as a function of time.

5.6 Capacity determinations are power measurements and are adequate to demonstrate system completeness. However, a single capacity measurement does not provide sufficient information to project the energy generation potential of the system over time. Factors that may affect energy generation over time include: module power degradation, inverter clipping and overloading, shading, backtracking, extreme orientations, and filtering criteria.

6. Reporting Conditions

6.1 The user of this test method shall select ~~an appropriate RC prior to the start of the test.~~ appropriate RC. In the case where this test method is to be used for acceptance testing of a photovoltaic system or reporting of photovoltaic system performance for contractual purposes, the ~~RC~~ RC, or the method that will be used to derive the RC, must be agreed upon by the parties to the ~~test prior to the start of the~~ test.

6.1.1 Reporting conditions may be selected either on the basis of expected conditions or actual conditions during the data collection period. Choose RC irradiance and ambient air temperature values that are representative of the ~~in-plane~~POA irradiance and ambient air temperature ~~expected~~ for the system location for a clear day in the data collection period. ~~Irradiance conditions~~ When the selection is based on expected conditions, irradiance can be evaluated ~~based on~~ from a year-long hourly dataset of projected POA values calculated from historical data measured directly on the system site or at a nearby site. Ambient temperatures can be evaluated by a review of historical data from the site or a nearby location. ~~Reference Conditions~~Reporting conditions should be chosen such that the system is not subject to frequent shading, inverter clipping or other non-linear operation at or around the RC. For instance, in larger photovoltaic systems, the ratio of installed DC capacity to AC inverter capacity may be such that the inverter limits the production of the modules under certain conditions. If this is the case, care should be taken to choose a reference within the normal operating range of the inverters.

Note 2—There are many publicly-available irradiance modeling tools that can be used to develop an hourly year-long dataset for POA irradiance at a project site based on historical global horizontal irradiance data or, if available, from data measured directly at the project site.

Note 3—Historically, a specific case of RC known as "Performance Test Conditions", or "PTC", have been used commonly. PTC conditions use plane-of-array irradiance equal to 1000 W/m^2, ambient temperature equal to 20°C, and wind speed equal to 1 m/s. The PTC parameters were based on the Nominal Terrestrial Environment (NTE) conditions that define the Nominal Operating Cell Temperature (NOCT) of an individual solar cell inside a module (see Annex A1 in Test Methods E1036). However, NTE differs from PTC in that it specifies a lower irradiance of 800 W/m^2.

7. Apparatus

7.1 *Ambient Air Temperature Measurement Equipment*—The instrument or instruments used to measure the ambient air temperature shall have a resolution of at least 0.1°C, and shall have a total error of less than ±1°C of reading. The sensor should be mounted in the immediate vicinity of the photovoltaic system under test, but should not be so close to the modules as to be in the thermal boundary layer of the array. The sensor shall be mounted with an aspirated radiation shield as defined in 3.2.3 of Practice D6176. Practice D6176 contains additional guidance for ambient air temperature measurements.

7.2 *Irradiance Measurement Equipment*—The irradiance measurement equipment shall be mounted coplanar (to within 1 degree) with the photovoltaic system under test and shall be connected to a data acquisition system. The equipment should be mounted in a location that minimizes, and ideally eliminates, shading of and reflections on the instrument.

7.2.1 A calibrated hemispherical pyranometer (instruments with fields-of-view approaching 180°, see Terminology E772) is the most common choice for measurement of the incident solar irradiance. Pyranometers used in this test shall be calibrated using Test Method E824 or Test Method G167. Test Method E E824 is a transfer calibration from a reference to a field pyranometer, while Test Method G167 involves calibration against either of two types of narrow field-of-view pyrheliometers. The uncertainty of the pyranometer calibration is a function of the calibration method, with the Type I calibration in Test Method G167 giving the lowest uncertainty.

7.2.2 Pyranometers are sensitive to both temperature and the angle of incidence of irradiance, so may require measurement of device temperature and angle of incidence during the data collection period. It is recommended that pyranometer responsivity be characterized to the extent practicable. Sections 5.5, 5.5.1, 5.5.2, and 5.5.3 in Practice G183, describes pyranometer characteristics which influence the level of uncertainty in solar radiation data and should be considered.

7.2.3 *Optional*—A calibrated photovoltaic reference device may be used in place of a pyranometer if it is mutually agreed by the parties to the test prior to the start of the test.

7.2.3.1 Annex A1 and Annex A2 present information and procedures related to the use of photovoltaic reference devices as radiometers. It is strongly recommended that these procedures be used if a photovoltaic reference device is chosen. Use of photovoltaic reference devices can significantly reduce uncertainty in the overall test result when they are calibrated with respect to the RC. This type of calibration introduces complexity (and therefore cost) to the test. The additional complexity and cost is justified for large-scale commercial and utility-scale photovoltaic plants, but will not be economically feasible for small commercial or residential installations. While the test may be carried out with a photovoltaic reference device without executing the corrections described in Annex A1 and Annex A2, it is critical that the user understand the information presented in them. If a photovoltaic reference device is used without applying the procedures for spectral correction, the test report must clearly state that the test result includes uncertainty of an unknown magnitude due to spectral mismatch in addition to the reported uncertainty.

7.2.3.2 Reference devices used in this test shall be primary or secondary reference devices as defined in Terminology E772. If the in-situ calibration procedure outlined in Annex A2 is not employed, the reference device must be calibrated according to Test Method E1362 using the hemispherical spectral irradiance distribution in Tables G173.

7.2.3.3 Recommended physical characteristics of photovoltaic reference devices are available in Specification E1040.

7.2.3.4 Note that the calibration values of photovoltaic reference devices are temperature-sensitive and require measurement of the reference device's temperature during the data collection period. Reference devices that adhere to Specification E1040 must have a temperature sensor.

7.3 *Wind Speed Measurement Equipment*—The instrument used to measure the wind speed shall have an uncertainty of less than 0.5 m/s, and should be mounted in the immediate vicinity of the system under test. Because of the many possible system configurations, care should be taken to minimize effects on the instrument readings from the system or nearby obstacles. Averaging readings from multiple instruments for large systems may be required.

7.3.1 Ultrasonic wind speed instruments are preferred because they do not have the dead band between 0 and 0.5 m/s in which mechanical cup-based wind speed instruments are unable to rotate.

7.4 *Power Measurement Equipment, ac*—System ac power is typically measured at the point of interconnection, however, the measurement point can be any point specified by the users of this test. The measurement point shall be specified and agreed to prior to the start of the test. AC power shall be measured with a total uncertainty of ± 1.5 % or less of the expected power value at RC.

7.5 *Power Measurement Equipment, dc*—System dc power is typically measured at the input of the inverter or other power conditioning units using calibrated shunt resistors and voltage dividers. IEEE 1526-2003 and Test Method E1036 shall be used to specify dc current and voltage measurements on photovoltaic systems.

8. Procedure

8.1 Connect the required instrumentation for the photovoltaic system under test to the data acquisition system.

8.2 For each averaging interval, measure and record the average system power, solar irradiance, ambient temperature, and wind speed over the interval.

8.3 Continue data acquisition until the end of the data collection period. This will constitute one complete data set. The data collection period shall be at least three (3) days and at most four (4) weeks. The default data averaging interval is 15 min. Data is collected until a minimum of 50 data points (averaging intervals, post filtering) are available for the regression. The data set shall include data from at least three separate days. If sufficient data is not collected in 4 weeks, then begin using a 4-week "moving window". For example, if the original test start date is January 1 and data collection begins on January 1, and by January 28, there are not 50 data points available for the regression, then adjust the start of the data collection period to January 2 and continue collecting data through January 29, and so on.

NOTE 4—50 data points using 15-min averaging intervals represents approximately 12.5 h of system operating time. If smaller averaging intervals are used, the minimum data point requirement may be increased. For example, if 5-min averaging intervals are used, then 150 data points would be needed to represent the same number of system operating hours.

8.3.1 The data collection period shall be chosen to ensure that all criteria described in 8.3 are met after excluding data per the data selection guidelines outlined in 9.1.

9. Calculation of Results

9.1 *Selection of Data:*

9.1.1 The following filter criteria (described further in 9.1.2 through 9.1.10) should be applied to the data set in the following order:

9.1.1.1 Visual examination (9.1.2)

9.1.1.2 Preliminary regression (9.1.3)

9.1.1.3 Missing data (9.1.4)

9.1.1.4 DAS equipment malfunction (see 9.1.5)

9.1.1.5 Irradiance outside of range (9.1.6)

9.1.1.6 Unstable conditions (optional, see 9.1.7)

9.1.1.7 Inverter not peak power point tracking (see 9.1.8)

9.1.1.8 Obscuration of the system or radiometer by shading (see 9.1.9)

9.1.1.9 Radiometer not co-planar with system under test (see 9.1.10)

9.1.2 *Visual Examination*—Most data that will be filtered out based on the filter criteria above can be quickly recognized using a simple visualization. Make a graphical plot of the output power versus irradiance for the entire data set. For systems that have power conditioning units that perform maximum power point tracking, such as inverters, this plot should have a linear relation between power and irradiance. Points that appear as outliers on this plot should be investigated and excluded if they are found to not meet the filter criteria. Additionally, nonlinear power-irradiance characteristics should be investigated; a common cause is an inverter that begins to malfunction at some time during the data collection period. Plots with two or more distinct lines can be the result of power losses. Irradiance measurement instruments that are not mounted coplanar with the system under test will split the power-irradiance relationship into double concave and convex curves between morning and afternoon data. Suspect data shall be investigated to find the root cause, and shall be excluded if they do not meet the filter criteria.

9.1.3 *Preliminary Regression*—Another method to quickly identify data that may be excluded is to perform a preliminary regression and search for statistical outliers. After computing the regression coefficients per 9.2, evaluate Eq 1 for each averaging interval and calculate the residual between the measured power and the power computed using the regression coefficients in Eq 1. Averaging intervals for which the residual exceeds two standard deviations of the mean residual should be investigated and may be excluded if they do not meet the filter criteria.

9.1.4 *Missing Data*—If any of the four regression parameters (power, plane-of-array irradiance, ambient temperature, or wind speed) are missing for an averaging interval, all data for this averaging interval shall be excluded.

9.1.5 *DAS Equipment Malfunction*—If any of the four regression parameters (power, plane-of-array irradiance, ambient temperature, or wind speed) is affected by a DAS recording error or sensor equipment malfunction, all data for this averaging interval shall be excluded. If more than a few averaging intervals in a data collection period are affected by DAS errors or equipment malfunctions, it is recommended that the sensing apparatus be investigated prior to proceeding with the test.

9.1.6 *Irradiance Outside of Range*—Select a range of irradiance values over which the regression will be performed, and exclude data outside of this range. Ranges of $E_{\omega RC} \pm 20\,\%$ have been shown to give reliable results. Larger ranges may be selected if the test is performed during a season in which the range $E_{\omega RC} \pm 20\,\%$ will yield an insufficient number of data points or will eliminate too many days from the data set. In general, a range that allows for a data set with 100 or more data points is preferred. Larger ranges (up to $E_{\omega RC} \pm 50\,\%$) may also be selected if data are limited to periods with stable sky conditions (see 9.1.7).

9.1.7 *Unstable Conditions (optional)*—When climate and season allow, limiting the selection of data to periods of clear, stable sky conditions is recommended. Selecting data exclusively from clear-sky periods will reduce the scatter in the regression significantly, reducing the statistical uncertainty in the regression result.[3] As with selection of an irradiance range, excluding data during unstable conditions can reduce the data set to too few data points or too few days. Stability criteria may be relaxed if they prove too stringent for the data collection period or climate. Limiting data to clear, stable sky conditions can be accomplished using one of the following techniques:

9.1.7.1 *Statistical Technique*—Calculate the mean and standard deviation of sampling intervals for each averaging interval (data point) in the data collection period. Next, compute the standard deviation as a percentage of the mean. For instance, if the data sampling interval is 5 s and the averaging interval is 5 min, compute the standard deviation of each of the 60 sampled points and compare it to the mean of those 60 points. This percent standard deviation for each period can then be used to assess operating stability and formulate data exclusion criteria. Typical maximum allowable values are on the order of 2 to 4 %.

9.1.7.2 *Visual Technique*—Alternately, make a graphical plot of the output power and irradiance versus time for the entire data set. Visually inspect the plot to identify days with little to no cloud cover, where irradiance changes relatively slowly throughout

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[3] Kimber, et al, Improved Test Method to Verify the Power Rating of a Phtovoltaic (photovoltaic) Project, Proceedings of the 34th IEEE Photovoltaic Specialists Conference, Philadelphia, PA, USA, June 7-12, 2009.
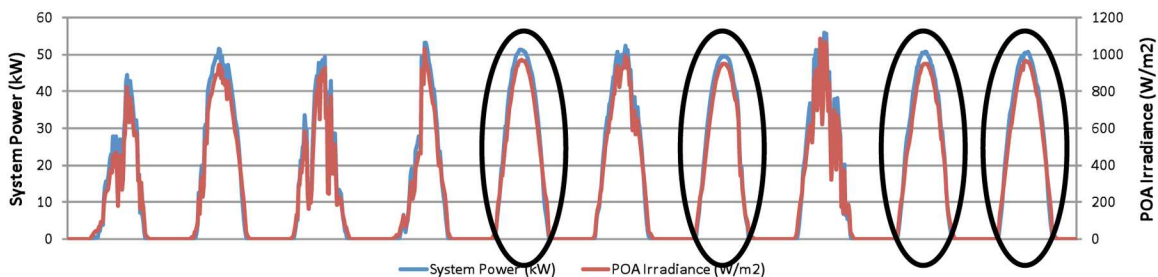

FIG. 1 Example Plot of Irradiance and System Power as a Function of Time, with Preferable Days Circled