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PV Capacity Evaluation Using ASTM E2848: Techniques for Accuracy and Reliability in Bifacial Systems

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Abstract

A variety of test methodologies are commonly used to assess if a photovoltaic system can perform in line with expectations generated by a computer simulation. One of the commonly used methodologies across the PV industry is an ASTM E2848. ASTM E2848-13, 2023 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. This test method is mainly used for acceptance testing of newly installed photovoltaic systems, reporting of DC or AC system performance, and monitoring of photovoltaic system performance. The purpose of the PV Capacity Test and modeled energy test is to verify that the integrated system formed from all components of the PV Project has a production capacity that achieves the Guaranteed Capacity and the Guaranteed modeled AEP under measured weather conditions that occur when each PV Capacity Test is conducted. In this paper, we will be discussing ASTM E2848 PV Capacity test plan purpose and scope, methodology, Selection of reporting conditions (RC), data requirements, calculation of results, reporting, challenges, acceptance criteria on pass/fail test results, Cure period, and Sole remedy for EPC contractors for bifacial irradiance.

Keywords

Photovoltaic System Capacity, ASTM E2848, Bifacial PV Modules, PV Capacity Testing, PVSyst Simulation, Solar Energy Performance, Regression Modeling

1. Introduction

A linear regression method for characterizing the output of a solar system was developed in the 1990s under the Photovoltaics for Utility Scale Applications (PVUSA) program in California. It has been adopted as a standard by the American Society for Testing Materials (ASTM) (E2848). The method calculates coefficients of performance using linear regression to fit the measured power output to a function of the measured irradiance, ambient temperature, and wind speed. This is a simple approach, but it tends to have higher uncertainty (greater weather dependence) than IEC 61724-2, especially if the reference test condition requires extrapolation. ASTM developed a methodology for identifying the test conditions in such a way as to avoid extrapolations. This improves the accuracy of the application of the ASTM approach but requires the definition of multiple test conditions to prepare for tests that might occur at different times of the year, complicating the initial contract.

Many of the standards for testing solar energy generation are based on foundational work performed at the National Renewable Energy Laboratory (NREL). Much of the data that is used to locate solar fields has been gathered and organized into searchable databases. ASTM is also currently working on a standard for determining reference conditions and the expected capacity of non-concentrating PV systems, which will augment E2848, and the standard will provide guidance on using historical data to determine reference conditions.

The Test Method E2848 procedure involves a multiple linear regression of output power as a function of plane-of-array irradiance, ambient air temperature, and wind speed data collected during the data collection period, which is a relatively short time period, typically between three and 30 days. Using the regression results, the expected capacity (in watts) is then calculated by substitution of a set of reporting conditions consisting of plane-of-array irradiance, ambient air temperature, and wind speed appropriate for the system under test into the regression equation.

The simulated power output that is used to calculate the expected capacity should be derived from a performance model designed to represent the photovoltaic system which will be reported per Test Method E2848.

The advantage of using historical data to calculate reporting conditions is that the reporting conditions and associated expected capacity can be calculated in advance of the construction of a project. This is beneficial when this practice and Test Method E2848 are used for the purpose of acceptance testing. The disadvantage of using historical data for calculating reporting conditions is that actual meteorological conditions during the test may differ from historical conditions. This may increase uncertainty in the comparison of expected capacity to capacity measured per Test Method E2848.

The procedure for the PV Capacity Test of the standard linear model specified in ASTM-2848-13 to identify power production at the specified conditions based on the performance of a horizontal single-axis (north-south) tracker PV system incorporating bifacial PV module technology.

This Capacity Test is based on ASTM E2848 but incorporates considerations for bifacial modules. PRC is the actual power measured at the Reporting

Conditions (RC). PMIN is the guaranteed power at RC. Pass/fail: PRC/PMIN *100 greater than or equal to 97% (depends on the calculation of test uncertainty). PRC is determined from filtered on-site data (5 min or 1 min), running multiple regression, and calculating from the resulting equation with its coefficients at RC. PMIN is determined by running PVSyst with site weather data (1 hr, averaged from site data) or, if not available from another source such as Solar Anywhere, filtering, running regression, and calculating at RC, and it is determined from site data.

The contractual Model is an extensive model of plant performance across all anticipated operating conditions that were used to produce the Pro Forma 8760 Dataset. The Contractual Model consists of the technical model and the inputs and assumptions (including meteorological data) used to evaluate the technical model. The hourly energy simulation tool, PVSyst, has been selected for use as the technical model for this Agreement. The inputs and assumptions used to evaluate the technical model of the Facility to produce the Pro Forma 8760 Dataset from the PVSyst report. The inputs, assumption, and model may be amended to reflect the design and construction of the Facility and shall exclude soiling, snow losses, and unavailability.

"Guaranteed Capacity" is the guaranteed AC capacity of the Facility. The Guaranteed Capacity is determined by performing the regression presented in Section 2 of ASTM E2848-13 on a sub-set of the Pro Forma 8760 Dataset data, as described in Section 3 of this test requirement. Guaranteed Capacity is determined by multiplying the Predicted Capacity by (1 - Capacity Test Tolerance).

The economic feasibility of solar PV has seen remarkable improvements due to ongoing technological advancements. According to the National Renewable Energy Laboratory (NREL), the levelized cost of energy from solar PV has significantly decreased, from about 10 units in 2015 to approximately 3 units in 2018. Despite these advancements, challenges such as the limited efficiency of solar cells and their comparative reliability issues against fossil fuels remain. However, the long-term benefits are undeniable. For example, a 3 kW solar PV system, though initially expensive, can achieve a return on investment within three to four years. Post this period, the system generates significantly more energy than the initial investment, thanks to the solar panels' 25-year lifespan [1]-[3].

2. PV Capacity Test Plan

No less than 45 days prior to the first day of the PV Capacity Test Measurement Period, a proposed PV Capacity Test Plan shall be submitted to the Owners' Representative by the Contractor for Owners' Representative review and comment. The PV Capacity Test Plan shall include (at a minimum) the following information:

- The test procedure
- The Project Model
  - For the purposes of the PV Capacity Test, the Project Model shall assume

fixed agreed-upon soiling losses, zero unavailability, and module degradation in accordance with the agreed-upon Project Model.

- Proposed maximum soiling losses and with supporting details (e.g., soiling station analysis (if available), date of proposed module cleaning prior to Test, etc.)
- Proposed module degradation
- Identification of the PV Project under test
  - Number and make/model of PV modules
  - Array orientation
  - Location (latitude, longitude, street address)
- Identification of interested parties, including contact information.
- The anticipated starting and ending dates of the PV Capacity Test Measurement Period.
- Identification of all sensors and transducers to be used, including cut sheets, calibration records, and map of sensor locations with sufficient detail to allow observers to locate the sensors and transducers. This includes sensors required for all applicable Input Parameters (MET station sensors, inverters, and Revenue Meter).
- Identification of SCADA nomenclature for data channels, and any SCADA calibration parameters (default or custom) for those data channels
- Identification of sensors intended for Redundant Measurement
- Identification of Multiple Measurement formulas and weighting factors
- The minimum number of redundant measurements needed to form a valid reading
- Identification of SCADA data channels intended for use as auxiliary parameter
- Identification of known data quality concerns, such as time intervals when direct inter-row shading may be expected to occur
- Time-stamp convention and data logger averaging technique/interval to be used in reporting data
- Identification of the Project Model, including software name and version, all input assumptions, hourly output data, and summary results, any post-processing steps needed to obtain final power estimates at the Revenue Meter, and description of how electronic files are stored in escrow (for example all PVsyst PRJ and VC files needed to simulate annual energy) [4] [5].

3. ASTM Target Test Methodology

3.1. Step 1—Gather Inputs-Data Collection

To avoid delays in conducting your test, be sure you prepare the proper items for a test. The following are the prerequisites for conducting this test:

- A valid PVSYST model.
- Experience in regression modeling and a working test sheet.
- A properly operating system, with functioning equipment and calibrated weather stations.
- A minimum of 5 - 7 days of system operation to gather data, this is also heavily

dependent on weather conditions.

3.2. Step 2—Export Data

Take the inputs and prepare the data for analysis:

- Take the PVSYST model and extract annual raw data. The raw data should include Global Horizontal (GHI) irradiance, ambient temperature, wind speed, all correction factors relevant to calculating plane of array (POA) irradiance, and a time/date stamp for each set of data points.
- Export climate and performance data from your data acquisition system. This raw data should include the date/time stamp, production meter, temperature, wind speed, and plane of array (POA) irradiance.
- Review the system's mechanical and electrical drawings. This will help the user determine if there are any peculiar issues that would impact the modeling, such as shading or severe inverter clipping.

3.3. Step 3—Filter the Data for Quality

The most complicated aspect of the test is the sorting of the data to exclude low-quality or erroneous points. The data shall be filtered such that the minimum data requirements for site data are:

- 50 - 15-minute data points or 750 minutes of data.
- Exclude data below 400 w/m^2 and at least above 98% nameplate capacity of the inverter.
- Reporting condition POA should be sorted in a ±20% range.
- There are technically no sorting requirements or limits for temperature or wind, but exclusions can be applied if they do not correlate with the performance.

3.4. Step 4—Run the Regression

The regression model is run to find the power capacity and the standard error of the regression measurements. If the ratio of power measured/power modeled is greater than 95%, and all regression errors are less than 5%, you have a valid test with a passing result!

If you are not getting satisfactory results, the most common pitfalls are:

- Depending on system design and season, it may take a month or longer to gather the required 50 valid data points that meet the test quality requirements.
- The test requires raw data from a PVSYST model that can provide the hourly requirements identified above. The summary pdf report from PVSYST is not enough for this.
- Not running a proper regression. Even though the ASTM standard spells out the methods, it doesn't provide the tools to run the analysis. It is typical to have an improper setup in the calculations the first time this test is attempted.
- Poorly calibrated sensors. Since the test is only as good as the accuracy of your measurement, it is critical to have the sensors properly calibrated prior to

gathering data [6] [7].

4. ASTM Measured Selection of Reporting Conditions (RC)

1) Data collected in accordance with the above shall be used to determine the reporting conditions, per the following procedure. A unique set of reporting conditions shall be determined for the fixed-tilt and tracking portions of the plant, according to this procedure.

2) For the Plane-of-Array (POA) Irradiance measurements, the data recorded from multiple pyranometers will be averaged for each time interval for both the tracking and fixed tilt portions of the system.

i) The calculation for the tracking RC shall use the data from the POA sensors mounted to the trackers, and the fixed RC shall use the data from the POA sensors mounted to the fixed racking.

ii) In the event that data from one of the pyranometers is excluded due to malfunction or sensor discrepancy, the data from the un-excluded pyranometers shall be averaged (in the case of malfunctions), or the data from all the pyranometers may be excluded (in the case of sensor discrepancy out of range of sensor accuracy).

3) The collected data set shall be filtered according to the following operations:

i) The procedure described per section 9.1 of ASTM E2848-13 will be followed, with the exception of section 9.1.6, "Irradiance Outside of Range". All data identified by the applied filters shall be excluded.

ii) Any test data points in which the power output of an inverter is recorded to be greater than 100% of the inverter's maximum output shall also be excluded.

iii) Data points affected due to snow or frost coverage of the Modules shall be excluded if one or both of the following apply:

- A snow depth sensor, other measurement equipment, or a visual inspection supported by photographic data.
- There is a significant difference between actual and expected output, based on statistical means or engineering judgment.

iv) After filtering, the resultant data set shall be used to determine the reference irradiance (Irr_0) for the reporting conditions.

4) In order to determine the Irr_0, the test data shall be sorted according to POA irradiance from highest to lowest, and examined to determine the highest POA irradiance value for which there is a nearly equal distribution of data points in the range of the selected POA irradiance ± 20%. This irradiance shall be considered Irr_0.

5) There shall be no more than a 40%/60% spread in the irradiance distribution, *i.e.*, no more than 40% of irradiance data above Irr_0 and 60% of irradiance data below Irr_0, or vice versa.

6) All test data where the irradiance is outside of the range of Irr_0 plus or minus the irradiance band (Irr_0 ± 20%) shall be excluded.

7) The minimum value for consideration as the Irr_0 will be calculated by

dividing the following Equation (1):

$$Irr_{min} = \frac{400\ \text{W/m}^2}{1 - Irr_{band}} = \frac{400\ \text{W/m}^2}{1 - 0.2} = 500\ \text{W/m}^2 \tag{1}$$

where:

Irr_{min} is the minimum value for Irr_0.

Irr_{band} is the size of half the irradiance band expressed as a number, so a band of ±20% would mean $Irr_{band} = 0.2$.

All irradiance values less than Irr_{min} shall be excluded from consideration as the Irr_0. A value of 300 W/m^2 may be used in place of 400 W/m^2 if more data points are required, as shown below.

i) The maximum irradiance value for consideration of the Irr_0 shall be determined by the following Equation (2):

$$Irr_{max} = \frac{Irr_{high}}{1 + Irr_{band}} \tag{2}$$

where:

Irr_{max} is the maximum value for Irr_0.

Irr_{high} is the highest irradiance value of the collected and filtered data set

All irradiance values greater than Irr_{high} shall be excluded from consideration as the Irr_0.

8) The filtered measurement data shall be defined as the resulting data set, and it shall have a minimum of five hundred (500) data points.

i) The five hundred (500) or more data points are under the assumption of a one-minute data interval.

ii) If the filtered data set does not contain enough data, then the Test Period will be shifted per ASTM 2848-13 section 8.3.

iii) At the agreement of the Contractor and Owner, the irradiance band in section (iv) above may be increased (not to exceed Irr_0 ± 40%) or reduced (not less than Irr_0 ± 15%), in order to obtain a necessary and reasonable number of data points.

iv) All data points with irradiance less than 400 W/m^2 (or 300 W/m^2 if more data points are needed) shall be excluded.

9) The average ambient temperature of the Filtered Measurement Data shall be calculated. This average ambient temperature shall be the reference temperature T_0. This T_0 may be different for the fixed and tracking systems.

10) The average wind speed of the Filtered Measurement Data shall be calculated. This average wind speed shall be the reference wind speed WS_0. This WS_0 may be different for the fixed and tracking systems.

k) We use various formulations to calculate Irradiance (G) and Power (P) to test the different rear irradiance instrumentation methods. Details of these formulations are listed in **Table 1**, and the ASTM approach is further illustrated in **Figure 1**.

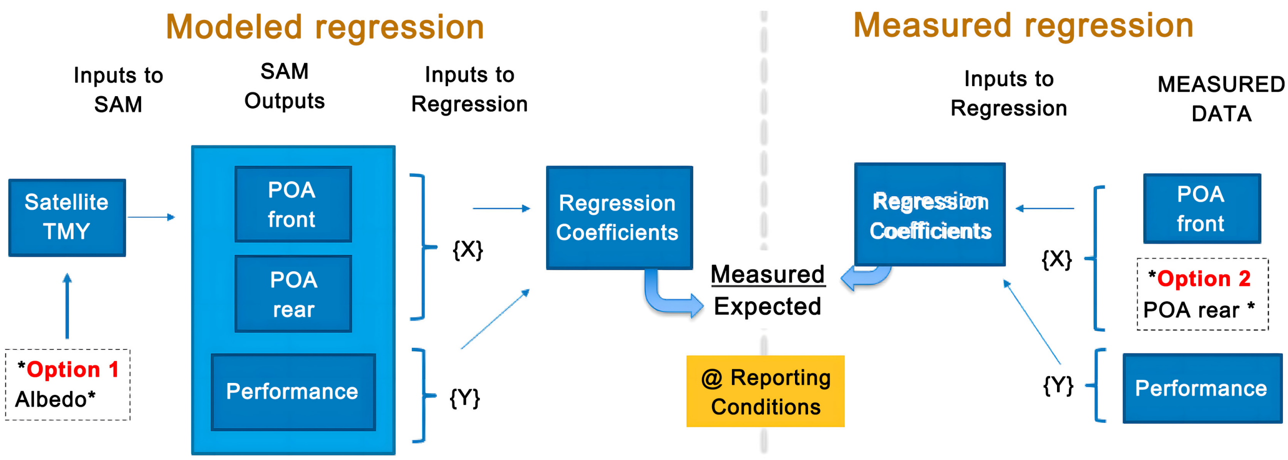

Figure 1. Flowchart diagram of the ASTM E2848 capacity test analysis.

Table 1. ASTM E2848 capacity test input variables for each method.

Method	Modeled Regression (Hourly average)		Measured Regression (15-min average)		Reporting Condition
	G Irradiance	P Power	G Irradiance	P Power	
Baseline (monofacial and bifacial)	G_{front} modeled based on historical weather data (NSRDB 2020), using DNI, DHI, albedo	Modeled power, from System Advisor Model (SAM), using historical weather data	Measured G_{front}	Measured power	Determined by PV CapTest defaults, based on ASTM E2939: 60th percentile of measured irradiance
1	G_{front} modeled based on field-measured GHI, albedo, and DHI	Modeled power, from SAM bifacial model with hourly field-measured albedo			
2A	G_{total} modeled from G_{front} and G_{rear}, where $G_{total} = G_{front} + \Phi * G_{rear}$ Based on historical DNI, DHI, and albedo weather data	Modeled power, from SAM bifacial model	G_{total} = measured front $G_{front} + \Phi * G_{rear}$	Measured power	
2B			G_{total} = measured G_{total} with reference module, calibrated		

4.1. Minimum Power Rating (P_{min})

1) The PV Simulation Model, as derived from PVsyst simulations, shall be used to establish the Facility's expected annual energy output as measured by the inverters and confirmed by the revenue meter.

i) The owner and Contractor shall agree on all inputs to PVsyst for the creation of the PV Simulation Model, including (but not limited to) losses, weather data files, and component model files.

2) The PV Simulation Model shall include separate outputs for the fixed and tracking portions of the plant.

3) Each of the PV Simulation Model outputs shall include, as a minimum, the following columns in the respective output .csv files (or 8760 files):

i) Date & Time (formatted with Month; Day; Hour in separate columns)

ii) POA Irradiance (GlobInc, W/m^2)

iii) Horizontal Irradiance (GlobHor, W/m^2).

iv) Ambient Temperature (T Amb, ˚C)

v) Wind Speed (WindVel, m/s).

vi) Near Shadings Beam Loss (ShdBLss, W/m^2)

vii) Inverter Loss Due to Low Voltage Maximum Power Point (MPP) Window (IL Vsmin, kW)

viii) Inverter Loss Due to Power Limitation (*i.e.* "clipping" loss) (IL Pmax, kW)

ix) Available Energy at Inverter Output (EOutInv, kW)

x) Energy Injected into Grid (E_Grid, kW)

4) For the purposes of this procedure, the Target Period shall mean the 90-day period extending an equal number of days prior to and after the Test Period. For example, if the Test Period is May 1-6, then the Target Period will be March 17-June 17. The Test Period may be concurrent for the fixed and tracking portions of the site.

5) The Minimum Power Rating ($P_{\min}$) at the Reporting Conditions shall be determined from the PV Simulation Model for each of the portions of the site in accordance with the following:

i) Filter the 8760 file for the plant to only include data within the 90-day Target Period.

ii) Apply the following filters to the resulting 90-day data file:

- Exclude any data points with beam shading values ShdBLss > 0.
- Exclude any data points where the inverter is not in 'Peak Power Point Tracking' mode, as such term is defined in section 9.1.8 of ASTM E2848-13.
- Exclude any data with irradiance values outside of the range established.
- Data points with POA irradiance < 400 W/m^2 (or 300 W/m^2, whatever is consistent with previous sections).

iii) After filtering, the resulting dataset shall have 50 or more data points.

- If less than 50 data points remain in the set, then the Test Period shall be shifted and a new Target Period shall be selected.

For the filtered Target Period dataset, a regression analysis shall be performed on the POA irradiance, ambient temperature, wind speed, and energy at the inverter output. The regression analysis shall be used to determine the regression coefficients in Equation (3).

$$P_{RCE} = \left(E + Eb\right)\left(a_1 + a_2\left(E + Eb\right) + a_3 T_a + a_4 v\right) \quad (3)$$

where:

a_1, a_2, a_3, and a_4 are the model coefficients,

Reporting conditions E is the POA,

Eb is the Back POA x bifaciality factor,

T_a is the temperature and

v is the wind velocity.

If all four model coefficients vary in the regression, the p-value for a_4 can exceed 0.05, indicating the influence of wind speed and poor statistical significance. In such case, the regression will be repeated keeping a_4 fixed at zero.

If modules are mixed bifacial and non-bifacial, the BPOA shall be scaled by the ratio of modules.

The Minimum Power Rating ($P_{\min}$) shall be calculated for each of the portions of the site by substituting in coefficients *A*, *B*, *C*, and *D* and the appropriate Reporting Conditions (Irr_0, T_0, and WS_0) as shown in the following Equation (4):

$$P_{\min} = Irr_0 * \left(A + B * Irr_0 + C * T_0 + D * WS_0\right) \quad (4)$$

4.2. Measured Capacity Ratio

The PV Capacity Test result shall be the ratio of Measured Capacity over the Target Capacity (the "Measured Capacity Ratio").

$$MCR = \frac{MC}{TC} \quad (5)$$

4.3. Performance Criteria

1) The Performance Criteria shall be calculated as defined above and expressed as a percentage:

$$PC = \frac{P_{RC}}{P_{\min}} * 100 \quad (6)$$

2) If the Performance Criteria is greater than or equal to the Guaranteed Facility Percentage, then the contractor has met the Capacity Guarantee.

Acceptance values of 95% - 97% of the mutually agreed upon simulation are common

$$\text{Capacity Test} = \frac{\text{Measured power}}{\text{Expected power}}$$

$$\text{Performance Test} = \frac{\text{Measured energy}}{\text{Expected energy}}$$

$$\text{Availability Test} = \frac{\text{Measured operational hours}}{\text{Expected operational hours}}$$

4.4. Calculation of Performance Ratio

The performance ratio (as defined in future IEC 61724-1, 10.3.1) reflects the electrical energy generated relative to the amount of irradiation and the array DC power rating of the plant. It is calculated from:

$$\text{Performance ratio} = \frac{\left(\frac{E_{out}}{P_0}\right)}{\left(\frac{H_i}{G_{i,ref}}\right)} = (1 - 0.03) P_{RC}^{E} \quad (7)$$

where:

E_{out} is in kWh,

P_0 is the array DC power ratio in kW,

H_i is the plane-of-array irradiation in kW/m^2, and

$G_{i,ref}$ is the irradiance used for ration the modules, usually 1 kW/m^2.

Acceptance criteria The expected capacity, PRC, of the System shall be determined in accordance with ASTM E2939-13, *Standard Practice for Determining Reporting Conditions and Expected Capacity for Photovoltaic Non-Concentrator Systems*, using the performance model for the System used to generate the expected annual energy production estimate provided in Schedule #1 together with historical, typical, or actual meteorological data for the site at the same time of year as the test period.

The Guaranteed Capacity, P_{RC}^{G}, shall be the expected capacity margined by a contract tolerance of 3%:

$$P_{RC}^{G} = (1 - 0.03) P_{RC}^{E} \quad (8)$$

The System shall be considered to have passed the Capacity Test if the upper confidence bound of the measured capacity is greater or equal to the Guaranteed Capacity, or the following equation is "True":

$$P_{RC} + U_{95} \geq P_{RC}^{G}$$

4.5. AC Losses

The AC side of the plant that is to be tested is from the inverter output to the PCC power meter.

The AC Losses shall not exceed 2% of the power measured at the PCC power meter. These losses include mainly transformer losses and wiring ohmic losses.

The losses shall be measured by simply subtracting the power measured at the inverter output from the power measured at the PCC meter. Power at these points shall be measured by means of the SCADA.

These losses shall be measured for a duration of 2 days. A test day will be considered valid only if there are no inverter or system failures, shutdowns, or interruptions.

4.6. Pre-Test Conditions for AC Loss Tests

1) Mechanical Completion

2) Commissioning and Reliability Test successfully completed

3) Test schedule and plan reviewed and approved by the owner

4.7. Inverter Test Description

The test procedures and schedule for the factory acceptance tests of the inverter shall witness factory acceptance tests. These tests shall include, at a minimum, the following:

1) Burn in at design DC voltage at stepped loads, 25% increments

2) Verify clipping at differing simulated insolation values and DC input voltages

3) Validate efficiency at differing loads at design DC input voltages

4) Simulate operation and performance at design environmental conditions of site

5) Verify operation of inverter at voltage limits

6) Demonstrate unit will not be damaged during normal failure modes such as loss of power, loss of single AC phase, loss of DC input, loss of communication link

7) Verify VAR and PF control of inverter at various conditions and phase voltages

8) Verify inverter operation up to 110% of rated power output

9) Demonstrate that inverters do not circulate current among phases or operating units

4.8. Liquidated Damages

Performance Liquidated Damages shall be an amount determined in accordance with the following formula:

(i) (A) Guaranteed Facility Percentage (expressed as a decimal) minus (B)

the Performance Criteria (expressed as a decimal) multiplied by (ii) the Contract Price.

X = Capacity ratio where the Capacity ratio is calculated as follows:

Measured Capacity divided by Guaranteed Capacity (expressed as a percentage).

If X is less than 98%, Capacity Guarantee Liquidated Damages shall be payable by Contractor to Owner. The Capacity Guarantee Liquidated Damages = (97% - X) * (Contract Price).

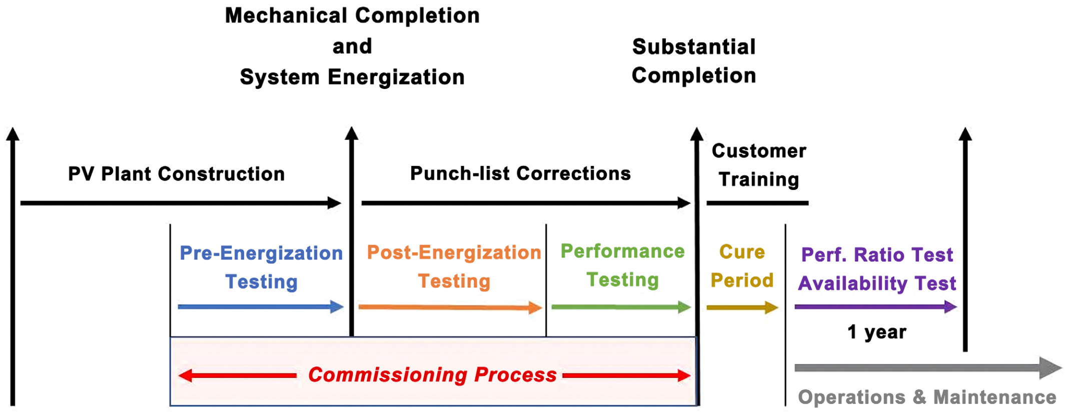

Figure 2. Flowchart diagram of the ASTM E2848 capacity test analysis.

Cure Period: If, when first tested, the test report does not meet the Guaranteed Capacity requirement, the EPC Contractor shall, upon reasonable notice to Client, be afforded thirty (30) continuous days (the "Cure Period") of unimpeded access to the System to undertake adjustments with the option to retest. During the Cure Period, the Client shall ensure that: (i) the necessary third-party interconnections are continuously available; (ii) the facility is operated as required to make the necessary adjustments and perform a retest; (iii) copies of the operational history of the System are available to the EPC Contractor as approach is further illustrated in Figure 2 and Figure 3.

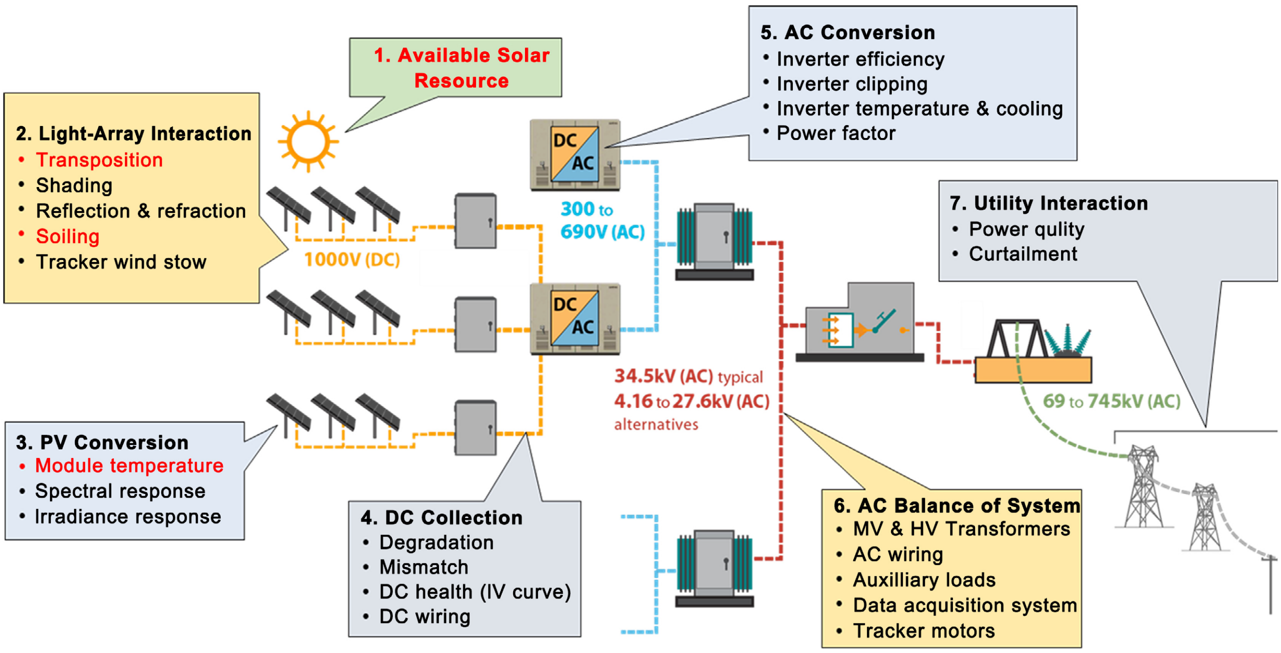

Figure 3. Site specific consideration.

Sole Remedy: If the System does not satisfy the Guaranteed Capacity requirement when first tested, the EPC Contractor, at its expense and sole option, shall thereafter correct such defect by repairing, replacing, and supplementing the power shortfall by providing additional modules as necessary to achieve the Guaranteed Capacity, per the initial design, or provide an equitable solution to compensate for the Guaranteed Capacity shortfall. The client is to provide sufficient space for the EPC Contractor to use and perform supplemental remedies as necessary. If a defect in the equipment or part thereof cannot be corrected by the EPC Contractor's reasonable efforts, the Parties will negotiate an equitable solution with respect to such equipment or parts thereof. The remedies contained here shall be the Client's exclusive remedies for and the EPC Contractor's sole obligations arising out of such deficiencies, and such remedy may only be exercised by the Client during the Capacity Test period [7] [8].

5. Challenges in Conducting Capacity Tests

Inverter and plant clipping are common occurrences in modern PV systems, where the inverter or point of interconnection (POI) reaches its maximum power output, restricting the collection of critical data points. This issue is especially prominent during periods of high irradiance, often resulting in the exclusion of nearly all daytime data from capacity tests. Additionally, low irradiance levels in the winter months pose a significant challenge to meeting the requirements of standard capacity tests. This problem is more pronounced in regions farther from the equator, where lower sun angles and shorter daylight hours make it difficult to collect enough data. External shading from topographical features or other obstructions further restricts valid data collection. Moreover, backtracking during early morning and late afternoon hours causes rapidly fluctuating irradiance, which adds to the complexity of gathering reliable data.

5.1. Nonlinear Phenomena in PV Systems

- Efficiency Curves: Both PV modules and inverters exhibit nonlinear efficiency curves, particularly at low irradiance levels. For example, PV module efficiency drops significantly below 400 W/m^2, and inverter efficiency is only linear between 20% and 80% of its rated output.
- I^2R Losses: The resistive losses in cables and transformers, proportional to the square of the current, add to the nonlinearity but generally have a minor impact on the overall system performance.
- Data Scatter: Various factors such as rapidly changing irradiance, wind direction, and auxiliary loads (like tracker motors) can introduce scatter in the data, complicating the analysis.

5.2. Mitigation Strategies

- Stowing Trackers Flat: By placing trackers in a horizontal stow position, the PV array behaves like a fixed array, flattening the power output curve and allowing more valid data points to be collected. This approach is especially effective when the system is likely to be power-limited at around 850 W/m^2.
- Reducing DC Capacity: Temporarily reducing the DC capacity by disconnecting some combiner boxes can prevent clipping and allow for the collection of valid data points. This method requires scaling the results to reflect the full system capacity after the test.
- Using High-Resolution Data: Collecting data at 1-minute intervals can capture more data points during ramp-up and ramp-down periods, which are typically excluded in lower resolution data (like 15-minute intervals). Although this method introduces some error due to thermal time lag, it can still provide a valid regression if carefully managed.
- Expanding Irradiance Range: The paper suggests using a wider range of irradiance values, even at levels higher than 400 W/m^2, to increase the number of valid data points. This approach is particularly useful in winter when high irradiance values are rare [9].

6. Conclusions

The ASTM E2848-13 standard test method remains a critical tool for evaluating the performance capacity of photovoltaic (PV) systems. Its methodology, based on linear regression models and real-time environmental data, ensures that PV systems perform in line with projected expectations. While the ASTM E2848-13 methodology provides a comprehensive framework for determining the capacity of newly installed PV systems, it has its limitations, particularly concerning variations between historical data and actual test conditions, which can introduce uncertainties that may affect the reliability of the results. Additionally, conducting capacity tests for PV systems presents several challenges, including inverter and plant clipping during high irradiance periods, low irradiance in winter, and external factors like shading and backtracking that impact data collection. These issues are further complicated by the nonlinear behavior of PV modules and inverters, particularly at lower irradiance levels.

However, advancements in modeling software like PVSyst have improved the ability to simulate expected performance and account for variables such as bifacial module technology, which adds complexity to capacity measurements. By integrating both the ASTM approach and simulation models, project developers can more accurately assess whether systems meet guaranteed capacity and performance standards. Implementing strategies such as stowing trackers flat, reducing DC capacity, using high-resolution data collection, and expanding the irradiance range further help mitigate these challenges. Adhering to industry standards like ASTM E2848 allows for more reliable and accurate results despite inherent limitations. While these strategies may introduce slightly higher uncertainty, they ensure that the integrity of capacity testing remains intact, providing valuable insights into system performance.

The challenges associated with data collection, filtering, and regression analysis can be mitigated through precise calibration of equipment and careful data management. Ensuring that these prerequisites are in place is essential to minimize uncertainties and achieve valid test results. The inclusion of bifacial module considerations in ASTM E2848-13 further demonstrates the flexibility of this standard in addressing evolving PV technologies.

As the PV industry continues to grow, standards like ASTM E2848-13 will play a crucial role in ensuring that installed systems meet contractual obligations and operate efficiently over their lifespan. The methodology's emphasis on detailed, site-specific data collection and analysis sets a high bar for performance verification, ensuring that stakeholders can rely on accurate and reproducible results for system acceptance testing [10].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Sheth, K. and Patel, D. (2024) Comprehensive Examination of Solar Panel Design: A Focus on Thermal Dynamics. *Smart Grid and Renewable Energy*, **15**, 15-33. https://doi.org/10.4236/sgre.2024.151002

[2] ASTM International (2023) ASTM E2848-13(2023): Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance.

https://cdn.standards.iteh.ai/samples/115933/0d59741b526b4b3fac3a195321568848/ASTM-E2848-13-2023-.pdf

[3] IEC (2016) Photovoltaic System Performance—Part 2: Capacity Evaluation Method. Standard TS 61724-2.

[4] U.S. Department of Energy (2024) Optimizing Solar Photovoltaic Performance for Longevity. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/femp/optimizing-solar-photovoltaic-performance-longevity

[5] Fakhfouri, V. (2015) Photovoltaic Devices—Part 1-2: Measurement of Current-Voltage Characteristics of Bifacial Photovoltaic (PV) Devices. Proposal 82/1044/NP. IEC.

[6] King, D., Boyson, W. and Kratochvil, J. (2004) Photovoltaic Array Performance Model. Sandia National Laboratories, SAND2004-3535.

[7] Sandia National Laboratories (2014) Solar PV O&M Standards and Best Practices-Existing Gaps and Improvement Efforts. https://energy.sandia.gov/wp-content/gallery/uploads/SAND2014_19432.pdf

[8] Law Insider Inc. (n.d.) PV Plant Capacity Test. https://www.lawinsider.com/clause/pv-plant-capacity-test

[9] National Renewable Energy Laboratory (2020) Suggested Modifications for Bifacial Capacity Testing. https://www.nrel.gov/docs/fy20osti/73982.pdf

[10] Reasor, G. and Forbess, J. (n.d.) Recommendations for Overcoming Limitations of Capacity Tests of Utility-Scale Photovoltaics Projects. Burns & McDonnell and Sunshine Analytics. https://info.burnsmcd.com/white-paper/recommendations-for-overcoming-the-limitations-of-capacity-tests-of-utility-scale-photovoltaics-projects?abm=true