Reliable methods for PV power plant performance testing

Evan S. Riley, Black & Veatch , San Francisco, California, USA

ABSTRACT

Using a prescribed test protocol to compare the measured performance of a solar PV power plant relative to its expected performance is often a means by which the value of the facility is determined. Performance testing is used contractually to determine matters such as the fee paid to a constructor, the price paid to a seller, and the cost of capital from a lender or investor. To ensure that performance testing produces consistent and independently verifiable results, it is essential that accurate and repeatable test methods be used. This paper outlines critical deficiencies in older solar PV performance testing protocols, and how the methods prescribed in ASTM E2848 and E2939 eliminate these deficiencies and enable test practitioners to produce consistent, verifiable results with a high degree of confidence.

Introduction

In the past five years, the renewable power generation market in much of the USA and Europe has undergone a fundamental shift. Driven by rapid declines in equipment prices and installation costs, improved performance, and strong policy support, market participants have deployed an unprecedented amount of renewable wind and solar generating capacity. Once viewed as niche resources, renewable generating facilities are now changing the electric power industry and expanding participation in the electricity supply market.

One of the most striking differences between fossil fuel-based and renewable power generating facilities is the way in which the projects are financed. Both require a significant amount of up-front capital to develop and construct. However, unlike fossil fuel power plants, renewable energy power plants typically have minimal operating costs. As a result, the up-front cost of a renewable energy facility is a significantly greater fraction of its overall lifetime cost than that of a fossil fuel facility.

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The cost of capital for long-term project financing is directly related to project risk. For fossil fuel power generating facilities, which have well-understood performance characteristics and operating costs, the primary risk is the uncertainty in the future price of fuel. In contrast, because renewable generation does not operate in a fuel price risk environment, the primary financial risk is the accuracy and uncertainty of the performance model used to estimate the expected production from the renewable energy facility. It is therefore critical to have reliable performance models and accurate performance-testing protocols for renewable generating facilities. Reliable performance models reduce uncertainty and risk, and accurate performance testing provides a means of demonstrating that a constructed facility will meet the expectations upon which the financial model of the project is based.

Performance modelling and testing of solar PV generating facilities

To determine the pro forma bankability of a potential future solar PV generating asset, a project developer typically begins by forecasting the expected energy production from the proposed facility by inputting historically typical solar resource and weather data (i.e. metrology or 'met' data) into a performance model that simulates the facility's efficiency in converting sunlight into electricity. For solar PV projects, a bankable performance model may include upwards of 50 parameters which specify a wide variety of important factors, including the characteristics of the solar resource, the PV module performance, the inverter performance, the DC and AC electrical losses, and other performance factors.

The combination of the large number of performance modelling parameters and the uncertainty in each produces an aggregate modelling uncertainty in an energy production estimate for a facility that can range from 1 to 10% based on the skill of the modeller, the capabilities of the performance modelling software used, and the quality of information provided to the modeller. This in turn directly determines the uncertainty in the expected revenue for the solar PV project from the sale of electricity it produces.

In addition to performance modelling uncertainty risk, project developers and financiers must also have a means of addressing construction quality risk. The construction quality of a solar PV facility can directly impact its performance and the revenue it will produce. Construction quality factors that can impact performance include:

- The types of PV modules, inverters, electrical cables and components used.
- The quality of the PV modules and other equipment.
- The correctness, quality and completeness of electrical connections.
- The correct programming of inverters and other equipment.

In order to mitigate the risk that a solar PV project will not perform as expected because of modelling and/or construction errors, the industry has begun to utilize comprehensive system-level performance testing in order to evaluate how completed projects perform, on a resource-adjusted basis, to the expectations established by their production estimate. Consequently, to reduce project financing risk and the associated cost of capital, both the modelled production estimates and the results of performance testing need to be valid. A valid performance testing protocol satisfies the following criteria:

- It is well defined, unambiguous and reproducible, such that two independent analysts will always arrive at the same result when analysing the same test data.
- It is effective at testing the ability of the project to convert the available solar resource into electricity, as modelled.

- It specifies a performance target in a manner that is consistent with how measured performance is determined.

- It specifies reference operating conditions, under which measured performance is compared with expected performance, that are within the operating conditions of the project.

- It produces a result that is not influenced (biased) by factors outside the control of the project, including variations in the solar resource, ambient temperature, wind speed and soiling of the PV modules by dust and dirt.

To achieve these goals, performance tests commonly used in the industry are being improved and evolving into trusted standards through the efforts of a wide range of industry participants who are working together to create more-comprehensive testing methodologies.

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The PVUSA performance test specification

The first well-documented performance test specification for solar PV generating facilities was developed by the Bechtel Corporation in 1995 and published by the United States Department of Energy in the "PVUSA model technical specification for a turnkey photovoltaic power system" [1]. This specification included a performance test which was intended to help ensure that the completed facility met the requirements set forth in the project specification, but did not necessarily reach a specific energy production target.

The PVUSA test specification defines the test target for a facility by applying a series of derating factors to its DC capacity (kWp), which is defined as the sum of module nameplate ratings (Wp) specified at PVUSA test conditions (PTC), i.e. 1000W/m^2 irradiance, 20°C ambient temperature and 1m/s wind speed. The idea is that each derate can be contractually stipulated in the technical specification of a construction contract, and that the expected energy production of the facility can be forecast using those contractual derates. In this *indirect* way, the test could be used to demonstrate to a potential project owner that the project was built as specified and is capable of performing as expected. The diagram shown in Fig. 1 illustrates the process flow of the PVUSA performance test method.

Shortcomings of the PVUSA test method

As discussed above, the most important aspect of modelling the performance of a solar PV facility from a project financing perspective is the *expected energy production* (MWh), which determines expected future revenue flows as a pro forma baseline. An assessment of the actual performance of a facility once it has been constructed is then performed by comparing its *measured energy production*, in a consistent way, with the baseline expectation. The goal is to provide a reliable basis for confidence in how the project will perform over its useful operating life, compared with expectations.

As shown in Fig. 1, the primary deficiency in the PVUSA test method is that the *target capacity* of the facility is determined solely by the project specification without referencing the expected energy production. This can, and often does, create inconsistencies which bias the performance test results.

Overall, there are five critical shortcomings of the PVUSA test method:

1. It does not specify what test equipment should be used to take the measurements, or how the instruments should be calibrated.

2. It does not specify how to filter the measured data, nor does it specify important data requirements, such as the minimum number of data points to be analysed and the time interval between them (over which measured data within each interval are averaged).

3. It requires a detailed and comprehensive project specification that is consistently applied in building the project and modelling its energy production; a weak or incomplete project specification may give a project constructor an opportunity to knowingly or unknowingly create a mismatch between the target capacity specified and what has actually been built.

4. It does not address the fact that the measured capacity of a PV power plant varies seasonally, often testing low in the summer and high in the winter.

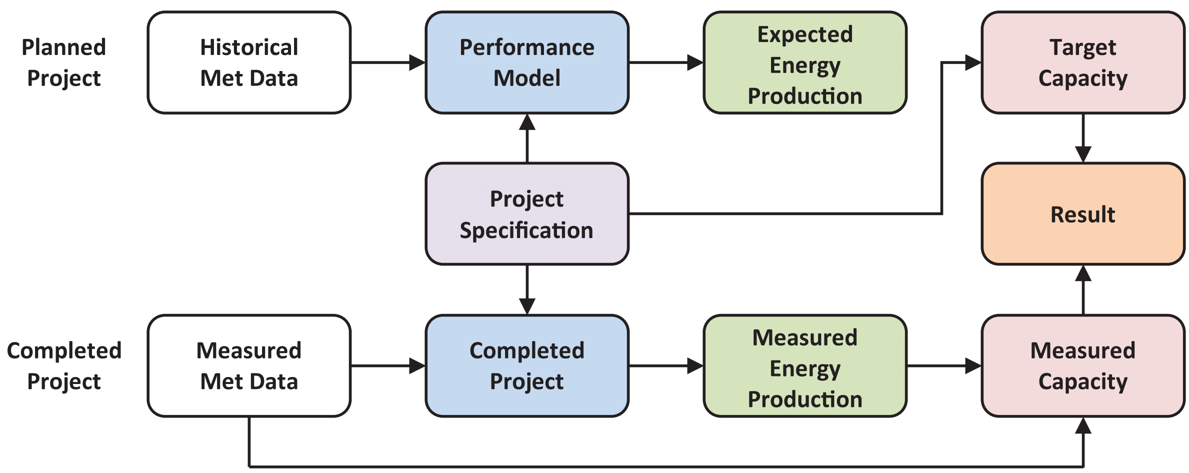

Figure 1. PVUSA performance test process flow.

5. It suggests, but does not mandate, how best to determine the test reporting conditions; this is problematic when a plant is operating far from the reporting conditions, because the test results would then need to be extrapolated far outside the measured performance dataset.

ASTM standards that address the shortcomings of the PVUSA test method

ASTM International, formerly known as the American Society for Testing and Materials, is a globally recognized leader in the development of international voluntary standards [2]. From 2009 to 2013, teams throughout the solar PV performance community worked with ASTM to develop two new standards:

- ASTM E2848 – Standard test method for reporting photovoltaic non-concentrator system performance [3].
- ASTM E2939 – Standard practice for determining reporting conditions and expected capacity for photovoltaic non-concentrator systems [4].

ASTM E2848 and ASTM E2939 address the shortcomings of the PVUSA test method: the E2848 standard addresses the first and second, and E2939 addresses the third, fourth and fifth.

> "ASTM E2848 and ASTM E2939 address the shortcomings of the PVUSA test method."

ASTM E2848

ASTM E2848 was developed as a first step in advancing the testing of solar PV facility performance from a rough guideline published in the PVUSA technical specification to a comprehensive suite of industry standards [3]. This ASTM standard does many things, including specifically:

- defining the scope of the test;
- defining terminology;
- defining measurement equipment and calibration;
- providing criteria for filtering data;
- specifying minimum data requirements.

One of the most important improvements provided by ASTM E2848 is to define the scope of the test as "useful for acceptance testing and performance monitoring of a solar PV power plant, but not for testing single modules or comparing different projects in different locations or of different technologies". For example, because of the complex nature of the performance of solar PV facilities, two co-located solar PV facilities with identical DC capacities but using different technologies, and/or with differences in row spacing or module tilt, can have significantly different capacity factors, generation profiles and measured capacity values under ASTM E2848.

To reduce measurement uncertainty, ASTM E2848 also specifies the requirements for the types, accuracy and calibration of the instrumentation used to collect measurement data during a performance test. It further specifies minimum data requirements and establishes data filtering criteria to remove ambiguities about how data should be aggregated, parsed and filtered. This reduces analysis uncertainty and allows test results to be repeatable. This is an essential feature of the specification because it enables different project stakeholders to independently calculate the test results in a consistent manner and arrive at the same result, which helps ensure the test's validity.

While ASTM E2848 establishes a foundation for a comprehensive capacity test protocol, by itself it does not address all the shortcomings of the PVUSA test method.

ASTM E2939

ASTM E2939 was specifically developed to create consistency in determining the *expected capacity* and *measured capacity* of a solar PV facility by recognizing seasonal variability and by specifying a better method for determining reporting conditions [4]. However, to do this required a restructuring of the process by which the test was carried out. The goal of this restructuring was to ensure consistency by directly tying the expected capacity to the performance model used in financing the project. This was done by applying the same regression curve to both the performance model used to determine the expected capacity, and the measured data used to determine the measured capacity. This was something that was not feasible when the PVUSA technical specification was issued, because sufficiently accurate solar PV performance modelling software did not exist at that time. The diagram

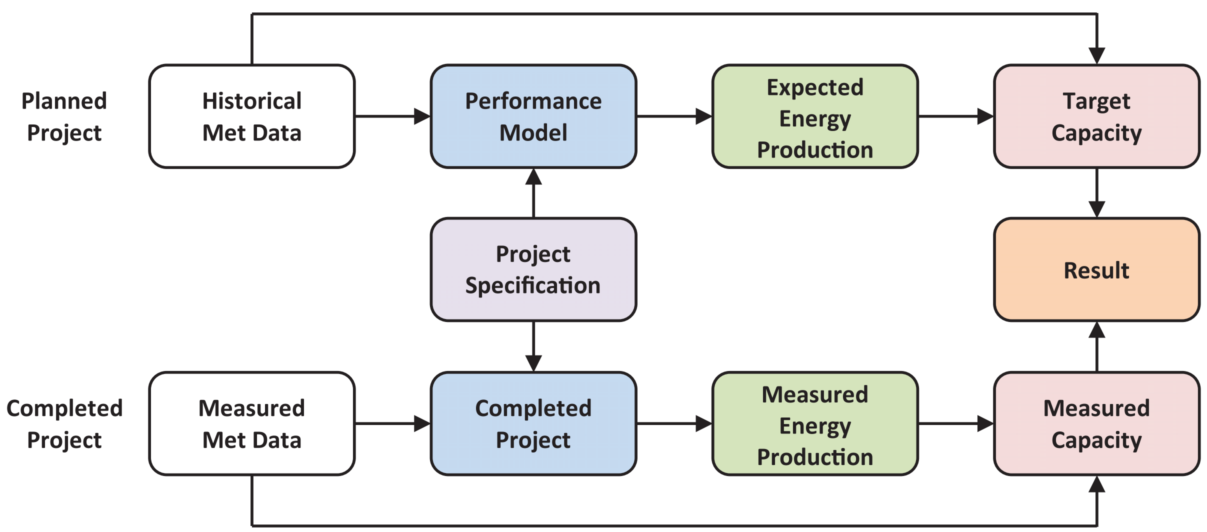

Figure 2. ASTM E2848–E2939 performance test process flow.

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shown in Fig. 2 illustrates the restructured process flow specified in the ASTM performance test standard.

Calculating the expected capacity according to the ASTM standards has three advantages over using the PVUSA test method:

1. The expected capacity of a facility is directly tied to its performance model.
2. Seasonal biases are minimized, because the performance targets display the same seasonality as the measured performance.
3. How performance targets and measured values are determined is specified in a consistent way.

The logic of the ASTM performance test protocol is based on ensuring symmetry, and therefore consistency, in the methods used to determine the expected capacity and those used to measure capacity. Another important advantage of this protocol is that the process of making consistent financial decisions based on a test result becomes straightforward for individuals who are not necessarily technically versed in photovoltaic performance.

> "The legacy PVUSA test method has been transformed into a comprehensive, bankable and trusted standard that can be used consistently by technical and financial practitioners across the industry."

Conclusions and the future of performance testing for PV power plants

ASTM E2848 and E2939 constitute the first published suite of comprehensive performance testing standards for flat plate (non-concentrator) solar PV facilities. Through the work of the ASTM committee, the legacy PVUSA test method has been transformed into a comprehensive, bankable and trusted standard that can be used consistently by both technical and financial practitioners across the industry. Black & Veatch has extensive experience with applying these protocols to performance acceptance test specifications and procedures on solar PV projects ranging from 2 to 50MW.

Although the performance testing for PV power plants has improved significantly since the time when the PVUSA model technical specification was developed, there is still more work to be done. Black & Veatch champions the idea of collaborative innovation and improvement, and actively contributes to these efforts by participating in industry working groups and publishing technical papers in the field of PV performance testing [5,6].

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About the Author

Evan Riley is a renewable energy consultant specializing in PV and other renewable energy technologies in the Renewable Energy Group of Black & Veatch's global energy business. In this role his work includes independent engineering, PV production estimation, technical and economic project evaluation, contract review, and preliminary design assignments for MW-scale PV projects. Evan has been involved in over 4000MW of PV capacity in late-stage development, construction or operation globally.

Enquiries

Evan Riley
Black & Veatch
353 Sacramento St #1900
San Francisco, CA 94111
USA
Tel: +1 415 292-3556
Email: RileyE@bv.com