



Calibration and Rating of Photovoltaics

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Calibration and Rating of Photovoltaics

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Abstract—Rating the performance of photovoltaic (PV) modules is critical to determining the cost per watt, and efficiency is useful to assess the relative progress among PV concepts. Procedures for determining the efficiency for PV technologies from 1-sun to low concentration to high concentration are discussed. We also discuss the state of the art in primary and secondary calibration of PV reference cells used by calibration laboratories around the world. Finally, we consider challenges to rating PV technologies and areas for improvement.

Index Terms—calibration, reference cell, peak watt, rating, Si wafer.

I. INTRODUCTION

The procedure to determine the current vs. voltage characteristics with respect to reference conditions defined by a reference spectrum, temperature, and total irradiance has been codified in IEC standards [1]. These conditions are typically called standard test conditions (STC) or standard reporting conditions (SRC). The reference cell method with spectral corrections has been used by calibration labs since 1984 [2]. There are four recognized primary reference cell calibration laboratories in the world—National Institute of Advanced Industrial Science and Technology (AIST) in Ibaraki, Japan; Physical Technical Laboratory (PTB) in Braunschweig, Germany; National Renewable Energy Laboratory (NREL) in Colorado, USA; and the European Commission Joint Research Center (JRC) in Ispra, Italy [3,4]. Most photovoltaic (PV) labs have secondary reference cells calibrated using primary or secondary reference cells calibrated by one of these four primary reference cell calibration laboratories. The calibration of modules as secondary standards are typically performed by one of the numerous accredited module calibration labs around the world or regional test centers such as AIST, NREL, Fraunhofer Institute for Solar Energy Systems (ISE), or JRC. The end user may or may not know the full calibration chain, which can impact the rating at the 1% level.

II. PRIMARY CALIBRATION METHODS

The primary calibration methods employed by AIST, PTB, NREL, and JRC are summarized in IEC Standard 60904-4, ISO Standard 15387, or in papers by the laboratories [4–9]. Unlike the other standards, which are general guides, the consensus standard ASTM E 1125

maintained since its adoption in 1986 details the primary calibration procedure followed by NREL [10]. These laboratories occasionally intercompare results, and Fig. 1 shows the level of agreement among primary calibration labs based on intercomparisons with NREL over the last five years. Figure 2 shows the calibration history for

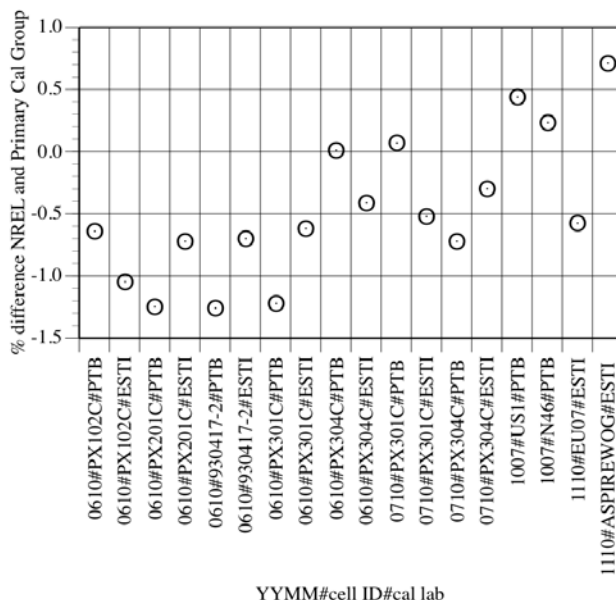


Fig. 1. Primary reference cell calibration agreement among labs since 2004. Positive values indicate that NREL was lower than the other lab.

NREL’s silicon working standard used to test silicon, CIGS, and other similar cells. A 3-year running average was adopted in 2003 to reduce random error. PTB claims to have the lowest 95% confidence limit uncertainty at around 0.6%; their calibrations also provide information to determine the short-circuit current (I_{sc}) temperature coefficient from the temperature-dependent quantum efficiency (QE) for a given spectrum [8]. The other laboratories perform calibrations under natural [2,4,7] or simulated [9] light, and apply spectral mismatch corrections. These methods are typically restricted to single-junction cells that are packaged with an attached temperature sensor. In ISO 15387, these methods are termed synthetic Air Mass Zero (AM0) standard cells [6]. It is possible to translate AM0 calibrations to terrestrial reference conditions without any loss of error if an accurate QE is known [11] following the procedures in [12] or [13].

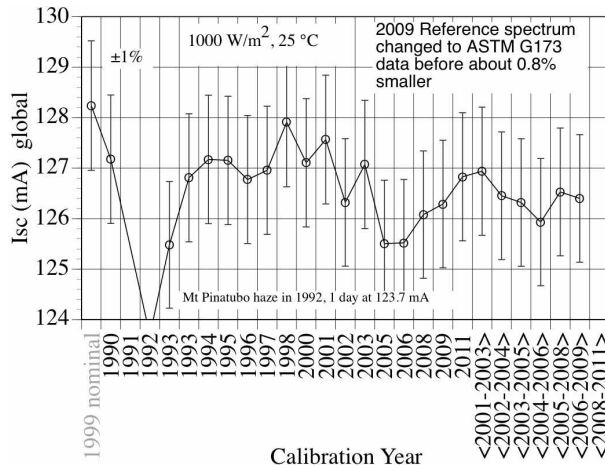


Fig. 2. Calibration history for S04, NREL's Si primary reference cell working standard for 1-sun cell calibrations.

PTB, AIST, and NREL all calibrate cells with normal incidence sunlight; hence, there is a potential error when using these cells outdoors because of the nonideal angular response [14]. Calibration procedures normally ignore this error partly because the reference spectrum has a 90% direct component and a 10% diffuse component that cannot easily be simulated. Internal reflections in the sensor package will introduce errors if the package is not completely illuminated during calibration and use [14–16] and to a small amount under global vs. direct sunlight [14].

III. SECONDARY CALIBRATION METHODS

Because primary reference cells are difficult or impossible to obtain, many PV measurement labs use secondary cells calibrated by the primary calibration laboratories. Commercial labs such as VLSI Standards, Newport Oriel, or RETC, which are accredited to perform secondary PV calibration measurements, provide a valuable service to the community by providing rapid measurements. Accreditation to recognized secondary measurement standards and ISO 17025 is important for these commercial vendors because it provides the customer with confidence that a formal quality system is in place; calibrations are periodically intercompared to verify that they agree with other labs within their estimated uncertainty and many other aspects to give the customer confidence that the data are valid.

Commercial PV accredited module qualification labs are ISO 17025 accredited to perform secondary reference module calibrations as part of their IEC module qualification capability. Other government and quasigovernment accredited test labs such as Fraunhofer ISE, NREL, Sandia, AIST, and Florida Solar Energy Center provide current vs. voltage (I-V) measurements under STC or equivalently SRC, including power ratings.

For multijunction modules, especially a-Si, none of these laboratories are able to adjust the spectral irradiance during measurement so that the photocurrent ratios match that which occurs under the reference spectral irradiance. This is evidenced by the 10% to 15% range in maximum power (P_{max}) observed in intercomparisons.

Based on measurement intercomparisons, the uncertainty of secondary module calibrations varies. The differences among laboratories is maximal when a test module is provided without a matched cell, and different primary reference standards are used [18]. Differences can be reduced by circulating a secondary reference cell with the test modules [19].

Some accredited commercial PV calibration laboratories such as Newport and VLSI have also shown competency for calibrating bare wafers and organic devices through multiple intercomparisons. For organic PV, calibration errors can be large and the cells unstable, so rapid measurements by the test laboratory is essential for credible efficiency claims.

IV. SILICON WAFER CALIBRATION METHODS

When calibrating silicon cells that lack attached bus bars, ribbons, or wire leads (i.e., “bare wafers”), differences between calibration labs for I_{sc} and power for commercial Si wafers are the same as those seen for commercial Si modules. A number of intercomparisons over the last several years between Fraunhofer ISE, AIST, and NREL have documented these differences, which vary between 2% and 5% and seem to depend on the width of the top metallization to which bus bars are attached. About 1% of the differences between the labs can be attributed to differences in primary reference cell calibration. Fraunhofer uses a two-step procedure to simulate a ribbon with zero resistance, zero shading, and zero contact resistance [20]. The first step is to obtain I_{sc} with minimum shading. Kelvin probes are attached to the end of each ribbon. The next step is to remeasure the I-V curve with a multipoint probe designed to minimize voltage drops after adjusting the light source to give the I_{sc} from the first step. NREL will do either or both methods for a client, but does not presently combine these two steps. AIST typically uses multipoint probes. Figure 3 shows these differences in I_{sc} for mono-Si and multi-Si wafers with and without ribbons from several manufacturers. This is significantly larger than the less than 1% differences in I_{sc} for a blind intercomparison sponsored by Energy Research Center of the Netherlands (ECN) between NREL and ESTI secondary calibrations and PTB primary calibration for a multi-Si wafer mounted on a metal plate [21]. This indicates that the level of agreement among calibration labs can vary from time to time and that intercomparisons must be done frequently to uncover subtle differences.

V. RESEARCH CELL CALIBRATION METHODS

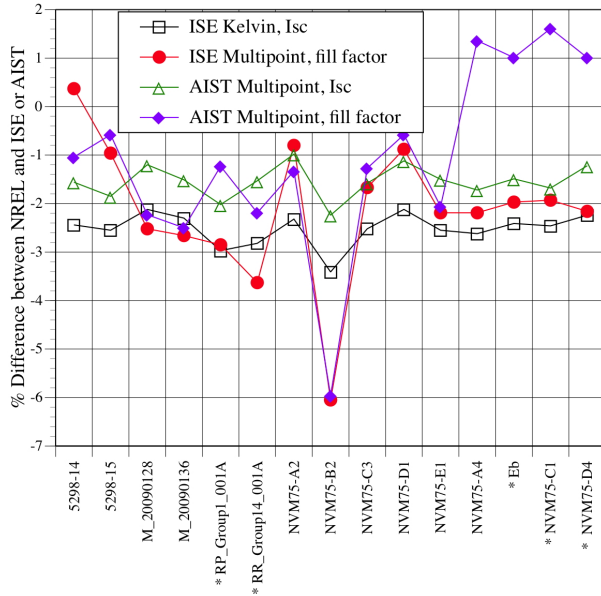


Fig. 3. Silicon wafer calibration agreement among recognized calibration laboratories. The cells with an asterisk (“*”) had ribbons attached to the front surface. AIST measured the cells with ribbons with Kelvin contacts.

The generally accepted procedures for determining the efficiency with respect to SRC are documented in IEC standards. Record cell and module efficiencies following these procedures are published in the *Progress in Photovoltaics* efficiency tables [22]. The standards do not directly address the area definition for efficiency calculations, but there is consensus among the calibration labs [23–24]. Independently measured record efficiencies are periodically summarized for the community in Fig. 4 by the author and L.L. Kazmerski [25].

There can be significant differences in the fill factor for high-current low-voltage such as silicon because of contacting-related differences even when separate current and voltage contacts are used. The largest difference between reported and independently measured efficiencies continues to be related to differences in what is called the cell area. This is primarily because research cell areas are usually small, and there can be excess current collected from light shining outside the cell area. For high-lifetime silicon, the diffusion length can be more than 1 mm, which effectively increases the size of a mesa-etched Si research cell. Light piping from regions outside the cell area is possible for devices with transparent covers or coatings. This is why test labs often require an

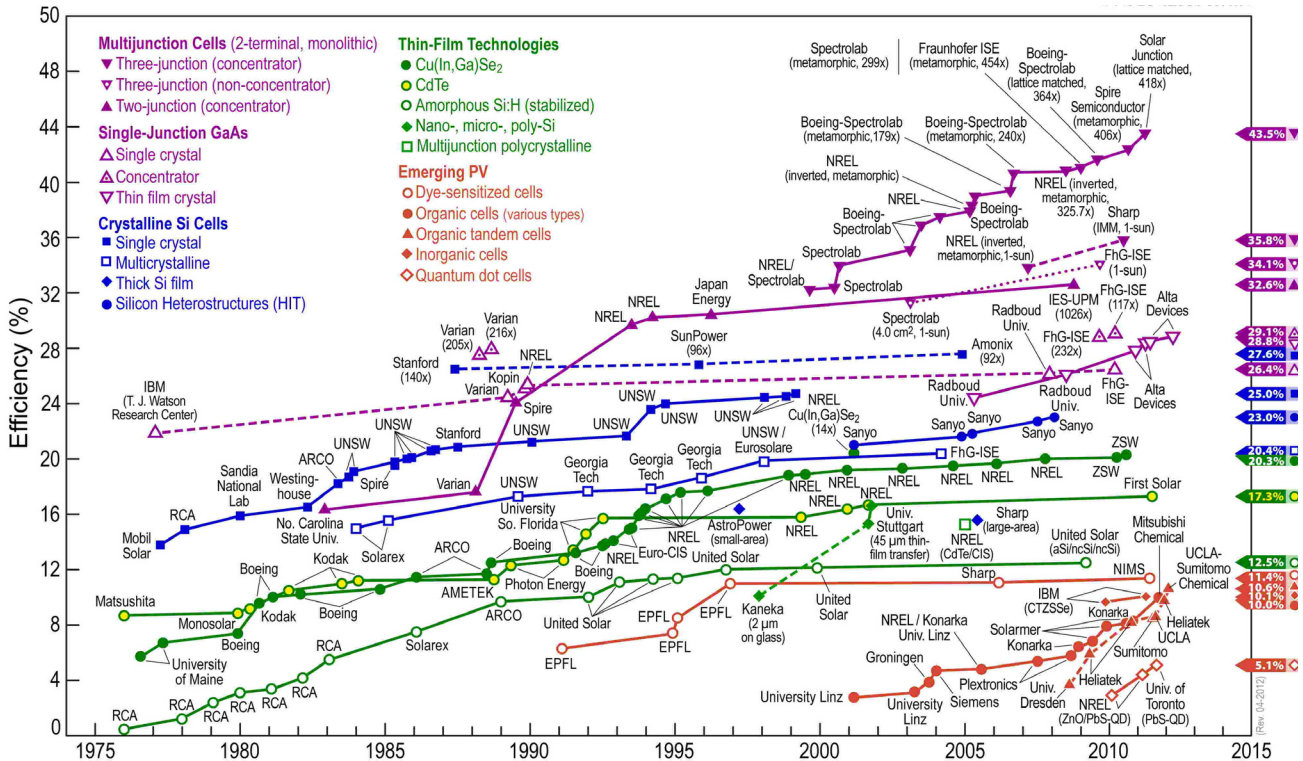


Fig. 4. Independently measured record cell efficiencies over time by technology [24]. There are no area or stability constraints beyond testing in air for inclusion in this table.

aperture to define the cell area. Many invalid efficiency claims in the literature could have been identified prior to publication if the current density had been measured both with and without an aperture to determine the magnitude of this artifact. Differences in I_{sc} or efficiency among calibration labs are about $\pm 3\%$ of the value depending on the technology, with many samples agreeing at the 1% level.

VI. CONCENTRATOR CALIBRATIONS AND RATINGS

Standard conditions for concentrators have not been standardized, although there is consensus for de facto standards [22,26]. At the cell level, IEC draft standard 62670-1 addresses the Concentrator Standard Test Conditions (CSTC) of 25°C cell temperature, ASTM G173 direct [26,27]. Since the 1975 Baton Rouge workshops established the first consensus standards for rating PV, the community has arbitrarily defined the 1-sun condition to be at 1000 Wm^{-2} for both the global and the direct reference conditions, regardless of the actual integrated value of the reference spectrum [22,28].

In the past, concentrator modules have been evaluated at 25°C cell temperature, but this value is difficult to measure and there is a lack of consensus on procedures to determine this value. ASTM has developed a standard that involves performing a linear regression to the PV power as a function of direct-beam irradiance, air temperature, and wind speed [29]. This method is time- and site-specific because there are no spectral corrections. IEC draft 62670-1 refers to this method as Concentrator Standard Operating Conditions (CSOC), but has slightly different proposed reference wind speeds (2 ms^{-1} vs. 4 ms^{-1}) and direct normal irradiance (900 Wm^{-2} vs. 850 Wm^{-2}) [26].

Rating the performance of concentrator cells and modules continues to be problematic. For concentrator cells, it is quite difficult to determine the light level on the cell without assuming linearity. This is complicated by luminescent coupling between the upper and lower junctions and the inability to measure the QE above several hundred suns.

Very few laboratories are able to adjust simulator spectra to ensure each junction is within 1% of the correct photocurrent. NREL attempts to do this for two junctions by measuring the spectrum vs. lamp voltage and determining the lamp voltage where the photo-current ratios under the simulator are the same as under the reference spectrum [30]. The Spectrolab Terrestrial High Intensity Pulsed Solar Simulator (THIPSS) with six adjustable wavelength regions will enable the spectrum to be properly set for most multijunction technologies of interest to PV power generation. This simulator will also allow, for the first time, the spectral metric to be fully

explored by mapping out the power as a function of total irradiance, temperature, and photo-current ratios for each junction pair. It is hoped that this will allow energy production to be predicted for any location given the temperature, spectral irradiance, and total irradiance vs. time. This space has been explored on a limited basis for two junctions and at a fixed temperature and light level [31].

Performance measurements of concentrator modules with attached optics under simulated light is problematic primarily because of the lack of collimation. For production-level testing, measurements in non-collimated light against a reference module may give acceptable results [32]. Other factors that complicate concentrator module testing include temperature measurement and control, inability to adjust the simulator spectral irradiance, and the lack of commonality in module designs among manufacturers. Techniques that work for one design may not be valid for other designs.

VII. NAMEPLATE RATINGS

PV modules that have passed the module qualification tests must have a nameplate that contains the manufacturer, model number, serial number, and maximum system voltage for which the module is suitable. The peak watt rating at STC is also typically included. The Solar America Board for Codes and Standards recommends that the power rating measured according to IEC standards be no more than 3% different than that of any module with the same serial number. Other standards organizations such as the IEC and EN 50380 for the European Union [33] are debating how random, third-party sampling of production modules should be performed to determine variances from nameplate ratings.

VII. BEYOND PEAK POWER AND EFFICIENCY

There is strong desire to rate PV in terms of energy. This is because among a set of modules collocated, a module with the highest power at STC may not be the module with the highest energy. This may be due to spectral effects, low shunt resistance, or differing temperature coefficients, which make the efficiency drop at low light levels.

There is still a lack of consensus on what the reference conditions should be for energy rating, although there is general consensus on what data to collect and how to collect the data. Ideally, concentrator energy rating would be based on air temperature, but the correlation between air temperature and cell temperature as a function of wind speed and irradiance is an active area of investigation.

There are also concerns that energy derived from hourly averaged data typically found in resource databases may not reflect energy based on instantaneous data since the power, in general, is a nonlinear function of temperature, total irradiance, and spectral irradiance. This issue is most important for high-concentration technologies where on partly cloudy days the direct-beam irradiance can be 0 for half of an hour and 1000 Wm^{-2} for the other half, leading to an hourly average irradiance of 500 Wm^{-2} . Perhaps more importantly is the implied assumption that the efficiency is the same for both cases even though nonlinear resistance losses and different multijunction photocurrent ratios will impact the efficiency.

There is also a lack of consensus on what type of energy rating should be on nameplates; IEC 61853-1 recommends a matrix of temperatures and irradiances to which a module is measured to facilitate energy predictions. Such predictions require consensus on reference conditions and the length of time that an energy rating represents (daily, weekly, monthly, yearly) [34].

Energy rating, identified as actual PV energy delivered divided by incident power based on a 180° field-of-view irradiance in the plane of array integrated over time, allows low-concentration modules to be compared with flat-plate and high-concentration modules. High-concentration technologies are not keen on this approach because it gives a lower efficiency than rating high-concentration modules on the direct beam. At present, low-concentration modules are rated the same as flat-plate modules using procedures in natural sunlight where there is a diffuse component. If low-concentration modules are evaluated as concentrators where the irradiance is measured with a 5° or 5.7° field-of-view pyrliometer, then they will get an artificial boost in their power or energy rating because of the small diffuse component. Sandia has extended their translation equations to rate in terms of the direct and diffuse components with a regression to the direct and diffuse components of the reference spectrum. In theory, this would allow rating from flat-plate to low concentration to high concentration with the same measured irradiances and translation equations. The resource data sets are not in this format, so they must be translated to a direct component and plane-of-array diffuse component. The IEC TC82 standards committee is actively working on energy-rating standards for flat-plate and concentrator modules.

VIII. SUMMARY

The differences among the calibration labs are generally within their estimated uncertainties in the maximum power of $\pm 1\%$ or less for primary calibrations and $\pm 2\%$ for most secondary calibration. The agreement at the wafer Si level among calibrations labs is worse than

expected and larger than for small-area cells that were in most of the previous cell intercomparisons between NREL, AIST, JRC, PTB, and other calibration labs.

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