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Characterization and Capture of Photovoltaic System Losses Due to Nonuniform Conditions

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CHARACTERIZATION AND CAPTURE OF PHOTOVOLTAIC SYSTEM LOSSES DUE TO NONUNIFORM CONDITIONS

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Characterization and Capture of Photovoltaic System Losses Due To Nonuniform Conditions

Thesis directed by Dr. Michael Brandemuehl

Abstract

This research develops a comprehensive methodology and model for accurate prediction of power losses caused by nonuniform electrical characteristics and operating conditions in grid-tied photovoltaic systems, as well as the potential for increased energy capture in systems which employ sub-array power optimizers (microconverters or microinverters). Investigation of these topics provides a framework for more accurate loss modeling and determination of power optimizers' value in a variety of scenarios, enabling future PV research and maximizing the value of PV systems in the built environment.

A custom multitracer, which records simultaneous module-level I-V curves, is designed and built to collect data on 27 PV installations in the Southwestern U.S. The resulting measured dataset, including over 500 modules of crystalline silicon and thin film technologies, indicates that commonly-used, single diode PV generator modeling methodologies often incorrectly predict PV performance at low and medium light levels. A new modeling methodology and parameters are proposed, demonstrating an improved way to incorporate low light data to increase prediction accuracy for crystalline silicon and thin film arrays.

A unique, detailed annual simulation environment for PV system modeling is developed, allowing user-input electrical characteristics and operating conditions at the PV cell level. It is designed specifically to model electrical mismatch and partial array shading, and use of power optimizers to mitigate related energy losses. The resulting simulations, combined with the module-level I-V curve dataset, are used to predict annual mismatch losses caused by module-to-module performance variation in each monitored array. The losses, representing energy that may be directly recovered using power optimizers, are moderately low for most of the tested arrays.

Annual simulations of realistic shading scenarios and PV array configurations show percent annual energy losses that are 2-3 times the annual percent incident light lost in partially shaded arrays. Sub-module or even module level simulations predict nearly the same shading losses as cell level simulations, demonstrating opportunities for model simplification. Arrays with power optimizers can recover 30-45% of the energy loss. In the example scenarios, power optimizers are most advantageous at the module or cell levels, adding little benefit at the string or bypass diode sub-module levels.

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CHAPTER 1

INTRODUCTION

1.1 Motivation and Relevance

1.1.1 Photovoltaic Systems in the Built Environment

Small scale residential or commercial sized grid-tied photovoltaic (PV) systems have gained greater popularity in recent years, fueled by new, more flexible module designs and government and utility sponsored incentives favoring solar technologies (Sherwood 2011). In many cases it makes good sense to mount PV components on buildings, or even to integrate them in a building façade. PV systems installed in the built environment have several advantages: they do not require additional land use, greater visibility allows them more opportunity to inspire and educate the public, grid infrastructure is already largely in place, and in the case of building integrated PV (BIPV) they can decrease system costs, as the modules serve both structural and energy producing functions for the building. However, the complex designs and landscapes of PV systems in urban and suburban environments often create situations that prevent these systems from maximizing their power output potential.

Building integrated or mounted PV systems frequently operate with a reduced power output per kilowatt installed, as compared to rack-mounted arrays in open areas. One reason for this is that modules attached to buildings often cannot be installed at an optimal orientation or tilt angle, due to building geometry or aesthetic considerations. Non-optimal positioning leads to reduced insolation throughout the year, reducing output energy. In densely populated urban areas, air pollution may also block part of the sun's radiation, reducing output power (Wang, et al. 2006). Also, modules mounted adjacent to a building's façade do not experience as much convective cooling on their back sides. This causes them to operate at a higher temperature; for conventional silicon modules each operating temperature increase of 1°C reduces the output power by ~0.5%, so a moderate temperature increase can easily affect array performance. It is very important to understand and correctly model the behavior of PV cells under these conditions, given that PV systems in the built environment often operate with lower insolation and higher cell temperatures.

In order for a conventional, series-parallel connected PV system to operate optimally, all modules in the system must have the same electrical characteristics and receive the same incident irradiation, while operating at the same cell temperature. Building-tied systems in particular are susceptible to environmentally-caused nonuniformities in radiation and operating conditions, as they must be tightly coupled to the building façade. Building design constraints frequently necessitate varied panel orientations within an array, or panel placement in the shading paths of nearby objects such as buildings, vegetation, poles, or wires. Variations in available radiation, and corresponding cell temperature differences, are among the leading causes of power loss in BIPV systems (Woyte, Nijs and Belmans 2003). Therefore, it is important to understand and be able to quantify these losses, particularly in cases where monetary incentives are based on system performance, as they are for many utility rebate programs (Pennington, et al. 2008).

1.1.2 Losses From Nonuniform Conditions or Characteristics

A typical grid-tied residential or small commercial PV system configuration, consisting of one or more parallel strings of photovoltaic modules connected to the electrical grid through an inverter, is shown in Figure 1.1. When modules are wired in series strings, the same current must pass through each module (and thus each cell in the module, assuming the cells are wired in standard configuration) in the series, while the modules' voltages are additive. Conversely, when any array elements, such as strings, are wired in parallel, each string must have the same voltage while the string currents are independent of one another. Modules are placed in series strings to build up higher voltages, which are desirable to reduce wire sizes and maximize inverter efficiency. Similarly, parallel strings of photovoltaic modules may be installed to increase the current of the system, increasing the power output while keeping the voltage at a desired level.

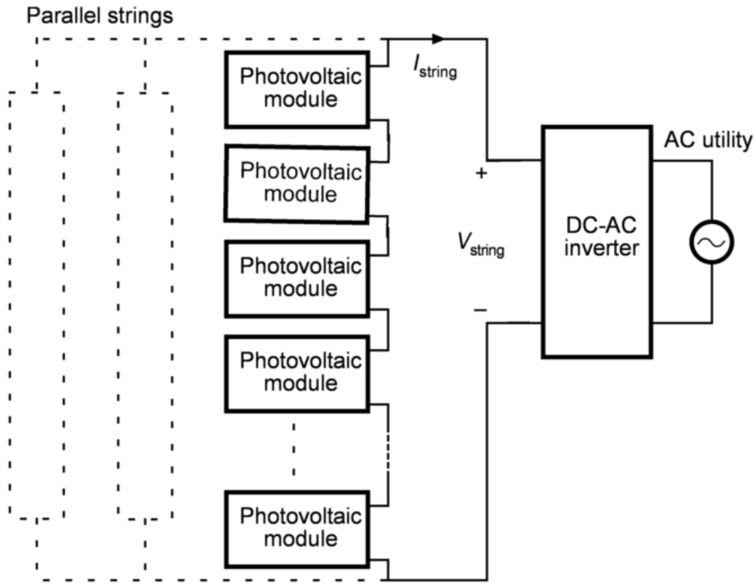


Figure 1.1. Conventional grid-tied PV system

Each PV generator in an array has its own operating point (current and voltage) that will produce maximum power; the point is determined by the generator's electrical characteristics, temperature and incident radiation. Variations in radiation or temperature between a PV system's modules or cells cause modules in the same array to have different maximum power operating points, yet in conventional PV installations all system elements must operate at one, centrally-determined point that maximizes the overall system power output. This is illustrated in Figure 1.2, where the maximum power point of a panel at 1000 W/m^2 occurs at a current of 5A, while the maximum point of a panel at 500 W/m^2 is at 2.5A. When operating conditions are not uniform for the entire array, portions of the array must sacrifice their individual power production potential, and the system does not operate at its maximum possible efficiency. In Figure 1.2 the system maximum (87W) is less than the sum of the maximum points from each panel individually (38W+78W=116W), as the system must operate at a lower current to ensure that the panel with lower irradiance is not bypassed and will contribute power. Power losses from nonuniform operating conditions are disproportionately large compared with the actual affected area, which indicates that they are "low hanging fruit" when looking for measures to improve system output.

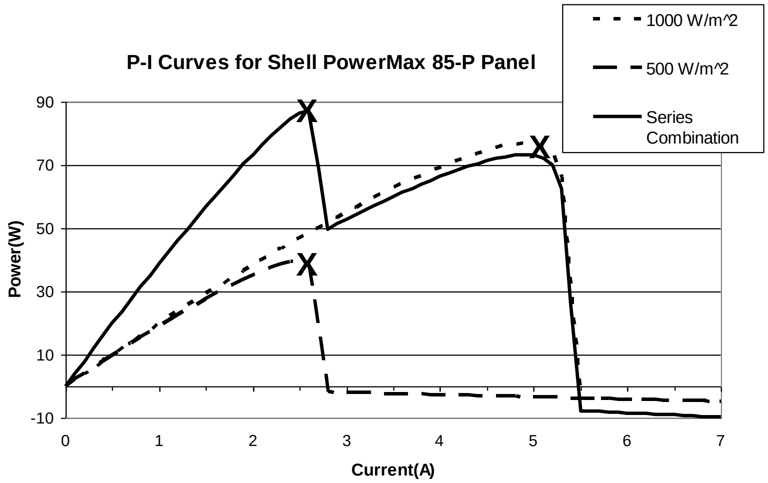


Figure 1.2. Power vs. current curves for modules with different radiation levels, and the power output for a series string consisting of the two modules combined. The three Xs mark the maximum power points of the three cases

Uniformity-related losses in PV systems have a variety of causes, including variation in panel orientation, partial shading, electrical characteristic mismatch, soiling, and snow (Driesse & Harris, 2010). Many authors have investigated these losses, but they tend to vary widely system to system and there are few general guidelines as to how they should be modeled in a detailed, accurate way. In commercially available tools, mismatch losses are usually accounted for using one or more simple derate factors, after the system's ideal energy output is calculated. While derate factors may be tuned for a specific array, to match a measured output, they do not provide a detailed or necessarily accurate picture of the system's true behavior.

1.1.3. Power Optimizers

One way to combat losses which arise from nonuniformities in PV arrays is to use modular power conversion and power point tracking, i.e. power optimizers, in PV systems. Power optimizers are power electronic devices – either DC-DC converters or DC-AC microinverters – incorporated in a PV systems at the sub-array level. These devices effectively decouple the modules from their series string as shown in

Figure 1.3, allowing each module to operate at its individual maximum power point while still satisfying the central inverter or grid current and voltage requirements. Power optimizers are available at the module level from several companies, including EnPhase, National Semiconductor, Tigo, eIQ, and others, and there is speculation that they may soon be offered directly integrated into PV modules, at the module or sub-module level (Wesoff, 2011).

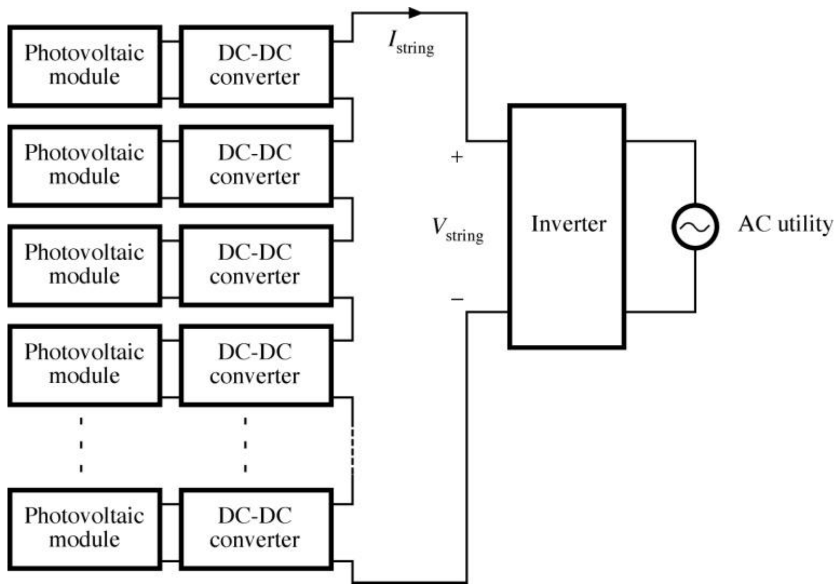


Figure 1.3: Grid-tied PV system with DC-DC converter power optimizers

As power optimizers are relatively new to the market, much of the published research regarding their performance [(Sridhar & Freeman, 2010); (Linares, Erickson, MacAlpine, & Brandemuehl, 2009); (Tsao, Sarhan, & Jorio, 2009)] is based on data taken under a limited set of conditions, using specific optimizers. Though it is clear that there are instances where these optimizers can provide a great benefit, published long-term monitoring data and/or simulations are scarce. While some authors [(Koirala, Sahan, & Henze, 2009); (Picault, Raison, & Bacha, 2010); (Poshtkouhi, Varley, Popuri, & Trescases, 2010); (Poshtkoui, Palaniappan, Fard, & Trescases, 2013)] have estimated the potential for these devices in different situations, there is not yet a set of guidelines for determining when they should be used in PV systems.

1.2 Research Objective and Scope

The goal of the proposed research is to develop a comprehensive methodology and model that allow accurate prediction of power losses caused by nonuniform electrical characteristics and operating conditions in grid-tied photovoltaic systems, as well as the potential for increased energy capture in systems which employ sub-array power optimizers. Investigation of these topics will provide a framework for more accurate loss modeling and determination of the value of power optimizers in a variety of PV system scenarios. This research focuses on the following:

- **PV generator (module or sub-module) model accuracy over the breadth of operating conditions that define nonuniformities**

- **System level power loss from mismatched electrical characteristics and nonuniform operating conditions**

- **Potential for power recovery and increased energy capture when using sub-array power optimizers**

- **Development of guidelines and methodology for determination of PV system level mismatch-related losses and resulting recoverable power, which may be incorporated into existing tools.**

1.3 Research Methodology

This research centers on the development of a unique, detailed, flexible simulation environment for modeling PV systems that permits specification of electrical characteristics and operating conditions at the PV cell level. Module and system level modeled performance are experimentally verified using I-V curve data collected on 27 arrays of different module technologies, including over 500 modules, installed in various locations in the Southwest U.S. Improvements are introduced to the module model to make it more robust over the full range of operating conditions commonly experienced by PV systems. The simulation environment and system model are then used for annual evaluation of losses and recoverable power, varying climate/weather conditions, array configuration and orientation, module electrical characteristics, shading, and power optimizer placement.

1.4 Significant Contributions

Significant contributions of this work, described in detail in the subsequent chapters, include the following:

(1) An extensive dataset of simultaneous module-level I-V curves, collected for 27 installed PV arrays in the Southwest U.S., ranging in age from newly installed to 11 years old.

These arrays are comprised of over 500 modules, representing six different PV technologies including mono- and polycrystalline silicon, hybrid silicon (a combination of mono and amorphous), and thin film including CdTe, CIS/CIGS and amorphous silicon. The data, taken under both high and low (and in some cases, medium as well) light conditions, will be extremely useful to the PV modeling and research communities.

(2) Investigation of parameter behavior with varied module operating temperature and incident irradiance for the standard single diode PV generator model, and proposed new methodology to improve model accuracy over the full range of typical PV operating conditions.

The proposed model modifications incorporate fully fitted I-V curves based on measured high and low light behavior of each module, and are shown to consistently improve performance predictions for arrays of different technologies under medium and low light conditions, which are more common in building integrated or mounted PV arrays.

(3) Statistical quantification of each array's performance variation coefficients (average absolute deviation of the module values from their array-level mean) at key I-V curve points.

These provide a representative set of guidelines for module-to-module variation of short circuit current, open circuit voltage, and maximum power point and its accompanying current and voltage, in arrays with realistic performance degradation. PV modelers may use this information to run statistical models of PV module performance variation and associated mismatch losses.

(4) Illustration of a variety of observed types of module-to-module performance variation found in installed PV arrays, as well as simulation and analysis of their associated annual mismatch-related energy losses.

This is accomplished using the measured module level I-V curve data described in (1) on this list. The mismatch-related energy losses are often less than 1%, even for arrays that have experienced field degradation, demonstrating that the commonly used “default mismatch derate” of 2% in many modeling tools is overestimating these effects.

(5) Development of detailed, cell-level shading simulation methodology and environment for calculation of annual energy losses due to partial shading on PV arrays.

These are used to assess the impact of shading and array configuration on PV array performance, as well as the impact of model simplification and granularity on predicted annual energy output. Such a detailed and flexible tool is not practical to include in commercial modeling software, but it is very valuable to use in developing guidelines that may be incorporated to augment the accuracy of other, simpler approaches.

(6) Assessment of the potential for use of sub-array power conversion and maximum power point tracking (via power optimizers) in residential PV arrays.

This includes examination of mismatched module electrical characteristics, partial array shading, and granularity of power optimization within an array.

1.5 Organization

The remainder of this work is divided into eight additional chapters. Chapter 2 is a review of current, relevant literature, including topics such as PV modeling, system performance under nonuniform conditions, and use of power optimizers. The literature review reveals that the topics covered in this research represent excellent opportunities to contribute to the body of knowledge in the PV research community.

Chapter 3 describes the multitracer data collection system design and methodology, as well as the arrays from which data were taken. It also includes a full uncertainty analysis, incorporating both measurement uncertainty and that which is derived from interpolation and extrapolation of different key points on the modules' current vs. voltage (I-V) performance curves. In Chapter 4, existing commonly-used single diode models of PV generators are compared and contrasted, and the I-V curves collected using the multitracer are used to reveal deficiencies in the existing models and their assumptions regarding parameter behavior. A new modeling methodology is proposed, and shown to improve model performance over a range of PV operating conditions, for both crystalline silicon and thin film technologies.

Moving on to annual PV simulation at the array level, Chapter 5 explains the detailed and flexible modeling environment developed and used in this work, which allows the user to specify different PV system characteristics down to the cell level. This modeling environment is used for all annual simulations of PV system performance under nonuniform conditions in subsequent chapters. The model is validated with experimental data at both the PV module and array levels under unshaded and partially shaded conditions.

Chapter 6 focuses on module-to-module electrical characteristic variation within PV arrays, again using the data collected with Chapter 3's multitracer system, and the resulting PV system output energy losses when arrays are unshaded. This chapter includes sections on statistical distributions of module performance, effects of measurement uncertainty, modeled vs. measured mismatch power losses, and variations in annual mismatch energy loss with different mismatch mechanisms and array configurations. The emphasis shifts to partially shaded PV arrays in Chapter 7, which examines different degrees of shading and their associated annual energy losses, as well as evaluation of more simplified shading models. Both Chapter 6 and Chapter 7 also focus on the opportunity for increased energy capture in arrays which employ power optimizers. Chapter 8 presents a case study comparison of different PV models used in this work, examining annual array performance, and mismatch and shading predictions for different PV technologies. Finally, Chapter 9 reviews the conclusions and contributions of the work, and suggests areas for future related work.

CHAPTER 2

BACKGROUND AND RELATED WORK

2.1 Climate and Radiation Models

PV simulations often use hourly climate data as an input, which in the US is most frequently provided as Typical Meterological Year (TMY) data (NSRDB, 2008). TMY data are selected by determining each month's average climate conditions for a site over a period of years, and then for each month using data from the year that is most representative of the average (Honsberg & Bowden, 2010). Given the fact that weather varies year to year, and that TMY data are only actually measured in a few sites, and calculated for the rest, it is fair to say that these data represent one of the largest sources of uncertainty in annual energy prediction models of PV systems. As loss estimation and the potential for power recovery involve comparison between simulations, rather than energy prediction, these uncertainties have little effect on the proposed research.

Ideally, irradiance is measured in the plane of the array, but oftentimes these data are not available and incident radiation must be found by performing a translation of horizontal global, beam, and/or diffuse radiation onto the tilted plane. This has been the subject of extensive study for decades, with numerous models proposed, many of which have been tuned to specific regions or climates. In the US, there are three main models used. One, the Liu and Jordan model, is isotropic (Liu & Jordan, 1963), and two, the HDKR (Reindl, Beckman, & Duffie, 1990), and Perez (Perez, Seals, Ineichen, Stewart, & Menicucci, 1987) (Perez, Iniechen, Seals, Michalsky, & Stewart, 1990) are anisotropic, accounting for circumsolar irradiance and horizon brightening. Other less frequently used models such as the Gueymard model (Gueymard, 2009) are not considered in this study.

Several authors [(Notton, Poggi, & Cristofari, 2006); (Loutzenhiser, Manz, Felsmann, Strachan, Frank, & Maxwell, 2007); (Abella, Lorenzo, & Chenlo, 2003); (Fanney, Dougherty, & Davis, 2009)] have compared these three models' ability to calculate the total irradiance on a tilted surface. In each of these studies, performed in a variety of US and European climates, the newest Perez model (Perez, Iniechen, Seals, Michalsky, & Stewart, 1990) is found to give the most accurate results, particularly for vertical walls. All subsequent references to the Perez model in this section refer to this newest version. For optimally tilted arrays, one investigation (Cameron, Boyson, & Riley, 2008) shows that the Perez and HDKR models give very similar values, but the Perez model is slightly more accurate. In all the listed studies the anisotropic models are found to give significantly more accurate predictions than the isotropic model, suggesting that only the anisotropic models should be considered for this research.

Other studies have also examined the models solely for the prediction of diffuse radiation, which is of particular interest in partially shaded arrays. It is difficult to draw specific conclusions from these studies. One (Diez-Mediavilla, de Miguel, & Bilbao, 2005) shows that on south-facing surfaces in a cloudy climate, the HDKR, Perez, and Liu-Jordan models perform similarly with a RMSE of ~20%, while others in Iran (Noorian, Moradi, & Kamali, 2008) compare the diffuse radiation predictions of twelve different models, finding that for south-facing surfaces, the HDKR is the best performer, followed closely by Perez. For west-facing surfaces, however, the Perez model definitively outperforms all of the other models. In all of these cases, the isotropic model does not perform particularly well. In Israel, one study (Evseev & Kudish, 2009) compares ten models in a latitude-tilted, south-facing scenario for cloudy, partly cloudy, and full sun conditions. It finds that the Perez model is the most accurate overall, but the Perez model in their climate was actually among the poorest performers in cloudy situations, and the HDKR model slightly outperformed the Perez model in full sun. Others (Mondol, Yohanis, & Norton, 2008) develop a site-specific global diffuse correlation correction and show it to be very effective; it is clear that the accuracy of diffuse radiation measurements is climate and location dependent, and that a variance from modeled diffuse radiation values should be considered to account for uncertainties.

2.2 Photovoltaic Generator Models

2.2.1 Diode Models

Single Diode

The single diode representation of a photovoltaic cell/module (Figure 2.1) is perhaps the easiest physical-parameter-based model to use, and thus most commonly found in research. The model is typically used to determine I-V curves using either four or five parameters: I_L is the light current, I_0 is the diode reverse saturation current, R_S is the series resistance, a is the modified ideality factor, and R_{SH} is the shunt resistance, which is assumed to be infinite in the four parameter version (Duffie & Beckman, 2006). Though the 4 parameter simplified model is less computationally intensive, its accuracy for different technologies is debatable: while some authors [(Cristea, Damian, Chiri Oiu, Zaharie, & Costache, 2008); (Cristea, Chiritoiu, Costache, Zaharie, & Luminosu, 2010)] have found that it matches module I-V curves over a wide range of irradiance, others [(Celik & Acikgoz, 2007); (Damian, Cristea, Luminosu, Zaharie, Costache, & Chiritoiu, 2008)] found that it overpredicts energy capture around solar noon under high irradiance conditions..

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{a}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad \textbf{2.1}$$

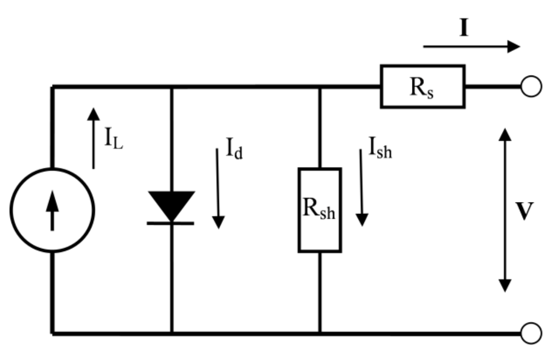


Figure 2.1: Single diode model

While the 5 parameter single diode model does require numerical methods to solve, it also has the advantage that it can be developed using only data provided by manufacturers at standard test conditions

(STC – 1000 W/m^2 and 25°C). However, when the model parameters are determined using only these conditions, accuracy is compromised at low irradiance [(Schumacher, Pietruschka, Eicker, & Catani, 2007); (De Soto, Klein, & Beckman, 2006)]. Newer performance data requirements for manufacturers [(CEC, 2008); (IEC, 2011)] dictate that data for a variety of irradiances and temperatures be made available, which may be used to improve the models' predictions. This is attempted in one study (Boyd, Klein, Reindl, & Dougherty, 2011) and it shows very little improvement, but the work was done in an environment with high incident irradiance uncertainty, which may have skewed the results. Given the availability of new PV module data, further investigation into this topic is warranted.

Two Diode

A difficulty with the single diode model is that it assumes that *n*, the diode ideality factor, remains constant when it in fact varies with voltage (Honsberg & Bowden, 2010). A more accurate representation is the double diode model (Figure 2.2), with the second diode in parallel with the first and designed to account for carrier recombination, as originally proposed decades ago (Sah, Noyce, & Shockley, 1957). In the two diode model, the first diode is representative of the diffusion and surface recombination, and the second diode accounts for recombination in the depletion region, which is most common at higher irradiances. (Wolf, Noel, & Stirn, 1977) studied the model and found that the division between diodes is not quite so straightforward, but the concept still holds. The two-diode model is especially suggested for accurate modeling of low irradiance conditions [(Schumacher, Pietruschka, Eicker, & Catani, 2007); (Stamenic, Smiley, & Karim, 2004)].

$$I = I_L - I_{o1} \cdot \left[\exp\left(\frac{V + I \cdot R_s}{a_1}\right) - 1\right] - I_{o2} \cdot \left[\exp\left(\frac{V + I \cdot R_s}{a_2}\right) - 1\right] - \frac{V + I \cdot R_s}{R_{sh}} \qquad \textbf{2.2}$$

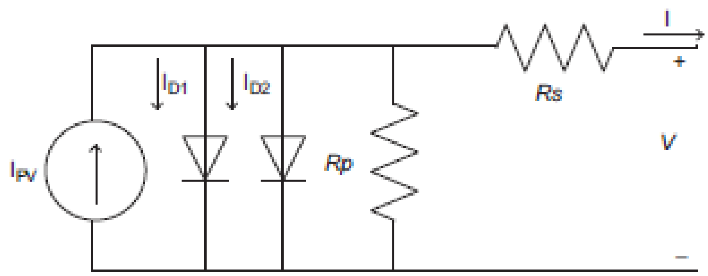


Figure 2.2: Two diode model

One downside to the two diode model is that its parameters can be difficult to accurately determine, often requiring natural log plots of dark measurements (King, Hansen, Kratochvil, & Quintana, 1997) By making a few simplifying assumptions, some authors (Ishaque, Salam, & Taheri, 2010) are able to solve the two diode model in the same way that the single diode model is solved, and they find that it gives closer results between simulations and measured data for a variety of panel types than the single diode model. It is noted though that in this work they do not indicate exactly how their single diode model's parameters are calculated. Several other authors [(Hyvarinen & Karila, 2003); (Charles, Mekkaoui-Alaoui, Bordure, & Mialhe, 1985); (Eikelboom & Reinders, 1997)] attempt to validate the two diode model at different irradiance and temperature levels, and find that like the single diode model, it is less accurate at low irradiance. Given its added complexity, unless the two diode model allows for a significant increase in accuracy, it likely makes more sense to continue to use and attempt to improve the single diode model.

2.2.2 Empirical Models

The most popular empirical PV generator model in the US is the King/Sandia Model (King, Boyson, & Kratochvil, 2003), which includes many detailed empirical factors derived from linear fits of hundreds of I-V curves taken at varying irradiance and temperature combinations. It is generally agreed that the K/S model provides the most accurate modeling across a wide range of operating conditions and technologies, particularly non-crystalline-silicon technologies, but the empirical coefficients have only been identified for a limited set of modules, as collection of the I-V curves necessary to generate the coefficients is very time consuming. A recent NIST study (Fanney, Dougherty, & Davis, 2009) compared K/S model predictions to measured data over a year for four different technologies mounted vertically, and found that agreement was generally good, within 5-6% on both a monthly and annual basis when using pyranometer in-plane irradiance data. Matching was worst during the summer months when the sun's angle of incidence was highest, suggesting reflective or other spectral light losses that may not have been accounted for in the model.

A comparison between the models available in NREL's System Advisor Model (SAM), including both the King/Sandia and the CEC single diode models, has been performed (Cameron, Boyson, & Riley, 2008), comparing them to measured data from a crystalline silicon array in Albuquerque, NM. In this sunny climate, the two models actually performed with similar accuracy, suggesting that there may be little benefit to using such a detailed model, at least for crystalline silicon technologies. The two models use different algorithms to determine absorbed radiation and cell temperature, so it is unclear to what extent the PV generator models actually agree, as opposed to being influenced by potential variances in input parameters. However, given the relatively good agreement in the comparison study, and the lack of availability of K/S model coefficients for many modules, this work focuses on the single diode model.

Current work at Sandia (Hansen, 2013) uses the PV I-V curve data that will be available from the requirements of IEC 61853 (IEC, 2011) to empirically determine the single diode model reference parameters. While this method is successful for many modules, the implementation does generate unrealistic coefficients for some, suggesting a need for improvement. Most importantly though, it is only calculating the single diode parameters under reference conditions (often Standard Test Conditions), and uses published modeling relations (De Soto, Klein, & Beckman, 2006) to translate the parameters to other irradiances and temperatures. These parameter translations should be further studied and modified as necessary as more data for each module become available.

2.2.3 Cell Temperature

Much research has been done to determine the best way to find the cell temperature for modules deployed in arrays. The King/Sandia model (King, Boyson, & Kratochvil, 2003) uses an empirical relation, derived through module testing, which is able to predict the module temperature within 5˚C accounting for the mounting method, giving an uncertainty of less than three percent. A recent model (Skoplaki, Boudouvis, & Palyvos, 2008) also predicts temperature based on panel mounting, while the standard NOCT model (Duffie & Beckman, 2006) is intended for modules with both sides exposed to the same ambient temperature. A comparison of modeled and measured cell temperatures, using these three models, shows that the King/Sandia model is accurate for both rack mounted and BIPV module temperatures, while the Skoplaki and NOCT models lose accuracy in the case of BIPV (Neises, 2010). For this reason this research will use the King/Sandia temperature model.

2.2.4 Absorbed Radiation

It is well understood that not all of the incident irradiance on a PV module is usable, and that usability varies with technology type and module construction. Two factors that have an important impact on absorbed radiation in PV modules are the spectral content of received radiation (which can be related to air mass) and the angle of incidence (AOI) of its beam component. Low irradiance conditions tend to be at high AOI and high air mass or high diffuse fraction (Ransome, 2010) so is important to account for how different modules and technologies respond to these conditions.

The glazing on solar modules causes some reflectance of a portion of the incident radiation, and this reflectance is angle-dependent. This leads to AOI modifiers, used to attenuate the useful absorbed radiation available to a PV cell. The AOI modifier may be determined analytically (Duffie & Beckman, 2006) using glass/glazing properties and solar angles, or it may be determined purely empirically, as in the King/Sandia model (King, Boyson, & Kratochvil, 2003). AOI modifiers ensure that short circuit current is not overestimated, particularly in building integrated or mounted systems that are not oriented optimally and thus receive a larger percentage of their incident irradiance at high AOI.

The useful/absorbed radiation is also affected by the incident spectral content, and the Sandia model (King, Boyson, & Kratochvil, 2003) uses empirical modeling to determine an air mass factor, used to determine changes in incident radiation spectra when the sun is at different angles relative to the PV modules. The equation for this air mass factor is also used in the Wisconsin/CEC model, though it was found that the coefficients used to determine the air mass factor can often vary without too much effect on predicted performance (De Soto, Klein, & Beckman, 2006). Thus it is possible to just use one set of coefficients for various technologies when correcting for spectral variation caused by air mass. Under clear skies, detailed calculations of spectral variance seem not to have a large effect in crystalline silicon. However, spectral variance and AOI have a large impact on the performance of multi-junction cells [(Marion, 2010); (Gottschalg, Betts, Infield, & Kearney, 2004); (Buflasa, Gottschalg, & Betts, 2007); (Krishnan, Schuttauf, van der Werf, Hassanzadeh, van Sark, & Schropp, 2009)], and in very cloudy climates spectral variance should be accounted for (TamizhMani, Dignard-Bailey, Thevenard, & Howell, 1998). None of these studies covers the response of modules in shade, which may receive the diffuse radiation portion and possibly some level of filtered beam radiation.

When predicting the performance of two or more PV systems using the same set of hourly radiation levels, use of AOI and air mass modifiers for a specific technology is the most practical accurate method. When comparing models to measured data, however, the concept of "effective irradiance" is often used. In this method, a module's short circuit current (I_{sc}) is measured at approximately 1000 W/m^2, and then assumed to vary linearly with irradiance [(King, Boyson, & Kratochvil, 2003); (Zhu, Betts, & Gottschalg, 2009); (Marion, Rummel, & Anderberg, 2004)]. Thus irradiance is determined not by a pyranometer or other sensor, but directly by the type of module under test. Even in controlled indoor test environments, such as on Class AAA testers, there are still significant uncertainties related to temporal and spatial distribution of light, as well as light spectrum, especially at low irradiances when filters are used (Herrmann, et al., 2010). Assuming a linear I_{sc} has potential to reduce uncertainty in radiation prediction for both indoor and outdoor testing, as it inherently accounts for module response to light uniformity and spectral variation.

However, it is noted that while the linear relationship between I_{sc} and effective incident irradiance holds to within 0.1% for crystalline silicon modules (Emery, Personal Communication, 2012), this is not the case for some other technologies. As noted in the single diode model in Figure 2.1, I_{sc} is not the equivalent of the generated photodiode current (I_L in the model); instead, I_{sc} includes the series resistance term, which inherently accounts for electron recombination and other cell processes. Some of these have been shown in thin film technologies to vary with voltage and light intensity (Hegedus, 2007). It is thus more accurate, if one wishes to measure irradiance with a linear current, to base it on photodiode current rather than I_{sc}.

2.3 Electrical Mismatch in Photovoltaic Generators

2.3.1 Standard Operation

Electrical mismatch in this work is defined as differences between PV generators' I-V curves, especially at "key" points such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power point current and voltage (I_{mp}, V_{mp}), for generators of the same make and model. Mismatch is most often caused by variations in manufacturing processes (manufacturing tolerances), defects/impurities, or physical degradation of PV generators as they age in working environments. In general, electrical mismatch arising directly from manufacturing tolerance in maximum power point current is thought to cause only minimal power loss in a PV array (Deline, Marion, Granata, & Gonzalez, 2011), as evidenced in Figure 2.3 where a 3% difference in maximum power point current results in only an 0.5% power loss. Electrical mismatch has received comparatively little attention when considering PV system design and modeling. However, some studies described later in this section attribute much larger power losses to mismatch, giving reason to believe that factors such as operating conditions and cell defects drive larger mismatch losses. Electrical mismatch is most often included in system models simply as a derate factor to be applied once all the annual calculations are finished.

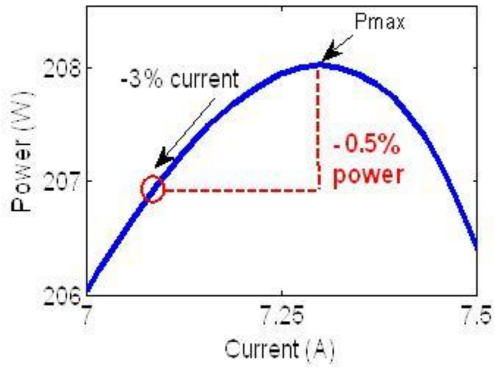


Figure 2.3: Power loss from variance in Imp (credit: C. Deline, 2011)

One primary reason for investigation of electrical mismatch is mitigation of power losses in a photovoltaic system. In this work loss from electrical mismatch is defined as the difference between the sum of each generator in an array's maximum power, and the maximum power actually produced when the generators are wired together. Electrical mismatch has the potential to cause greater panel losses when photovoltaic generators are wired together in a series, rather than parallel, configuration [(Bucciarelli, 1979); (Saha, Bhattacharya, & Mukherjee, 1988); (Zilles & Lorenzo, 1993); (Kaushika & Rai, 2007)], which leads to the conclusion that variance in current-related parameters has more impact than variance in other parameters, as current is constant for all of the elements in a single series string. For typical residential or small commercial sized PV arrays this is significant, as they usually are configured mostly in series strings with little parallelization.

In modeling electrical mismatch, some authors [(Bucciarelli, 1979); (Iannone, Noviello, & Sarno, 1998) (Bakas, 2012)], and those creating tools which can simulate mismatch at the cell level [(Bishop, 1988); (King, Dudley, & Boyson, 1996)] make one or two faulty assumptions regarding the variances of input parameters. First, they assume normal distribution, yet this is not always the case. In a study of 792 commercially available mono and poly crystalline modules, it was found that while some parameters did follow a normal distribution, the short circuit current had a Weibull distribution, which lead to greater current mismatch losses (Zilles & Lorenzo, 1990). In another study (Chamberlain, Lehman, Zoellick, & Pauletto, 1995) only the short circuit current had a normal distribution in a test group of 192 modules. It is clear from these results that parameters may have a variety of distributions; use of the incorrect distribution will result in incorrect mismatch predictions, particularly as the variances increase.

Second, many authors [(Bucciarelli, 1979); (Bishop, 1988); (Iannone, Noviello, & Sarno, 1998); (King, Dudley, & Boyson, 1996)] allow for independent variance of all of the physical input parameters that they consider. Many electrical parameter variances are instead correlated (Chamberlain, Lehman, Zoellick, & Pauletto, 1995), which indicates that electrical mismatch simulations by the other authors may include cell or module parameter combinations that likely could not occur together. A more accurate method for modeling mismatch would be to collect simultaneous module or even cell level I-V curves in an array, to ensure realistic parameter combinations and resulting mismatch.

Other authors [(Chamberlain, Lehman, Zoellick, & Pauletto, 1995); (Damm, Heinemann, & Pukrop, 1995)] take a different approach to simulating variations in electrical parameters between modules, using empirical module I-V curves to create prototypical modules for simulations. They build arrays from distributions of these modules so that their simulations include correlations between parameters. In simulations of 200 four-module, single or two-string arrays comprised of randomly selected I-V curves from an actual installed array of 192 modules (Chamberlain, Lehman, Zoellick, & Pauletto, 1995), all of the combinations show a loss due to electrical mismatch of less than 1%, so it is concluded in this work that typical electrical mismatch between modules causes little power loss in PV arrays. However, these simulations were conducted under conditions similar to NOCT (1000 W/m^2 and 47°C) and then normalized to NOCT, so do not account for mismatch at lower irradiance which is common in BIPV systems.

Judging mismatch losses at only NOCT neglects other operating conditions, which is important because one study shows that mismatch loss increases when irradiance is less than 500 W/m^2, though it may be virtually constant with temperature (Janoch, 1984). Another study (Damm, Heinemann, & Pukrop, 1995) focuses on annual simulations of arrays with characteristics taken from varying distributions of I-V curve characteristics from a 36-module installation. I-V curves are found for each module from 600-1000 W/m^2 and it is unclear whether their accuracy was tested at lower irradiances. Simulations are performed for both sunny and cloudy climates, and mismatch losses are found to range from ~1-4.5%, with larger losses found in arrays with fewer parallel strings located in cloudy climates. This work also touches on the concept of recoverable power at the module level, though it is not the main focus. The losses found are significant, and illustrate the importance of examining mismatch losses over an annual range of operating conditions, perhaps with added scrutiny of model accuracy at lower irradiance.

2.3.2 Reverse Bias

When PV generators are wired together in series, and all must pass the same current, those that would optimally operate at a lower current (because of shading, defects, etc) may be forced to operate at the higher current of the other generators. If the higher current exceeds their short circuit current, they will operate in reverse bias with a negative voltage potential across them, dissipating power. Reverse bias characteristics of PV generators are not generally tightly controlled by manufacturers, leading to large variation which has been noted for decades [(Lopez Pineda, 1986); (Spirito & Albergamo, 1982); (Spirito & Albergamo, 1984)]. In some generators the reverse bias behavior is predominately controlled by shunt resistance, while in others it is governed by avalanche breakdown. Even when the operation of PV cells is fairly consistent in the forward bias region, it can vary widely in reverse bias (Alonso-Garcia & Ruiz, 2006).

Reverse bias behavior is often modeled using Bishop's equation (Bishop, 1988), which includes an extra term for breakdown voltage and an avalanche multiplication factor. More detailed models have also been developed (Alonso-Garcia & Ruiz, 2006) but are not necessarily more accurate in simulations given the often unknown variability of reverse bias characteristics. Instantaneous shading simulations [

(Alonso-Garcia, Ruiz, & Herrmann, 2006); (Deline, 2009)] show that losses do depend on reverse bias characteristics, with system losses varying depending on which cell in a module is shaded. This behavior may or may not have a significant effect in annual simulations; further investigation is warranted.

2.3.3 Degradation

As PV generators are exposed to field conditions, their performance may degrade as a result of encapsulant discoloration, increased series resistance (such as from weak solder bonds), and reduced shunt resistance (such as from damaged crystals or other impurities) (Meyer & Van Dyk, 2004). This degradation is often not uniform throughout an array, which has the potential to lead to more mismatch between PV generators as an array ages. While many researchers [(Jordan & Kurtz, 2011); (Jordan, Smith, Osterwald, Gelak, & Kurtz, 2010); (Skoczek, Sample, & Dunlop, 2008); (Ishii, Takashima, & Otami, 2011)] examine degradation rate over time for various technologies, they tend to focus only performance at standard test conditions, as this is what manufacturers' warranties cover. Most studies also concentrate only on system-level degradation losses, though one (Jordan, Wohlgemuth, & Kurtz, 2012) does view module-to-module mismatch reported in literature, showing a correlation in most studies between array age and increased mismatch in short circuit current and maximum power point, especially for arrays that are over 20 years old. This illustrates the importance of investigating mismatch in arrays which have been deployed in the field for a period of time.

2.4 Partially Shaded PV Arrays

In a series string of both unshaded and shaded PV panels, the unshaded panels will have a higher optimal power producing current. If the shaded panels in a string are forced to operate at the higher optimal current of the string's unshaded panels, which may exceed their short-circuit current, it is likely that their cells will become reverse biased (negative voltage) and actually dissipate power rather than produce it. To limit power losses associated with this dissipation, and also to keep the array from being damaged from heat generation, most PV panels have bypass diodes in their junction boxes, each serving a group of 12-24 cells. These allow a string of modules to operate at the higher optimal (unshaded) current, bypassing groups of shaded cells that would otherwise produce a large negative voltage at this high current. However, when groups of shaded cells are bypassed, any power that they could have produced at their lower optimal operating current is lost. A partially shaded string of modules essentially has two options for operation, both of which result in sub-optimal power output. It can either operate at a current that maximizes the unshaded modules' output but bypasses the shaded modules, or it can operate at a lower current which allows the shaded modules to produce some power, but decreases the power produced by each unshaded module.

In a multi-string system, the power lost under partially shaded conditions is determined not only by the diffuse fraction of the available radiation and percentage of the array shaded, but also much more by the location of the shade pattern on the array. For instance, in a system with two parallel strings, if an equal portion of each of the strings is shaded, then each operates in a manner similar to that described in the previous paragraph. If instead just one of the strings has bypassed cell groups, there are three possibilities: a) the unshaded string must operate at the lower voltage of the partially shaded string, b) the un-bypassed panels of the shaded string must operate at a higher-than-optimal voltage such that the string voltage is equal to that of the unshaded string but with fewer contributing panels, or c) a combination of the two. All of these cases lead to less-than-optimal power production, and this adds a layer of complexity when attempting to predict the performance of a partially shaded, multi-string PV system.

2.4.1 Shade Modeling

In the research on partial shading, the shade itself is modeled in a variety of different ways. Some authors model the light available in shade as the diffuse fraction, taken from anisotropic or isotropic sky models, where the circumsolar diffuse (if applicable) is lumped in with the beam radiation, i.e. not available. This model has been shown to agree well with measured irradiance in a shading test case (Drif, Perez, Aguilera, & Aguilar, 2008). Others [(German Energy Society, 2008); (Rogalla, Burger, Goeldi, & Schmidt, 2010); (Paraskevadaki & Papathanassiou, 2010)] simply assume that the light in shade is a fraction of the total available, somewhere between thirty and seventy percent depending on obstacle location and opacity. These two methods lead to very different light levels predicted in shade, but the impact of this has not been studied. Furthermore, there are differing opinions as to how shade light levels should be modeled spatially. While some authors [(Johansson, Gottschalg, & Infield, 2003); (Catani, Gomez, Pesch, Schumacher, Pietruschka, & Eicker, 2008)] model the light available in shade as the average across a partially shaded cell or cell group, others [(Drif, Perez, Aguilera, & Aguilar, 2008); (Sera & Baghzouz, 2008)] model arrays with only two discrete light levels, "shaded" and "unshaded." Since the boundaries of shading obstacles near PV arrays are often not known with a great degree of precision, it is likely that this distinction has little consistent impact on simulation accuracy.

In addition, the effects of shading may be modeled at different levels (i.e. assuming that shade affects the array in cell, bypass diode substring, module, or string-sized "blocks") and it is unclear what level of granularity is advisable for a detailed simulation. Several authors [(Quaschning & Hanitsch, 1995); (King, Dudley, & Boyson, 1996); (Pongratananukul & Kasparis, 2004)] suggest simulating at the cell level, but this is only practical when examining single modules or small systems due to computation time. In a limited comparison between cell and substring (bypass diode) level modeling, it is found that there are some differences in maximum power point prediction between the two with shading, but the impact of this is not directly analyzed (Karatepe, Boztepe, & Colak, 2007). Other authors [(Deline, 2010); (Martinez-Moreno, Munoz, & Lorenzo, 2010)] advocate modeling shade at the substring level, as this reduces complexity with what is assumed to be low loss of data fidelity. Still others (Patel & Argawal, 2008) indicate that modeling may be done at the module level without sacrificing data quality, though this is not substantiated by any experiments or simulations. It is clear that modeling partial array shading at the cell level has potential to be the most accurate method, assuming one is able to map the exact shape of the shading object onto the array. However, the need to simplify calculations dictates that other levels should be further explored as potentially adequate modeling solutions.

2.4.2 Shade Impact

It is very difficult to determine a PV system's response to partial shading, as shading losses are complicated in conventional systems and depend on array configuration, shading extent and pattern, module type, and climate. To address this, the California Energy Commission has proposed a default "shade impact factor" (SIF) of two, meaning that shade on a system will reduce the power output by twice the percentage of the system's area that it covers (CEC, 2008). In another work (Deline, 2010), it has been proposed that the SIF should be proportional to the percentage of substrings in the array that are shaded, rather than the area, to address the importance of shade orientation. However the SIF in this work is still system-specific, rather than generalizable. Using the substring based SIF, it is estimated that annual shading losses are 17-22% for a residential rooftop system with higher than average shading. Inter-row shading effect on large field arrays has also been studied (Thakkar, Cormode, Lonij, Pulver, & Cronin, 2010), with an equation for shade impact in cases with regular shading, but this does not address the variable shade patterns often found on building integrated or mounted arrays.

With more moderate shading, other authors [(Woyte, Nijs, & Belmans, 2003); (van der Borg & Jansen, 2003); (Chaintrueil, Barruel, Le Pivert, Buttin, & Merten, 2008)] find that long-term shading losses are on the order of 4-10%. A variety of authors [(Karatepe, Boztepe, & Colak, 2007); (Sera & Baghzouz, 2008); (Candela, Di Dio, Sanseverino, & Romano, 2007); (Qingshan, Jing, Haihong, Yukita, & Ichiyanagi, 2010); (Picault, Raison, & Bacha, 2010); (Ramabadran & Mathur, 2009); (Driesse & Harris, 2010); (Zanger, Bettenwort, & Laschinski, 2010)] have shown that the impact of partial shading decreases when PV modules or even cells within the modules are wired in parallel or cross tied, rather than wired in series – most shade losses arise from current mismatch rather than voltage. Strategies for mitigation of shading losses are well researched and understood, but analysis of shading-related losses thus far has been system-specific, rather than focusing on generalizable guidelines. It would be useful to monitor or simulate larger numbers of partially shaded PV systems to develop relevant guidelines for shading loss, as the opportunity for recoverable power in these systems can only be determined in comparison to accurate shading loss calculations.

2.5 Power Optimizers

Power optimizers, devices which allow for power conversion and maximum power point determination at the sub-array level, have gained more research interest in recent years as more have become commercially available. These include both microconverters, which interface portions of the array to a central inverter, and microinverters, which interface the portions directly to the grid. At present there are at least six commercial manufacturers of microconverters and eight of microinverters at the module level (Burger, Goeldi, Rogalla, & Schmidt, 2010) with other products available at the string level as well. Over the past decade there have been a variety of papers regarding specific converter and inverter topologies and control strategies [(Sridhar & Freeman, 2010); (Linares, Erickson, MacAlpine, & Brandemuehl, 2009); (Tsao, Sarhan, & Jorio, 2009); (Walker & Sernia, 2004); (Roman, Alonso, & Ibanez, 2006); (Roman, Martinez, Jimeno, Alonso, Ibanez, & Elorduizapatarietxe, 2008)]. A more recent work (Alonso, Roman, Ibanez, Martinez, & Egido, 2010) focuses on the limitations of microconverter conversion range when used in situations with significant mismatch. All of these works are predominately focused on the technologies themselves, rather than the potential for their use.

There are also numerous publications dealing with the potential for power optimizers using short-term or instantaneous examples of array scenarios to illustrate their operation. Some of these come from the manufacturers themselves [(Sridhar & Freeman, 2010); (Mann, Bar-Asher, Fishelov, Rosner, Handelsman, & Berdner, 2010)], and they tend to include scenarios selectively chosen to paint products in a favorable light. Their claims that power optimizers improve array performance by 30% or more because of soiling or moderate shading may be misleading, as exact information on the experiments is not included. Other authors [(Koirala, Sahan, & Henze, 2009); (Picault, Raison, & Bacha, 2010); (Poshtkouhi, Varley, Popuri, & Trescases, 2010)] also look at instantaneous conditions with partial shading on different array configurations, finding that the potential benefit of power optimizers varies from <5% to 30% or more, depending on the array layout and light distribution. Again though, these are for specific scenarios which may not normally occur throughout the year, so longer term monitoring or simulations are preferred.

In an annual simulation of a residential roof-mounted array with fairly extensive shading (Deline, 2010) it is suggested that power optimizers can provide a 5-10% improvement in total power output, with certain assumptions made about shaded behavior of the array. This study examines two shading scenarios on a dual-string array, assuming that the shading is either isolated or distributed, but is not verified against actual array performance using power optimizers. Conversely, another study with less shading (Woyte, Nijs, & Belmans, 2003) finds that there is almost no advantage to having inverters at the module or string level over the central level. An investigation of power optimizers at different levels (module, string) in a utility-scale array (Elasser, Agamy, Sabate, Steigerwald, Fisher, & Harfman-Todorovic, 2010) indicates that there could be benefit if the array experiences significant shading, as from cloud cover, and annual simulations in this case indicate potential increased energy capture of 4-12%. In this case the array is simulated only at the module level, which may affect shade loss prediction. A very recent study using a detailed, cell-level annual simulation tool (Poshtkoui, Palaniappan, Fard, & Trescases, 2013) found that power optimizers could provide annual gains of 12-62% in partially shaded systems; however, correspondence with the author indicated that the partially shaded modules were not simulated with bypass diodes, invalidating the results.

In a general assessment of the potential for power optimizers in shaded conditions, it is noted that while they may provide large gains in instantaneous situations, there are several factors that decrease the gains over time: shadows move so the worst case losses are fleeting, shade tends to occur late in the day when there is less power to harvest, and most arrays are designed to avoid shade in the first place (Rogalla, Burger, Goeldi, & Schmidt, 2010). Thus it becomes very important to properly model an individual array, using a well-designed simulation tool to determine the best power conversion solution.

Extensive testing of prototype DC-DC converters in situations with shading and soiling on side-by-side identical control and test arrays (Sanz, Vidaurrazaga, Pereda, Alonso, Roman, & Martinez, 2011) shows that there is a large range of potential benefit, depending on degree of mismatch, climate, and reliability of inverter maximum power point tracking. For many cases with little mismatch, the converters actually have a negative impact on power production due to their inherent insertion and efficiency losses. While the results of this work may be skewed by the devices used (prototypes are not highly efficient) and the possibility of undetected differences between the side-by-side arrays, it is likely that power optimizers do have a negative effect on power production under certain conditions. A review of the current state and best practices using power optimizers (Deline, Marion, Granata, & Gonzalez, 2011) indicates that while there are very general guidelines for their use, the ultimate decision must still be system-specific, as sometimes they provide benefit and sometimes they do not. Unfortunately, there are no generally accepted comprehensive guidelines or detailed modeling tools currently available to accurately assess the mismatch losses and potential for recoverable power in PV systems.

2.6 Photovoltaic System Modeling Tools

A recent review of available PV system modeling tools (Klise & Stein, 2009) indicates that there are many simulators used worldwide, with user inputs ranging from simple to extremely detailed. These tools use a range of models for climate, radiation, and PV generator performance, but most relevant to this research is the way that they handle system losses, specifically losses due to mismatch within the system. All systems, simple or detailed, model electrical mismatch using a single default or user-entered derate factor, applied after the system power for a particular time step is calculated. Calculation of shading losses vary from tool to tool, with the simplest modeled simply as a derate factor. At a mid-level of complexity, tools such as System Advisor Model (NREL, NREL System Advisor Model (SAM), 2011) allow users to enter derate factors hourly, either individually or for the entire year on a month-by-month basis. The most detailed tools, such as PVsyst (PVsyst, 2011), PV*SOL (Solar Design Company, 2011), and insel (insel, 2011) use 3D shading obstacle simulation to map the object's shadow onto the array for each simulated timestep. However they then account for the effects in a simplified manner, avoiding full system I-V curve calculation, so the results are not necessarily accurate – in the case of PVsyst for instance they are only meant to give an upper and lower bound on the shade impact (Mermoud & Lejeune, 2010). Though the detailed tools do allow simulation of arrays with commercially-available power optimizers, it is difficult to use the simulations to determine the benefit from the optimizers if the original loss calculations are not correct.

Publications comparing simulated and measured array data for a partially shaded array, or an array known to have significant mismatch between modules, are difficult to come by. While insel is shown to correctly model the luminance on a partially shaded array (Catani, Gomez, Pesch, Schumacher, Pietruschka, & Eicker, 2008), no data are provided demonstrating that the predicted system power output matched the actual measured output. In one study using PVsyst (van der Borg & Jansen, 2003) it is shown that the tool over-estimates the magnitude of the mismatch loss. It is clear from this published research, or lack thereof, that more guidelines for accurate modeling of mismatch losses, and verification of methods for this type of modeling, would be very useful.

2.7 Summary

The preceding literature review clearly supports all of the goals of this research:

(1) Improve and/or validate PV generator (module or sub-module) model accuracy over the breadth of operating conditions that define nonuniformities

Extensive research on the accuracy of diode models for PV generators has shown that they are less accurate at low irradiance; however, new availability of low irradiance data will enable the modification of models to account for non-standard test conditions, making this a timely research topic.

(2) Develop methodology to define and quantify system level power loss from mismatched electrical characteristics and nonuniform operating conditions.

Studies of mismatched electrical characteristics in PV arrays have shown large variance in the magnitude of mismatch between generators, and increased mismatch losses under low irradiance conditions, yet there is not analysis of the factors affecting how it should be estimated or modeled at the system level. Since electrical mismatch is directly tied to the opportunity for recoverable power, this is clearly something that should be examined.

Similarly, though there is a large collection of research on power loss from partial shading in PV arrays, few studies focus on a methodology for modeling shade impact. Given the disproportionate losses that are found in many shading case studies, it is clear that such a methodology is desirable, particularly since the opportunity for recoverable power in partially shaded arrays is directly related to the initial losses.

(3) From the mismatch losses, develop guidelines and methodology for quantification of resulting recoverable power, which may be incorporated into existing tools.

Research on power optimizers and their effect in PV systems is gaining momentum, but thus far it mostly covers specific technologies or the potential for optimizers under specific conditions. There is evident interest in guidelines for the use of power optimizers, but at this point this topic has not been rigorously covered, creating a meaningful opportunity for the research described in this proposal to contribute valuable information to the PV community.

CHAPTER 3

DATA COLLECTION AND PROCESSING

To form a basis for models and analysis, simultaneous, module-level I-V curve data are collected over a range of ambient conditions for 27 arrays of 6 different PV technologies (over 500 modules total) in the southwestern U.S. This is done using a custom multitracer data acquisition system designed and built in partnership with the National Renewable Energy Laboratory (NREL). The following sub sections detail the system design, methodology for data acquisition and processing, and measurement uncertainty associated with the multitracer.

3.1 Array Identification

Data were collected for over 500 modules, deployed in 27 arrays located in Tucson, Arizona, Albuquerque, New Mexico, and the greater Denver area of Colorado. These arrays include six different PV technologies: mono- and polycrystalline silicon, amorphous silicon, hybrid silicon (a multijunction combination of mono and amorphous), cadmium telluride (CdTe), and copper indium (gallium) selenide (CIS/CIGS). All of the datasets are for arrays sized 6kW or smaller, typical of residential installations. Each of the arrays had been deployed for approximately 11 or fewer years at the time of testing in 2012, and they are fairly evenly divided between newer (5 years old or less) and older (more than 5 years old) PV systems. The arrays are either ground mounted or roof mounted (Figure 3.1) with unobstructed airflow on the modules' back sides.

A

B

Figure 3.1. Ground mounted PV systems in Tucson, AZ (A) and roof mounted PV system in Boulder, CO (B)

Table 3.1 and Table 3.2 show a summary of array characteristics for the crystalline silicon and thin film arrays, respectively. The technology type of the crystalline arrays is indicated in their names, while the thin films technologies are excluded to preserve data source anonymity. An "A" in the array name designates newer arrays, while a "B" designates those which have been deployed longer. More details for each array are found in Appendix A.

Table 3.1 Details for crystalline silicon arrays

Array	# Panels	Age (yrs)	Configuration
Mono 1A	24	1	mult. strings
Mono 2A	9	3	single string
Mono 1B	21	8	single string
Mono 2B	21	8	single string
Mono 3B	27	8	single string
Mono 4B	20	9	mult. strings
Mono 5B	9	8	single string
Mono 6B	18	6	mult. strings
Poly 1A	30	4	mult. strings
Poly 2A	15	5	mult. strings
Poly 3A	11	1	single string
Poly 1B	21	7	single string
Poly 2B	21	7	single string
Poly 3B	18	6	mult. strings
Poly 4B	10	9	single string
Poly 5B	32	11	mult. strings
Hybrid 1A	12	5	mult. strings
Hybrid 2A	15	3	mult. strings
Hybrid 1B	8	9	mult. strings
Hybrid 2B	8	9	mult. strings

Table 3.2 Details for thin film arrays

Array	# Panels	Age (yrs)	Configuration
Thin 1A	20	1	mult. strings
Thin 2A	24	1	mult. strings
Thin 3A	24	1	mult. strings
Thin 4A	24	1	mult. strings
Thin 1B	14	6	mult. strings
Thin 2B	32	9	mult. strings
Thin 3B	27	9	mult. strings

3.2 System Design

I-V curve data are collected using a custom multitracer designed and built in partnership with NREL. This portable system controls and records simultaneous, module-level I-V curves for up to 3 strings of 9 panels each, subject to a 400V DC string voltage limit. Simultaneous curves were desired for this research, as module-to-module mismatch is more accurately judged when data are taken under the same or very similar operating conditions. A custom system was necessary as commercially available solutions are either not portable or not able to handle the number of panels found in typical residential-sized PV arrays.

The following list summarizes the main components of the multitracer and their functions; a full parts list is found in Appendix A.

- DC Load -- The NHR 4750-3 is a 3kW DC load which is used to step through string voltages during I-V curve sweeps.

- Printed Circuit Boards (PCBs) -- The three custom-designed PCBs include 100:1 voltage dividers to bring the panels' voltages down to a level suitable for data acquisition, a shunt resistor to measure string current, and fuse protection for each PV array input.

- Data Acquisition (DAQ) -- String level currents and panel level voltages are recorded using the MCC DAQ USB-2416 datalogger and AI_EXP32 channel expansion pack, which give a total of 32 24-bit, 1kS/s differential analog inputs. The temperature and irradiance sensors' outputs are recorded using the Advantech USB-4718, which can acquire up to 8 channels of thermocouple and analog voltage inputs.

- Wiring/Connectors -- Wires carrying significant current (the system home runs and attachments to the DC load) are 10-gauge PV wire. Voltage sense wires are 12-gauge. The system can support panels with MC3 or MC4 connectors.

- Pyranometer -- Plane-of-array irradiance is measured using an Eppley Precision Spectral Pyranometer (PSP) calibrated at NREL in June, 2010.

- Module Temperature Sensors -- Back-of-panel temperatures are measured using Omega CO1 T-type thin film thermocouples.

- Control Software -- DC load operation and data acquisition were controlled in LabVIEW, using a modified version of the NREL single panel I-V curve sweep code.

A schematic of the multitracer system with a single string is shown in Figure 3.2. When data are taken for multiple strings, the additional strings are connected to the DC load in parallel with the first. Figure 3.3 shows a detailed photo of the data acquisition hardware.

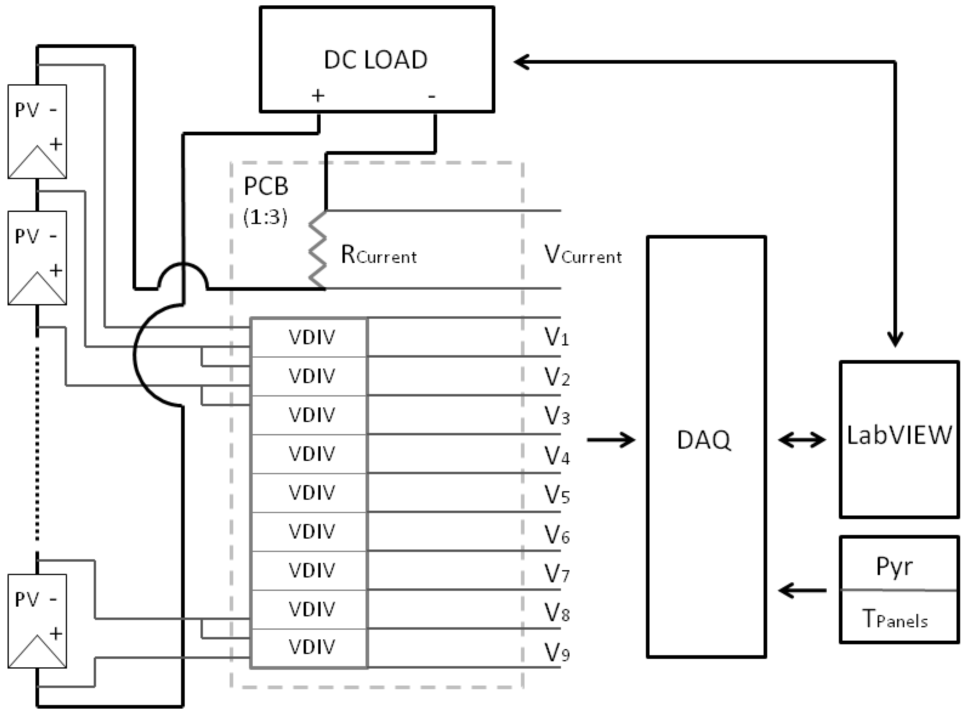


Figure 3.2. Multitracer system schematic

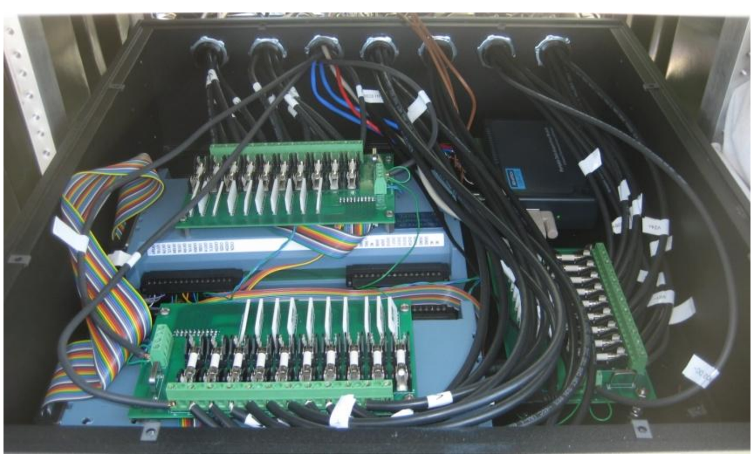


Figure 3.3. Multitracer data acquisition hardware

3.3 I-V Curve Acquisition

Before an I-V curve trace, the system's panels are disconnected from the inverter and each panel connection is fitted with a Y-connector so that their input and output voltages may be recorded using sense wires while the string current still flows through the series strings as during normal operation. Each string's positive and negative home runs are connected to the DC load and positive current shunt terminal, respectively, so that the DC load controls the string voltage. The pyranometer is mounted in the plane of the array, and 3-5 temperature sensors are affixed to the back of selected PV panels in the array (Figure 3.4), with effort made to measure temperature both in the middle and around the edges, thereby accounting for variations that may occur across the array due to airflow. As shown in Figure 3.4, the multitracer is located in the shade or under a light colored covering during runs so that the equipment temperature is kept as close to ambient temperature as possible.

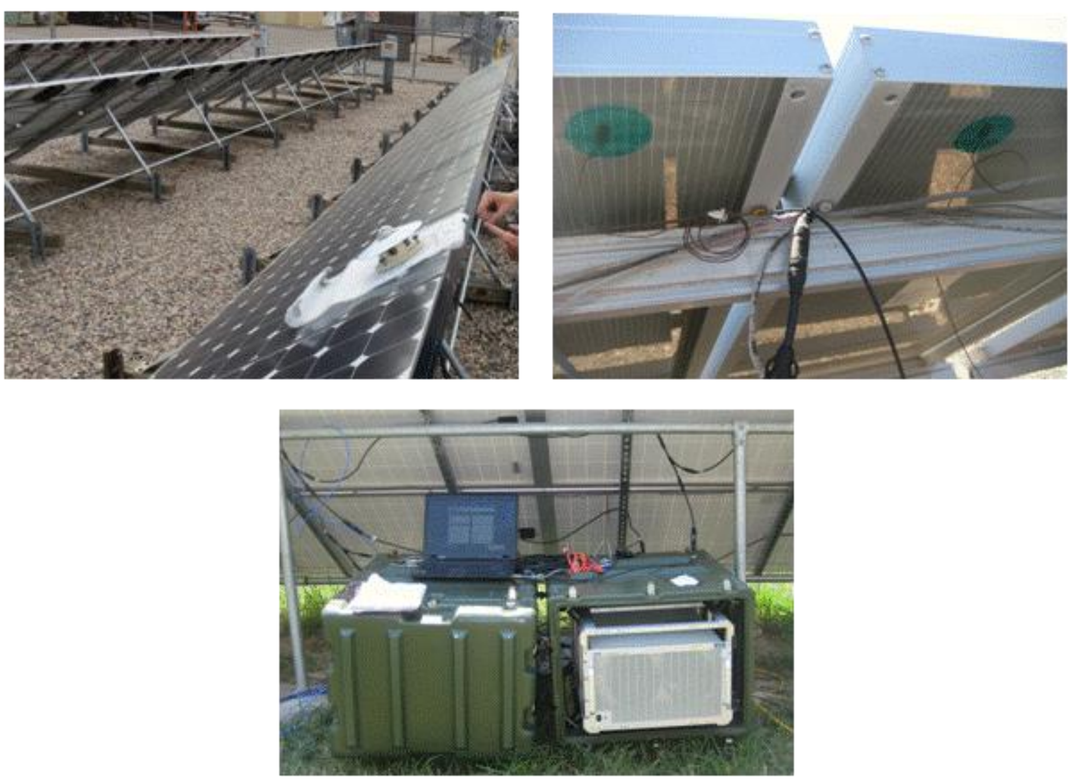


Figure 3.4. Pyranometer (top left), temperature sensors (top right) and multitracer system (bottom)

At the beginning of an I-V curve trace, the plane-of-array irradiance and back-of-panel temperatures are recorded. The DC load is then used to step the string voltage from its open circuit voltage (V_{oc}) down to zero in equal sized voltage steps, with 60-80 steps per run. At each voltage step the panel level voltages and string current(s) are scanned and recorded. As each step takes approximately one second, the entire run takes between one and two minutes. When the voltage sweep is completed, the temperatures and irradiance are again recorded, and these are averaged with those taken at the beginning of the run to determine the run's incident irradiance and panel temperature.

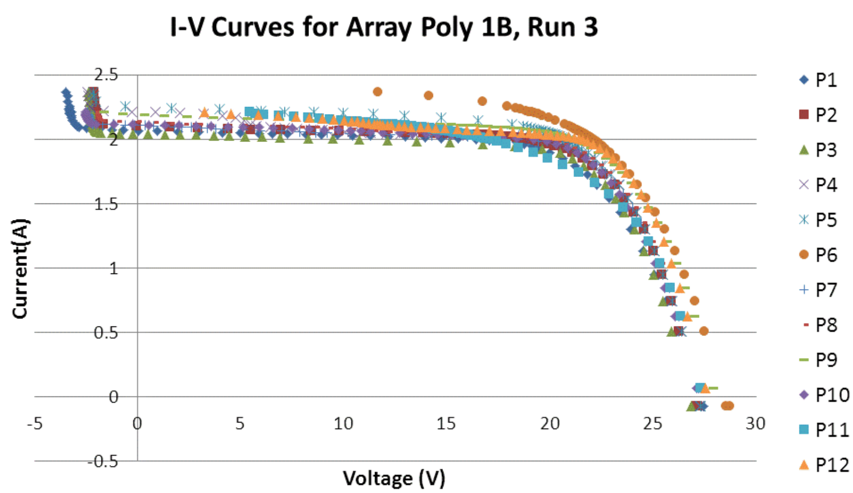


Figure 3.5 I-V curve data

Figure 3.5 shows a single run of I-V curve data taken for 12 panels in two series strings in a polycrystalline array. The panels clearly have a distribution of short circuit current, open circuit voltage, and maximum power point even though they are operating under the same conditions.

Each array has panel level data collected under ambient operating conditions, including both high (>850 W/m^2) and low (<300 W/m^2) irradiance. Some arrays or portions thereof also have medium irradiance data, typically 500-600 W/m^2. Panel temperature is not independently controlled, so varies with incident irradiance as expected. High irradiance data are gathered in the hours around solar noon on sunny days, and low irradiance data are obtained either early or late in the day, or under constant cloud cover. Because this system's I-V curve sweeps take longer than they typically would for just a single module, and because light conditions vary more quickly early and late in the day, incident irradiance may vary by as much as 3% over the course of a run, and panel temperature may vary by approximately 10%. These variations are discussed in the next section's uncertainty analysis. Additionally some arrays' module-level I-V curves are swept in more than one run under a given light level (high or low) because of DAQ, PV system, or wiring constraints, . For most of these arrays, the different runs' data are taken within minutes of one another, so operating conditions do not change drastically between panels in the same array. A full listing of each array and its data collection details is found in Appendix A.

3.4 Data Processing and Uncertainty Analysis

For use in model development and mismatch analysis, the measured I-V curves are processed to find each panel's critical points: I_{sc}, V_{oc}, P_{mp}, I_{mp}, and V_{mp}, as well as incident irradiance and back-of-panel temperature during each sweep. Methods to derive these characteristics and values are adapted from the NREL guide to outdoor I-V curve test method measurement uncertainty (NREL PERT Group, 2012). Measurement uncertainty is reported following the International Organization for Standardization (ISO) Guide to the Expression of Uncertainty in Measurement (GUM). (ISO, 1995) The expanded uncertainty for each measurement is evaluated with an approximately 95% confidence interval (coverage factor k=2), assuming that the combined uncertainty probability density follows a near-normal distribution with a large number of degrees of freedom.

3.4.1 Measured Voltage

Measurement

Module-level voltage is measured and recorded using the MCC USB-2416 data logger with channels configured differentially. The voltage inputs are sense wires which do not carry the PV system current, and the voltages are stepped down by a 100:1 ratio at the input to the DAQ.

Uncertainty

The main contributions to uncertainty in measured voltage are the uncertainty of the data acquisition device ($u_{V,MCC}$) and voltage dividers (u_{VDIV}) , and the precision with which the result is reported (u_{res}). In this and each of the following subsections, any resistive wiring loss is ignored, as the currents flowing through the sense wires are very small and the wire runs are either very short or the wires are oversized. Uncertainty in the standards which determine calibration of equipment and devices is also neglected, as these values are not known but usually contribute only a small amount to the total uncertainty.

The combined standard uncertainty is calculated as the square root of the sum of the squares (RSS) of the standard uncertainties of each individual component. In most cases manufacturers' uncertainties are assumed to have a rectangular distribution such that each component's standard uncertainty is

$$u_X = \frac{a}{\sqrt{3}} \qquad \textbf{3.1}$$

where *a* is its given uncertainty interval. This equation also applies to the resolution uncertainty of measurements; for the multitracer all are reported to three significant digits.

The uncertainty of the MCC DAQ voltage inputs includes an offset as well as parts based on the input value, range, and device temperature. Detailed uncertainty calculations are found in Appendix B. For the Caddock 1776-C681 voltage divider, the ratio uncertainty is 0.05%, and the resolution is of the voltage measurements is δ=0.0005V. Expanded uncertainty of the voltage measurements is then calculated as

$$U_V = 2 * \sqrt{\left(\frac{u_{V,MCC}}{\sqrt{3}}\right)^2 + \left(\frac{\delta}{\sqrt{3}}\right)^2 + \left(\frac{u_{VDIV}}{\sqrt{3}}\right)^2} \qquad \textbf{3.2}$$

With respect to those uncertainties which vary with temperature, it is assumed that the equipment in the shipping containers may reach temperatures of up to 50°C during operation under high and medium irradiance conditions, and up to 35°C under low irradiance conditions. As the voltage measurement uncertainty is dependent on temperature and quantity measured, Table 3.3 and Table 3.4 show the expanded uncertainty for several different voltages at varying irradiance levels.

Table 3.3 Uncertainty in voltage measurements -- high and medium irradiance

Vmeas	Standard Uncertainty (%)			Expanded Uncertainty (%)
	DAQ	*Volt Div.*	*Resolution*	
1	1.3770	0.05	0.05	1.59
5	0.2890	0.05	0.01	0.34
10	0.1530	0.05	0.005	0.19
20	0.0850	0.05	0.0025	0.11
50	0.0442	0.05	0.001	0.08

Table 3.4 Uncertainty in voltage measurements -- low irradiance

Vmeas	Standard Uncertainty (%)			Expanded Uncertainty (%)
	DAQ	*Volt Div.*	*Resolution*	
1	1.0680	0.05	0.05	1.23
5	0.2200	0.05	0.01	0.26
10	0.1140	0.05	0.005	0.14
20	0.0610	0.05	0.0025	0.09
50	0.0292	0.05	0.001	0.07

The measurement uncertainty is low in the range of typical PV maximum power point and open circuit voltages, less than 0.5%.

3.4.2 Measured Current

Measurement

String level current for up to three strings is measured across a current shunt resistor located on each custom PCB. The voltage across the resistor is recorded directly on the MCC data logger using differential inputs.

Uncertainty

Because current is measured from voltage across a resistor, the sources of uncertainty in the current measurement include uncertainty of the current shunt resistor calibration (u_{Rshunt}), uncertainty of the data acquisition device's voltage channels ($u_{V,MCC}$), and uncertainty introduced by the resolution of the measurements (u_{res}). The current shunt resistors have a manufacturer's tolerance of 1%, but were further calibrated under outdoor conditions; all three have a resistance of 5.3mΩ with an uncertainty of 0.35%. Details of the resistor calibration and calculations are found in Appendix B.

Calculation of the DAQ's voltage measurement uncertainty for the shunt resistors follows Equation 3.2, with uncertainty values for these measurements again detailed in Appendix B. The uncertainty of the current is determined using the Kline-McClintock method for error propagation as shown below.

$$u_{I,MCC} = \sqrt{\left(\frac{dI}{dR} * u_{Rshunt}\right)^2 + \left(\frac{dI}{dV} * u_{V,MCC}\right)^2} \qquad \textbf{3.3}$$

In this equation, *I* is the current, *V* is the measured voltage across the current shunt resistor, *R* is the nominal value of the resistor, and u_{Rshunt} and $u_{V,MCC}$ are the uncertainties of the resistor and voltage measurements, respectively. The partial derivatives of the current are given in equations 3.4 and 3.5.

$$\frac{dI}{dR} = \frac{-V}{R^2} \qquad \textbf{3.4}$$

$$\frac{dI}{dV} = \frac{1}{R} \qquad \textbf{3.5}$$

The expanded uncertainty of the string current is then

$$U_I = 2 * \sqrt{\left(\frac{u_{I,MCC}}{\sqrt{3}}\right)^2 + \left(\frac{\delta}{\sqrt{3}}\right)^2} \qquad \textbf{3.6}$$

with a maximum measured value resolution of δ=0.0005A.

Once again this uncertainty depends on the quantity measured, as shown in Table 3.5 and Table 3.6. Measured current uncertainty is higher than that of the measured voltage in part because the voltage values across the shunt resistor are so small. The measurement uncertainty is approximately 0.5% over the typical range of short circuit and maximum power currents for crystalline silicon modules. Some thin film modules have much lower current values, especially when operating under low light conditions, and their uncertainties approach 2% or more at these key points.

Table 3.5 Uncertainty in current measurements -- high irradiance

I	Vmeas	Expanded Uncertainty (%)
0.25	0.001325	2.89
0.5	0.00265	1.50
1	0.0053	0.84
2	0.0106	0.55
4	0.0212	0.45
6	0.0318	0.43

Table 3.6 Uncertainty in Current Measurements -- low irradiance

I	Vmeas	Expanded Uncertainty (%)
0.25	0.001325	1.60
0.5	0.00265	0.88
1	0.0053	0.57
2	0.0106	0.45
4	0.0212	0.42
6	0.0318	0.41

3.4.3 Short Circuit Current

Calculation

Short circuit current (I_{sc}) is found for each panel using linear extrapolation or interpolation. According to the NREL outdoor test uncertainty guidelines (NREL PERT Group, 2012), I_{sc} may be found using a linear fit of at least five data points, where $I > 0.96 * I_{sc}$ and $V < 0.2 * V_{oc}$. The multitracer datasets present an interesting challenge as the nature of series string runs of mismatched panels dictates that some will not reach their I_{sc} before the curve sweep ends (Figure 3.5). As the string voltage is stepped down and string current increases, some panels are forced to operate at currents higher than their I_{sc}, which causes them to have a negative voltage. When an array has one or more panels with an I_{sc} that is higher than the others, the sum of the string's positive and negative panel voltages reaches zero before the higher performing panels reach their I_{sc}.

To address this challenge, several modifications have been made to the standard rules governing I_{sc} fitting. First, the linear fit is required to have a minimum of only three data points. For curves with negative voltage data points, only the first (least negative) is included in the linear fit, as the modules' bypass diodes change the I-V curve shape in the negative voltage region. Second, if the requisite number of points are not found in the standard range, it is increased to $I>0.92*I_{sc}$ and $V<0.3*V_{oc}$ which allows fitting for more than 90% of the measured panels. Finally, for panels with a very high I_{sc} relative to others in their string (such as Panel 6 in Figure 3.5), I_{sc} is determined by fitting the curve to a single diode model.

Uncertainty

Uncertainty in the short circuit current for each panel depends on the uncertainty of the current at I_{sc} ($u_{I,Isc}$) (which is simply the expanded current uncertainty without the coverage factor -- see Equation 3.6) and the uncertainty of the linear fit of I_{sc} ($u_{fit,Isc}$). The linear fit uncertainty is expressed as

$$u_{fit,Isc} = \frac{s_{IscFit}}{N_{Isc}} \qquad \textbf{3.7}$$

where s_{IscFit} is the standard error of the y-intercept of the linear fit and N_{Isc} is the number of data points in the fit. Thus the expanded uncertainty for I_{sc} is

$$U_{Isc} = 2 * \sqrt{\left(u_{I,Isc}\right)^2 + \left(\frac{s_{IscFit}}{N_{Isc}}\right)^2} \qquad \textbf{3.8}$$

The expanded I_{sc} uncertainty for each module in each array[1] is shown in Figure 3.6. It is approximately 0.5% for all of the crystalline silicon arrays operating under medium and high irradiance conditions, and is less than 1% for all of the low irradiance cases. Some of thin film arrays see slightly higher uncertainty in I_{sc}, mostly because they have lower current values, giving more weight to some of

[1] Array Thin 1B is excluded from this and all other uncertainty calculations, as its data were taken with a slightly different equipment configuration. Its uncertainty will be less than or equal to that of the other thin film arrays.

the sources of uncertainty. Still, the uncertainty under high irradiance conditions is approximately 1% or less, and it is only over 2% for modules in two of the arrays, and then only under low irradiance conditions.

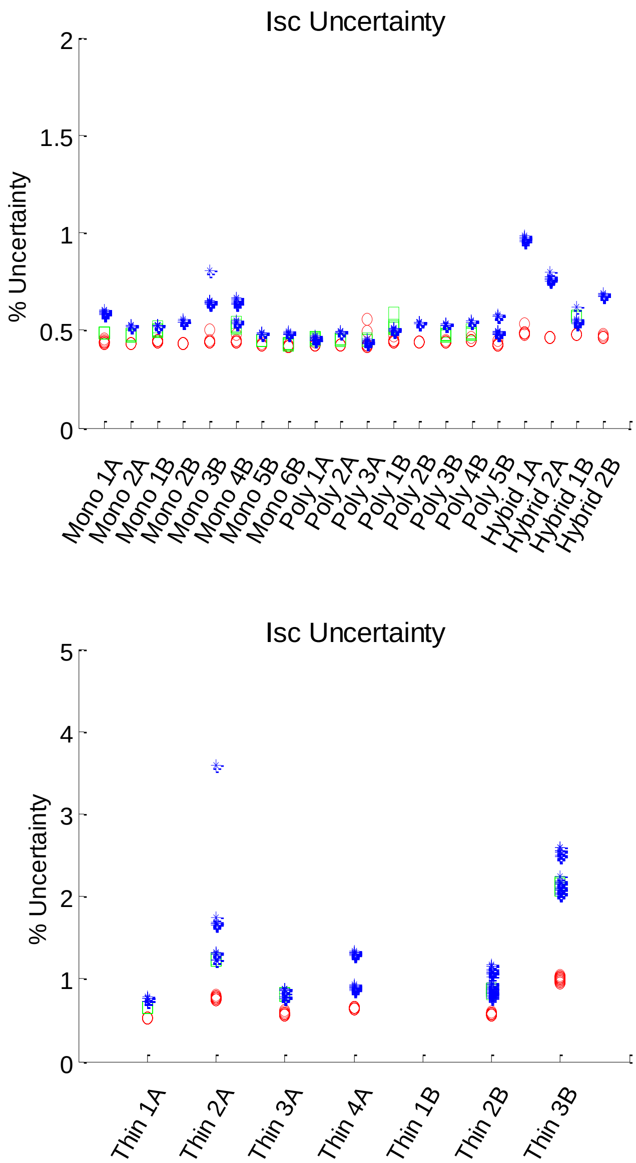


Figure 3.6 I_{sc} uncertainty for crystalline silicon modules (top) and thin film modules (bottom). Modules with modeled I_{sc}, as opposed to extrapolated/interpolated, are excluded. Red circles are high irradiance conditions, green squares are medium, and blue stars are low irradiance conditions.

3.4.4 Open Circuit Voltage

Calculation

Open circuit voltage (V_{oc}) is also found for each panel using linear extrapolation or interpolation. The NREL outdoor test uncertainty guidelines (NREL PERT Group, 2012) indicate that V_{oc} may be found from linear fitting of at least 5 data points where $V > 0.9 * V_{oc}$ and $I < 0.2 * I_{sc}$. As in the previous section it is found that for some of the measured I-V curves, there are not five points that fit these criteria. In these cases, a linear fit is performed on the three points in the curve with the highest voltage. As the I-V curve is fairly linear in the region around V_{oc} (see Figure 3.5), this is assumed not to introduce undue uncertainty to the results.

Uncertainty

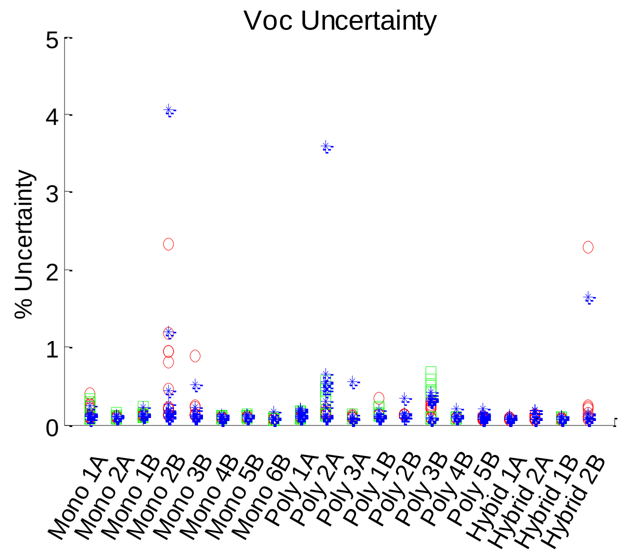
Uncertainty in the open circuit voltage for each panel depends on the standard uncertainty of the voltage at V_{oc} ($u_{V,Voc}$) and the uncertainty of the linear fit of V_{oc} ($u_{fit,Voc}$). The linear fit uncertainty is similar to that for I_{sc} and is expressed as

$$u_{fit,Voc} = \frac{s_{VocFit}}{N_{Voc}} \qquad \textbf{3.9}$$

where s_{VocFit} is the standard error of the x-intercept of the linear fit and N_{Voc} is the number of data points in the fit. The expanded uncertainty for V_{oc} is then

$$U_{voc} = 2 * \sqrt{\left(u_{V,Voc}\right)^2 + \left(\frac{s_{VocFit}}{N_{Voc}}\right)^2} \qquad \textbf{3.10}$$

The expanded V_{oc} uncertainty for each panel is shown in Figure 3.7. It is less than 1% under all operating conditions for most panels in the crystalline silicon and thin film arrays. There are a few outliers which have uncertainty as high as 4%; these are due mostly to poor linear V_{oc} fit rather than voltage uncertainty from the data acquisition device. For most PV modeling and analysis purposes, an error of this magnitude in V_{oc} will have a negligible effect.



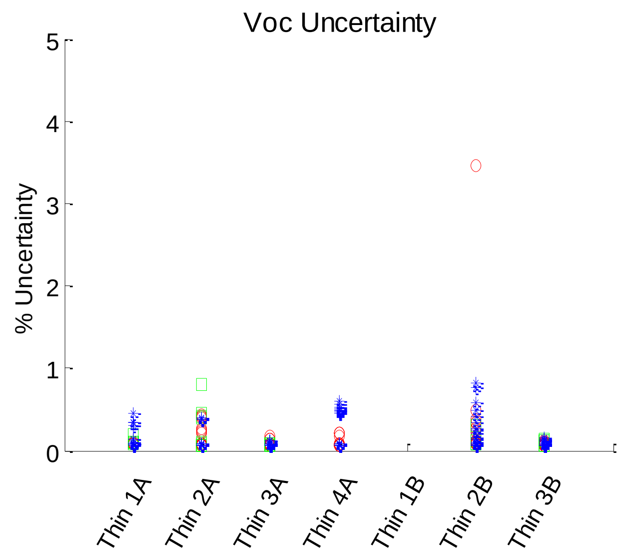


Figure 3.7 V_{oc} uncertainty for crystalline silicon modules (top) and thin film modules (bottom). Red circles are high irradiance conditions, green squares are medium, and blue stars are low irradiance conditions

3.4.5 Maximum Power Point

Calculation

Unlike I_{sc} and V_{oc}, which are found with linear fits, the maximum power point of each panel (P_{mp}) is determined by finding the maximum of a 4th order polynomial fit of the power vs. voltage curve as recommended by NREL (NREL PERT Group, 2012). The fitted curve is comprised of all data points that satisfy $V > 0.8 * V_{max,meas}$ and $P > 0.85 * P_{max,\mathrm{meas}}$, where V and P are data points' measured voltage and power and $P_{max,meas}$ and $V_{max,meas}$ are the measured maximum power point and voltage at measured maximum power point, respectively. To maximize accuracy, the fitted curves must each contain at least seven points. An example of the curve fitting is shown in Figure 3.8.

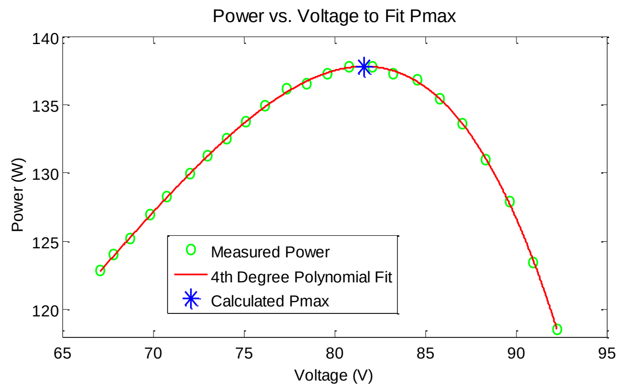


Figure 3.8 Fitted module P_{mp}

Uncertainty

According to one study (Emery, 2009), the maximum uncertainty found using this polynomial fitting method (u_{PFit}) was <0.06%. The uncertainty for P_{mp} is calculated using the Kline-McClintock method for error propagation, with the addition of the fitting uncertainty.

$$U_{Pmax} = 2 * \sqrt{\left(\frac{dP}{dI} * u_{I,mp}\right)^2 + \left(\frac{dP}{dV} * u_{V,mp}\right)^2 + \left(\frac{u_{PFit}}{2}\right)^2} \quad \textbf{3.11}$$

In this equation, *I*, *V*, and *P* are taken at the module's maximum power point, and $u_{I,mp}$ and $u_{V,mp}$ are the standard uncertainty of the maximum power point current and voltage, respectively, calculated using equations 3.6 and 3.2 without the coverage factor. The partial derivatives of the power are given in the following two equations.

$$\frac{dP}{dI} = V \quad \textbf{3.12}$$

$$\frac{dP}{dV} = I \quad \textbf{3.13}$$

Figure 3.9 shows the uncertainty in the maximum power point calculations for each array's modules. These uncertainties are similar to those found for I_{sc}; most are under 1%, though as irradiance (and thus current) decreases, they may be as high as 2-4% for some arrays. These higher uncertainties generally correspond to cases where the maximum power point current is much less than 1A.

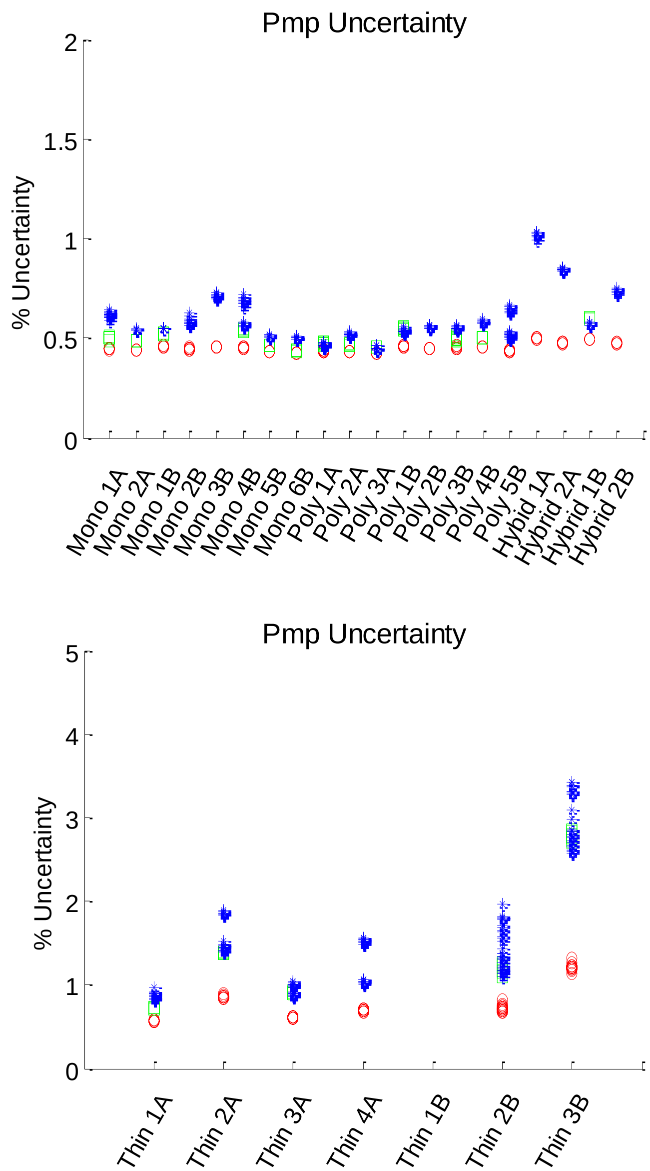


Figure 3.9 P_{mp} uncertainty for crystalline silicon modules (top) and thin film modules (bottom). Red circles are high irradiance conditions, green squares are medium, and blue stars are low irradiance conditions

3.4.6 PV Cell Temperature

Calculation

The back-of-module temperatures are recorded for 3-5 panels at the beginning and end of each run, and an average of these is taken to be the overall run temperature, assumed for modeling purposes to be the same for each module. Measured back-of-module temperature T_{back} is converted to PV cell temperature T_{cell} using the Sandia Model method (King, Boyson, & Kratochvil, 2003) detailed in Equation 3.14.

$$T_{Cell} = T_{Back} + \frac{Irr_{POA}}{1000} * dT \qquad \textbf{3.14}$$

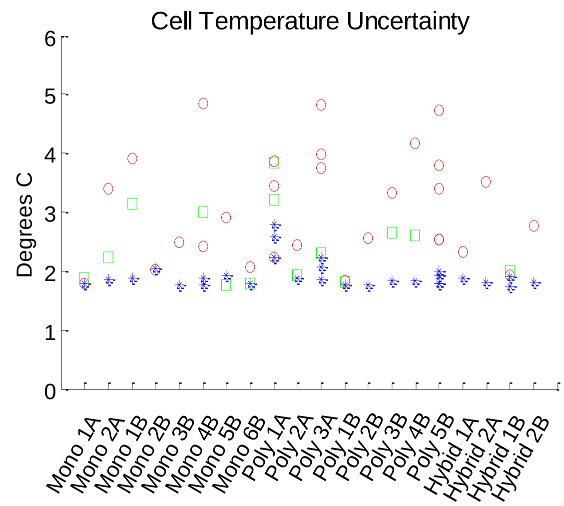
In this equation Irr_{POA} is the measured irradiance incident in the plane of the array and dT = 3 for open rack mounted PV systems.

Uncertainty

Measured panel temperature during an outdoor I-V curve has uncertainty from three elements: thermocouple sensor uncertainty (u_{TC}), uncertainty from the sensor mounting method (u_{Mount}), and uncertainty from the data acquisition device ($u_{T,Advantach}$). Uncertainty due to the resolution of the measurement is comparatively small and ignored. Temperatures are measured using Omega CO-1 type T thermocouple sensors, which have a stated uncertainty of 1°C. Additional uncertainty introduced by the mounting method (Smith, 2011) is 0.5°C for thin film thermocouple sensors attached to a panel with adhesive tape. The Advantech 4718 data acquisition device adds another 1°C uncertainty for type T thermocouple inputs. These three sources of uncertainty are for standard I-V curves, but because the multitracer curves take longer to run and are for multiple modules across an array, a fourth term, the standard deviation of the temperature measurements (σ_T), is also included. This term helps to account for the temporal and spatial variability in temperature over the array. Any uncertainty contributed by use of the Sandia model is not considered. The expanded uncertainty of the PV cell temperature is thus calculated as

$$U_{Tcell} = 2 * \sqrt{\left(\frac{u_{TC}}{\sqrt{3}}\right)^2 + \left(\frac{u_{T,Advantech}}{\sqrt{3}}\right)^2 + \left(\frac{u_{Mount}}{\sqrt{3}}\right)^2 + (\sigma_T)^2} \quad \mathbf{3.15}$$

Temperature uncertainties in degrees Celsius for each array's I-V curve sweep runs are shown in Figure 3.10. For most arrays, the expected variance from each run's average value is within plus or minus 5°C, with greater variance seen under high irradiance operating conditions where the back-of-module temperature is higher. This may contribute significant uncertainty to the module performance model, and is further evaluated in Chapter 4.



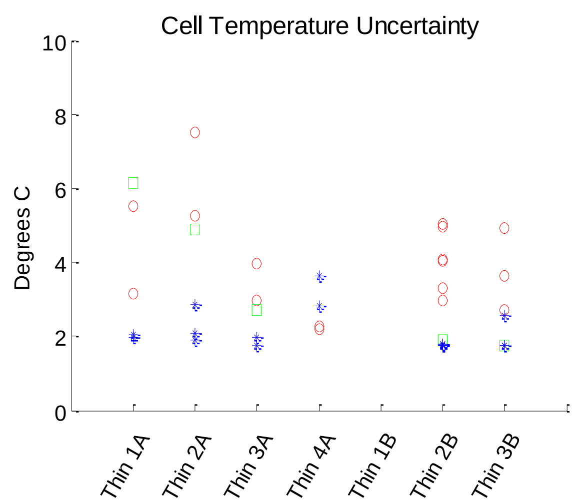


Figure 3.10. PV cell temperature uncertainty for I-V curve sweep runs of crystalline silicon modules (top) and thin film modules (bottom). Red circles are high irradiance conditions, green squares are medium, and blue stars are low irradiance conditions

3.4.7 Incident Irradiance

Calculation

Incident irradiance data are collected for each array using an Eppley Precision Spectral Pyranometer (PSP) mounted in the plane of the array as seen in Figure 3.4, with irradiance measurements (in volts) taken at the beginning and end of each I-V curve sweep. The pyranometer calibration report includes a 45 degree incident angle response, and this single condition response is all that is used to convert pyranometer voltage output to irradiance values in many applications. However, this calibrated response and associated uncertainty are only meant for instances where the incident angle between the sun and pyranometer/array plane is between 30 and 60 degrees. Many of the I-V sweeps taken in this work were recorded under conditions with higher or lower incident angles; the incident angle for each run is given in Appendix A, and incident angle calculation is described in Appendix C.1. To maximize accuracy in this work, the pyranometer's output voltage is converted to incident irradiance using the detailed, zenith-angle-dependent set of calibration responses found in Appendix B.5.

The calibration report includes different AM and PM voltage responses at each recorded incident angle, which are in increments of two degrees. Though the pyranometer did not always have the same orientation during data collection that it did during calibration, it is demonstrated in Appendix B.6 that the pyranometer has little orientation-dependent response variation when mounted in the tilted plane of a PV array. To attempt to account for any other potential time or site dependent differences, its AM and PM responses are averaged at each measured angle and then fitted with a cubic spline as described in Appendix B.5.

Eppley PSPs also have an infrared (IR)/thermal offset which occurs because of temperature gradients and IR exchange within the instrument (Haeffelin, 2001). This causes the irradiance output to be under-predicted. At the NREL Colorado site this offset has been measured as high as 20 W/m^2, (Emery, 2012) and the response should be similar in other dry southwestern climates such as Albuquerque and Tucson. Measured net IR radiation from the NREL Solar Radiation Research Laboratory (SRRL) indicates that the IR effects are slightly lower early and late in the day, and it is logical to assume that the offset during these times will not exceed 15 W/m^2. Cloudy days have even less IR, with a maximum offset of 10 W/m^2 (Appendix B.7). These offsets are accounted for in the total irradiance calculation by adding half of the offset indicated by the operating conditions to the total, minimizing the associated uncertainty. The total plane-of-array irradiance is then calculated as:

$$\mathrm{Irr_{POA}} = \frac{\mathrm{V_{Pyr,start}} + \mathrm{V_{Pyr,end}}}{2 * \mathrm{R_{Pyr,avg\,spline}}} + \frac{\mathrm{Offset_{IR}}}{2} \quad \textbf{3.16}$$

where V_{pyr} is the measured pyranometer voltage at the start and end of the I-V curve sweep, R_{Pyr} is the pyranometer's AM/PM averaged spline response in μV/W/m^2, derived from calibration data, and $Offset_{IR}$ is the condition-specific maximum pyranometer IR offset in W/m^2.

Uncertainty

As detailed in the NREL outdoor measurement uncertainty guidelines (NREL PERT Group, 2012), measured irradiance has many uncertainty components. These include uncertainty in the data acquisition device ($u_{V,Advantech}$), pyranometer calibration ($u_{PYR,CAL}$), pyranometer temperature response ($u_{PYR,TEMP}$), pyranometer linear response ($u_{PYR,LIN}$), pyranometer calibration stability ($u_{PYR,STAB}$), pyrometer mounting angle ($u_{PYR,ANGLE}$), and pyranometer IR offset ($u_{PYR,IROFF}$). Uncertainty for the multitracer I-V curve sweeps also includes uncertainty due to the change in irradiance over the run ($u_{IrrChange}$). Contributions from the resolution of the measurement are comparatively small and ignored. Details of these uncertainties follow.

- $u_{V,Advantech}$ -- The Advantech 4718 has an accuracy uncertainty of 0.1% over an 0-15mV range as well as temperature-based offset and drift detailed in Appendix B.4.
- $u_{PYR,CAL}$ -- The pyranometer calibration uncertainty is based on the calibration report's zenith angle and AM/PM response uncertainty and is detailed in Appendix B.5.
- $u_{PYR,TEMP}$ -- The Eppley PSP has a temperature dependence of 1% over the typical range of ambient temperatures
- $u_{PYR,LIN}$ -- The Eppley PSP has an 0.5% response tolerance from 0-2800 W/m^2

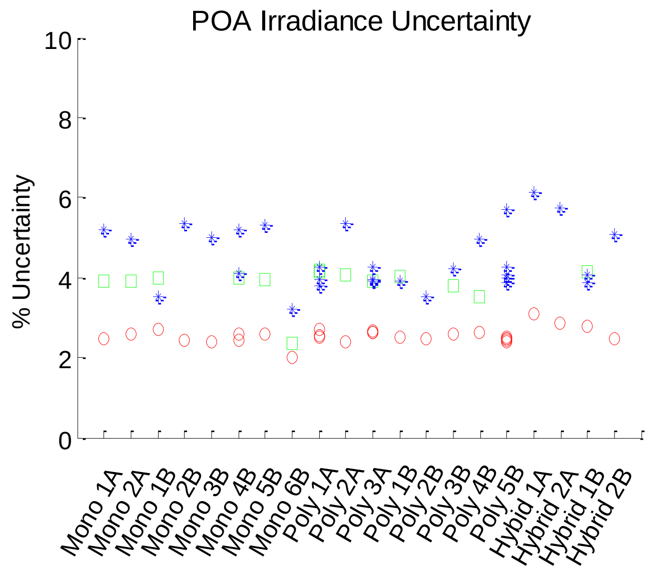
- $u_{PYR,STAB}$ -- Pyranometer stability is approximately 0.5% per year, and data were taken in the pyranometer's second year after calibration, so this is 1%
- $u_{PYR,ANGLE}$ -- As the pyranometer was typically mounted directly in the plane of the array under test, this uncertainty component is ignored
- $u_{PYR,IROFF}$ -- The pyranometer's IR offset is partially accounted for in the calculation of plane of array irradiance, and additional uncertainty is 5 W/m^2 for cloudy measurements, 10 W/m^2 for high and medium irradiance measurements (>400 W/m^2), and 7.5 W/m^2 for clear-sky low irradiance measurements.
- $u_{IrrChange}$ -- This uncertainty in W/m^2 is half the difference between the irradiance measured at the beginning of the I-V sweep and that measured at the end.

The total expanded uncertainty calculation for irradiance is presented in Equation 3.17.

$$U_{Irr,POA} = 2\sqrt{\left(\frac{u_{V,Advantech}}{\sqrt{3}}\right)^2 + \left(\frac{u_{PYR,CAL}}{\sqrt{3}}\right)^2 + \left(\frac{u_{PYR,TEMP}}{\sqrt{3}}\right)^2 + \left(\frac{u_{PYR,LIN}}{\sqrt{3}}\right)^2 + \left(\frac{u_{PYR,STAB}}{\sqrt{3}}\right)^2 + \left(\frac{u_{PYR,IROFF}}{\sqrt{3}}\right)^2 + \left(\frac{u_{IrrChange}}{\sqrt{3}}\right)^2}$$

3.17

Uncertainty in the measured plane-of-array irradiance, shown in Figure 3.11, is fairly high for all of the arrays. It is especially so for low and medium irradiance conditions where the IR offset and variation in irradiance during the I-V curve sweep make up larger percentage of the total measured irradiance. As with the cell temperature uncertainty, the impacts of this uncertainty on model development are discussed in detail in Chapter 4.



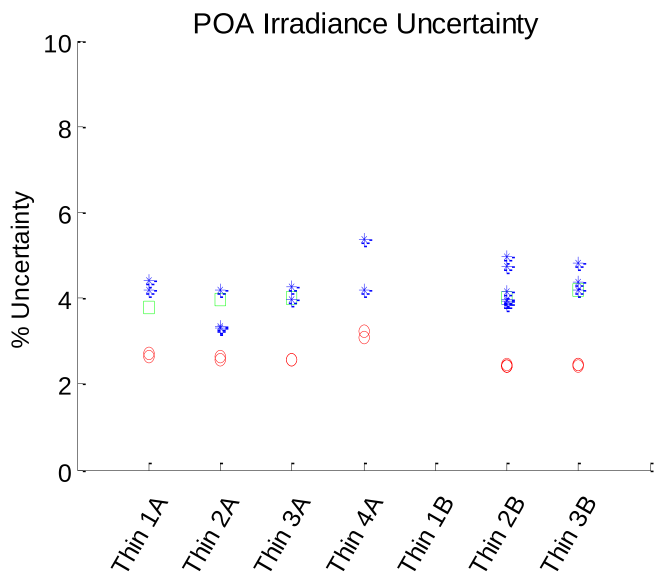


Figure 3.11 Plane-of-array irradiance uncertainty for I-V curve sweep runs of crystalline silicon modules (top) and thin film modules (bottom). Red circles are high irradiance conditions, green squares are medium, and blue stars are low irradiance conditions

Relative Uncertainty

As previously mentioned, the multitracer limits on number of inputs and string voltage required that some arrays have their module-level I-V curves recorded in multiple runs, rather than all together, under a particular set (high, medium, or low) of irradiance conditions. For this reason, it is important to consider uncertainty in runs' irradiance relative to one another, for the arrays whose module-level I-V curves could not all be recorded simultaneously. In these cases, because the data for an individual array were all taken under very similar conditions, many of the contributions to irradiance uncertainty seen in Equation 3.17 are minimized by the relative comparison. The two remaining are the data acquisition uncertainty and the uncertainty caused by irradiance changes during the run, as shown in Equation 3.18.

$$U_{Irr,POA,REL} = 2\sqrt{\left(\frac{u_{V,Advantech}}{\sqrt{3}}\right)^2 + \left(\frac{u_{IrrChange}}{\sqrt{3}}\right)^2} \qquad \textbf{3.18}$$

As expected, the irradiance uncertainty in these relative cases is greatly reduced. It remains highest under low irradiance conditions, as these runs were often taken early or late in the day when the sun's position about the array is changing more rapidly. However, unlike the absolute uncertainty, which is often as high as 4-6%, the relative uncertainty is less than 3% for most runs. This type of uncertainty is most important when considering module-to-module mismatch, and its impact will be evaluated in more detail in Chapter 6.

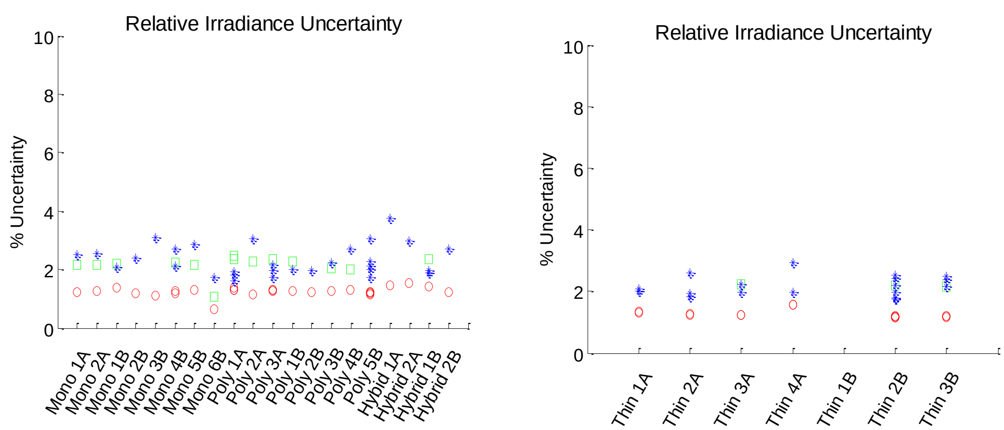


Figure 3.12 Plane-of-array irradiance uncertainty for I-V curve sweep runs of crystalline silicon modules (left) and thin film modules (right), relative to other runs taken under similar conditions. Red circles are high irradiance conditions, green squares are medium, and blue stars are low irradiance conditions.

3.4.8 Effective Irradiance

Only a portion of the measured plane-of-array incident irradiance is actually used to generate electricity, depending on the PV modules' characteristics, the solar spectral content, and the position of the sun relative to the array. PV modules of any technology may have a different response to the same measured irradiance, depending on conditions under which data are taken, making their performance difficult to model. Using effective, or absorbed, irradiance rather than measured values minimizes this difficulty, and the PV models considered in this work use effective irradiance when translating from measured data (taken under reference weather conditions) to other conditions in annual, hourly energy simulations.

Calculation

The effective irradiance *S* (Equation 3.19) is calculated from the measured plane-of-array irradiance Irr_{POA} in several steps. First, Irr_{POA} is separated into its constituent beam, diffuse, and ground reflected parts as described in Appendix C.2. Each of these three components is then multiplied by a separate transmittance-absorptance factor (τα) which accounts for the PV modules' use of incident light at different angles. Finally, all components are multiplied by spectral correction factor *M*. These variables are described in detail in Appendix C.3.

$$S = M\left(\mathrm{Irr}_{\mathrm{POA,BEAM}} * (\tau\alpha)_{\mathrm{b}} + \mathrm{Irr}_{\mathrm{POA,DIFFUSE}} * (\tau\alpha)_{\mathrm{d}} + \mathrm{Irr}_{\mathrm{POA,GNDREF}} * (\tau\alpha)_{\mathrm{r}}\right) \qquad \textbf{3.19}$$

In Chapter 4, these calculations of *S* from measured data are used as the reference irradiance for each PV module's simulation model. Effective and measured irradiances for all I-V curve sweeps of each array are found in Appendix A.

Uncertainty

Several aspects of the effective irradiance calculation add uncertainty to these values. First, as noted in Appendix C.2, the beam, diffuse, and ground reflected components of the measured plane-of-array irradiance are calculated using empirically developed relations, which inherently have associated variability which is not directly quantified in literature. Next, the ($\tau\alpha$) values for each of these components are found based on approximations, such as treating the PV module encapsulant as a glass-air interface , or on empirical relations as well. Finally the spectral correction *M* is calculated using values from a single crystalline silicon module, which is noted to be representative of many different modules, but becomes a poorer match at high solar incidence angles, particularly for non-silicon technologies (De Soto, Klein, & Beckman, 2006).

The effects of these sources of uncertainty are difficult to quantify without extensive, detailed, per-module measurement and analysis, which is outside the scope of this work. Methods to minimize the impact of effective irradiance uncertainty in the PV models are presented in Chapter 4.

3.5 Summary

Simultaneous, module-level I-V curve data are collected for 27 PV arrays (approximately 500 modules) of six different PV technologies located in the southwestern US. The data are collected using a custom multitracer designed and built at NREL. Each module's I-V curves are measured under both high and low light conditions for performance modeling purposes as well as comparison to other modules in the same array. This rich and unique dataset may be useful to many PV researchers and modelers, and the majority of the modules' measured I-V curves will be made publicly available on the PV Performance Modeling Collaborative website pvpmc.org.

During the I-V curve sweeps, current and voltage are recorded on a 24-bit data acquisition system to ensure a high level of accuracy. Uncertainties in voltage and current measurements are approximately 0.5% over typical ranges of operation, though the current uncertainty may reach 2% for some thin film modules operating under very low irradiance. The I-V curve data are used to extrapolate/interpolate key points on each module's I-V curve, including I_{sc}, V_{oc}, P_{mp}, and its corresponding current and voltage, I_{mp} and V_{mp}. These values are found following the NREL Guide to Outdoor Test Measurement and

Uncertainty (NREL PERT Group, 2012), which is also used to calculate their associated uncertainty. Most arrays' modules have low uncertainty for all of these parameters, less than 1%.

Plane-of-array irradiance and back-of-module temperature are averaged for the array over each curve sweep run, with the former calculated using a detailed calibration methodology for the Eppley PSP and the latter translated to cell temperature using the Sandia temperature model. Uncertainty for both measurement types is found based on the NREL guidelines mentioned above. Temperature uncertainty ranges from 2-8ºC, with higher uncertainty associated with high irradiance (and thus higher temperature) measurements. For plane-of-array irradiance measurement uncertainty is on the order of 2-6%, with the highest levels associated with low irradiance measurements. The irradiance measurement uncertainty for modules in the same array with data taken in separate runs, relative to one another, is less: 1-4%. None of these irradiance uncertainties include translation to effective irradiance, which is done for modeling purposes and which may add significantly to these percentages. Effects and significance of the measurement uncertainty are discussed in more detail in Chapters 4 and 6.

CHAPTER 4

PV GENERATOR MODEL

In order to properly assess the impact of nonuniform operating conditions across PV arrays, such as partial array shading or mismatched electrical characteristics between modules, it is essential to have a model that is reasonably accurate over the full I-V curve, as well as the commonly-experienced set of operating conditions (incident irradiance and cell temperature), for all PV technologies under consideration. Until very recently, many PV performance models have been primarily based on operation under Standard Test Conditions (STC – 1000 W/m^2 and 25ºC), as these data are readily available from manufacturers. This methodology of creating a model from such limited data, however, has the potential to mispredict module performance under other operating conditions.

The new IEC 61853 standard, which requires manufacturers to provide module performance data for a matrix of varied temperatures and irradiances (IEC, 2011), should enable creation of more robust models. However, at present these data are expensive and time-consuming to collect, and not generally available from many manufacturers. Furthermore, for modules which have experienced years of field degradation, such as those in this work, the manufacturer-provided, new-module parameters have limited applicability. As such, it is relevant and useful to consider development of an improved modeling methodology, which uses a more practical set of module-level data taken under high and low light conditions to establish PV performance parameters. The goals of this section are to analyze the accuracy of the existing single diode PV generator model, to provide insight into the ways that its parameters vary under actual operating conditions, and to demonstrate the value and ability of additional data to improve model accuracy.

This section is comprised of several main parts. First, the Wisconsin/CEC single diode PV generator models are described and discussed. Next, the single diode model is used to create module level I-V curves under known "reference" conditions, and these reference curves are compared to measured data taken under the same conditions, to determine how well the model is able to represent the full I-V curve for different PV technologies. The modeled high irradiance reference curves for each module are then translated to medium and low light models, using the existing methodologies for parameter translation, and the model predictions are compared to corresponding measured medium and low light data at key PV performance points on the I-V curve. Finally, as these existing model predictions are found to be inaccurate in many cases, improvements to the existing modeling methodology are proposed. Results using the new methodology and analyzed and demonstrate the benefits of a new modeling approach to increase performance prediction accuracy.

4.1 Wisconsin/CEC Single Diode Models

This work focuses on the standard single diode model, chosen for its ease of use and ability to model a full I-V curve, which is necessary when nonuniform operating conditions cause modules to operate away from their maximum power point. While there are many implementations of this model, discussed in Chapter 2, the model most commonly used in the U.S. is referred to here as the Wisconsin/California Energy Commission (CEC) single diode model, with either five, six, or seven parameters. It models PV generators (cell, sub-module, module, etc.) as a current source in parallel with a diode, with parasitic losses, as shown in Figure 4.1.

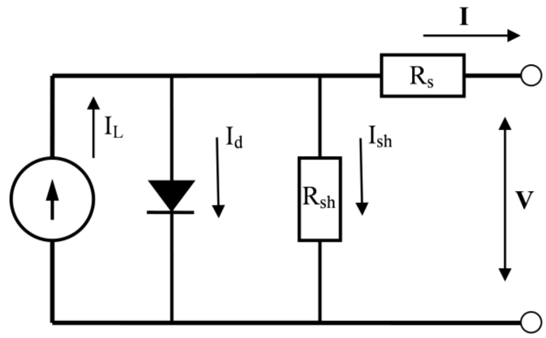


Figure 4.1. Single diode model

The underlying equation for all of these single diode models is:

$$I = I_L - I_o \cdot \left[\exp\left(\frac{V + I \cdot R_s}{a}\right) - 1\right] - \frac{V + I \cdot R_s}{R_{sh}} \qquad \textbf{4.1}$$

In this equation, I_L is the light current, I_o is the diode reverse saturation current, R_s is the series resistance, R_{sh} is the shunt resistance, and a is the modified diode ideality factor. I and V are the generator's current and voltage, respectively. Though these parameters are meant to represent physical characteristics of PV generators, they do not always do so exactly, as this is a simplified model.

4.1.1 Reference I-V Curve Parameter Calculation

The single diode model is generally used by solving for its five parameters I_L, I_o, R_s, R_{sh}, and a at a reference condition (fitting them to measured data), and then translating these parameters using relationships with irradiance and cell temperature to model other operating conditions. A typical reference is STC (effective irradiance S_{ref} = 1000 W/m^2, cell temperature T_{ref} = 25ºC), using information provided by the manufacturer (Duffie & Beckman, 2006), but one may also use other irradiances or cell temperatures for which one has measured data (DeSoto, 2004). Inputs to the model include open circuit and maximum power point voltages ($V_{oc,ref}$ and $V_{mp,ref}$), short circuit and maximum power point currents ($I_{sc,ref}$ and $I_{mp,ref}$), and temperature coefficients of open circuit voltage (β_{Voc}), short circuit current (α_{Isc}), and maximum power point (γ_{Pmp} – 6 and 7 parameter models only). The equations used to solve for the reference parameters are as follows (Duffie & Beckman, 2006):

At short circuit conditions (voltage =0)

$$I_{sc,ref} = I_{L,ref} - I_{0,ref} \cdot \left[\exp\left(\frac{I_{sc,ref} \cdot R_{s,ref}}{a_{ref}}\right) - 1\right] - \frac{I_{sc,ref} \cdot R_{s,ref}}{R_{sh,ref}} \qquad \textbf{4.2}$$

While at open circuit conditions (current = 0)

$$I_{L,ref} = I_{0,ref} \cdot \left[\exp\left(\frac{V_{oc,ref}}{a_{ref}}\right) - 1\right] + \frac{V_{oc,ref}}{R_{sh,ref}} \qquad \textbf{4.3}$$

Then using the given/measured maximum power point current and voltage at reference conditions

$$I_{mp,ref} = I_{L,ref} - I_{0,ref} \cdot \left[\exp\left(\frac{V_{mp,ref} + I_{mp,ref} \cdot R_{s,ref}}{a_{ref}}\right) - 1\right] - \frac{V_{mp,ref} + I_{mp,ref} \cdot R_{s,ref}}{R_{sh,ref}} \qquad \textbf{4.4}$$

Also, the derivative of power with respect to voltage is zero at the maximum power point

$$I_{mp,ref} = V_{mp,ref} \cdot \left[\frac{\frac{I_{0,ref}}{a_{ref}} \cdot \exp\left(\frac{V_{mp,ref} + I_{mp,ref} \cdot R_{s,ref}}{a_{ref}}\right) + \frac{1}{R_{sh,ref}}}{1 + \frac{I_{0,ref} \cdot R_{s,ref}}{a_{ref}} \cdot \exp\left(\frac{V_{mp,ref} + I_{mp,ref} \cdot R_{s,ref}}{a_{ref}}\right) + \frac{R_{s,ref}}{R_{sh,ref}}}\right] \qquad \textbf{4.5}$$

Finally, using the given/measured temperature coefficient of open circuit voltage, and assuming a cell temperature 10°C higher than reference conditions

$$\beta_{Voc} = \frac{V_{oc}(T_{cell}) - V_{oc}(T_{ref})}{T_{cell} - T_{ref}} \qquad \textbf{4.6}$$

It is noted here that while the five reference condition parameters do not explicitly depend on the reference irradiance or temperature, S_{ref} or T_{ref}, model inputs β_{Voc} and γ_{Pmp} are indicated to vary minimally with irradiance for crystalline silicon modules, and potentially more so for thin film technologies (U. Jahn, 2010). They generally increase in negative magnitude as irradiance decreases, while α_{Isc} shows no clear relationship to irradiance. Quantification of individual modules' $\beta_{Voc,}$ $\gamma_{Pmp,}$ and α_{Isc} values over a range of irradiances is unfeasible in this work; instead these temperature coefficients are taken from manufacturers' datasheets, where they are reported at STC. In this and the following sections, the impact of uncertainty introduced by the use of temperature coefficients from the modules' respective manufacturers' datasheets is considered to be negligible; all are modeled as constant at their STC values.

Determination of temperature coefficient variation from module to module, and variation with irradiance and temperature, is well outside the scope of this work.

The Wisconsin 7 parameter single diode model (Boyd, Klein, Reindl, & Dougherty, 2011) has its reference parameters calculated in the same way as the 5 parameter model described above, but also has two additional translation parameters, δ and *m*. In contrast, the CEC 6 parameter single diode model includes the use of an "adjust" parameter, which alters the reference parameters slightly using the γ_{Pmp} input as described in (Dobos, 2012). As the 5 parameter model provides the core PV generator representation in many commercial tools (Klise & Stein, 2009) it is the model that will be used to find reference parameters in this work.

4.1.2 Translated I-V Curve Parameter Calculation

With the five parameters determined at reference conditions, they may then be converted to other operating conditions and used to calculate the resulting module I-V curves and performance characteristics (Duffie & Beckman, 2006). Translations are considered for both the 5 and 7 parameter diode models, as they are closely related and the 7 parameter model was shown in one work to improve annual prediction accuracy by over 10% for some simulated arrays (MacAlpine & Brandemuehl, 2011). In both the 5 and 7 parameter diode models, the parameter *a* varies only with cell temperature, given in degrees Kelvin.

$$\frac{a}{a_{ref}} = \frac{T_{cell}}{T_{cell,ref}} \qquad \textbf{4.7}$$

The light generated current I_L in both models varies with effective absorbed irradiance, *S*, and also the short current temperature coefficient $\alpha_{I,sc,}$ which is given by the manufacturer at STC.

$$I_L = \frac{S}{S_{ref}} \cdot \left[I_{L,ref} + \alpha_{Isc} \cdot \left(T_{cell} - T_{cell,ref}\right)\right] \qquad \textbf{4.8}$$

Shunt resistance R_{sh} varies with absorbed irradiance in the models, though this is only an empirical relation and does not have a known physical explanation[2].

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{S_{ref}}{S} \qquad \textbf{4.9}$$

In the 5 parameter model, series resistance R_s is assumed to be constant, again with no specific grounding in device physics.

$$R_s = R_{s,ref} \qquad \textbf{4.10}$$

However, in the 7 parameter model (Boyd, Klein, Reindl, & Dougherty, 2011) R_s is allowed to vary with temperature relative to reference conditions. The associated δ parameter (6th parameter in the 7 parameter model) is found using the manufacturer-provided coefficient for temperature dependence of the maximum power point, to determine the array's predicted power output at 10°C higher than STC. One then simultaneously solves equations 4.4 and 4.5 at this new temperature, with only the new R_s parameter ($R_{s,10}$) unknown as the others are determined using equations 4.7-4.9 and 4.13, and the maximum power point current and voltage are determined through knowledge of the maximum power value. After solving for $R_{s,10}$, one can then say that

$$R_{s,10} = R_{s,ref} \cdot \exp(\delta \cdot \Delta T) \qquad \textbf{4.11}$$

where $\Delta T = 10°C$ so this equation is used to solve for δ. Then under actual operating conditions

$$R_s|_T = R_{s,ref} \cdot \exp(\delta \cdot \Delta T) \qquad \textbf{4.12}$$

The other difference between the 5 and 7 parameter models is that in the former, I_0 varies only with cell temperature T (again in degrees Kelvin)

$$I_0 = I_{0,ref} \cdot \left(\frac{T}{T_{ref}}\right)^3 \exp\left(\frac{Eg_{ref}}{k \cdot T_{ref}} - \frac{Eg}{k \cdot T}\right) \qquad \textbf{4.13}$$

whereas in the latter I_0 is allowed to vary with both temperature and irradiance. The *m* parameter (7th parameter in the 7 parameter model) is found using the module's maximum power current and voltage at

[2] Translations of series and shunt resistance, and both of the new parameter dependencies, δ and m in the 7 parameter model, were determined empirically according to email correspondence with the models' creator, Dr. William Beckman. The physical meanings of these four parameters are not always well defined.

200 W/m^2 and 25°C (standard low irradiance conditions - SLC), which manufacturers are required to provide according to current CEC guidelines and the new IEC 61853 standard. A simultaneous solver (EES) is used to find I_0 from equation 4.5, with all of the other parameters determined by equations 4.7-4.9 and 4.12, under SLC. *m* is then calculated using equation 4.14, with reference conditions at STC and actual conditions at SLC, and can subsequently be used to translate I_0 to any set of operating conditions.

$$I_0 = I_{0,ref} \cdot \left(\frac{S_{ref}}{S}\right)^m \left(\frac{T}{T_{ref}}\right)^3 \exp\left(\frac{Eg_{ref}}{k \cdot T_{ref}} - \frac{Eg}{k \cdot T}\right) \quad \textbf{4.14}$$

In equations 4.13 and 4.14, *Eg* is the material bandgap energy and *k* is Boltzmann's constant. Because manufacturers do not provide band gaps for their respective technologies in module datasheets, this work uses reasonable estimates of 1.5eV for CdTe, 1eV for CIS/CIGS, and 1.12eV for all crystalline, thin film, and hybrid silicon technologies at a temperature of 25ºC. The band gap varies with temperature (Duffie & Beckman, 2006) according to the equation

$$Eg = Eg_{ref} \cdot (1 - 0.0002677(T - 25)) \quad \textbf{4.15}$$

with cell temperature *T* given in degrees Celsius. Though this relationship is given explicitly for crystalline silicon modules, it is also assumed to apply reasonably well to thin film.

4.2 Single Diode Model Fitted Reference I-V Curves

As described in Section 4.1.1, the Wisconsin 5 and 7 parameter single diode models are based on data from PV generators' I-V curves under reference conditions. In this work, the reference conditions are established using measured data, rather than STC values provided by the manufacturers, with the exception of temperature coefficients which come from the module datasheets. The ~500 modules included in this analysis have measured I-V curves taken under naturally-occurring high and low irradiance conditions, enabling creation of high and low light reference models for each individual module.

Because the reference models are directly fitted to key I-V curve operating points (I_{sc}, V_{oc}, P_{mp}), the models will always match the measured data at those points. However, if a module is operating away from its maximum power point, which frequently occurs in arrays experiencing nonunifrom operating conditions, the model predictions may not be as accurate, even with a directly fitted reference curve. Figure 4.2 shows examples of good and poor reference model fits, with error bars on the current and voltage measurements calculated as discussed in Chapter 3. Even after accounting for measurement uncertainty, it is clear that in some cases the model does a poor job of performance prediction over the full I-V curve; the shapes of the modeled and measured curves are not the same.

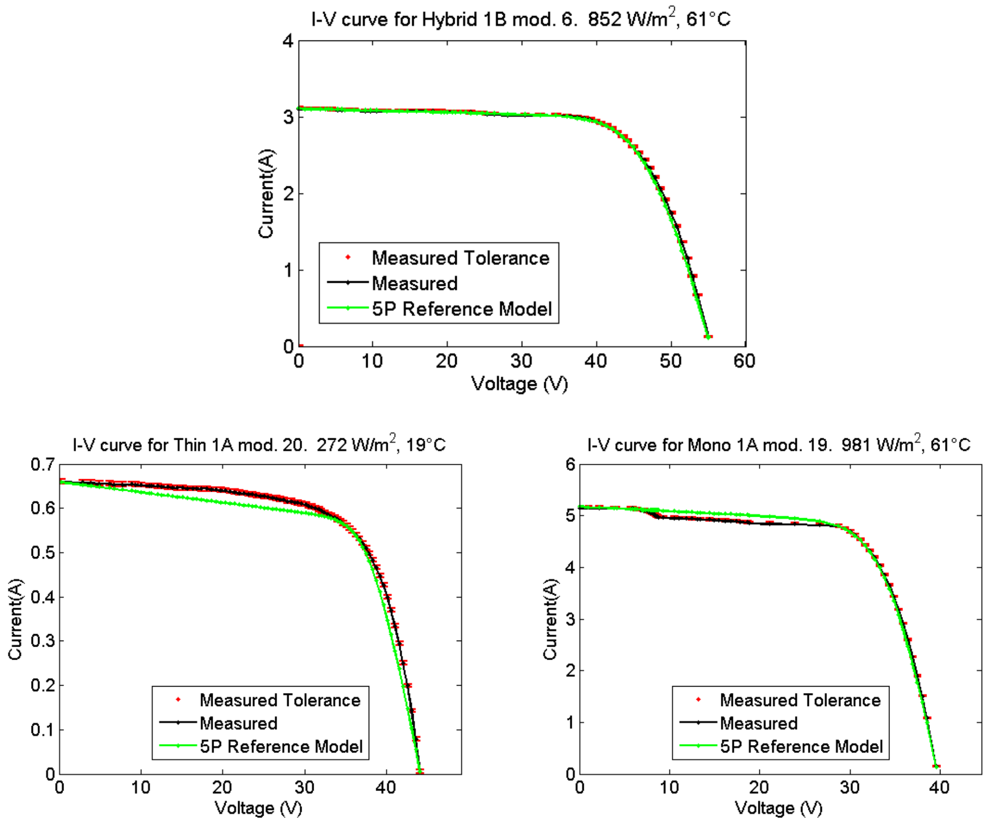


Figure 4.2. Measured I-V curves and corresponding fitted reference models. The top curve represents an accurate fit, while the bottom two curves show misprediction by the model.

In simulations of arrays with perfectly matched modules and operating conditions, the discrepancies between models and measurements in Figure 4.2 are unimportant, as each module will operate at its maximum power point for a given set of operating conditions. However, in arrays which experience mismatch within a series string (which is most, given that PV performance varies slightly between even new, high quality modules), lower-performing modules will tend to operate at a current that is higher than their I_{mp} and higher performing modules will operate at a current that is lower than their I_{mp}, to maximize the output of the string or array as a whole. In these cases it is useful to examine the modules' predicted and measured power vs. current curves, found in Figure 4.3, to better understand the impact of model inaccuracy.

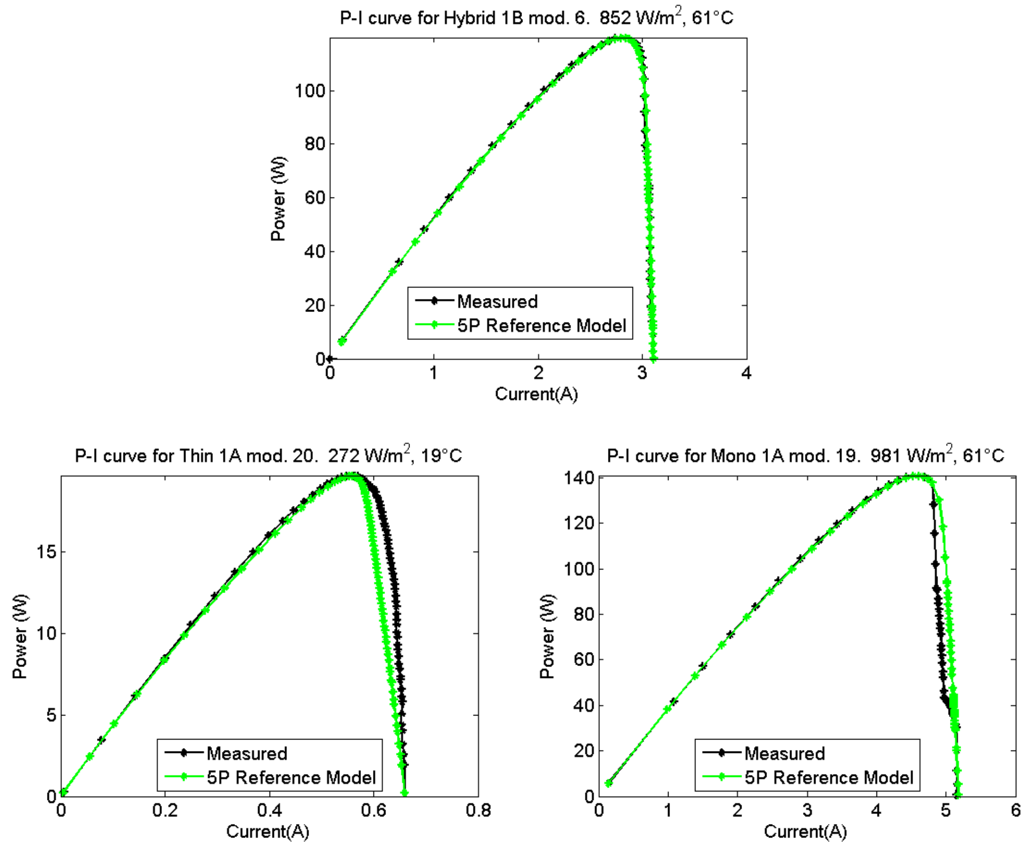


Figure 4.3. Measured P-I curves and corresponding fitted reference models. The top curve represents an accurate fit, while the bottom two curves show misprediction by the model.

When the model does not match the measured I-V curve, it leads to disproportionately large over or under-prediction of power output if a module is forced to operate at a current above its maximum power point current. Poorly-matching reference models may occur for degraded/damaged modules, such as the one with mismatched bypass diode submodules depicted on the lower right side of Figure 4.3, or for more "ideal" modules with behavior that does not exactly follow a single diode model (lower left side of Figure 4.3). Table 4.1 shows the percentage of modules in each of this work's arrays which have "poor" reference models under high and/or low light operating conditions; the total number of modules in each array is found in Tables 3.1 and 3.2. Reference model quality is determined by comparing the measured and modeled currents at I-V curve voltages $V_{mp}/2$ and $(V_{oc}+V_{mp})/2$, which are the two extra curve points predicted by the Sandia PV array model (King, Boyson, & Kratochvil, 2003). Poor models are designated as those which show a difference of greater than 5% between predicted and measured current at the $V_{mp}/2$ or $(V_{oc}+V_{mp})/2$ points.

Table 4.1. Single diode reference model goodness-of-fit

Array	% Modules with Poor Reference Fit	
	Low Irradiance	High Irradiance
Mono 1A	17%	4%
Mono 2A	11%	0%
Mono 1B	10%	76%
Mono 2B	84%	32%
Mono 3B	96%	15%
Mono 4B	20%	5%
Mono 5B	56%	0%
Mono 6B	0%	0%
Poly 1A	7%	0%
Poly 2A	0%	7%
Poly 3A	0%	0%
Poly 1B	57%	62%
Poly 2B	0%	0%
Poly 3B	22%	67%
Poly 4B	11%	0%
Poly 5B	3%	3%
Hybrid 1A	8%	0%
Hybrid 2A	27%	0%
Hybrid 1B	0%	0%
Hybrid 2B	0%	0%
Thin 1A	100%	100%
Thin 2A	100%	100%
Thin 3A	75%	8%
Thin 4A	63%	0%
Thin 1B	93%	0%
Thin 2B	72%	66%
Thin 3B	93%	33%

Table 4.1 shows that over half of the arrays have at least one module with a reference model that does not properly fit the measured data over the full I-V curve. Newer and older arrays (designated by “A” and “B”, respectively) are approximately equally affected, and the model fitting appears to be slightly worse under low light conditions. From these data, it appears that the fitted reference model is

especially good for arrays of hybrid technologies, and has more instances of poor fitting for thin film arrays.

Adjustments to the reference model, to improve the agreement between model and measured data over the full I-V curve, are discussed further in Chapter 6. These adjustments are especially important when considering the lower-impact, unshaded module-to-module mismatch reported in that section. The remainder of this section will focus on basic model performance prediction at key points I_{sc}, V_{oc}, and P_{mp}, which by design are always accurate for the reference model.

4.3 Single Diode Model Translated I-V Curves

In this section the high irradiance reference model for each module (fitted to measured data) is used to predict its performance under low and in some cases medium irradiance "target" conditions, using the model parameter translations described in Section 4.1.2. This methodology closely follows the way that the 5 and 7 parameter single diode models are commonly used, often with the reference model established using data that the manufacturer provides at STC. The low and medium target conditions for each module are those at which measured data have been collected, enabling comparisons between the predictions and the measured data at key I-V curve points I_{sc}, $V_{oc,}$ and P_{mp}. This facilitates analysis of the accuracy of the 5 and 7 parameter models for arrays of many different technologies and for a range of modules that have experienced field degradation.

4.3.1 Operating Conditions

Cell Temperature

The reference and target cell temperatures for each module are those from the measured data, and their measurement and subsequent calculation using the King-Sandia temperature model (Equation 3.14) are described in Chapter 3. Because the temperatures are averaged over the whole array, as well as over the duration of the I-V curve sweep, the cell temperature uncertainty (Equation 3.15) is significant, between 2 and 5ºC for each module.

Incident Irradiance

Each module has measured high irradiance (reference) and low or medium irradiance (target) values. However, as indicated in Section 3.4.7, these irradiance measurements, especially at low light levels, have relatively high uncertainty. It is furthermore difficult to quantify the added uncertainty introduced by the angle-of-incidence and spectral corrections used to calculate effective absorbed irradiance (Equation 3.18), which is the parameter required by the single diode model for translation from reference to target conditions. Fortunately in this work, because the single diode model's fitted reference parameters do not depend on the value of the absorbed irradiance S_{ref}, and because the target conditions have measured data, it is possible to obtain fitted model parameters under both reference and target conditions while ignoring the measured irradiance values. Given the two resulting fitted values for the photodiode current, $I_{L,ref,HIGH}$ and $I_{L,fitted,TARG}$, one can easily rearrange equation 4.8 to calculate the ratio S_{TARG}/S_{ref} which is needed for parameter translation between the reference and target cases.

$$\frac{S_{TARG}}{\mathrm{S_{ref,HIGH}}} = \frac{\mathrm{I_{L,fitted,TARG}}}{\left[\mathrm{I_{L,ref,HIGH}} + \alpha_{\mathrm{Isc}} \cdot \left(\mathrm{T_{cell,TARG}} - \mathrm{T_{cell,ref,HIGH}}\right)\right]} \qquad \textbf{4.15}$$

Photodiode current I_L is chosen as the parameter to determine the effective irradiance ratio because by physical definition, the number of electrons generated by sunlight varies linearly with photovoltaic generators' effective absorbed solar radiation. To say otherwise would completely invalidate the principles of the model, as the relationship between I_L and incident radiation is strongly grounded in semiconductor device physics. Even though R_{sh}, and I_0 in the 7 parameter model vary with irradiance as well, those are merely empirical correlations [(Duffie & Beckman, 2006), (Beckman, 2011)] and do not hold as much weight.

Use of measured photodiode current I_L eliminates the model uncertainty related to pyranometer measurements. There is still slight uncertainty in irradiance due to its dependence on the measured temperature, which must be accounted for when comparing modeled and measured data.

4.3.2 Five-Parameter Model Translation to Non-Reference Conditions

` Comparisons between the measured and predicted module performance at low and medium light operating conditions must account for their respective uncertainties. This is done as follows:

Measured Data Uncertainty

The module-level measured data for I_{sc}, V_{oc}, and P_{mp} have associated uncertainty calculated and shown in Chapter 3. These uncertainties are generally small, less than 1% for most modules at all three points.

Modeled Data Uncertainty

Modeled data uncertainty comes from uncertainty in the measured temperature under both reference and target operating conditions ($T_{cell,ref,HIGH}$ and T_{TARG}), which affects the irradiance ratio $S/S_{ref.}$ Uncertainty in both temperature and irradiance leads to correlated uncertainties in all of the calculated model parameters under target conditions.

To find the nominal values, as well as the upper and lower uncertainty bounds for the key points I_{sc}, V_{oc}, and P_{mp} at the target conditions, the translation from reference to target conditions is performed five times for each module. First, the nominal value of each key point is determined running the translation with $T_{cell,ref,HIGH}$ and T_{TARG} at their nominal values. Then the translation is conducted four more times, once for each combination of $T_{cell,ref,HIGH} = T_{cell,ref,HIGH} \pm U_{Tcell}$ and $T_{TARG} = T_{TARG} \pm U_{Tcell,}$ where U_{Tcell} is the measured temperature uncertainty calculated in Equation 3.15. Uncertainty bounds for each key point (I_{sc}, V_{oc}, and P_{mp}) are established by their resulting minimum and maximum modeled values.

Results

The translated model and measured data under the target operating conditions are said to be in agreement at each key I-V curve point when their measured and modeled uncertainty ranges overlap. Detailed information on the measured and modeled uncertainty range for each module's I_{sc}, V_{oc}, and P_{mp} is found in appendix E.1; these tables also include the percent difference between the modeled and measured values for each module. The percent root mean square error (RMSE - Equation 4.16) between modeled and measured values, and model agreement for each array[3], are summarized in Table 4.2 for medium irradiance target conditions and Table 4.3 for low irradiance conditions; Tables 3.1 and 3.2 include the number of modules in each array (though in some cases only a subset have medium irradiance data, as seen in Appendix E).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\#\mathrm{Modules}=1}^{n}\left(\frac{Z_{\mathrm{Meas}} - Z_{\mathrm{Mod}}}{Z_{\mathrm{Mod}}}\right)^2}{n}} \qquad \textbf{4.16}$$

Equation 4.16 is used to calculate the percent RMSE for each array's modules' I_{sc}, V_{oc}, and P_{mp}. In these calculations, n is the number of modules in the array and the variable Z represents the curve point for which the RMSE is to be calculated.

The 5 parameter model's predictions under medium irradiance conditions (Table 4.2) are generally good for I_{sc}, though it is overpredicted for some thin film modules, suggesting that the series resistance translation is incorrect. Nearly all of the arrays have one or more modules with disagreement between the modeled and predicted P_{mp} and V_{oc}, with thin film arrays again tending to show a higher level of disagreement. While the maximum power point RMSE does not appear extremely large for most arrays, it is important to note that even 2% under medium irradiance conditions is significant, since in many climates a large portion of a PV array's output energy is generated under these conditions.

[3] Array Thin 1B is excluded from this analysis, as its data were taken with a slightly different equipment configuration. Its uncertainty would be less than or equal to that of other thin film arrays, and its results would likely be similar to those of the crystalline silicon arrays.

Table 4.2. Comparisons between 5 parameter model and measured module performance under medium irradiance conditions ($S_{TARG}/S_{ref,\ HIGH} \approx 0.5$)

Array	Isc		Voc		Pmax	
	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement
Mono 1A	0.1%	0%	0.8%	21%	1.5%	25%
Mono 2A	0.0%	0%	0.5%	11%	1.0%	11%
Mono 1B	0.2%	0%	0.6%	0%	2.2%	29%
Mono 4B	0.2%	0%	1.0%	10%	1.8%	20%
Mono 5B	0.1%	0%	1.1%	56%	2.1%	67%
Mono 6B	0.1%	0%	0.6%	6%	1.1%	6%
Poly 1A	0.3%	0%	2.7%	100%	2.7%	80%
Poly 2A	0.2%	0%	0.7%	13%	1.0%	13%
Poly 3A	0.1%	0%	0.4%	0%	0.8%	0%
Poly 1B	0.3%	0%	2.1%	33%	3.6%	52%
Poly 3B	0.6%	6%	1.0%	11%	3.3%	11%
Poly 4B	0.1%	0%	0.9%	0%	2.4%	33%
Hybrid 1B	0.2%	0%	1.0%	100%	3.9%	100%
Thin 1A	0.2%	0%	1.7%	10%	1.2%	0%
Thin 2A	0.4%	0%	0.6%	8%	3.2%	83%
Thin 3A	0.5%	0%	1.8%	100%	7.0%	100%
Thin 2B	14.4%	100%	12.0%	100%	46.2%	100%
Thin 3B	1.5%	0%	3.9%	100%	14.9%	100%

Table 4.3. Comparisons between 5 parameter model and measured module performance under low irradiance conditions ($S_{TARG}/S_{ref,\ HIGH} \approx 0.2$)

Array	Isc		Voc		Pmax	
	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement
Mono 1A	0.1%	0%	2.2%	100%	4.9%	92%
Mono 2A	0.1%	0%	1.0%	56%	3.8%	100%
Mono 1B	0.1%	0%	1.2%	33%	2.3%	52%
Mono 2B	0.5%	11%	49.2%	74%	82.7%	95%
Mono 3B	0.7%	15%	4.9%	100%	16.9%	100%
Mono 4B	0.1%	0%	0.7%	10%	1.6%	25%
Mono 5B	0.5%	0%	2.4%	100%	9.1%	100%
Mono 6B	0.1%	0%	1.1%	72%	2.8%	89%
Poly 1A	0.3%	0%	5.0%	100%	6.8%	90%
Poly 2A	0.4%	0%	0.6%	13%	5.6%	80%
Poly 3A	0.2%	0%	1.6%	36%	4.3%	82%
Poly 1B	0.5%	0%	3.9%	100%	9.1%	95%
Poly 2B	0.0%	0%	2.1%	100%	3.2%	81%
Poly 3B	0.4%	0%	1.4%	89%	7.0%	67%
Poly 4B	0.3%	0%	3.2%	100%	9.7%	100%
Poly 5B	0.3%	0%	3.4%	100%	12.0%	100%
Hybrid 1A	0.1%	0%	0.9%	75%	1.8%	17%
Hybrid 2A	0.4%	0%	1.9%	93%	11.5%	100%
Hybrid 1B	0.2%	0%	1.2%	63%	5.3%	63%
Hybrid 2B	0.3%	0%	14.1%	100%	18.7%	100%
Thin 1A	1.8%	85%	1.8%	90%	13.5%	100%
Thin 2A	1.2%	13%	0.7%	42%	8.3%	100%
Thin 3A	0.9%	42%	3.2%	100%	14.9%	100%
Thin 4A	0.8%	4%	2.8%	100%	13.3%	100%
Thin 2B	35.4%	100%	23.0%	100%	117.0%	100%
Thin 3B	3.1%	0%	6.1%	100%	26.3%	100%

Under low irradiance conditions, there are more discrepancies between the measured data values and the 5 parameter model's predictions (Table 4.3), with the model nearly always over-estimating the key I-V curve points' values. The modules' maximum power RMSE is 10% or higher for ten of the arrays, and again tends to be worse for thin film. This may result in significant errors in annual performance prediction, especially for arrays with non-optimal orientation, or those in cloudy climates. It is clear from these data that the 5 parameter model is not well suited to performance prediction when the operating conditions are very different from the reference case.

4.3.3 Seven-Parameter Model Translation to Non-Reference Conditions

The 7 parameter single diode model, with its extra translation parameters determined in part by low irradiance data from manufacturers, is intended to be more accurate over a wide range of PV operating conditions. The use of these extra parameters has shown up to a 20% increase in model accuracy at maximum power point under medium and low light conditions (MacAlpine & Brandemuehl, 2011), but has also shown mixed results in other literature (Boyd M. , 2010). In this section, the 7 parameter model's predictions are compared to the measured data for several of the arrays, using the same low and medium irradiance operating conditions and methodology for determining modeled and measured uncertainty bounds that were used for the 5 parameter model. Detailed results for each module are again found in Appendix E.1 and a summary of the differences is shown in

Table 4.4 (medium irradiance) and Table 4.5 (low irradiance).

Table 4.4. Comparisons between 7 parameter model and measured module performance under medium irradiance conditions ($S_{TARG}/S_{ref, HIGH} \approx 0.5$)

Array	Isc		Voc		Pmax	
	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement
Mono 1A	0.1%	0%	0.8%	25%	2.4%	67%
Mono 5B	0.0%	0%	4.4%	100%	5.2%	100%
Poly 1A	0.5%	0%	0.9%	95%	3.7%	100%
Poly 1B	0.5%	0%	2.4%	90%	4.2%	90%
Hybrid 1B	0.1%	0%	0.6%	100%	0.7%	75%
Thin 1A	0.2%	0%	4.1%	100%	3.7%	70%
Thin 3A	0.4%	0%	1.3%	100%	2.4%	100%
Thin 2B	16.2%	100%	9.9%	100%	35.9%	100%
Thin 3B	1.3%	0%	0.9%	89%	8.3%	100%

Table 4.5. Comparisons between 7 parameter model and measured module performance under low irradiance conditions ($S_{TARG}/S_{ref, HIGH} \approx 0.2$)

Array	Isc		Voc		Pmax	
	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement
Mono 1A	0.1%	0%	1.5%	75%	2.8%	46%
Mono 5B	0.5%	0%	13.0%	100%	10.1%	100%
Poly 1A	0.4%	0%	1.7%	33%	3.8%	53%
Poly 1B	0.4%	0%	3.3%	90%	3.4%	62%
Hybrid 1B	0.2%	0%	1.3%	75%	1.8%	50%
Thin 1A	1.5%	55%	4.1%	100%	5.8%	85%
Thin 3A	0.9%	29%	2.7%	100%	6.8%	100%
Thin 2B	37.2%	100%	11.0%	91%	86.6%	100%
Thin 3B	2.9%	0%	4.4%	96%	15.2%	96%

Figure 4.4 and Figure 4.5 show a comparison of each array's modules' error in predicted maximum power output as compared to their measured values, under medium and low irradiance conditions, respectively, using the 5 and 7 parameter single diode models. Additional comparison between the two models is shown in Table 4.6, which includes the selected arrays' root mean square

prediction errors (RMSE) for maximum power, averaged over the crystalline silicon arrays, the thin film arrays, and the entire set of selected arrays.

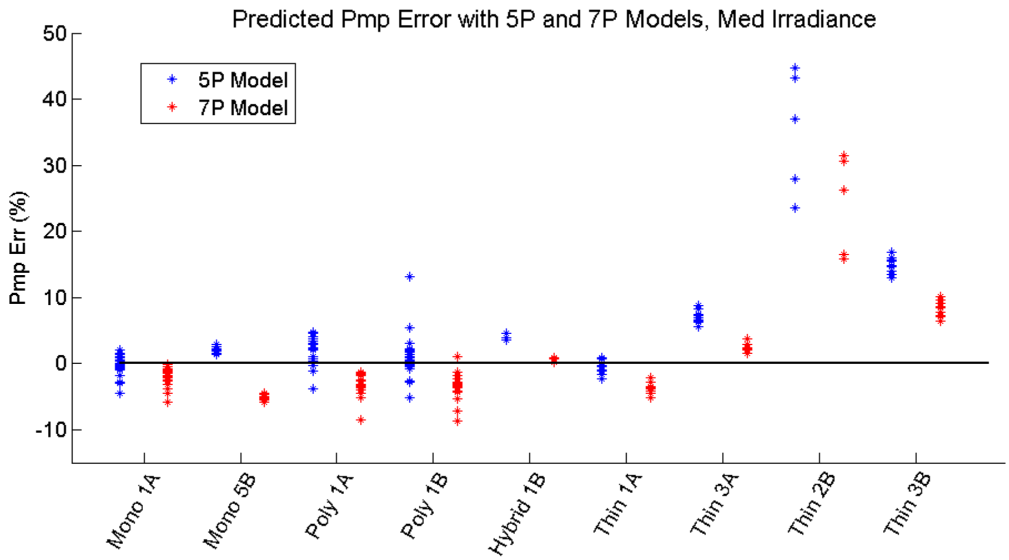


Figure 4.4. Error in predicted vs. measured maximum power point for various arrays' modules under medium irradiance conditions

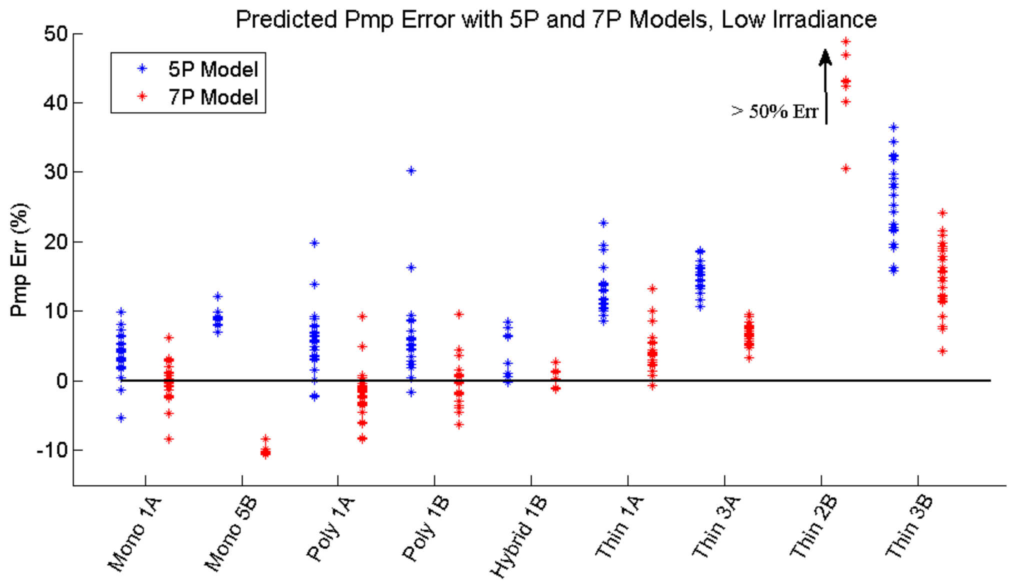


Figure 4.5. Error in predicted vs. measured maximum power point for various arrays' modules under low irradiance conditions

Table 4.6. Maximum power point RMSEs under low and medium light conditions for the 5 and 7 parameter single diode models, averaged over subsets of the measured arrays as well as the full set. "Selected" arrays are those listed in the first column of Table 4.4.

Arrays	5P Model		7P Model	
	Low Light	Med Light	Low Light	Med Light
Si, Selected	7.1%	2.8%	4.4%	3.2%
TF, Selected	42.9%	17.3%	28.6%	12.6%
All, Selected	23.0%	8.3%	15.1%	7.4%

While the 7 parameter single diode model is better at predicting maximum power than the 5 parameter model under low irradiance conditions for most arrays (Figure 4.5, Table 4.6), there is still a wide dispersion of error, approximately +/-10% for silicon modules and 10-50% for modules in thin film arrays. As seen in Table 4.5, most arrays also show significant misprediction in V_{oc}, and even I_{sc} for Thin 2B, when using the 7 parameter model. This indicates that though the model is fitted to some extent to the low irradiance conditions, the parameters and/or methods chosen for fitting are not always effective.

Under medium irradiance conditions (Figure 4.4, Table 4.6) the 7 parameter single diode model shows mixed results when compared to its 5 parameter counterpart. Maximum power point predictions are worse for the 7 parameter model in five of the nine arrays under consideration, including all of the crystalline silicon arrays; the average RMSE is higher for the 7 parameter model than it is for the 5 parameter model (Table 4.6) for crystalline silicon arrays, 3.2% vs. 2.8%. While the 7 parameter model's predictions do show improvement for the hybrid and some of the thin film arrays, the fact that the model mispredicts significantly at medium irradiance, by 10% or more for some modules, and by several percent on average for many arrays, is concerning, as many PV installations generate a large fraction of their output energy under these conditions. I-V curves from each model, along with the fitted reference curve, are shown in Figure 4.6 under low and medium light conditions for a single module in each of arrays Poly 1A and Thin 3A. These results demonstrate the potential and need for a new improved model which further improves translation accuracy and does not cause added misprediction at medium light levels.

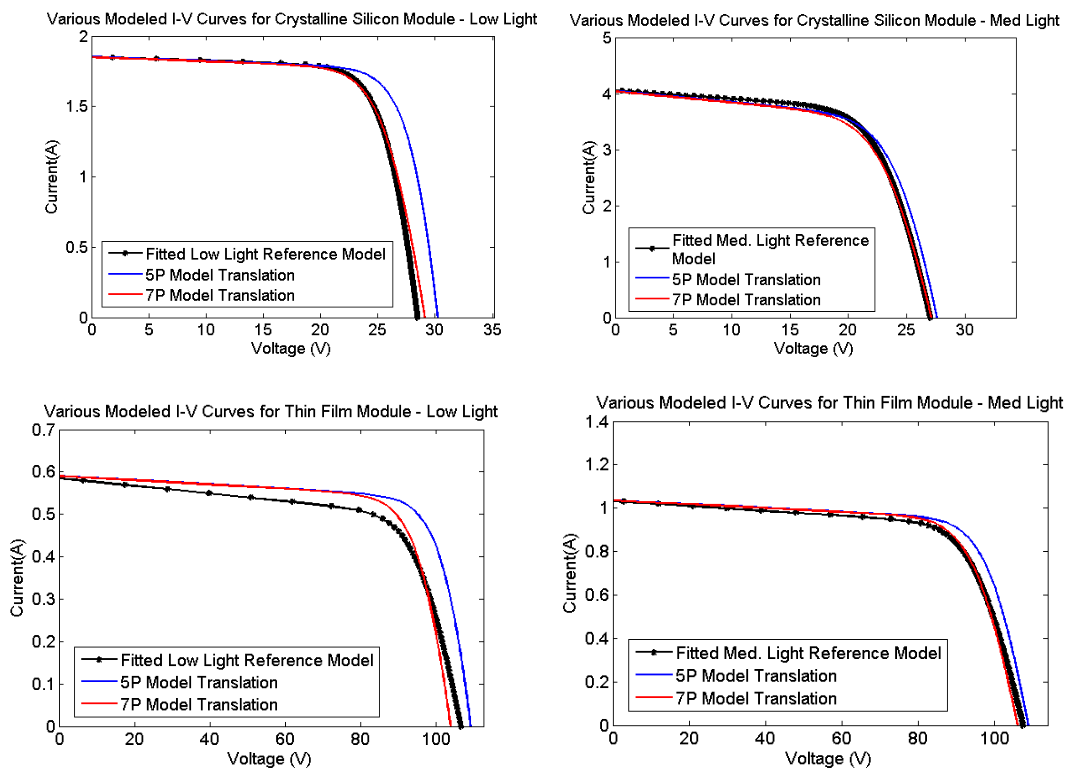


Figure 4.6. Comparisons between module-level I-V curves predicted by the 5 parameter and 7 parameter single diode models. Clockwise from top left: crystalline silicon low light, crystalline silicon medium light, thin film medium light, and thin film low light.

4.4 Improved Model Modifications

A subset of the arrays are chosen for further analysis, with the goal of examining the single diode model parameters' behavior under realistic operating conditions to determine how modifications to the parameter translation methodology may increase model accuracy. The chosen arrays, all of which have measured module I-V curves at high, medium, and low light levels, include examples of different technologies, and different installation duration. Three representative (i.e. non-defective by visual inspection of I-V curves, which are found in Appendix D) modules are chosen at random from each array to be the focus of this investigation. The arrays and their associated modules are listed in Table 4.7.

Table 4.7. Arrays and modules for model improvement analysis

Array	Modules
Mono 1A	1,8,14
Mono 5B	1,5,8
Poly 1A	20,21,27
Poly 1B	2,12,16
Hybrid 1B	5,6,7
Thin 1A	2,10,14
Thin 3A	6,7,15
Thin 2B	18,25,27
Thin 3B	13,16,18

4.4.1 Observed Parameter Variation

Each of the modules listed in Table 4.7 has its measured data fitted to corresponding 5 parameter single diode reference models. The following figures for each array show the actual fitted parameter values at each measured irradiance/temperature combination (asterisk points) and the 5 parameter model's predicted parameter values, using the high irradiance case as a reference (dashed lines). Parameter I_L is not shown, as it is used to predict the irradiance ratio for the medium and low light conditions, and thus its fitted and predicted values will always be the same.

Incident irradiance and cell temperature were not controlled separately during data collection, so they cannot be separated in this analysis. In following figures, the resistances will be shown with a varying irradiance ratio, as it is assumed that they depend more on irradiance than temperature, based on the irradiance dependence of shunt resistance in the existing 5 parameter model. Parameters I_0 and *a* are assumed to depend primarily on temperature, as this is how they are represented in the existing 5 parameter model, and device physics indicate that this is how their behavior is governed.

Monocrystalline Silicon

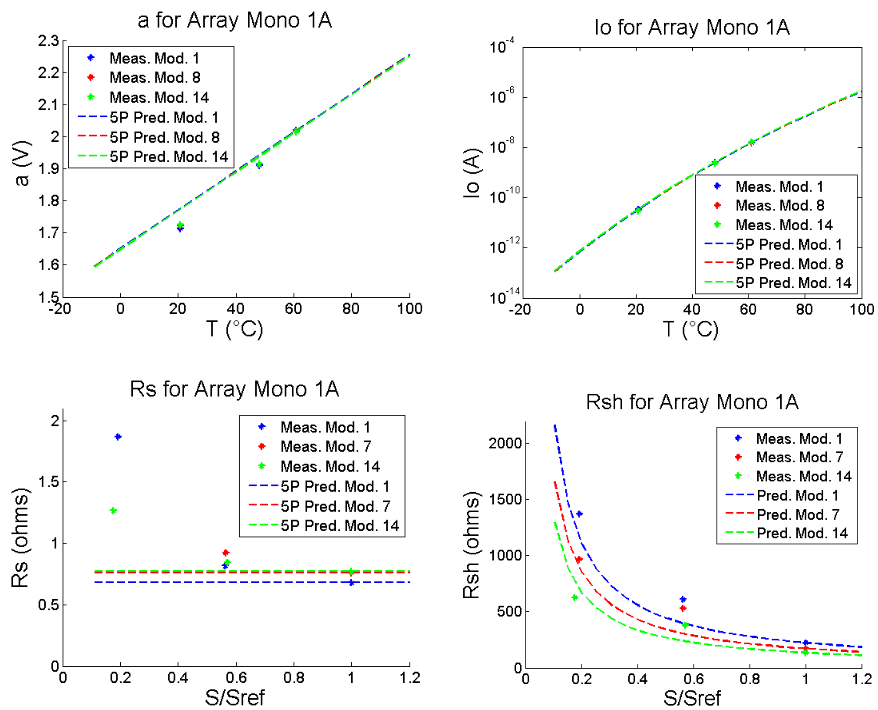


Figure 4.7. Modeled and measured (fitted) parameters for Mono 1A

The 5 parameter single diode model's predicted values for parameter I_0 in array Mono 1A (Figure 4.7) are very similar to those of the fitted measured curve at medium and low irradiance. Values for the parameter *a* are similar as well; while the model increasingly overpredicts at lower temperatures, it is only by 5% or less. Prediction of shunt resistance R_{sh} is less consistent; the three modules have different behaviors for this parameter as the light levels decrease, but the predicted resistance is lower than its fitted counterpart under medium irradiance levels in all cases, which will tend to underpredict power output. This is likely counteracted somewhat by the predictions for $R_{s,}$ which is assumed constant but clearly increases as irradiance and/or temperature decrease, in a pattern not unlike that of $R_{sh.}$ A model that underpredicts R_s will overpredict module power output.

Similar behavior is noted for Mono 5B (Figure 4.8) with the exception that the fitted R_{sh} behavior is similar for all three modules, and that the predicted values of R_{sh} are too high under low irradiance conditions, which will tend to underpredict array output power.

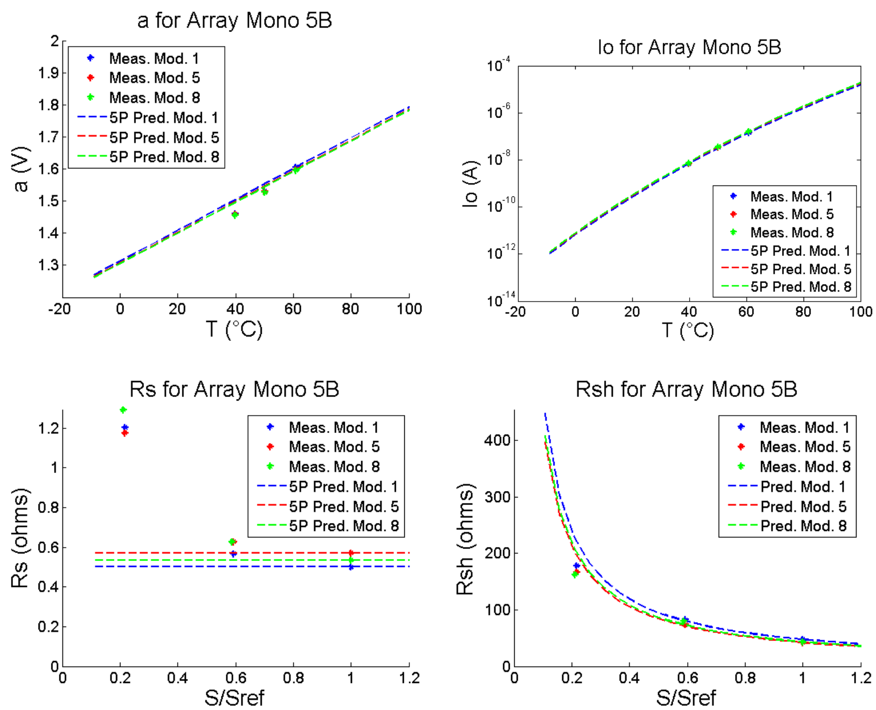


Figure 4.8. Modeled and measured (fitted) parameters for Mono 5B

Polycrystalline Silicon

Both polycrystalline silicon arrays (Figure 4.9, Figure 4.10) show results similar to those of the monocrystalline silicon arrays. There is some module-to-module variation in each of the arrays, with one in Poly 1A showing a nearly flat trend in R_s while one in Poly 1B has a nearly flat R_{sh}. These demonstrate the effect that degradation can have on module modeling, and the importance in this work (where modeling module-to-module mismatch is a goal) of having individual module models that are characterized by data taken under varied operating conditions.

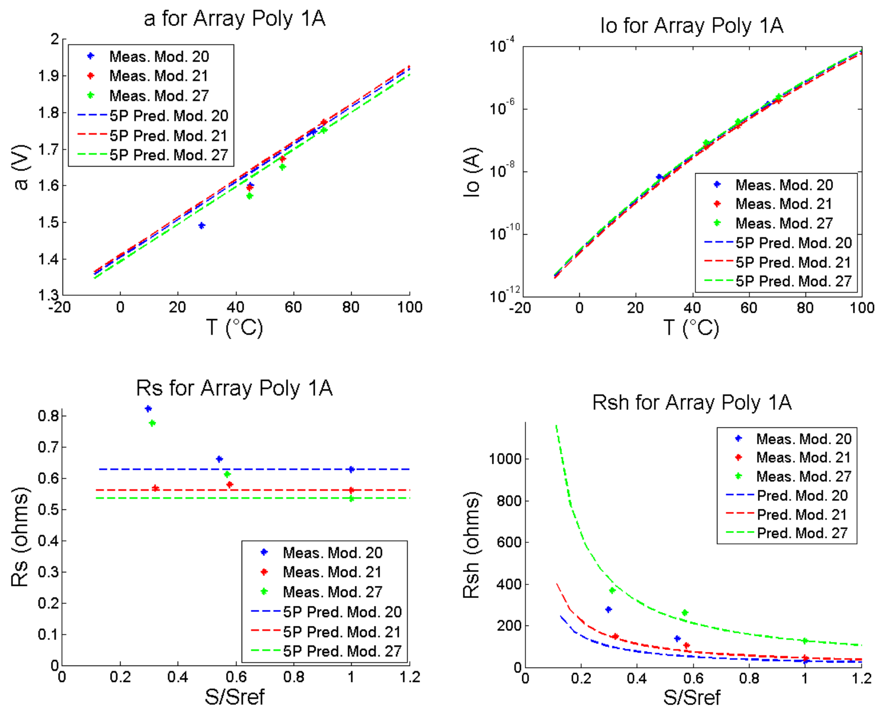


Figure 4.9. Modeled and measured (fitted) parameters for Poly 1A

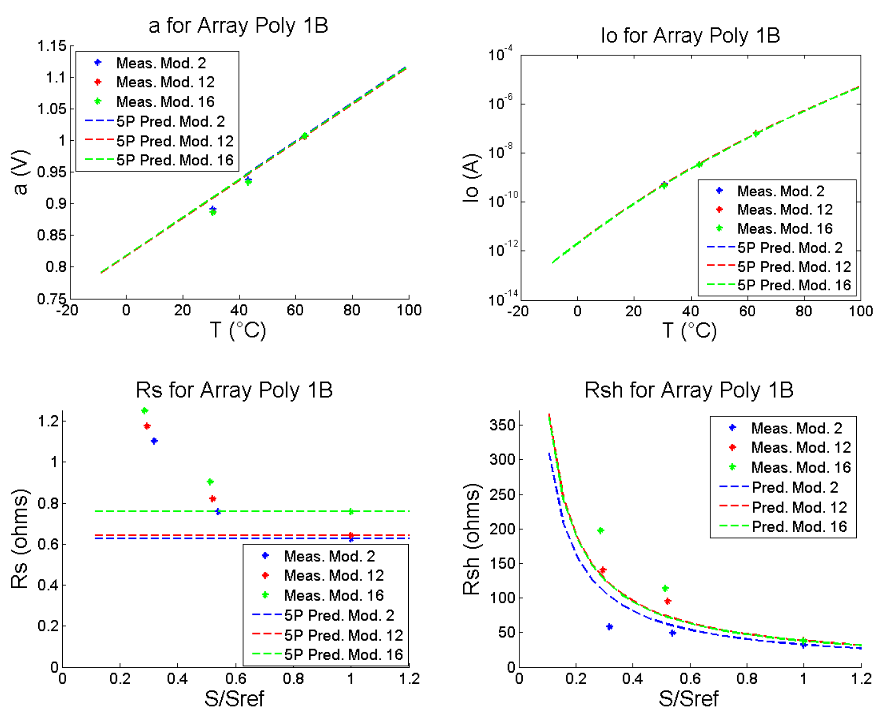


Figure 4.10. Modeled and measured (fitted) parameters for Poly 1B

Hybrid

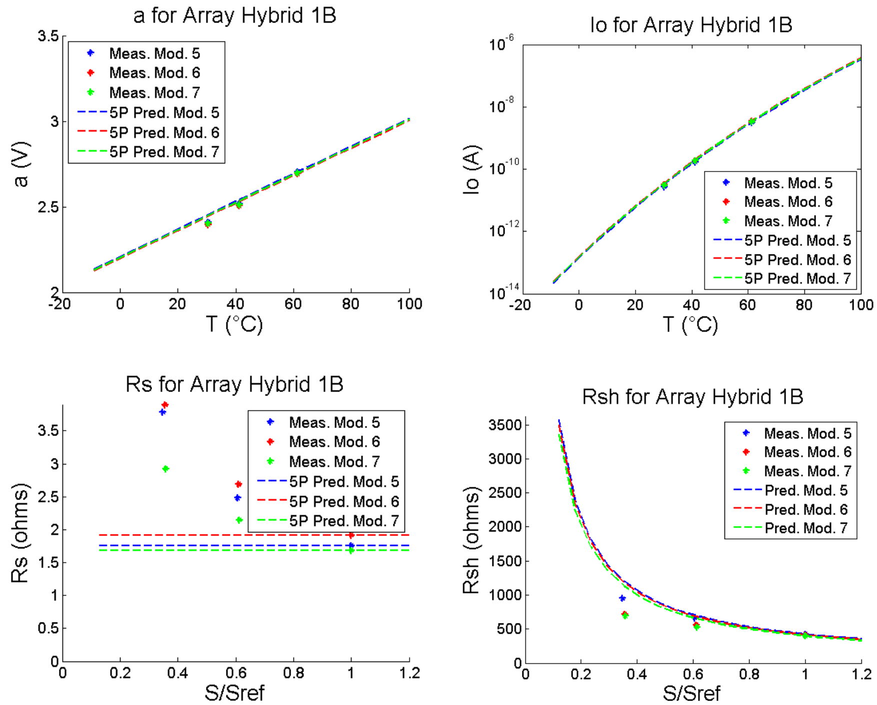


Figure 4.11 Modeled and Measured (fitted) parameters for Hybrid 1B

The hybrid array's parameters (Figure 4.11) show light and temperature related behavior similar to that of the crystalline silicon arrays. It appears that with this technology, the major opportunities for meaningful parameter translation modification come from the existing model's misprediction of the behavior of series and shunt resistances.

Thin Film

Though the four thin film arrays in this investigation represent four different technologies, their fitted 5 parameter models show similar trends in parameter variation with light and temperature, and these variations are also similar to those of the crystalline silicon and hybrid modules. The two newer arrays, Thin 1A and Thin 3A (Figure 4.12, Figure 4.13) again show good agreement between the measured/fitted and translated model for parameters I_0 and a. Shunt resistance R_{sh} tends to be overpredicted by the model at low irradiance. The series resistance R_s increases with decreasing irradiance and/or temperature, as has been seen with the other technologies, but in the thin film modules it has a larger magnitude and increases more dramatically, which is likely a large part of the reason that the thin film modules' models experienced such pervasive poor agreement with the measured data under medium and low irradiance operating conditions.

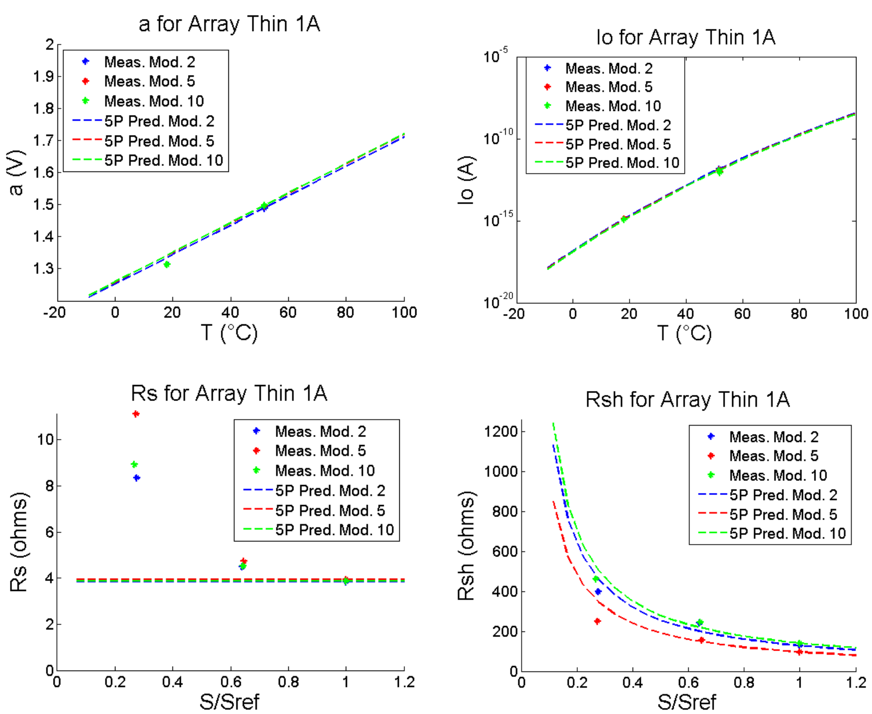


Figure 4.12. Modeled and measured (fitted) parameters for Thin 1A

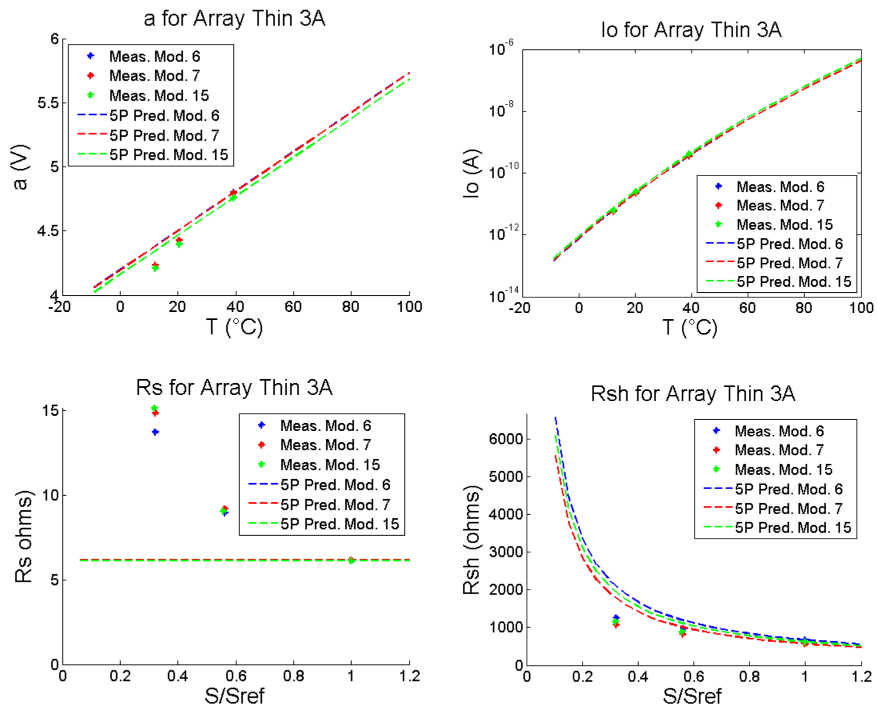


Figure 4.13. Modeled and measured (fitted) parameters for Thin 3A

Older array Thin 2B (Figure 4.14) is a unique case, as the modules of this array were developed early in their manufacturer's adoption of the technology, and have significant module-to-module performance variation, either from the manufacturing process or from degradation. In this array parameters a and I_0 do not show particularly good agreement between measured/fitted and translated model values. The two resistances, however, appear to follow the same trends seen in all of the other arrays. Thin 3B's parameters (Figure 4.15) also follow the trends of the other arrays.

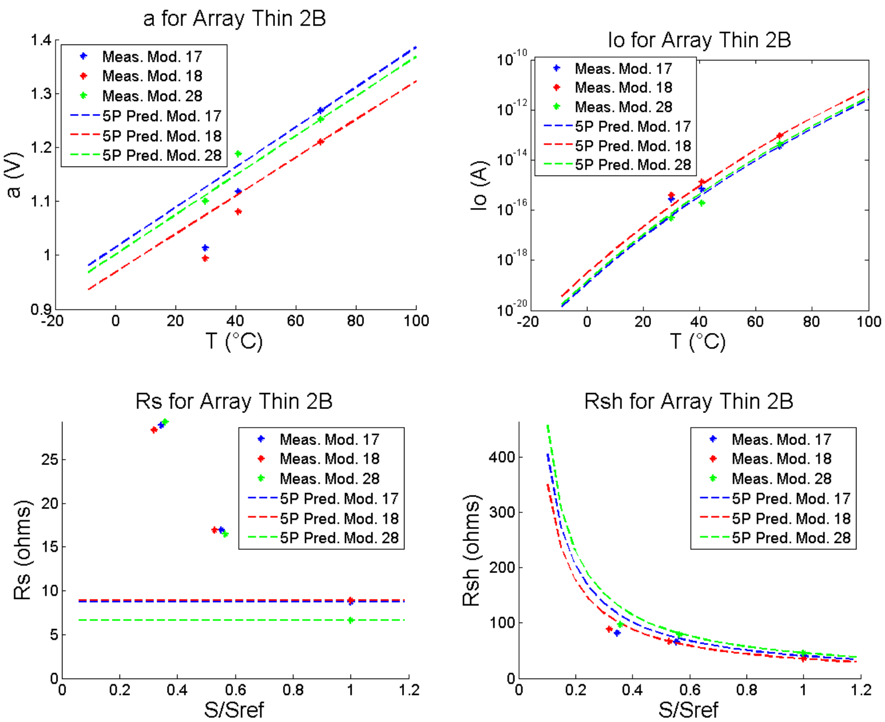


Figure 4.14. Modeled and measured (fitted) parameters for Thin 2B

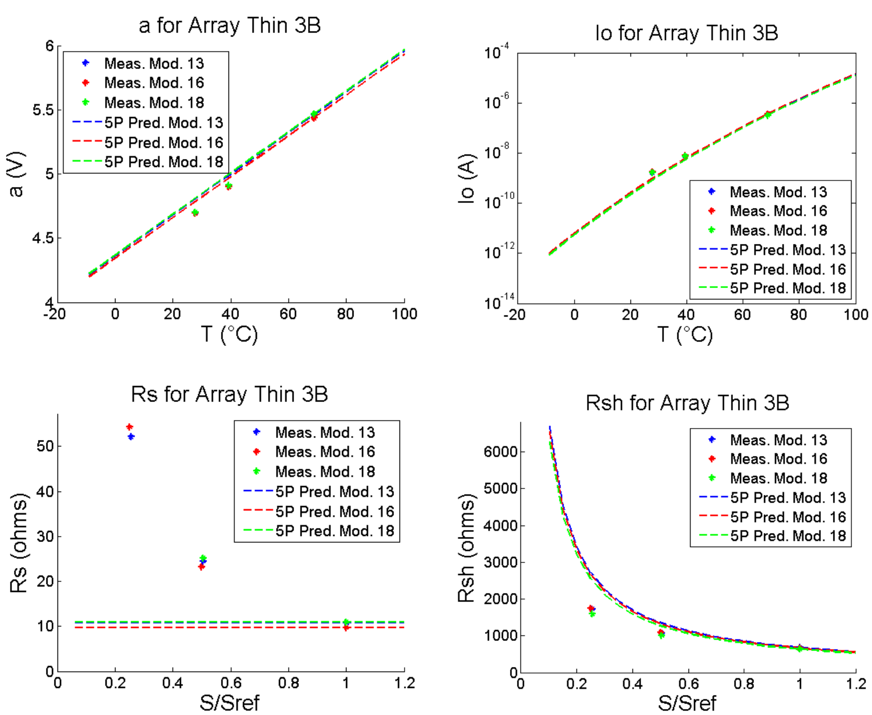


Figure 4.15. Modeled and measured (fitted) parameters for Thin 3B

4.4.2 Proposed Modifications

There are many possible approaches to improving the translation of the single diode model's parameters to increase accuracy under low and medium light levels. This work focuses on a new methodology where fitted reference data from high irradiance conditions are combined with fitted reference data from low light conditions to govern the behavior of the model parameters under different light and temperature combinations. Though a full matrix of data, such as that required by IEC 61853 (IEC, 2011) would allow for a potentially more accurate model (or even straightforward bilinear interpolation between known I-V performance curves), it is also useful to have a modeling methodology that achieves high accuracy with a more limited input dataset; that is the goal of the proposed modifications in this section.

Section 4.3.1 shows that the core parameters of the 5 parameter diode model behave in certain ways with changing operating conditions, that these behaviors are mostly similar across different modules of different technologies, and that some of these behaviors are not well reflected in the existing model. Based on these results, the following modifications are proposed:

Series Resistance R_s

Model series resistance parameter R_s increases with decreasing irradiance and/or temperature, yet is held constant in the current model as operating conditions change. Closer examination of the data suggests (based on some arrays with data taken at similar cell temperatures, yet different irradiances – and different values for a fitted curve R_s) that the irradiance may be the dominant factor, though further investigation with a larger dataset with separate control of irradiance and temperature would be advisable. The proposed calculation for R_s (at irradiance S) is:

$$\mathrm{R_s} = \mathrm{R_{s,ref,HI}} + \left(1 - \frac{\mathrm{S}}{\mathrm{S_{ref,HI}}}\right) * \mathrm{X_{RS}} * \left(\frac{\mathrm{S_{ref,HI}}}{\mathrm{S}}\right)^2 \qquad \textbf{4.17}$$

where

$$X_{RS} = \frac{R_{s,ref,LO} - R_{s,ref,HI}}{1 - \frac{S_{ref,LO}}{S_{ref,HI}}} * \left(\frac{S_{ref,LO}}{S_{ref,HI}}\right)^2 \quad \textbf{4.18}$$

In these equations, $R_{s,ref,HI}$ and $R_{s,ref,LO}$ are the series resistances fitted to the high and low light measurements. Similarly, $S_{ref,HI}$ and $S_{ref,LO}$ are the effective absorbed irradiances under the high and low light measurement operating conditions. They may be known explicitly, or their ratio may be calculated using Equation 4.15. X_{RS} is the new series resistance modifier term, which accounts for the module's behavior under both high and low light conditions.

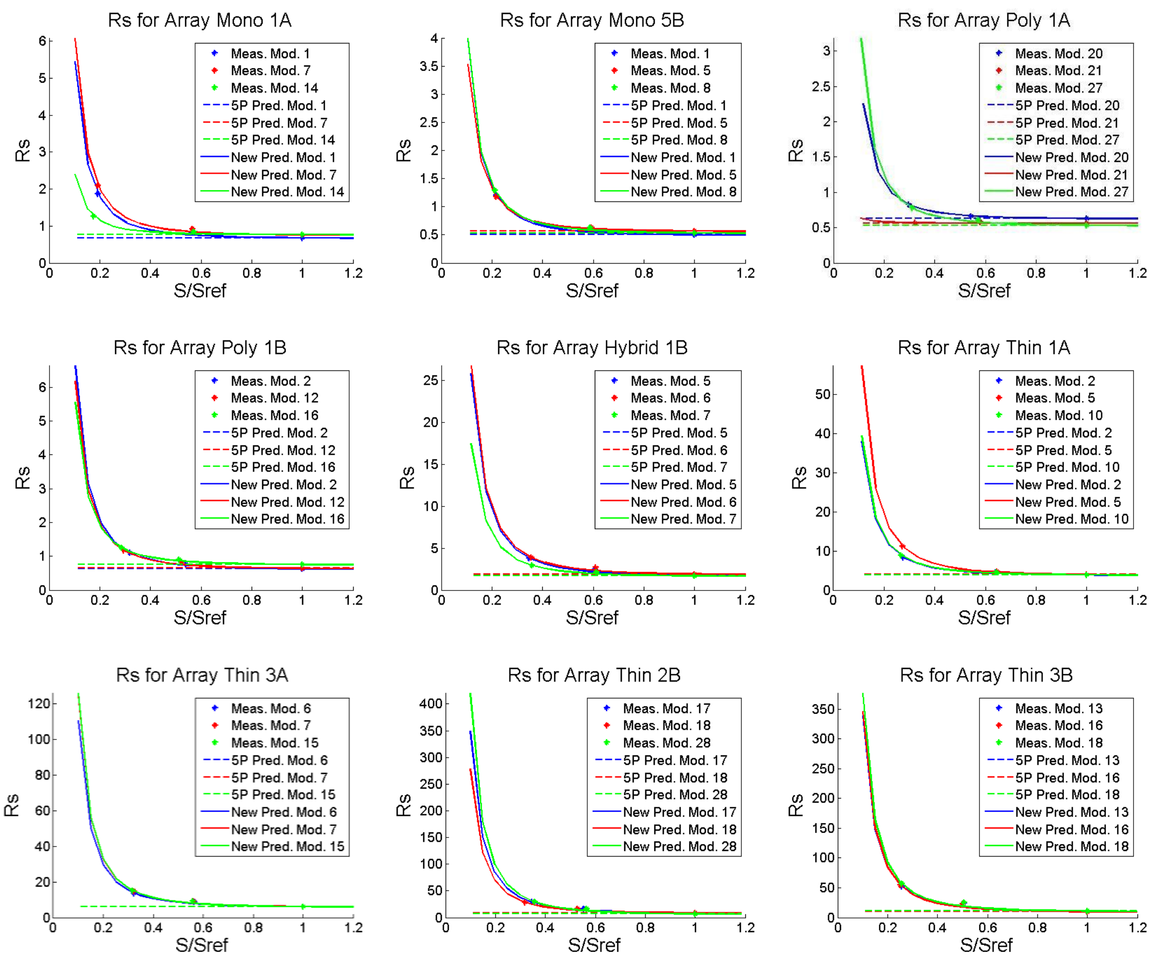


Figure 4.16. Measured (fitted) and modeled (5 parameter and new proposed improved model) R_s for the different arrays. R_s is given in ohms.

Figure 4.16 shows the measured (fitted) values for R_s, at high, medium, and low irradiance, as well as the 5 parameter model predicted values (dashed line), and values predicted with the new improved model modification. In all cases the new model exactly matches the fitted R_S under low irradiance conditions, and predicts values closer to the fitted R_S in the case of medium irradiance.

Shunt Resistance R_{sh}

Shunt resistance R_{SH} is also assumed to vary predominately with irradiance, as that is what it does in both the 5 and 7 parameter models, though a module performance dataset with independently varying irradiance and temperature could be used to verify this. As with the series resistance, the high and low measured reference data are used to modify the way that parameter R_{SH} changes with light level. The new calculation of shunt resistance at irradiance S is:

$$R_{sh} = R_{sh,ref,HI} + \left(\sqrt{\frac{S_{ref,HI}}{S}} - 1\right) * X_{RSH} \qquad \textbf{4.19}$$

where

$$X_{RSH} = \frac{R_{sh,ref,LO} - R_{sh,ref,HI}}{\sqrt{\frac{S_{ref,HI}}{S_{ref,LO}}} - 1} \qquad \textbf{4.20}$$

In these equations, $R_{sh,ref,HI}$ and $R_{sh,ref,LO}$ are the shunt resistances fitted to the high and low light measurements. $S_{ref,HI}$, $S_{ref,LO}$ and S are the effective absorbed irradiances, described below Equation 4.18, and X_{RS} is the new shunt resistance modifier term, which accounts for the module's behavior under both high and low light conditions.

Figure 4.17 shows the measured (fitted) values for R_{sh}, at high, medium, and low irradiance, as well as the 5 parameter model predicted values (dashed line), and values predicted with the new improved model modification. In all cases the new model exactly matches the fitted R_{sh} under low irradiance conditions. The new model's predicted values under medium irradiance conditions are as good as or better than the existing model, yet for some modules have room for improvement. Shunt resistance can vary greatly from module to module, as it is one of the parameters that is most affected by manufacturer's performance tolerances and degradation, and it is thus difficult to predict correctly for all modules.

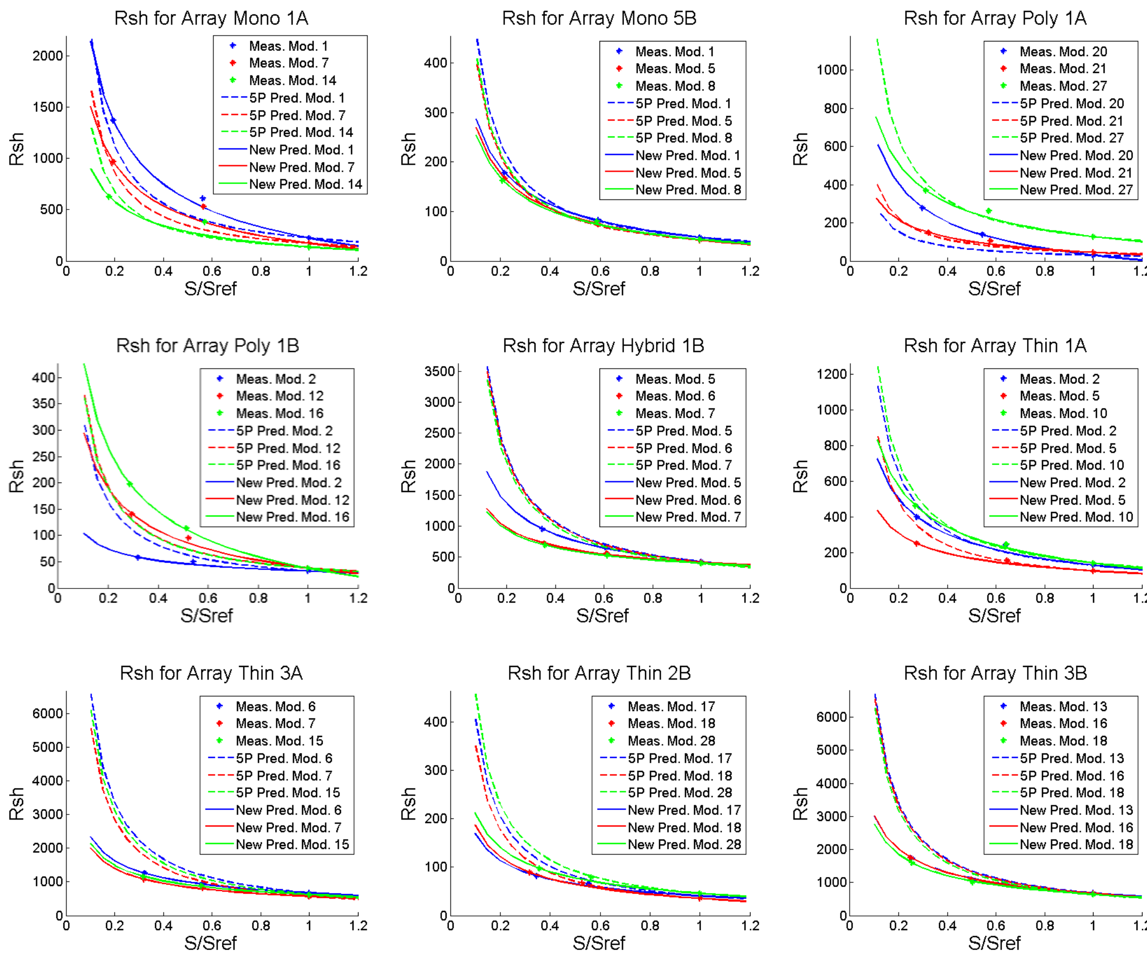


Figure 4.17. Measured (fitted) and modeled (5 parameter and new proposed improved model) Rsh for the different arrays. R_{sh} is given in ohms.

Reverse Saturation Current I_0

While analysis of the existing 5 parameter single diode model shows that the series and shunt resistances are predicted the farthest away from their fitted values, modifying only their translations still leaves significant inaccuracies in the single diode model's power and open circuit voltage prediction at low and medium irradiance. Thus a third modification is proposed, to compensate for some of the inaccuracy still found in the model.

Though the modified diode ideality factor *a* is shown in the previous subsection to consistently be slightly overpredicted by the existing model under lower temperature conditions, there is not a strong physically meaningful justification for modifying this parameter. However, the parameter I_0 also shows some misprediction, and basic device physics suggest that the translation of this parameter (Equation 4.12) may be oversimplified (Honsberg & Bowden) . The reverse saturation current I_0 is commonly estimated to vary with the cube of the cell temperature, but this neglects the fact that the diffusion length and diffusion of the minority carrier may change with temperature, i.e. that recombination in a solar cell may vary differently with temperature depending on the module or technology type.

It is proposed that I_0 be allowed to vary with temperature as seen in Equation 4.21 such that the new model's predicted open circuit voltage at the low irradiance reference conditions, $V_{oc,ref,LO}$, matches the measured value.

$$\mathrm{I_0} = \mathrm{I_{0,ref,HI}} \cdot \left(\frac{\mathrm{T}}{\mathrm{T_{ref,HI}}}\right)^{X_{I0}} \exp\left(\frac{\mathrm{Eg_{ref,HI}}}{\mathrm{k}\cdot\mathrm{T_{ref,HI}}} - \frac{\mathrm{Eg}}{\mathrm{k}\cdot\mathrm{T}}\right) \qquad \mathbf{4.21}$$

In this equation, as in Equation 4.13, the *Eg* terms are band gaps, *k* is Boltzmann's constant, and the cell temperatures *T* are all in degrees Kelvin. The new saturation current modifier term, X_{I0}, is found by first determining the reverse saturation current value $I_{0,Voc,LO}$ needed at low irradiance, given the predicted values of the other parameters, to predict that open circuit voltage is equal to $V_{oc,ref,LO.}$ This is done by rearranging Equation 4.3 to obtain

$$\mathrm{I_{0,Voc,LO}} = \frac{I_{L,ref,LO} - \dfrac{V_{oc,ref,LO}}{R_{sh,NewModel,LO}}}{e^{\frac{V_{oc,ref,LO}}{a_{5PModel,LO}}} - 1} \qquad \mathbf{4.22}$$

The value of this $I_{0,Voc,LO}$ uses the 5 parameter model's prediction for parameter *a*, and the new improved model's prediction for parameter R_{sh}. With this target saturation current determined, one can then calculate the value of X_{I0}

$$X_{I0} = \frac{\log\left(\frac{I_{0,Voc,LO}}{I_{0,ref,HI}} * \frac{1}{e^{\left(\frac{Eg_{ref,HI}}{k*T_{ref,HI}} - \frac{Eg_{ref,LO}}{k*T_{ref,LO}}\right)}}\right)}{\log\frac{T_{ref,LO}}{T_{ref,HI}}} \quad \textbf{4.23}$$

With the exception of the target saturation current $I_{0,Voc,LO}$ (Equation 4.22), the variables in this equation come from high and low reference conditions, as noted. Cell temperature *T* is in degrees Kelvin.

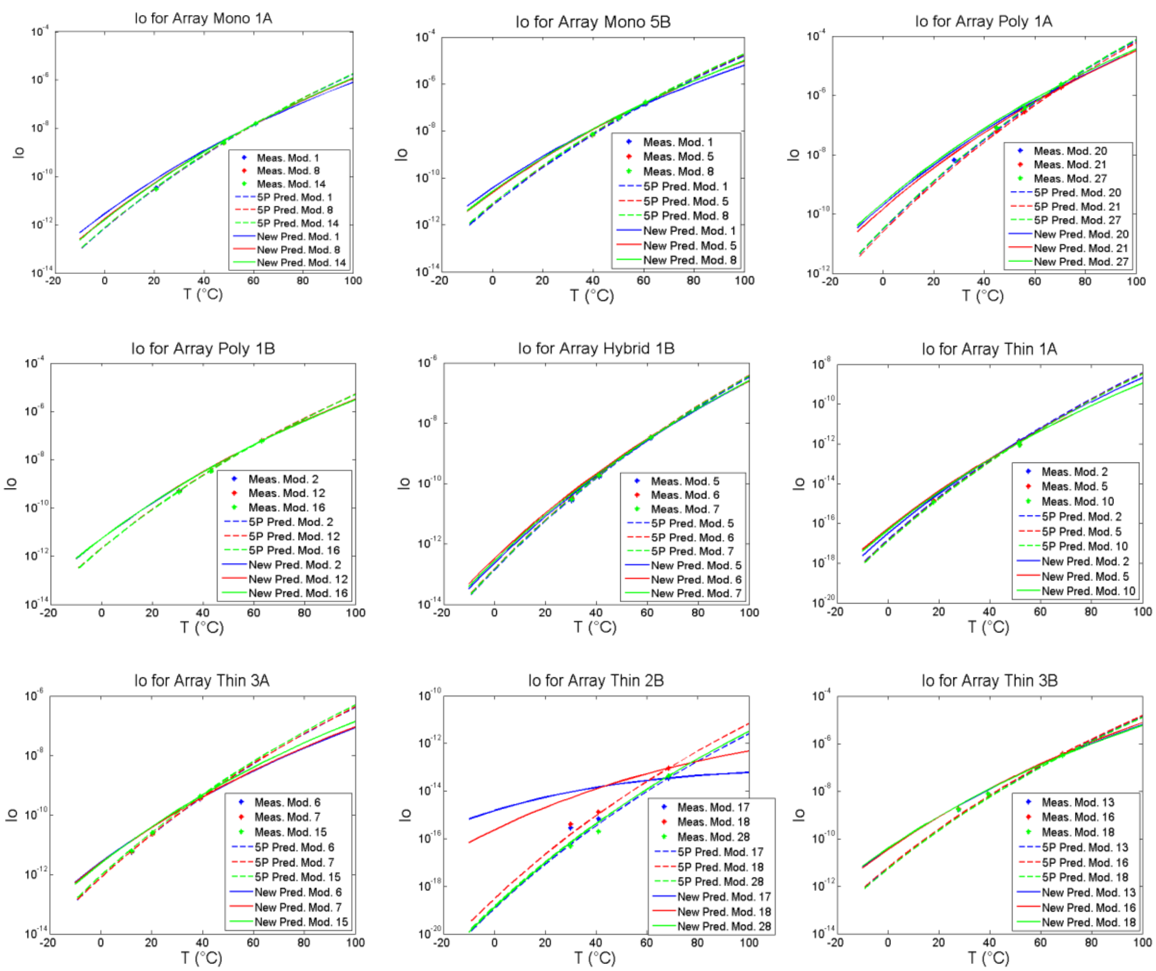


Figure 4.18. Measured (fitted) and modeled (5 parameter and new proposed improved model) I_0 for the different arrays. I_0 is given in amperes.

As shown in Figure 4.18, this modification to parameter I_0 causes it to make very different predictions from the 5 parameter diode model, and these predictions often do not align well with the values of I_0 that are indicated by the measured (fitted) data. However, the goal with the adjustment of

I_0's translated values is not to match each of them exactly, since I_0 is being used to compensate for other model inaccuracies, but to enable better prediction of open circuit voltage and maximum power.

4.4.3 New Model Summary

Three new translation parameters, X_{RS}, X_{RSH}, and X_{I0}, in combination with the standard 5 parameter single diode model, form the new, improved "Double Reference" 8 parameter single diode model, henceforth referred to as the DR model. The DR model's required inputs include V_{oc}, I_{sc}, V_{mp}, and I_{mp} under high and low light conditions, as well as temperature coefficients β_{Voc} and α_{Isc} from the manufacturer, mimicking the data required by the 7 parameter single diode model. A key difference, however, is that the DR model uses these module characteristics to generate a 5-parameter reference I-V curve under both high and low light conditions. The resulting two sets of reference parameters are then used to find the new translation parameters, which fundamentally change the way that series resistance, shunt resistance, and reverse saturation current are calculated under the target irradiance and temperature conditions. The flow of the DR model is as follows:

- **Using manufacturer's or measured data, calculate the five single diode model parameters a, I_L, I_0, R_s, and R_{sh} under both high and low irradiance reference conditions (Equations 4.2 – 4.6)**

- **If exact high and low light levels are not known, use the resulting high and low irradiance fitted I_L to calculate the ratio of the high and low effective irradiance $S_{REF,LO}$ / $S_{REF,HI}$ (Equation 4.15)**

- **Calculate the three new translation parameters X_{RS}, X_{RSH}, and X_{I0} (Equations 4.18, 4.20, 4.22/4.23)**

- **Calculate the five translated parameters a, I_L, I_0, R_s, and R_{sh} under the target irradiance and cell temperature conditions (Equations 4.7, 4.8, 4.23, 4.19, 4.21, respectively)**

- **Use these translated parameters to calculate module performance (I-V curve) under the target conditions (Equation 4.1)**

4.5 Improved DR Model Evaluation

Low Irradiance

Comparisons between the new DR model's predicted I_{sc}, $V_{oc,}$ and P_{mp} and their measured values under low irradiance conditions are shown in Table 4.8. As expected, given that the DR model is partially fitted to these specific conditions, the agreement between the model and measurements is very good. The predictions of I_{sc} and V_{oc} show nearly exact agreement, whereas the existing models tended to overpredict the former, especially for thin film modules, and the latter for most arrays. The DR model's series resistance correction is responsible for most of the increased agreement in I_{sc}, and V_{oc} is influenced by both the shunt resistance correction and the fitting of the reverse saturation current.

Table 4.8. Comparisons between DR model and measured module performance under low irradiance conditions ($S_{TARG}/S_{ref,\ HIGH} \approx 0.2$)

Array	Isc		Voc		Pmax	
	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement
Mono 1A	0.0%	0%	0.0%	0%	0.4%	0%
Mono 2A	0.0%	0%	0.0%	0%	0.2%	0%
Mono 1B	0.0%	0%	0.0%	0%	0.3%	0%
Mono 2B	0.2%	0%	0.0%	0%	2.8%	21%
Mono 3B	0.0%	0%	0.0%	0%	1.7%	100%
Mono 4B	0.0%	0%	0.0%	0%	0.3%	0%
Mono 5B	0.0%	0%	0.0%	0%	0.5%	0%
Mono 6B	0.0%	0%	0.0%	0%	0.2%	0%
Poly 1A	0.0%	0%	0.0%	0%	0.6%	0%
Poly 2A	0.0%	0%	0.0%	0%	0.1%	0%
Poly 3A	0.0%	0%	0.0%	0%	0.1%	0%
Poly 1B	0.0%	0%	0.0%	0%	0.4%	0%
Poly 2B	0.0%	0%	0.0%	0%	0.3%	0%
Poly 3B	0.0%	0%	0.0%	0%	0.4%	0%
Poly 4B	0.0%	0%	0.0%	0%	0.5%	0%
Poly 5B	0.0%	0%	0.0%	0%	0.2%	0%
Hybrid 1A	0.0%	0%	0.0%	0%	0.4%	0%
Hybrid 2A	0.0%	0%	0.0%	0%	0.2%	0%
Hybrid 1B	0.0%	0%	0.0%	0%	0.2%	0%
Hybrid 2B	0.0%	0%	0.0%	0%	1.0%	13%
Thin 1A	0.0%	0%	0.0%	0%	0.2%	0%
Thin 2A	0.0%	0%	0.0%	0%	0.1%	0%
Thin 3A	0.0%	0%	0.0%	0%	0.5%	0%
Thin 4A	0.1%	0%	0.1%	0%	0.4%	0%
Thin 2B	0.0%	0%	0.0%	0%	1.1%	0%
Thin 3B	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%

Most of the arrays have a maximum power point RMSE of less than 1% (Table 4.8) though there are several that are slightly higher. Nearly all modules show excellent agreement between the modeled and measured maximum power points, within uncertainty tolerances, with the exception of those in array Mono 3B. A comparison of the maximum power prediction between the 5 parameter, 7 parameter, and DR models for several selected arrays under low irradiance conditions is shown in Figure 4.19. The three models' maximum power point RMSEs are averaged across the crystalline silicon, thin film, and total set of all arrays in Table 4.9. It is obvious that the DR model shows significantly improved performance prediction under low light conditions for arrays of all technologies.

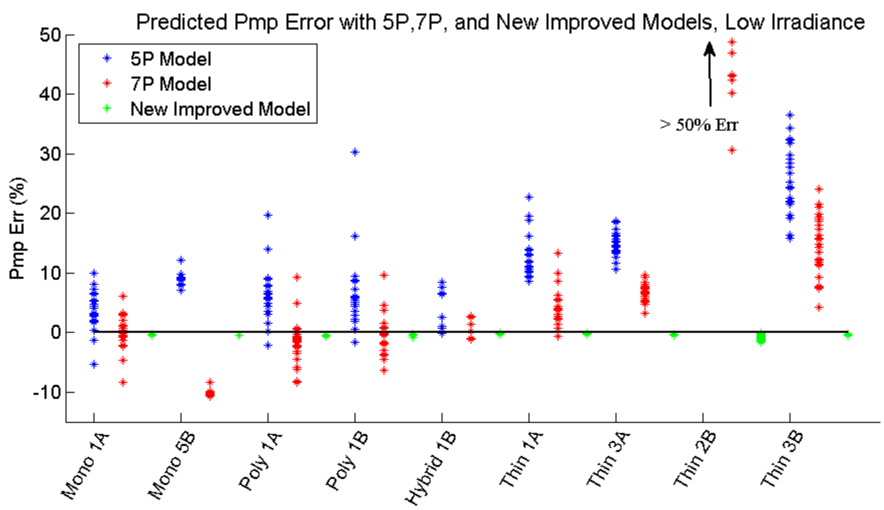


Figure 4.19. Error in predicted vs. measured maximum power point for various arrays' modules under low irradiance conditions – 5P, 7P, and new improved DR models

Table 4.9. Maximum power point RMSEs under low light conditions for single diode models, averaged over subsets of the measured arrays as well as the full set. "Selected" arrays are those listed in the first column of Table 4.7.

Arrays	Maximum Power RMSE		
	5P Model	7P Model	DR Model
Si, Selected	7.1%	4.4%	0.4%
TF, Selected	42.9%	28.6%	0.5%
All, Selected	23.0%	15.1%	0.5%
Si, All Available	11.0%	---	0.6%
TF, All Available	32.2%	---	0.4%
All Available Arrays	15.9%	---	0.5%

To further illustrate the difference between the models, Figure 4.20 shows a comparison of low light I-V curves generated by the fitted (low light) reference model, and the 5 parameter, 7 parameter, and DR models. The DR model matches the entire I-V curve better than either of the other two models, with a more dramatic difference seen for the thin film module.

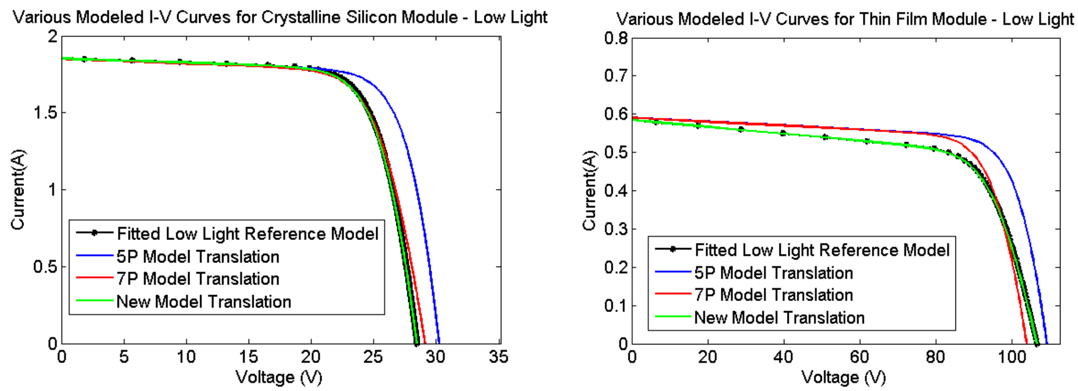


Figure 4.20. Comparisons between module-level I-V curves predicted by the 5 parameter, 7 parameter, and new improved DR models when predicting performance under low light conditions.

Medium Irradiance

Comparisons between the DR model's predicted I_{sc}, $V_{oc,}$ and P_{mp} and their measured values under medium irradiance conditions are shown in Table 4.10. The DR model's prediction of I_{sc} is generally good, though two arrays have modules with predictions that do not match their measured I_{sc} within uncertainty tolerances. These two arrays, Poly 3B and Thin 2B, each have multiple modules with very non-standard performance characteristics (Appendix D), likely caused by degradation. The affected modules would require more data or more extensive fitting to replicate their behavior. Prediction of V_{oc} shows general improvement in the DR model, with most modules' predictions within 1-2% of their measured values. There is a slightly higher magnitude of misprediction for thin film arrays, especially Thin 2B.

Table 4.10. Comparisons between DR model and measured module performance under medium irradiance conditions ($S_{TARG}/S_{ref,\ HIGH} \approx 0.5$)

Array	Isc		Voc		Pmax	
	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement	RMSE (mod vs. meas)	% Modules Not in Agreement
Mono 1A	0.1%	0%	0.3%	4%	1.1%	13%
Mono 2A	0.0%	0%	0.2%	0%	0.3%	0%
Mono 1B	0.1%	0%	0.7%	5%	1.0%	0%
Mono 4B	0.0%	0%	0.5%	0%	0.9%	0%
Mono 5B	0.0%	0%	0.3%	11%	0.6%	11%
Mono 6B	0.1%	0%	0.3%	0%	0.6%	6%
Poly 1A	0.2%	0%	0.2%	75%	1.5%	65%
Poly 2A	0.1%	0%	0.4%	0%	0.7%	0%
Poly 3A	0.0%	0%	0.2%	0%	0.7%	0%
Poly 1B	0.2%	0%	0.7%	24%	1.7%	43%
Poly 3B	1.2%	17%	0.6%	6%	7.2%	56%
Poly 4B	0.0%	0%	0.5%	0%	0.6%	0%
Hybrid 1B	0.0%	0%	0.1%	50%	0.6%	50%
Thin 1A	0.2%	0%	1.7%	20%	2.9%	20%
Thin 2A	0.5%	0%	0.7%	8%	3.6%	75%
Thin 3A	0.1%	0%	0.4%	100%	0.1%	0%
Thin 2B	5.1%	100%	8.1%	100%	18.7%	67%
Thin 3B	0.6%	0%	0.7%	100%	2.5%	11%

Under medium irradiance conditions, the 5 and 7 parameter diode models overpredict maximum power output for some modules and arrays, while underpredicting others (Figure 4.21). This variability holds true for the DR model as well, though on the whole there are fewer modules with P_{mp} predictions that are outside of the modeled/measured uncertainty tolerance range, and the magnitude of the mispredictions is typically lower (Table 4.10, Table 4.11, Figure 4.21). As noted in Table 4.11, the DR model reduces the average RMSE across the silicon, thin film, and full set of arrays by approximately half compared to either the five or seven parameter models. It is noted that the 5 parameter model does a slightly better job of predicting maximum power point for arrays Thin 1A and Thin 2A under medium irradiance conditions; this is something that would need to be investigated before using the DR model on arrays of this type.

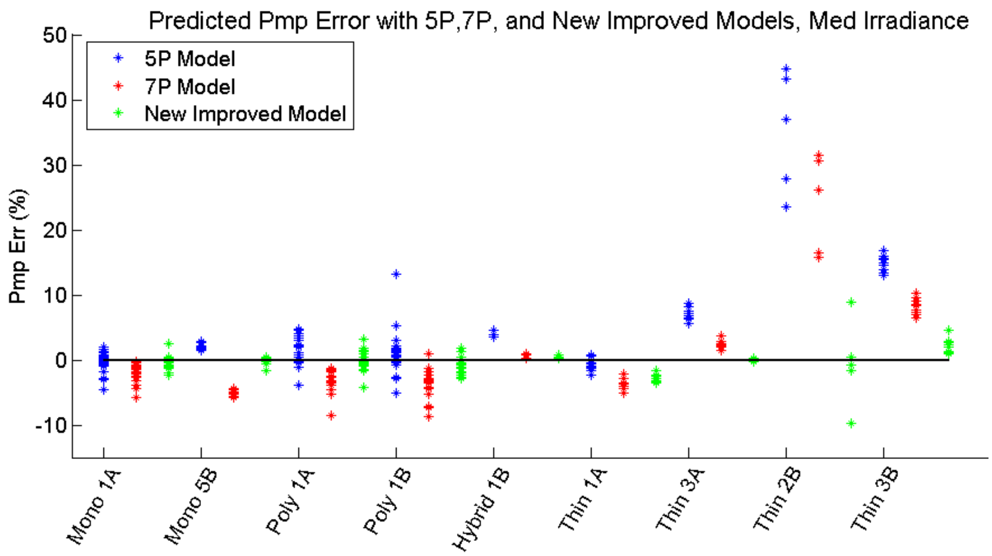


Figure 4.21. Error in predicted vs. measured maximum power point for various arrays' modules under medium irradiance conditions – 5P, 7P, and new DR models

Table 4.11. Maximum power point RMSEs under medium light conditions for single diode models, averaged over subsets of the measured arrays as well as the full set. "Selected" arrays are those listed in the first column of Table 4.7.

Arrays	Maximum Power RMSE		
	5P Model	7P Model	DR Model
Si, Selected	2.8%	3.2%	1.1%
TF, Selected	17.3%	12.6%	6.1%
All, Selected	8.3%	7.4%	3.3%
Si, All Available	2.1%	---	1.3%
TF, All Available	14.5%	---	5.6%
All Available Arrays	5.6%	---	2.5%

Figure 4.22 shows a comparison of medium light I-V curves generated by the fitted (medium light) reference model, and the 5 parameter, 7 parameter, and DR models. In addition to more accurate maximum power point prediction, the DR model matches the entire I-V curve's shape better than either of the other two single diode models.

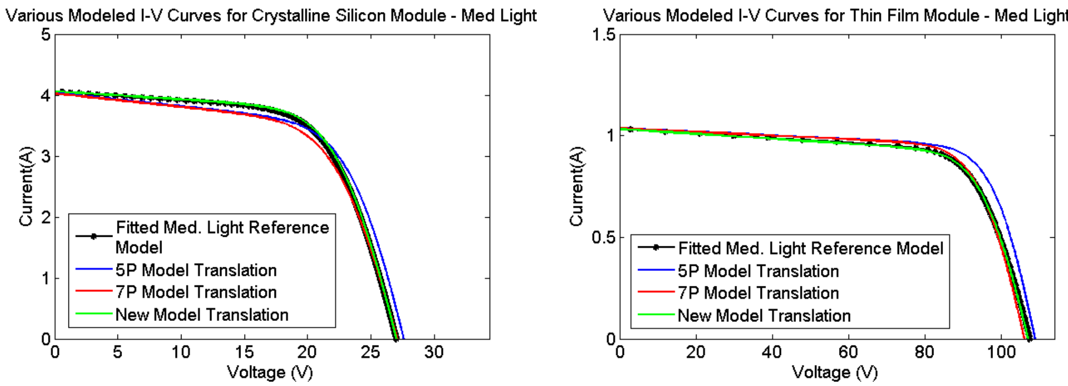


Figure 4.22. Comparisons between module-level I-V curves predicted by the 5 parameter, 7 parameter, and DR models when predicting performance under medium light conditions

4.6 Summary

The goal of this section is to identify a PV generator performance model which is accurate over the breadth of operating conditions (temperature and irradiance) commonly experienced by PV arrays. Because this work focuses on nonuniform operating conditions within arrays, forcing modules to operate away from their maximum power points, it is desired that the model provide a correct representation of the entire I-V curve. Ideally this model would require limited input data, which could easily be provided by manufacturers or gathered in the field or on indoor flash testers.

A detailed description of the existing standard Wisconsin 5 parameter single diode PV model, as well as a recently modified version with 7 parameters, is provided, including information on the translation of parameters from standard test conditions (STC – 1000 W/m^2 and 25ºC) to more common operating conditions. This model is chosen as a starting point for analysis, as single diode PV performance models are relatively straightforward, require limited computation, and are used in many commercially-available tools in the U.S. and internationally. Furthermore, the 5 parameter model requires only data taken under STC or similar high irradiance conditions, and the modified 7 parameter version requires only one other dataset, taken under low irradiance conditions.

The single diode model is then used to create module level I-V curves under high and low irradiance "reference" conditions, fitted to measured data (described in Chapter 3), and these reference curves are compared to the measured data at different points on the I-V curve, to determine how well the model is able to represent the full curve for different PV technologies. It is found that over half of the 27 arrays with available data have at least one module which is not well represented by a fitted reference curve, which impacts performance prediction, especially if a module is forced by string current constraints to operate at a current that is higher than its maximum power point current. This problem is especially prevalent in thin film arrays, and its impact will be addressed in Chapter 6.

When the modeled high irradiance reference curves for each module are used to predict performance under medium and low light conditions, using translations from the Wisconsin 5 parameter and 7 parameter models, it is found that the predicted performance does not match well with measured data for most of the arrays. In particular, at low irradiance the average root mean square error (RMSE) for the modules' maximum power point in crystalline silicon arrays is found to vary from 4-7%, depending on which model is used, and for thin film arrays it is even higher at 29-43%. Under medium irradiance conditions the RMSEs are lower, with the average over the crystalline silicon arrays ranging from 2-3%, and the thin film arrays' average RMSE ranging from 12-17%. As much of an array's power may be generated under medium irradiance conditions, these numbers represent a significant opportunity for improvement.

Several arrays of different ages and technologies are chosen for further analysis, with three non-defective modules from each selected to examine the behavior of the single diode model's five parameters under measured high, medium, and low light conditions. It is found that the series and shunt resistance do not behave in the way that is assumed by the 5 or 7 parameter models. A new modeling methodology is proposed, using two reference I-V curves fitted to measured high and low light I-V curve data. This methodology modifies the way that these resistance parameters are translated to different operating conditions, and an additional fitting parameter is also suggested for the model's diode reverse saturation current. In total three new translation parameters, X_{RS}, X_{RSH}, and $X_{I0,}$ are introduced to establish a new improved modeling process based on the available data. These parameters are easily determined by a limited set of module level PV performance data, requiring only one set from high irradiance conditions and one from low..

The resulting improved model (the “DR model,” for "Double Reference"), which incorporates these three new translation parameters, is found to enhance the performance predictions for modules in most arrays under medium and low light conditions, as compared to the existing single diode models. RMSE in the prediction of modules’ maximum power output is reduced to less than 1% under low light conditions for most arrays (both crystalline and thin film) using the DR model. Under medium light conditions, the maximum power point RMSEs, averaged across the crystalline silicon and thin film arrays, are reduced by approximately half for both types. These results indicate that the methodology of the DR model provides significantly better performance prediction than the typical existing models, and should be pursued further. There is great opportunity for better, more accurate PV models if manufacturers provide more performance data over a range of operating conditions, such as what is required by the new IEC standard 61853.

CHAPTER 5

SIMULATION ENVIRONMENT

A model to simulate the performance of PV systems with and without power optimizers under nonuniform operating conditions has been created in the MATLAB environment. This unique, flexible suite of simulation tools allows for user-input irradiance, temperature, and PV electrical characteristics at the cell level so that mismatch scenarios may be simulated in detail. It is designed for annual simulations of PV systems with a wide array of orientations, panel technologies, and configurations, and includes 3-D shade simulation. While some commercial tools have many of these capabilities, none allow simulation with this degree of detail. Other tools which model at the cell level ((King, Dudley, & Boyson, 1996); (Pongratananukul & Kasparis, 2004)) are intended to assess performance on a small, instantaneous scale rather than for annual simulations of entire arrays. A more recent, detailed annual shading simulation tool (Poshtkoui, Palaniappan, Fard, & Trescases, 2013) does not account for bypass diodes in PV modules, and does not simulate mismatched electrical characteristics between modules.

Simulation inputs include PV generator -- cell, submodule, or module -- details (electrical parameters, dimensions, tilt and orientation, cell and bypass diode layout), array size (panels per row and number of rows) and configuration (single series string or division of parallel series strings). 3-D shading analysis requires inputs for each shading object's height, diameter, and position relative to the array, which are used to map shadows onto the array plane. The flow of operation using this toolset is shown in Figure 5.1.

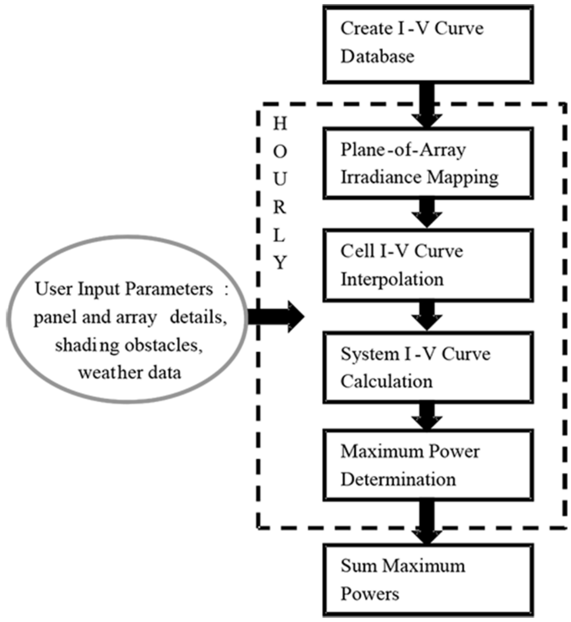


Figure 5.1. Flow of operation for detailed PV system simulation toolset

Before the annual, hourly simulations are run, I-V curves are created for each of the system's PV generators (usually module or sub-module). These curves are generated over a range of irradiance and cell temperatures encompassing normal PV system operating conditions (50-1200 W/m^2 irradiance and -20 to 100°C), and compiled into a database that becomes an input to the annual simulation.

On an hourly basis, shading is mapped onto the array plane at the cell level using the sun's calculated position and simplified ray tracing, giving the incident irradiance on each of the array's cells (Section 5.4.2). An I-V curve for each cell is then found by bilinear interpolation (interpolating irradiance and temperature) from the I-V curve database. The voltages of these curves are summed at each current for all elements in a series string, taking into account bypass diodes if applicable. In the case of arrays with multiple parallel strings, I-V curves for each string at common voltages are then created, so that the string currents may be summed at common voltages to find system power. The hourly maximum power is then found for the system assuming ideal maximum power point tracking at the central (standard), string, module, sub-module, and cell levels. Finally, the hourly maximum powers at various levels in the array are summed over the year for comparison, and the user may choose which level(s) are applicable to his or her specific task. More details of various aspects of this process follow in this section.

5.1 Radiation and Climate Models

Different climates are simulated using "Typical Meteorological Year" (TMY) hourly data for irradiance and ambient temperature as a basis (NSRDB, 2008). When considering only annual performance prediction, use of TMY data introduces significant uncertainty, and is often considered the largest source of uncertainty in the model. However, simulations for this research are performed as comparisons, examining identical systems with and without power optimizers, or with and without shading or other mismatch, which significantly reduces the impact of any deviations between TMY and current climate years.

Radiation is translated to a tilted plane using the HDKR anisotropic (Reindl, Beckman, & Duffie, 1990) sky model. Air mass (AM) and angle of incidence (AOI) modifiers are also applied hourly, to convert the calculated plane of array irradiance to effective absorbed irradiance required by the PV generator models. Equations for all of these calculations are found in Appendix C.2.

Cell temperature is calculated using the empirical King/Sandia model relation (King, Boyson, & Kratochvil, 2003), because it was shown in literature to be the most accurate for building applications (Neises, 2010). Equation coefficients are chosen to be for a "close roof mount" system to simulate typical building-related temperature effects. The equation for the back-of-module temperature is

$$\mathrm{T_{Back}} = \mathrm{Irr_{POA}} + \mathrm{e^{a+b*WS}} + \mathrm{T_{amb}} \qquad \textbf{5.1}$$

where Irr_{POA} is the calculated plane-of-array irradiance, *WS* is the wind speed (m/s), T_{amb} is the ambient temperature (ºC), and *a* and *b* are model coefficients with *a*=-2.98 and *b*=-0.0471 for the close roof mount case (PVPMC, 2012). From the back of module temperature, one finds the cell temperature using Equation 3.13; in this case *dT*=1 for the close roof mount modules.

5.2 PV Generator Model

At the cell, submodule, or module level, PV generators may be modeled using either the 5 parameter, 7 parameter, or DR single diode models described in Chapter 4. These curves are generated over a range of irradiance and cell temperatures encompassing normal PV system operating conditions (50-1200 W/m^2 irradiance and -20 to 100°C), and compiled into a performance database that becomes an input to the annual simulation. During each hourly timestep, each PV generator's effective incident irradiance and cell temperature are calculated, and an I-V curve for each generator is then found by bilinear interpolation (interpolating irradiance and temperature) from the I-V curve database.

Bilinear interpolation is done in the manner of (Marion, Rummel, & Anderberg, 2004). First, the conditions most similar to each hour's effective irradiance (S) and cell temperature (T) are found in the performance database; these are denoted with the subscript DB. The short circuit current I_{sc} and open circuit voltage V_{oc} are then found for the actual hour's actual operating conditions using the following two equations

$$I_{sc} = \frac{S}{S_{DB}} * I_{sc,DB} * [1 + \alpha_{Isc} * (T - T_{DB})] \qquad \textbf{5.2}$$

$$V_{oc} = V_{oc,DB} * [1 + \beta_{Voc} * (T - T_{DB}] * [1 + (mT + b)\ln\left(\frac{S}{S_{DB}}\right)] \qquad \textbf{5.3}$$

In these equations, α_{Isc} and β_{Voc} are the temperature coefficients of short circuit current and open circuit voltage, respectively. Variables *m* and *b* are part of the temperature-dependent irradiance correction for V_{oc}. While α_{Isc} is taken directly from the manufacturer's datasheet, the other three variables must be solved for at each irradiance-temperature pair in the performance database.

This is done after the performance database is generated, but before the annual simulation is run, by setting Equation 5.3 equal to zero, and solving this equation three times, as a nonlinear set of equations. In each of the three equations, the variables with a DB subscript are the values at the irradiance and temperature where β_{Voc}, *m*, and *b* are to be found. The other values (V_{oc}, T, and S) are substituted in from performance database pairs (T_{DB}, D_{DB+1}), (T_{DB+1}, S_{DB}), and (T_{DB+1}, S_{DB+1}). Resulting values of β_{Voc}, *m*, and *b* are stored in an interpolation database, which is also passed as an input to the simulations.

With I_{sc} and V_{oc} determined under the actual operating conditions, one may then use them to scale the rest of the I-V curve datapoints. The I-V curve under actual operating conditions is scaled relative to the most similar I-V curve in the performance database (again designated by subscript DB). While this introduces some potential error by not accounting for fill factor changes under different operating conditions, the small temperature and irradiance steps in the performance database (5ºC and 50-100 W/m^2) ensure that any error is minimized.

$$I = \frac{I_{sc}}{I_{sc,DB}} * I_{DB} \tag{5.4}$$

$$V = \frac{V_{oc}}{V_{oc,DB}} * V_{DB} \tag{5.5}$$

5.3 Other System Component Models

All of the PV system's modules have a user-input number of bypass diodes, each with an assumed forward voltage drop of 0.7V. Parallel strings of modules are each assumed to have a combiner blocking diode with a forward voltage drop of 1V, to prevent reverse string currents when the strings are operating under nonuniform conditions. The simulations in this work focus on system DC (pre-inverter) power, with the string voltage constrained to a typical MPPT input voltage range for central inverters, 250-480V. Simulations of arrays including power optimizers model them simply as ideal distributed maximum power point tracking (DMPPT), to better illustrate the maximum, device-independent potential for increased energy capture. For any simulation, the only system losses considered are those under test, such as electrical mismatch or shading; standard losses from other factors such as system wiring are not included.

5.4 Mismatch Models

5.4.1 Module Electrical Characteristics

To account for mismatched electrical characteristics between an array's PV generators, the simulation tool allows each generator (typically module or sub-module) to have its own single diode model parameters previously described. These parameters may be determined either by measurement of actual installations or by statistical distributions. During the hourly portion of the simulation, each cell in the array has its I-V curves at actual irradiance and temperature conditions interpolated from the reference curves of its corresponding generator, inherently including electrical mismatch in the simulation under both shaded and unshaded conditions.

5.4.2 Shading

In the case of arrays with shading obstacles, each PV cell is divided into nine subcells (3x3) for shade mapping, and the simulation tool calculates the center point of each subcell in the plane of the array. For each hourly iteration, the sun's position (azimuth and altitude – Appendix C.1.) is found relative to the array and the nearby shading obstacles, which have user-entered placement coordinates relative to the array. From the solar position, the sun's rays are traced to the array using geometric relations, and subcells with a shading obstacle between the sun and their center are considered to be shaded.

Elements of the array shaded by opaque objects receive the reflected and non-circumsolar diffuse portions of the total available irradiance, as recommended in (Drif, Perez, Aguilera, & Aguilar, 2008). Those that are shaded by semi-transparent objects may receive in addition a corresponding fraction of the beam and circumsolar diffuse portions. The total available irradiance is averaged over the cell, based on the shaded vs. unshaded state of its subcells, to simulate instances with partial cell shading, and then converted to effective irradiance as noted in Equation 3.18. An example of shading (opaque tree) mapped onto a PV array is seen in Figure 5.2.

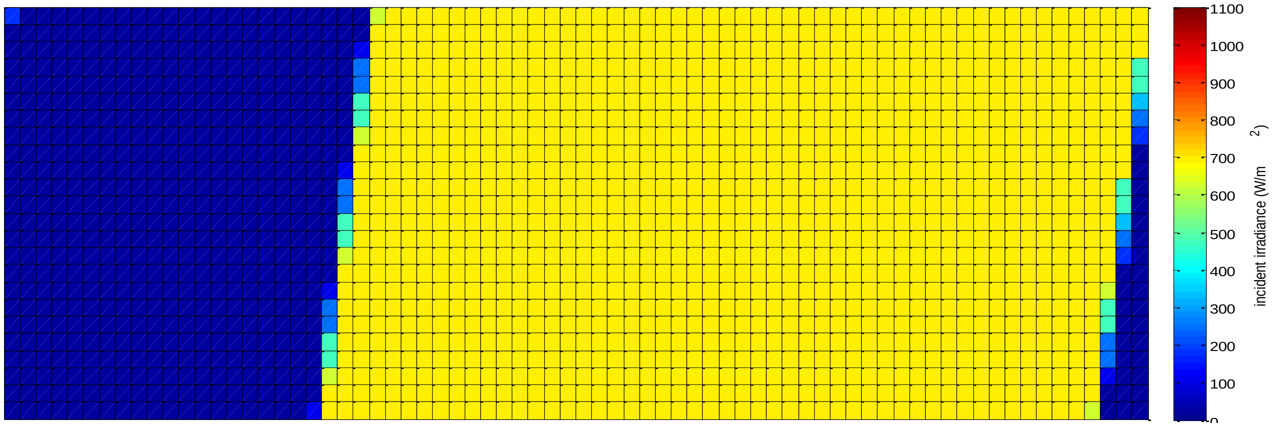


Figure 5.2. Shading mapped onto PV array (each square represents one PV cell)

5.5 Validation

5.5.1 Module Level

Validation of the partial shading model at the module level was performed by casting a shadow over a single module from array Mono 1A (Figure 5.3), with the shadow's coverage of the module increasing as shown in Figure 5.4a. As the shade edge moves across the module, increasing the fraction of area shaded, different bypass diode substrings are affected, creating a "stair step" pattern. Figure 5.4b shows that the model does an excellent job of predicting the performance of a partially shaded module. Figure 5.4b's root mean squared error (RMSE) in power generation is 2.4%, which is well within the range of uncertainty generated by the measurement and shading devices.

Figure 5.3. Diffuse shadow cast on array

(a)

(b)

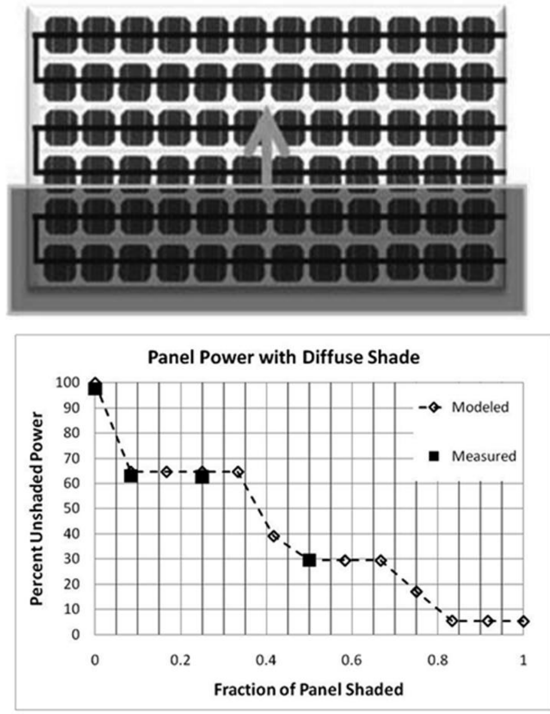


Figure 5.4. Partial shading model validation. Conditions: full sun=833 W/m2, shade=50W/m2 , cell temperature=16°C

5.5.2 System Level

With the partial shading model for a module validated above, the simulation environment must also be validated for partial shading at the PV system level. This is achieved using array Mono 1B, configured in 3 parallel strings of 7 modules each. Measurements were taken on a calm, sunny day around solar noon, with effective incident irradiance of 900-1000 W/m^2 and cell temperatures of 59-61ºC (slightly less for shaded modules). Partial shading of the array was achieved using a spectrally-neutral black mesh, which was tested at NREL and found to transmit 27% of the light incident on it. The test setup may be seen in Figure 5.5.

Figure 5.5. System level simulation validation

The array's modules are modeled using the new DR single diode model described in Chapter 4, with parameters generated from I-V curve data that were collected separately from the validation effort. The measured and modeled system-level I-V curves are compared to one another for the following cases

- **Unshaded**
- **One module in one string shaded**
- **One module in each of two different strings shaded**
- **One module in each of the three strings shaded**
- **Four modules in one string shaded**

It is evident in Figure 5.6 that the simulation tools do a relatively good job of modeling both the modules themselves (unshaded case) and the different amounts and distributions of partial shading in the array. The model tends in all cases to underpredict the current in the lower voltage portion of the curve, but this is expected, as Table 4.1 shows that three quarters of Mono 1B's modules have poorly matched single diode reference curves. Otherwise, in cases with partial shading, the model shows "knees" in the I-V curve in the correct places, and with generally the correct magnitudes. The RMSE for prediction of system level current at given measured/modeled voltages ranges from 2-4%, which is satisfactory for model validation.

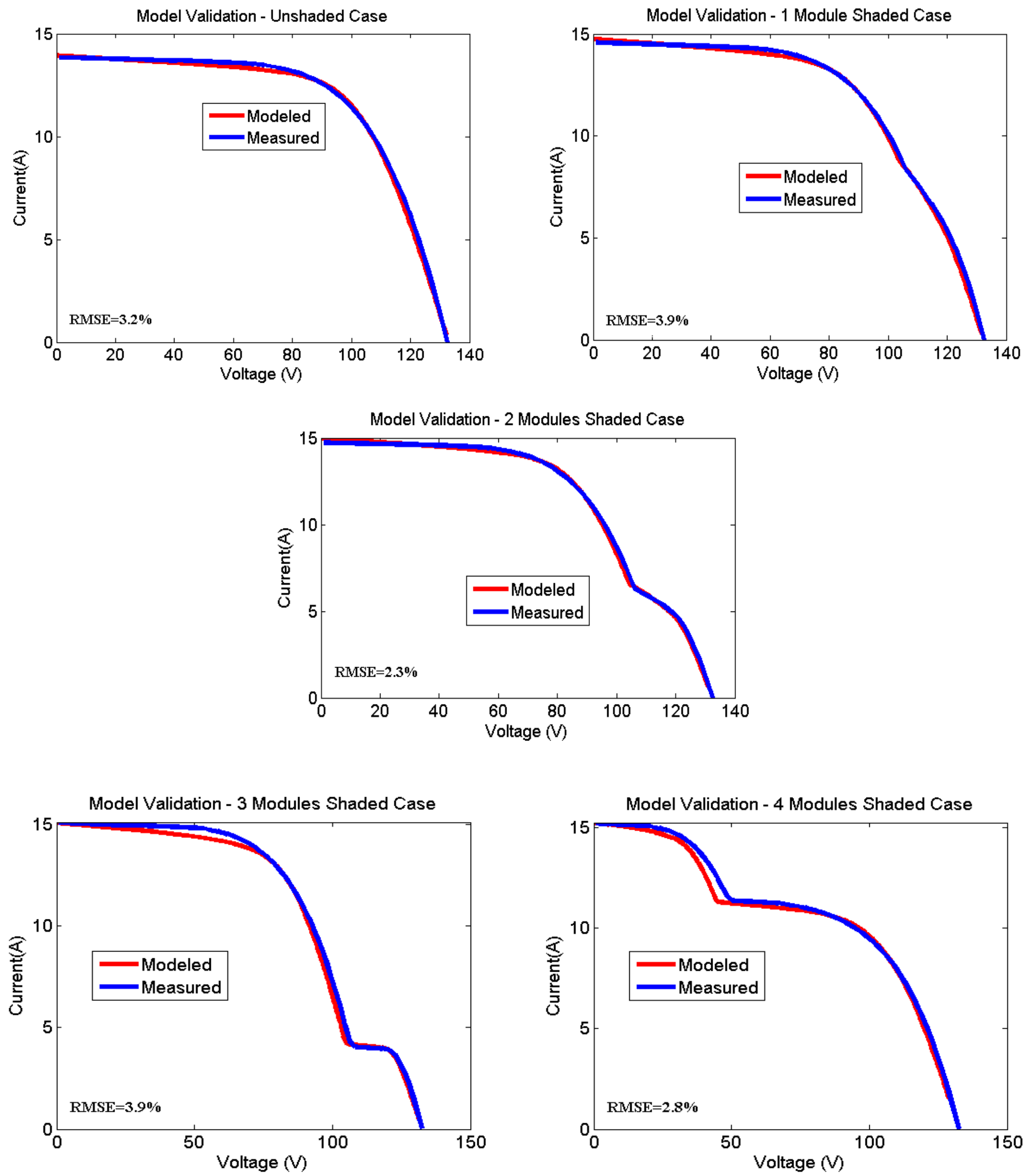


Figure 5.6. System level model validation

CHAPTER 6

MODULE PERFORMANCE MISMATCH

While most PV systems are designed to avoid significant shading or other substantial variations in irradiance or temperature during peak generation hours, there is still a degree of dispersion of module electrical characteristics, as well as incident irradiance and cell temperature, across any PV system. Performance differences between modules will cause power loss in conventional grid-tied arrays, as some modules are forced to operate away from their individual maximum power points. Distributed power electronics such as microinverters or microconverters (power optimizers) allow each module to operate at its individual maximum power point, recovering the power lost from module mismatch (less power optimizers' efficiency and operating losses). The definition of electrical mismatch loss in this work is given in Equation 6.1.

$$\text{Electrical Mismatch Loss} = \frac{\sum \mathrm{P}_{\mathrm{mod,max}} - \mathrm{P}_{\mathrm{sys,max}}}{\mathrm{P}_{\mathrm{sys,max}}} \qquad \textbf{6.1}$$

As indicated in this equation, electrical mismatch loss is the difference between the power (DC) that an array could produce, if all of its modules were operating at their individual maximum power points, and the DC power that a conventional system with a central inverter actually produces, subject to string current and voltage constraints, relative to the conventional system scenario.

Some prior publications consider the effects of module mismatch on power output, but those with goals most similar to this work – attempting to quantify electrical mismatch loss [(Damm, Heinemann, & Pukrop, 1995) (Neuenstein, 2011) (Bakas, 2012) (Herrmann, 2006) (Deist, 2006)] each model module-to-module performance variation based on data from newer, crystalline silicon modules, theoretical parameter distributions, or on manufacturer-provided sorting data for new modules. Module models are typically created using only high irradiance performance data, neglecting possible effects of light level or PV cell temperature on mismatch. Furthermore, these studies neglect the effects of degradation, which may change the distribution of module parameters within arrays (Jordan, Wohlgemuth, & Kurtz, 2012), and they do not consider variation that may arise from a wide set of PV technologies or manufacturers.

The multitracer described in Chapter 3 was specifically designed to acquire simultaneous, module level I-V curve datasets ideal for quantification and analysis of module-to-module performance variation and resulting electrical mismatch losses. Data acquired with this hardware provide the basis for all analysis in this chapter, which is divided into three main parts. First, module-to-module variation at key I-V curve points is quantified for each array. Next, the resulting mismatch power loss is calculated at high and low light levels, using measured data. Finally, the individual module models are combined and simulated in their respective arrays to determine the degree of meaningful annual energy loss, and thus potential for power optimizers in unshaded PV arrays. Some of the results and analysis in this section have been presented in (MacAlpine, Deline, Brandemuehl, & Erickson, 2012) and (MacAlpine, Deline, Erickson, & Brandemuehl, 2013).

6.1 Module Performance Variation

Mismatch losses are most often modeled in commercially-available tools as a standard derate factor. However, with the increased availability of module level power optimizers, there is also increased interest in understanding their potential benefits in different scenarios and with realistic levels of mismatch. Most PV modelers will not have module level data for full arrays, and instead may model mismatch using statistical distributions of critical module I-V curve points (such as I_{sc}, V_{oc}, I_{mp}, $V_{mp,}$ and P_{mp}) [(Folsom Labs, 2013), (Bakas, 2012)]. A recent comprehensive review of module degradation research (Jordan, Wohlgemuth, & Kurtz, 2012) indicates that there are few available sets of module mismatch data, and those that have been the subject of various studies are most often only for crystalline silicon modules, taken only under high light conditions. The data collected for this work provide a unique opportunity to understand the realistic module performance distributions of a broad range of PV technologies, in arrays that have experienced natural degradation, under both high and low light conditions.

6.1.1 Measured Variation

Most arrays' I-V curve data under each operating condition (high, low, and in some cases, medium light levels) were collected in a single system-level I-V curve sweep, such that the data for all of the modules were collected under nearly identical circumstances. However, some of the arrays were configured in such a way that the multitracer could not acquire data from all of the modules at the same time; in these cases, data were collected in separate runs under similar conditions, usually within minutes of one another. Table 6.1 shows the number of runs required for each array for the high and low light data; more specific run information is found in Appendix A.

Table 6.1. Array data collection runs

Array	Runs	
	Low Irradiance	High Irradiance
Mono 1A	1	1
Mono 2A	1	1
Mono 1B	1	1
Mono 2B	1	1
Mono 3B	1	1
Mono 4B	2	2
Mono 5B	1	1
Mono 6B	1	1
Poly 1A	3	3
Poly 2A	1	1
Poly 3A	2	2
Poly 1B	1	1
Poly 2B	1	1
Poly 3B	1	1
Poly 4B	1	1
Poly 5B	5	5
Hybrid 1A	1	1
Hybrid 2A	1	1
Hybrid 1B	1	2
Hybrid 2B	1	1
Thin 1A	2	2
Thin 2A	2	3
Thin 3A	2	2
Thin 4A	2	2
Thin 1B	1	1
Thin 2B	6	6
Thin 3B	3	3

Single and multiple run arrays must be processed slightly differently from one another when comparing variation in module parameters and determining the associated uncertainty.

Single Run Arrays

Since single run arrays have all of their modules' data collected simultaneously, irradiance and temperature may be ignored when comparing module performance. There is some naturally-occurring variation in available light and PV cell temperature across an array during operation, but when examining the potential for module level power point tracking, the effects of that variation are included in the mismatch losses that power optimizers are able to mitigate, so they may be simply included as part of the general module-to-module mismatch. In single run arrays, the key module performance points (I_{sc}, V_{oc}, I_{mp}, $V_{mp,}$ and P_{mp}) are interpolated or extrapolated directly from the measured data as described in Chapter 3.

Distributions of the five key I-V curve points -- I_{sc}, V_{oc}, I_{mp}, $V_{mp,}$ and P_{mp} -- were found for the modules in each single run array under both high and low light conditions (Figure 6.1). In many instances the distributions were not Gaussian, so the variation coefficient for each array's parameter sets was calculated using the average absolute deviation (AAD) of its modules' values from the mean over the array, as opposed to the standard deviation. The AAD is calculated as

$$\mathrm{AAD} = \frac{\sum|\mathrm{x} - \overline{\mathrm{X}}|}{\mathrm{n}} \qquad \textbf{6.2}$$

where *n* is the number of modules in the array, *x* is the value of each module's parameter under consideration, and $\bar{X}$ is the mean value of that parameter over all of the array's modules.

In Figure 6.1, it is noted that the AAD for I_{sc} is minimal for most of the arrays, ~2% or less under high light conditions, and ~3% or less for low light. I_{mp} generally follows suit, though one notable exception is array Poly 3B, which is analyzed in detail in the extended analysis later in this chapter. The small variation in I_{sc} indicates only small differences in usable light over the array, due to factors such as manufacturer's tolerances, variable soiling, and module-to-module installed tilt variation. I_{mp} also varies little between modules in many arrays, but the distribution broadens in some suggesting degradation related fill factors.

Voltage variation is also small in the majority of the monitored arrays, with an AAD of 2% or less. However, some of the arrays do show a higher module-to-module voltage distribution. Poly 3B demonstrates low V_{oc} variation, but higher variation in V_{mp}, pointing to a fill factor issue. Other arrays showing high (>5%) variation in both V_{oc} and V_{mp} indicate failed module substrings with constantly activated bypass diodes. This is especially notable in Mono 2B and Hybrid 2B, which have failed substrings in many of their modules, maximizing the average voltage variation for the array (I-V curves seen in Appendix D). P_{mp} variation follows that of I_{mp} and V_{mp} for each array as expected.

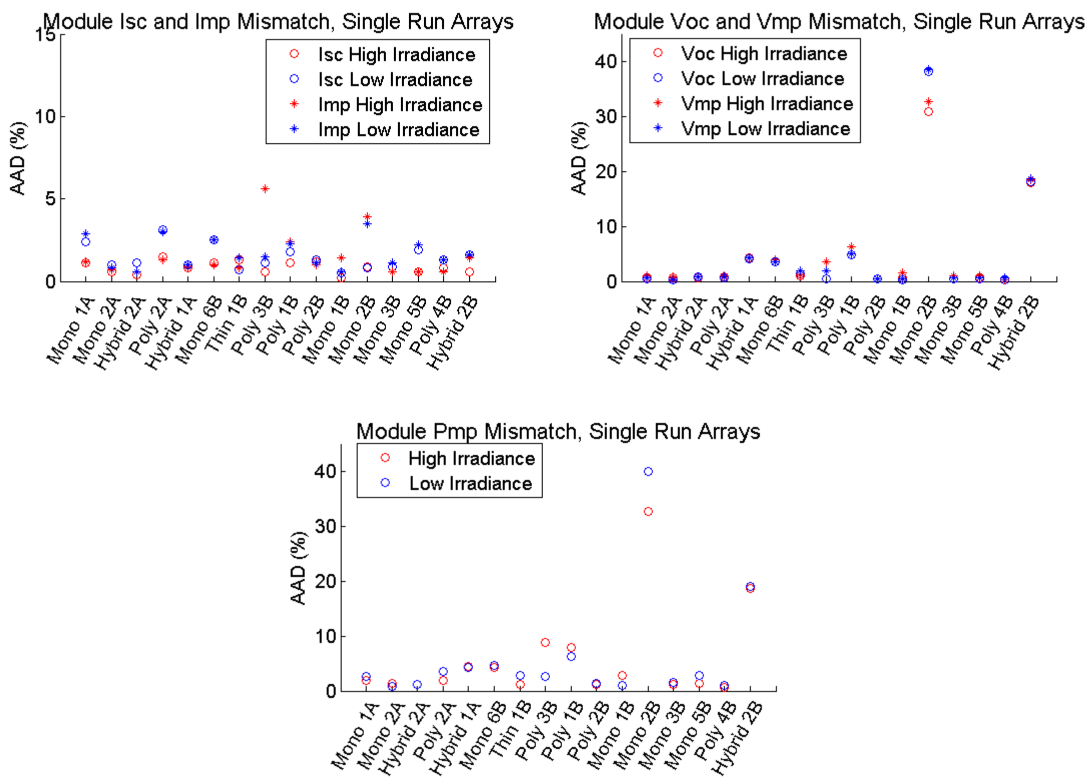


Figure 6.1. Average absolute deviation (AAD) of each array's modules' I_{sc} and I_{mp} (top left), V_{oc} and V_{mp} (top right), and P_{mp} (bottom) for arrays with high and low light data taken in single runs

Multiple Run Arrays

In arrays that require high and/or low light module I-V curve data to be taken in multiple runs, each module's measured I-V curve is first fitted to a five parameter single diode model as described in

Chapter 4. The module models are then used to translate each module's performance from its measured irradiance and temperature (which vary between runs) to a common irradiance and temperature (averaged over the array's runs). Because the data are taken under similar conditions (Appendix A) the irradiance and temperature translations are small, and five parameter model is sufficiently accurate under both high and low light conditions.

A single effective irradiance and PV cell temperature under high light conditions is calculated for each run as described in Chapter 3 and Appendix C. Each run has associated uncertainty in its temperature and irradiance measurements, relative to the other runs from the same array, and additional uncertainty from the effective irradiance calculation which accounts for the angle-of-incidence and air mass effects. High light measurements are all taken around solar noon, when variance in these two factors is minimal, so under these conditions the effective irradiance calculation does not introduce relative uncertainty between the runs. However, low light measurements are taken under faster-changing conditions, and the effective irradiance calculations are less accurate with high incident angles. This increases the likelihood that low irradiance runs' effective irradiance calculations will cause more uncertainty between them.

For this reason, the effective low light irradiance for each run is determined using the scaled photodiode current I_L from the fitted high and low irradiance module models, similar to Equation 4.15. The difference here is that each module in a run is assumed to have the same incident irradiance, so the scaled values are based on the average of the high and low light I_Ls as shown in Equation 6.3.

$$\frac{\overline{S_{low}}}{\overline{S_{high}}} = \frac{\overline{I_{L,fitted,low}}}{\left[\overline{I_{L,fitted,high}} + \alpha_{Isc}\left(T_{cell,low} - T_{cell,high}\right)\right]} \qquad \textbf{6.3}$$

In this equation, S_{low} and S_{high} are the low and high light effective irradiances, $I_{L,fitted,low}$ and $I_{L,fitted,\ high}$ are the module models' fitted photodiode currents, and $T_{cell,low}$ and $T_{cell,high}$ are the PV cell temperatures, calculated from the back of module temperature (Equation 3.13). All of these parameters are averaged across the run's constituent modules.

The AADs for each of the arrays with multiple runs are shown in Figure 6.2. Variation in I_{sc} and I_{mp} is generally slightly higher than it was for the single run arrays, especially under low light conditions. This effect may be introduced by the multiple runs, or it may be an observation of real, increased mismatch. However, the variation in voltage and maximum power is similar to the single run arrays, suggesting that these results are reasonable. A statistical analysis (two-sample Kolmogorov-Smirnov hypothesis test) of each array's short circuit current and maximum power was performed to determine whether or not the translated module data from different runs are likely to have come from the same underlying distribution (Appendix F.2). Results show that there is not enough evidence to refute this assumption of homogeneity for most arrays, though two (Thin 1A and Poly 5B) do show higher than expected variation between runs' I_{sc}s and two others (Thin 2A and Thin 2B) show the same for maximum power point, exclusively under low light conditions.

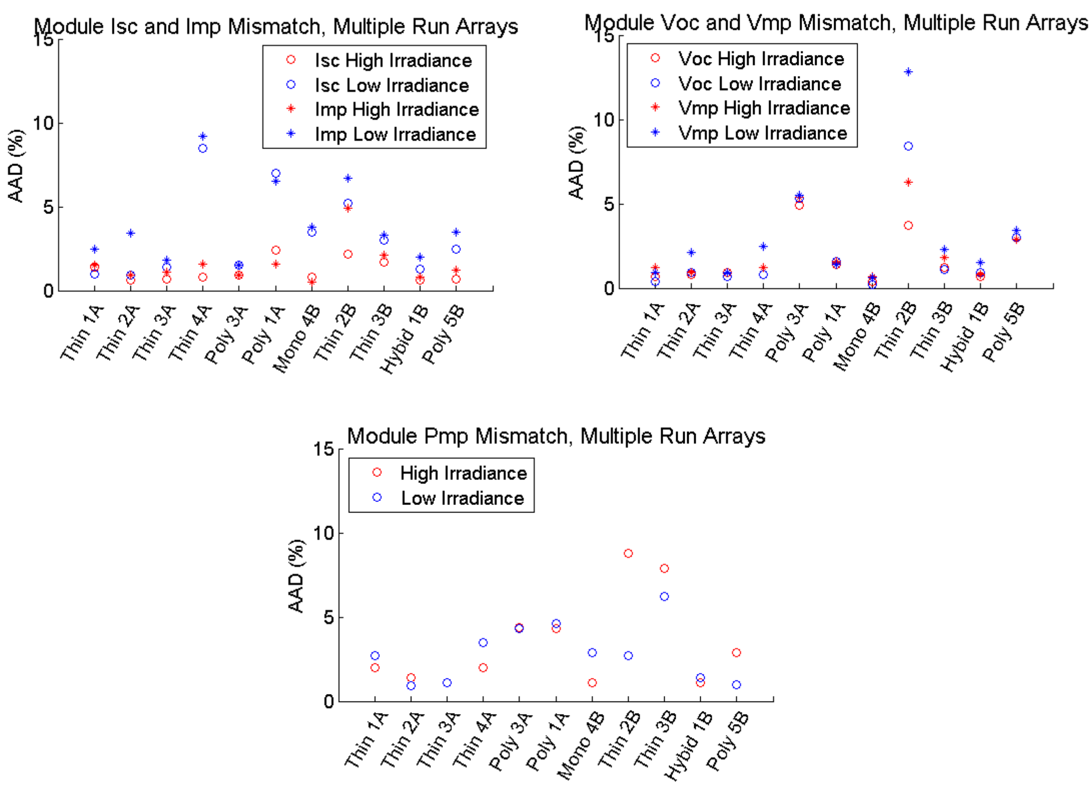


Figure 6.2. Average absolute deviation (AAD) of each array's modules' I_{sc} and I_{mp} (top left), V_{oc} and V_{mp} (top right), and P_{mp} (bottom) for arrays with high and/or low light data taken in multiple runs

6.1.2 Uncertainty

Single Run Arrays

Uncertainty for single run arrays' I_{sc}, V_{oc}, and P_{mp} distributions is determined simply by adding the corresponding calculated uncertainty (95% confidence interval, averaged across the array) from Chapter 3 to each parameter's AAD. The uncertainty bars are shown in Figure 6.3. Uncertainty ranges are small in all cases, showing that the observed variation in module performance for each array is significant. From these results, it would be reasonable to say that for modeling purposes, module currents could vary by +/-5% relative to one another, and 2-3% on average. Voltage variation has similar values, though it is also reasonable to run some simulations with more variation, including modeling failed bypass diode substrings.

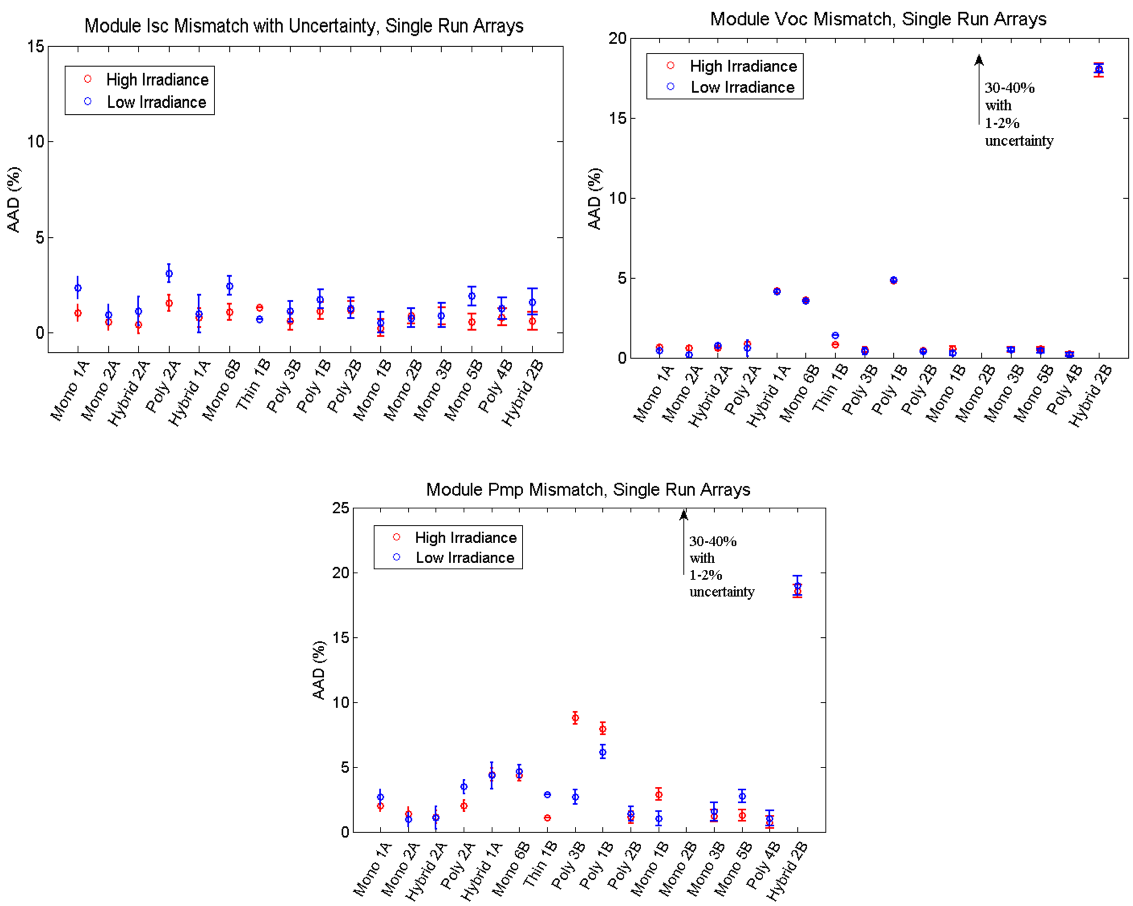


Figure 6.3. Average absolute deviation (AAD) with associated uncertainty of each array's modules' I_{sc} (top left), V_{oc} (top right), and P_{mp} (bottom) for arrays with high and low light data taken in single runs

Multiple Run Arrays

Arrays with data taken in multiple runs must account for measurement uncertainty of the key I-V curve points, which is done in the same way as for the single-run arrays. However, since different run data are taken under different conditions, the uncertainty in each run's measured irradiance and temperature also add uncertainty to the calculated AADs. Run-to-run uncertainty is thus estimated using Monte Carlo simulations, with each run of each array simulated 100 times, varying S_{high}, $T_{cell,high,}$ and $T_{cell,low}$ with flat distributions according to their 95% confidence intervals found in Chapter 3. Each of these parameters is assumed to be independent of the others, which gives conservative uncertainty estimates. Variation in these values leads to varied calculated values of S_{low} (Equation 6.3).

The Monte Carlo simulations for each array give a Gaussian distribution of the AAD for each key curve point, with the means and 95% confidence intervals presented in Figure 6.4. The uncertainty ranges are notably higher for the multiple run arrays in all cases as expected; this may increase the variance that a modeler would wish to use if modeling mismatch with statistical distributions. In most cases the calculated mismatch mean is still higher than the uncertainty range, indicating that it is significant. As the mean AAD values are similar to those seen in the single run cases, it is reasonable to expect that they are representative of typical arrays.

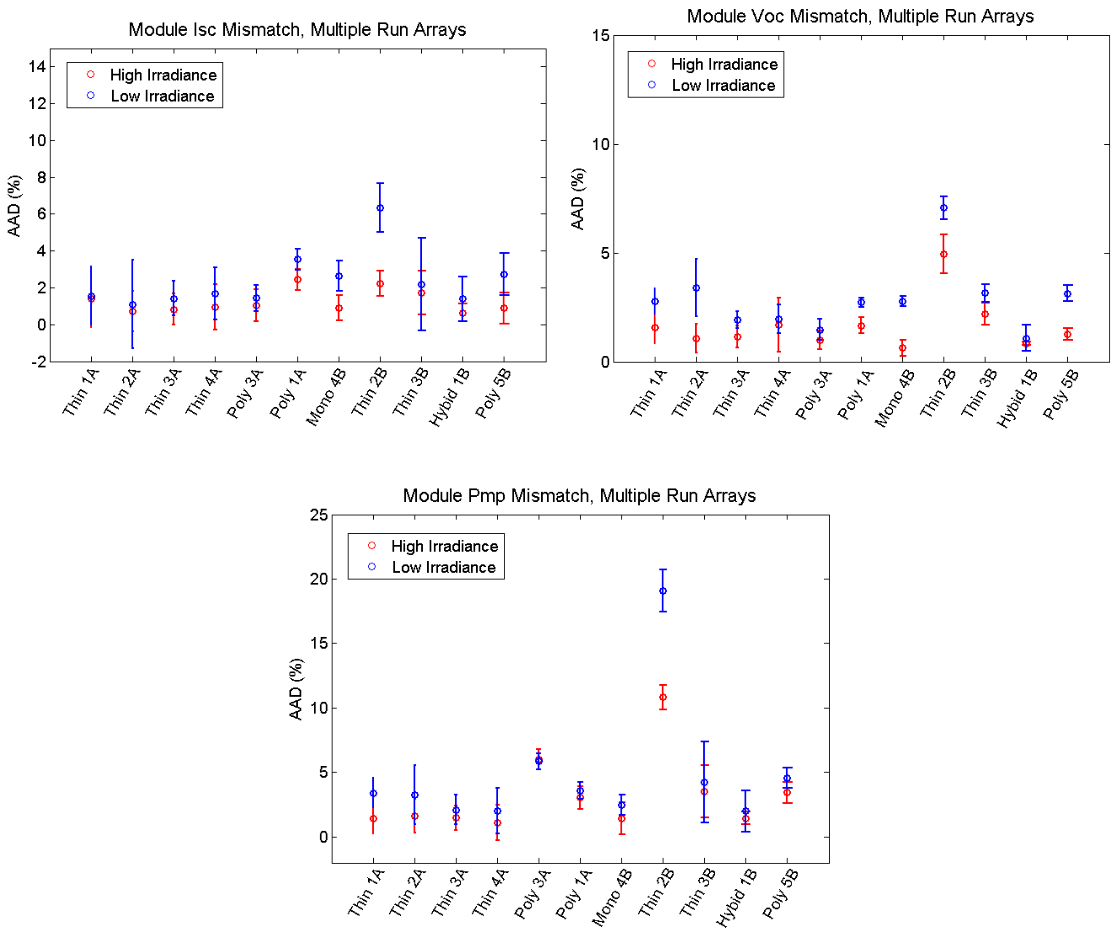


Figure 6.4. Average absolute deviation (AAD) with associated uncertainty of each array's modules' I_{sc} (top left), V_{oc} (top right), and P_{mp} (bottom) for arrays with high and low light data taken in multiple runs

6.2 Observed Mismatch Losses

In this and following sub sections on mismatch losses, the arrays' modules are modeled based solely on the measured data, in a discrete analysis of mismatch made possible by the wealth of simultaneous module I-V curve data collected in this work. While there is some uncertainty associated with these data, the goal is not to model these arrays exactly, but to model representative mismatch, which is exhibited in the measured data and resulting single diode models.

6.2.1 Model modifications

As noted in Chapter 4, the single diode model may not match entire I-V curve well, even in reference cases where it is directly fitted to the I-V curve points I_{sc}, V_{oc}, and P_{mp}. In these simulations of electrical mismatch, most modules will not operate far off of their maximum power points, as indicated by most arrays' small AAD for P_{mp} in Section 6.1. However, it is very important for the model to be as accurate as possible over the expected range of operation since electrical mismatch losses are often small and could be eclipsed by model inaccuracies.

In this mismatch evaluation, the chosen standard for accuracy is that the model must predict the power output within 5% of its measured value over range of I_{mp} +/- 2*$AAD_{(Imp)}$ for each module. This range is based on the modules' current characteristics because all of the arrays include series strings, and as all modules in a series string must conduct same current, module current is more likely to vary more than voltage. Most modules will operate within the +/-2*AAD range of their maximum power point current. Table 6.2 shows arrays which have modules with models that fall outside this requirement. This occurs mostly under low light operating conditions, in part because low light conditions tend to have a higher $AAD_{(Imp)}$.

Table 6.2. Arrays that have modules with a poor reference fit over the expected operating range (module maximum power point current Imp +/- 2*$_{AAD(Imp)}$) Left side: original single diode model, Right side: adjusted Rs and Rsh parameters to optimize curve fit over the operating range.

Array	Total Modules	Modules with Poor Reference Fit Over I Range of Interest			
		Original Single Diode Model		Modified Rs,Rsh	
		Low Irradiance	High Irradiance	Low Irradiance	High Irradiance
Mono 1A	24	15	0	4	0
Mono 2B	21	9	2	7	0
Mono 4B	20	10	0	0	0
Mono 6B	16	1	0	0	0
Poly 1A	30	8	0	3	0
Poly 3A	11	9	0	9	0
Poly 1B	21	2	0	1	0
Poly 3B	18	1	6	0	0
Poly 5B	32	2	0	0	0
Thin 1A	20	13	0	0	0
Thin 2A	24	23	0	0	0
Thin 2B	32	6	1	0	0

There are fewer modules with a poor reference fit in Table 6.2 than in the modeling chapter's Table 4.1 because the focus in that section was more on the whole I-V curve rather than the limited range of likely operation associated with unshaded module-to-module mismatch. The difference between these two regions is illustrated in Figure 6.5 for both I-V and P-I curves, in an array with a common level of module-to-module I_{mp} variation (AAD=+/-2%).

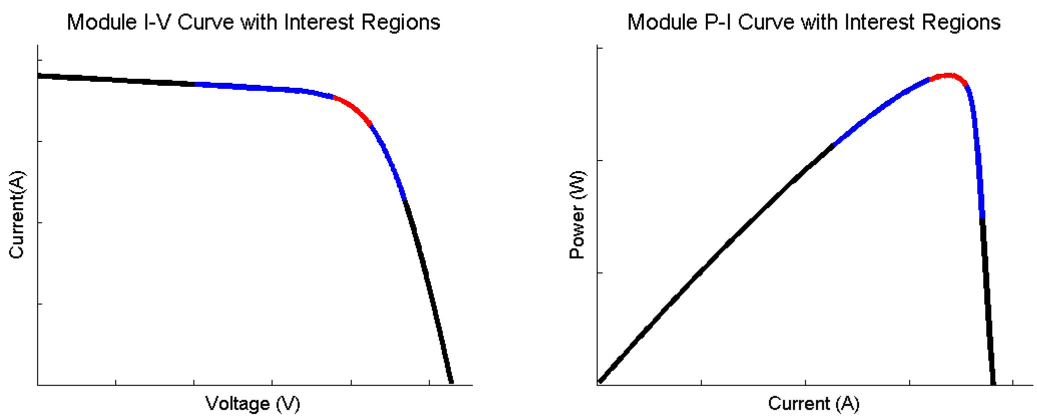


Figure 6.5. Regions of the I-V curve which define "poor reference fit." Blue spans the curve from V_{mp}/2 to (V_{mp}+V_{oc})/2 and red is centered on I_{mp} +/- 2*$AAD_{(Imp)}$.

Adjustments to series and shunt resistance can be used to optimize the reference fit for modules with poor agreement between predicted and measured performance curves. These parameters are adjusted (where possible) such that the predicted power is within the +/-5% tolerance in the region of interest, while keeping the maximum power prediction within +/-1% of its measured value. As noted in the shaded portion of Table 6.2, this improves the models' predictive capabilities in all high irradiance and most low irradiance cases with poor reference fits. Those that remain out of tolerance tend to be modules with current mismatch between their bypass diode submodules, which could only be modeled correctly by modeling each submodule separately.

Figure 6.6 shows the effects of the adjustments to series and shunt resistance on a module's I-V and P-I curves. The adjusted model increases power prediction accuracy over the module's expected operating region, though it does slightly increase the predicted maximum power output. Power prediction accuracy is most dramatically improved in the region where the module operates above its maximum power point current, which frequently happens in cases of module-to-module performance mismatch.

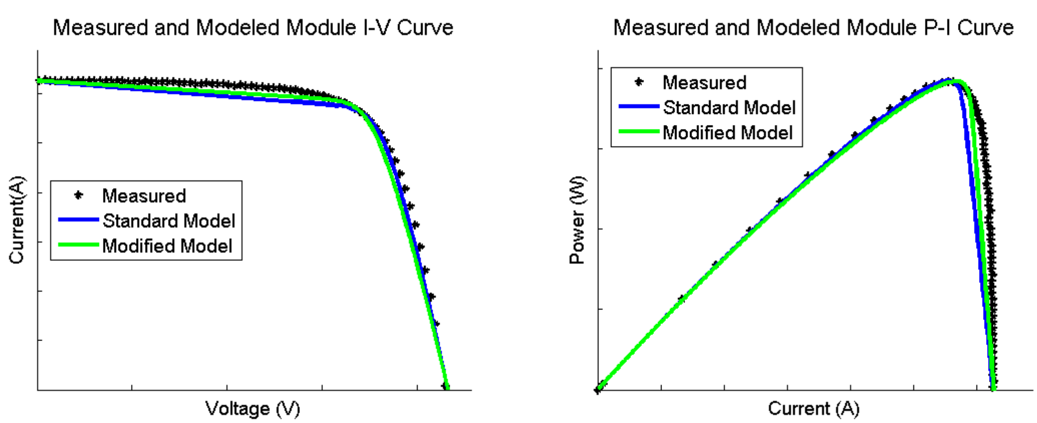


Figure 6.6. Effects of adjusted series and shunt resistance on module performance prediction

6.2.2 Measured and Predicted Mismatch Power Losses

Even with the modifications above, there is still some discrepancy between the module model predictions and measured performance data. The appropriateness of the model for estimation of mismatch losses may be judged by comparing its array-level predicted power losses under high and low light conditions to those that were measured during the I-V curve sweeps. Measured array power losses are determined by interpolating each module's measured I-V curves and then summing the voltages and/or currents as indicated by the arrays' series and parallel configurations. This is effective only for the single run cases, as multiple run cases would need to be fitted to models and translated to common irradiance and temperature for mismatch analysis – which would be effectively comparing models to models.

As noted in Table 6.3, the model's predicted losses are within 1-2 tenths of a percent of the measured mismatch power losses in almost all cases. The one exception is array Hybrid 2B, which has higher mismatch losses than any of the other arrays, and even in this case, the model only underpredicts the losses in the low irradiance case. This indicates that model is suitable for predicting mismatch losses. The model is then also used to predict in mismatch power losses in the arrays with multiple high and/or low light runs, wired in their as-installed, default configurations, with results found in Table 6.4.

Table 6.3. Measured and modeled mismatch power loss for single run arrays

Array	Native Array Config.	Measured Mismatch Loss		Modeled Mismatch Loss	
		High Irradiance	Low Irradiance	High Irradiance	Low Irradiance
Mono 1A	3 strings of 8	0.3%	1.3%	0.4%	1.5%
Mono 2A	1 string of 9	0.2%	0.3%	0.1%	0.3%
Mono 1B	1 string of 21	0.1%	0.1%	0.2%	0.0%
Mono 2B	1 string of 21	1.1%	0.7%	1.2%	0.6%
Mono 3B	1 string of 27	0.0%	0.1%	0.0%	0.1%
Mono 5B	1 string of 9	0.0%	0.4%	0.0%	0.5%
Mono 6B	2 strings of 9	0.4%	0.4%	0.4%	0.4%
Poly 2A	3 strings of 5	0.1%	0.9%	0.1%	1.1%
Poly 1B	1 string of 21	0.3%	0.5%	0.4%	0.6%
Poly 2B	1 string of 21	0.0%	0.2%	0.0%	0.2%
Poly 3B	2 strings of 9	1.3%	0.3%	1.3%	0.4%
Poly 4B	1 string of 10	0.0%	0.2%	0.0%	0.2%
Hybrid 1A	2 strings of 6	0.9%	1.1%	1.0%	1.0%
Hybrid 2A	3 strings of 5	0.0%	0.3%	0.0%	0.1%
Hybrid 2B	2 strings of 4	3.3%	4.8%	3.3%	4.3%
Thin 1B	2 strings of 7	0.1%	0.2%	0.0%	0.2%

Table 6.4. Modeled mismatch power loss for multiple run arrays

Array	Native Array Config.	Modeled Mismatch Loss	
		High Irradiance	Low Irradiance
Mono 4B	2 strings of 10	0.1%	1.0%
Poly 1A	3 strings of 10	0.3%	1.0%
Poly 3A	1 string of 11	0.1%	0.4%
Poly 5B	4 strings of 8	0.6%	1.8%
Hybrid 1B	2 strings of 4	0.0%	0.3%
Thin 1A	2 strings of 10	0.3%	0.9%
Thin 2A	4 strings of 6	0.3%	0.7%
Thin 3A	6 strings of 4	0.0%	0.3%
Thin 4A	6 strings of 4	0.1%	0.5%
Thin 2B	16 strings of 2	1.5%	3.5%
Thin 3B	3 strings of 9	0.4%	1.2%

Module-to-module parameter variation leads to minimal high and low-light losses, <0.5% and <1% respectively for most arrays (Table 6.3, Table 6.4). While the low-light loss percent tends to be slightly higher, most of each array's energy is generated under high light conditions, so low-light mismatch losses have a reduced impact on overall array performance.

6.3 Annual Simulation

6.3.1 Installed Configuration

While quantification of the high and low light mismatch power losses is informative, annual mismatch losses have more of an impact on the value of a PV array. As such, each array is simulated annually, unshaded in its native configuration and installed climate (Appendix A), to determine the energy lost due to electrical mismatch. This is done using the simulation tool described in Chapter 5, and each module is modeled using two different five parameter single diode models, one fitted to its high irradiance I-V data, and one fitted to its low irradiance counterpart. The high irradiance model is used as reference for all effective irradiance values above 400 W/m^2 and the low irradiance reference model is used for all lower light levels. Annual climate information comes from the TMY3 database file (NSRDB, 2008) nearest to each array's installed site. It is noted that use of these hourly data may overestimate the fraction of energy generated under medium light conditions, especially in climates with frequent variable weather where periods of sun and clouds are averaged over the hour (Riley, Cameron, Jacob, Granata, & Gailbraith, 2009). However, as sub-hourly data are not available for this work, this effect is not considered.

Simulated annual mismatch losses for each array are shown in Figure 6.7. The arrays are ordered by installed age on the x-axis, from newest to oldest. Annual energy losses fall within or very close to the range of measured high and low light losses for each array, demonstrating the realistic nature of the simulation model. Annual losses are less than 1% for most of the arrays, though one of the newer arrays and five of the older arrays have losses ranging from 1-3.3%. Both the highest and lowest losses are found in older arrays, and the highest losses occur in different types of arrays, indicating that mismatch losses are manufacturer specific rather than particularly dependent on array age or technology.

These annual losses directly represent potential for increased annual energy capture in arrays which employ module-level power optimizers, which allow each module to operate at its individual maximum power point. The results above indicate that in most cases, even with naturally occurring variable PV degradation, there is a modest potential for gain, approximately 1% or less. Many commercially available PV modeling tools, such as SAM, PVSyst, PV*SOL, and PVWatts, all have a default mismatch loss of 2% [(NREL, 2011), (PVsyst, 2011), (Valentin Software, 2011), (NREL, 2013)]. This work indicates that a lower value should be used, unless the modeler has knowledge about the PV array's modules or system configuration that would suggest a higher than average degree of mismatch loss.

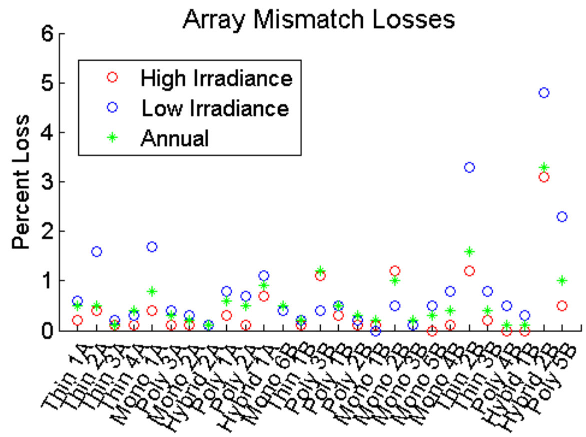


Figure 6.7. Simulated annual mismatch losses as well as loss directly calculated from data at high and low irradiance for each array

6.3.2 Extended Analysis

Five arrays are chosen for extended analysis, including investigation of the impacts of orientation, module ordering, array size, and string configuration on mismatch losses (and thus potential for increased energy capture with the use of power optimizers), and are described below. Their high and low irradiance I-V curves are found in Figure 6.8.

- **Mono 3B (Figure 6-8a)** is one of the oldest monitored arrays, yet it has some of the most uniform module I-V curves. It is typical of PV arrays that have not experienced significant variable degradation.
- **Mono 1A (Figure 6-8b)** is one of the newest arrays, but has one module with a low fill factor relative to the others, as well as a single "high performer" which was installed to replace a broken module. Module replacement is not uncommon in small installations.
- **Poly 3B (Figure 6-8c)** is an array with module-to-module fill factor variation which is exacerbated at high irradiance and temperature conditions where the array produces most of its power.
- **Hybrid 2B (Figure 6-8d)** has 75% of its modules affected by failed bypass diode substrings, though the modules themselves show little visible degradation. One might expect modules with these characteristics to be replaced under warranty, but this array is included in the analysis to show how voltage mismatch can affect system losses.
- **Thin 2B (Figure 6-8e)** is a thin film technology fairly early in development. Degradation and/or process control have led to wide spread in both current and voltage characteristics. This array shows how significant mismatch affects the potential for energy capture in an array of modules with a low fill factor.

More on each of these arrays, detailing their mismatch losses and loss mechanisms, is found in Appendix F.

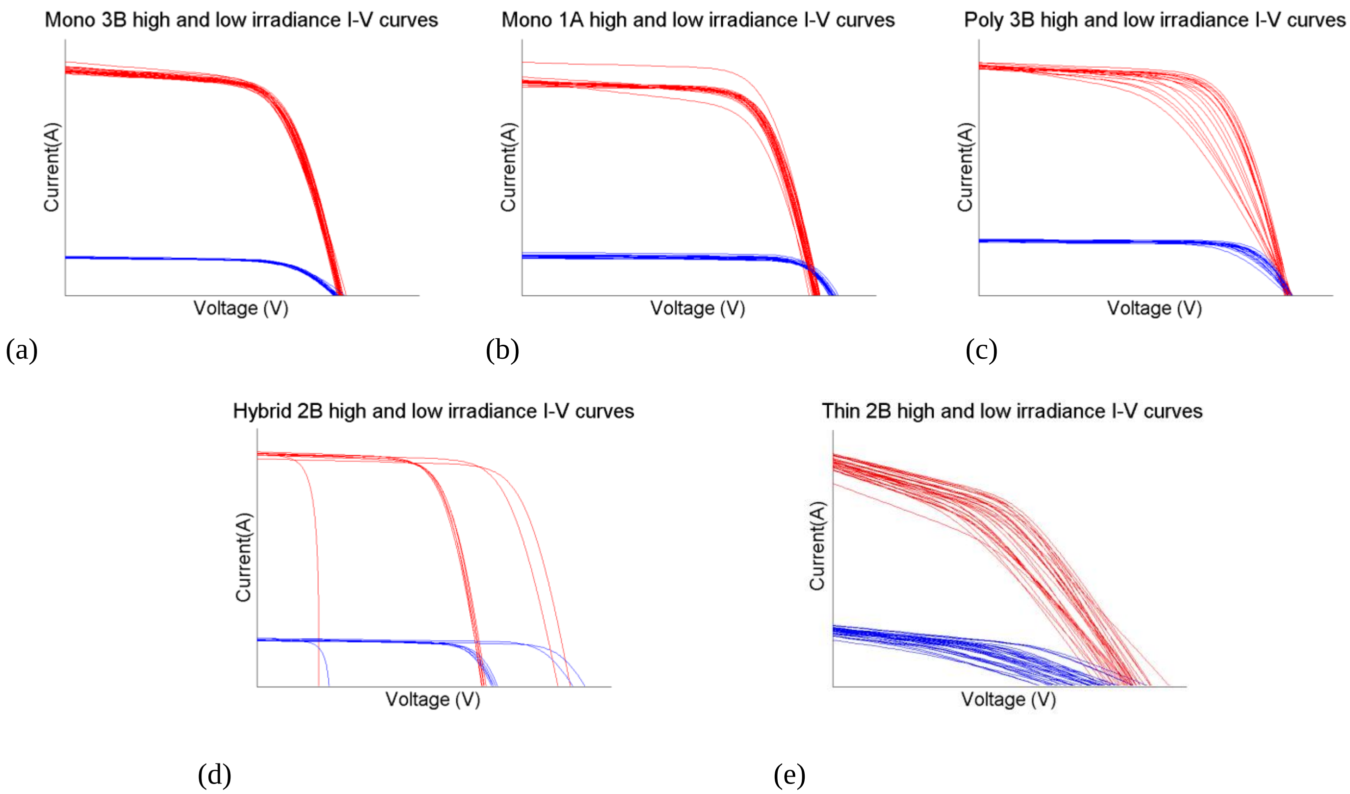


Figure 6.8. High and low irradiance I-V curves for five of the monitored arrays. High irradiance curves are red and low irradiance curves are blue.

Extended Mismatch Analysis – Available Light

First, the impact of available light on mismatch losses is evaluated for each of these arrays, wired in their installed string configuration. This is done by comparing annual simulations of each array in Boulder, CO for two orientations: south facing latitude tilt (optimal light availability) and west facing vertical tilt (more hours with lower light). Results of this comparison are found in Table 6.5.

As expected losses in Mono 3B are very low and do not appreciably vary with light level. Mono 1A, Hybrid 2B, and Thin 2B showed greater percent loss at low light levels (Figure 6.7) and this is reflected in their slightly greater mismatch losses when operating in a non-optimal light harvesting orientation. Poly 3B's increased losses under high light conditions (optimal orientation) are likewise reflected in these results. This shows the importance of understanding the degree of module-to-module mismatch under the light conditions predominately experienced by the array. From these results, it appears that the impact of array orientation and available light on mismatch losses is as much as +/- 0.5%.

Table 6.5. Annual mismatch losses for selected PV Arrays with different orientations

Array	Size	Config	% Annual Mismatch Loss	
			Lat Tilt South	Vertical West
Mono 3B	2 kW	1 string of 27	0.2%	0.2%
Mono 1A	4.3 kW	3 strings of 8	0.8%	1.0%
Poly 3B	3 kW	2 strings of 9	1.2%	0.8%
Hybrid 2B	2.2 kW	2 strings of 4	3.3%	3.8%
Thin 2B	1.5 kW	16 strings of 2	1.7%	2.2%

Extended Mismatch Analysis – Module Ordering

Next, the selected arrays are simulated in Boulder, CO, oriented south-facing with latitude tilt, varying module ordering and distribution in the arrays' strings. Each system is again simulated in its native string configuration, but this time with its modules randomly placed in the array. The annual simulations are performed twenty times for each array, with the modules randomly distributed each time, to find the average and range of mismatch losses (Table 6.6).

Table 6.6. Annual mismatch loss ranges and averages for selected PV arrays with varied module ordering

Array	Size	Config	% Annual Mismatch Loss	
			Range	Average
Mono 3B	2 kW	1 string of 27	0.2%	0.2%
Mono 1A	4.3 kW	3 strings of 8	0.8-0.9%	0.8%
Poly 3B	3 kW	2 strings of 9	0.8-1.2%	1.0%
Hybrid 2B	2.2 kW	2 strings of 4	0.2-14.9%	8.6%
Thin 2B	1.5 kW	16 strings of 2	1.3-1.9%	1.6%

Module ordering does not matter in Mono 3B, a single string array, and also makes little difference in Mono 1A, an array with little module-to-module performance variation outside of two outliers. In the two arrays with significant variation in both I_{mp} and V_{mp}, Poly 3B and Thin 2B, the range of possible mismatch losses is approximately half a percent, which adds moderate uncertainty to overall array loss estimations.

Unlike the other arrays, Hybrid 2B has very large and pervasive module-to-module voltage variation, and is wired in short parallel strings; the possible range of mismatch losses for this array is thus very high when considering module ordering. This shows that in array with very high level of mismatch, there is considerable potential for module level power optimizers to increase energy capture. However, it is not known how frequently arrays with this degree of mismatch occur in real world installations, and it is difficult to generally quantify the potential, given the large range found for just this one array and the high dependence on module ordering and other factors.

Extended Mismatch Analysis – Array Size & Configuration

Finally, each of the selected arrays is simulated at four times its installed size, with each module occurring four times in the array and the modules randomly distributed throughout the array's strings. This is done to examine the effect of string length and system size on mismatch loss. Simulations are again run twenty time for each array to find the range and average of the mismatch losses; results are listed in Table 6.7.

Table 6.7. Annual mismatch loss ranges and averages for larger arrays with varied module ordering and string lengths

Array	Size	Config	% Annual Mismatch Loss	
			Range	Average
Mono 3B	8 kW	4 strings of 27	0.2%	0.2%
		12 strings of 9	0.2%	0.2%
Mono 1A	17.2 kW	8 strings of 12	0.7-0.8%	0.75%
		12 strings of 8	0.7-0.9%	0.8%
Poly 3B	12 kW	8 strings of 9	0.9-1.0%	0.95%
		12 strings of 6	0.9-1.0%	0.95%
Hybrid 2B	8.8 kW	4 strings of 8	1.0-10.9%	6.6%
		8 strings of 4	3.2-26.7%	11.6%
Thin 2B	6 kW	16 strings of 8	1.1-1.3%	1.2%
		64 strings of 2	1.5-1.8%	1.6%

Once again, in arrays with very little mismatch such as Mono 3B, losses are virtually independent of array size and configuration. Annual mismatch losses for the larger versions of Mono 1A and Poly 3B are also virtually independent of string length and are very similar to the losses found in their corresponding smaller arrays. The larger Hybrid 2B and Thin 2B, however, do show differences. In these arrays, performance improves with longer series strings, in large part because the longer strings tend to minimize voltage mismatch between parallel strings, resulting in decreased mismatch loss.

6.4 Summary

This chapter explores the module-to-module electrical performance mismatch in PV systems and the resulting energy losses, which define the potential impact of per-module power optimizers in PV arrays that are not subject to shading or other obvious nonuniform operating conditions. All of this work is based on the simultaneous, module-level I-V curves collected as described in Chapter 3. The diverse set of data ensures that the analysis accounts for arrays of different ages and technologies, and for mismatch under high and low light operating conditions.

The measured I-V curves for each array's modules are evaluated to find the average absolute deviation (AAD) of the modules' key curve points (I_{sc}, V_{oc}, P_{mp}, and its associated current and voltage) from the array mean. These are presented, along with their respective uncertainties, under high and low light operating conditions. Most arrays show a low level of module-to-module mismatch (AAD<3% for all curve points) though some of the older systems exhibit significant parameter or fill factor variation, and several arrays have one or more bypass diodes that are always conducting. PV modelers may use this information to determine realistic boundaries for running statistical models of PV module performance mismatch and its associated losses.

Annual mismatch loss (and equivalently the potential for increased energy capture in arrays with per-module power optimizers) is found to range from 0-3% for the monitored arrays in their native, installed string configurations, though can exceed 10% for one of the arrays depending on string configuration and module distribution. Approximately three quarters of the arrays have simulated annual mismatch losses of less than 1%. This demonstrates that the commonly used 2% "default mismatch derate" in many modeling tools is overestimating these effects. Mismatch losses are found to depend mostly on module manufacturer and array configuration, rather than array age or technology type. Extended analysis of a subset of arrays shows that mismatch losses vary little with array orientation, size, module ordering, or string configuration except in PV systems with a high degree of module-to-module variation.

CHAPTER 7

PARTIAL ARRAY SHADING

This chapter describes a detailed, cell-level methodology for accurate prediction of partial shading and electrical mismatch related losses in PV arrays, and uses this methodology to determine and analyze these losses and then demonstrate the potential for increased annual energy capture in a set of realistic PV systems employing distributed maximum power tracking (DMPPT) at various sub-array levels. It extends previous investigations on the subject (MacAlpine, Brandemuehl, & Erickson, 2011) by adding electrical mismatch to the model at the sub-module level and simulating a more realistic and diverse set of shading scenarios. In addition, the latter part of the chapter focuses on effects of modeling partial array shading in different ways, quantifying the differences that may occur with certain types of simplified shade modeling. Results in this chapter have also been presented in (MacAlpine, Erickson, & Brandemuehl, 2013) and (MacAlpine, Brandemuehl, & Erickson, 2012).

7.1 Energy Loss From Partial Shading

When a PV array receives partial shading during operation, its performance becomes difficult to predict because of nonlinear module behavior and system string current and voltage constraints. The simulation environment described in Chapter 5 is designed to allow for annual, hourly, cell-level simulation of partially shaded arrays, which explicitly accounts for these complexities. Annual simulations of PV arrays with high, medium, and low levels of shading and different array configurations are run in this section to better understand shading effects.

7.1.1 PV Generator Models

Simulations in this section are based on data from a 4kW array of 24 monocrystalline modules mounted on a roof at the University of Colorado Boulder. The tested array is shown in Figure 7.1a. In order to record sub-module data, a custom printed circuit board (PCB) with a microcontroller and bypass diode level voltage sensors (Figure 7.1b) was designed by an undergraduate student and mounted in each panel's junction box. These PCBs allow collection of rapid, concurrent voltage measurements from each sub-module.

(a)

(b)

Figure 7.1. (a) University of Colorado PV array and (b) PCB for sub-module data collection

Modules were connected in series with a programmable DC load in order to sweep I-V curves of multiple array elements simultaneously. I-V curves were taken under high (~1000 W/m2) and low (~250 W/m2) irradiance conditions, with in-plane irradiance measured by pyranometers calibrated at the National Renewable Energy Laboratory, and cell temperature measured using several type-T thermocouples mounted on the panels' back sides. The high and low irradiance I-V curves were recorded around solar noon on sunny days to decrease temporal irradiance variability; low irradiance conditions were achieved using a ~75% opaque, spectrally neutral black mesh (described in Chapter 5) shown in Figure 7.1a. This work is unique in reporting I-V curves recorded at the sub-module level; they may be found in Appendix G.1.

The measured I-V curves for each sub-module were fitted to the 7-parameter diode model using methods described in Chapter 4.1; parameters for each sub-module are found in Appendix G.2. A separate diode model for each sub-module is included in the simulations to account for their performance differences. It should be noted that while the fit was generally good for most sub-modules, there is some room for improvement particularly for PV generators which exhibit slightly “nonstandard” I-V curves. However, the modeled I-V curves are very realistic and representative of performance behavior exhibited by several of the arrays considered in this work. Figure 7.2 illustrates the modeled power vs. current curves under standard high irradiance test conditions (1000 W/m2, 25°C). While most of the sub-modules have similar maximum power point currents, there are a few that are lower than the rest at both high and low irradiance; these outliers create more opportunity for power optimizers in series strings.

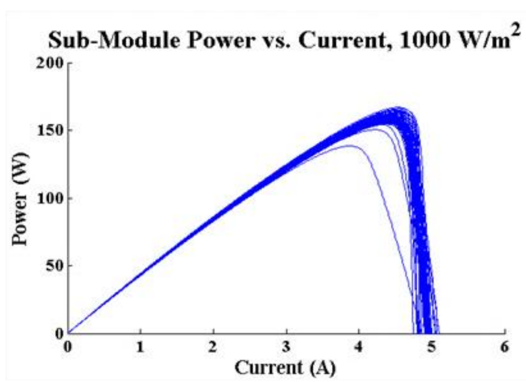


Figure 7.2. Sub-module power curves at high irradiance

7.1.2 Shading Cases

Shading cases for simulation were chosen based on a survey of Solmetric solar access data for installed PV sites described in (Deline, Meydbray, Donovan, & Forrest, 2012). Solmetric solar access (the percent of incident irradiance that is available to the array throughout the year) is calculated using sun paths and fish-eye images taken at key points in the array, assuming that any part of the array that is shaded at any time receives no radiation. According to the distribution of survey results, “light” shading corresponds to a 5-15% loss of solar access over the year, “moderate” is 15-20%, and “heavy” is any solar access loss greater than 20%.

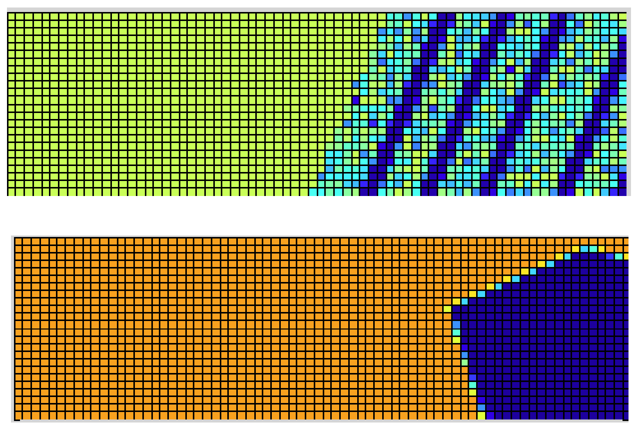
The definition of solar access loss is slightly different for these simulations, because 1) the shadows are directly mapped onto the array for every hour during the year and 2) shaded portions of the array do receive the diffuse irradiance fraction. In this work the solar access loss is defined in Equation 7.1. The cases to be simulated were chosen such that if shade is modeled without receiving the diffuse light fraction, the percent solar access loss falls into the previously-defined (by Solmetric standards) light, moderate, or heavy shading categories indicated in the installer data.

$$\text{Solar Access Loss} = 1 - \frac{\text{Total Annual Insolation with Shading}}{\text{Total Annual Unshaded Insolation}} \qquad \textbf{7.1}$$

Each of the simulated shading scenarios, illustrated in Figure 7.3, is modeled after actual residential installations in the southwest United States. These are described in more detail in Appendix H. Shading obstacles include chimneys, pine trees, and deciduous trees. Chimneys and pines are modeled as fully opaque cylinders throughout the year. Deciduous trees are modeled as cylinders containing a number of fully opaque cylindrical “branches” surrounded by leaves. The “leaf” portions of the cylinder are assumed to have varying transparencies, following a normal distribution. During the warmer seasons, the leaf distribution is centered at 20% transparent, and during the winter it is centered at 75% transparent to account for leaf drop. Examples of the shadows mapped onto the array plane at the cell level are shown in Figure 7.4, and their movement across the array throughout the year is depicted in Appendix H. An unshaded case is also simulated to investigate the potential for increased energy capture in arrays with no appreciable shading.

(a) (b) (c)

Figure 7.3. Heavy (a), medium (b) and light (c) shading scenarios



(a)

(b)

Figure 7.4. Shading mapped onto the array at the cell level for (a) deciduous tree and (b) pine tree

7.1.3 Annual Shading Loss Simulations

Annual simulations are run using TMY3 data for Boulder, Colorado (sunny climate), and Orlando, Florida (cloudy climate). In all cases the modeled array is oriented due South, with a 22.6 degree (5:12 roof pitch) tilt, illustrated in Figure 7.5. The simulated arrays are made up of twenty-four 180W monocrystalline panels (modeled after those described in the preceding subsection), each with three bypass diodes, arranged in two parallel strings of twelve panels. This array configuration was chosen for simulation as it was found to be one of the most common configurations in a survey of California PV systems (BEW Engineering, 2009). The simulations in this work focus on system DC (pre-inverter) power, with the string voltage constrained to a typical MPPT input voltage range for central inverters, 250-480V (SMA).

Figure 7.5. Simulated array

The light, moderate, and heavy shading cases address the way that the amount of shade on the array affects annual energy losses and the potential benefits of power optimizers, but do not directly depict the influence of shade position on the array. In order to better understand the degree of variability in shading losses, the array was additionally simulated with its strings divided in the two different ways in Figure 7.6, top-bottom, and left-right, for the different amounts of shading in Boulder and Orlando.

Figure 7.6. Array configured in top-bottom or left-right strings

Percent annual energy loss due to shading is calculated as in Equation 7.2. Comparisons of the annual power loss caused by partial shading are shown for these twelve cases in Table 7.1.

$$\%\text{Shade Loss} = \frac{\text{Unshaded Energy} - \text{Shaded Energy}}{\text{Unshaded Energy}} \qquad \textbf{7.2}$$

Table 7.1. Annual shading losses

	Annual % Light Loss	System % Energy Loss		SIF	
		top/bot strings	side strings	top/bot strings	side strings
Denver Heavy	13.7%	32.5%	29.6%	2.4	2.2
Denver Moderate	6.6%	18.7%	16.6%	2.8	2.5
Denver Light	3.8%	8.3%	9.7%	2.2	2.6
Orlando Heavy	9.5%	24.9%	22.1%	2.6	2.3
Orlando Moderate	4.2%	13.7%	11.9%	3.3	2.8
Orlando Light	3.2%	8.3%	9.0%	2.6	2.8

These annual shading losses show two interesting trends. First, shading losses do depend on array configuration; they are greater for the top-bottom string division in the heavy and moderate shading cases, and greater for the left-right string division when shading is light. While the differences are only as much as a few percent, they are still significant because in each case the differences account for ~10% of the total loss. This is attributed to the shade patterns and the way that they are distributed on the panels, rather than the level of shading on the array, and clearly shows the importance of detailed modeling of partially shaded systems.

Second, the energy losses from shading are much greater than the amount of light lost, i.e. blocked by the shading obstacles, over the course of the year. Previous works such as (Deline, 2009) have discussed a shade impact factor (SIF) based on the fraction of the array's area that is shaded. In this work, SIF is defined in terms of annual energy loss and annual light loss, as in Equation 7.3. SIF=1 would indicate ideal shaded operation of the array, with the energy output directly correlated with the amount of available radiation. In all of the cases above, the SIF varies from ~2-3, indicating substantial opportunities for increased energy capture with DMPPT. It is not possible, given the limited set of test arrays and module type, to say that all partially shaded arrays' SIFs fall in this range, but this is something that warrants future investigation as a general guideline for SIF range could be useful as a first-pass shade impact predictor.

$$\text{SIF} = \frac{\%\ \text{Annual Energy Loss}}{\%\ \text{Annual Light Loss from Shading}} \qquad \textbf{7.3}$$

7.2 Potential for Power Optimizers in Partially Shaded Arrays

Shading-related power losses generally consist of a fixed and a recoverable component as depicted in Figure 7.7. The latter of these creates opportunities for sub-array power optimizers and distributed maximum power point tracking (DMPPT), as in Figure 7.8, to increase energy capture throughout the year. It is important to be able to quantify this benefit of power optimizers, to determine their usefulness in different PV installations, yet as described in Chapter 2 there are few accurate and unbiased sources of information on this topic. In this section, the preceding shading simulations are modified to include power optimizers at the string, module, sub-module, or cell level. Simulations of arrays including power optimizers model them simply as ideal DMPPT, maximizing the arrays' DC power output, to better illustrate their device-independent potential for increased energy capture.

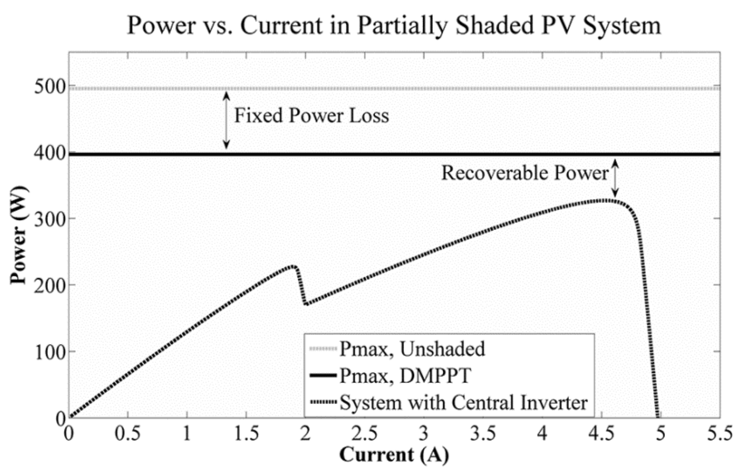


Figure 7.7. Fixed and recoverable power losses in a partially shaded PV system

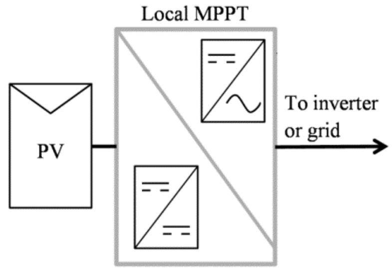


Figure 7.8. PV with distributed maximum power point tracking

The annual energy gain potential for power optimizers and DMPPT at different levels in the array (string, panel, sub-module, and cell) is shown in Table 7.2. Only results for the top-bottom string division described previously are included in this table; results for the left-right division were similar, with slightly less potential for the moderate and heavy shading cases, and more for the light shading case (unshaded was unchanged). Both the shaded and unshaded scenarios show generally greater potential in a sunny climate (Boulder) than a cloudy climate (Orlando), indicating less benefit from DMPPT under overcast conditions. Without shading, power optimizers show little advantage; the electrical mismatch between sub-modules of the modeled array creates the opportunity for energy gains of <1%. This agrees well with the results of Chapter 6.

Table 7.2. Annual energy gain potential for partially shaded PV arrays with power optimizers

	Annual % Energy Gain			
	string	panel	sub-module	cell
Denver Heavy	1.6%	16.3%	18.2%	29.7%
Denver Moderate	0.8%	9.3%	10.4%	16.7%
Denver Light	0.9%	3.4%	4.1%	7.2%
Denver Unshaded	0.1%	0.7%	0.8%	---
Orlando Heavy	1.4%	12.5%	13.9%	20.8%
Orlando Moderate	0.7%	6.7%	7.5%	11.5%
Orlando Light	0.9%	3.7%	4.4%	6.8%
Orlando Unshaded	0.1%	0.6%	0.7%	---

The shaded cases show a variety of potential gains, depending on amount of shading and the granularity of power optimizers in the array. While the string level shows limited opportunity for DMPPT, gains of 3.4%-16.3% at the panel level are significant. Sub-module optimizers show just a slight advantage over those at the panel level (~1-2%), but may still be an attractive option if they allow use of lower voltage parts, since they could easily be put in a panel junction box. Cell level DMPPT shows the highest benefit (6.8%-29.7%), nearly twice that of the panel level; however, current PV panel designs and cost considerations may make this approach impractical. These percentages represent the potential for increased energy using ideal DMPPT; efficiency and insertion losses associated with actual power optimizer designs may decrease gains, though other mismatch factors not considered in this study, such as soiling or temperature variation over the array, may help to balance out any device-specific losses.

Percent annual energy gains are one way of looking at the potential energy gain from power optimizers, but as evidenced above they can span a wide range of values, depending on shading extent and other factors, and are often not presented with accompanying system information to aid in their interpretation. It also makes sense to examine a different metric, percent shade loss recovered (Equation 7.4), which relates (normalizes) the power recovered to the initial shade-related losses experienced by the PV system.

$$\%\text{Shade Loss Recovered} = \frac{\text{Optimized Shaded Energy} - \text{Shaded Energy}}{\text{Unshaded Energy} - \text{Shaded Energy}} \qquad \textbf{7.4}$$

This metric is examined for DMPPT at the panel level, and results are displayed in Table 7.3. Results indicate that for all of the simulated shading scenarios, it is possible for module-level power optimizers to recover 34% - 42% of the energy lost from partial system shading. Viewing the potential for energy recovery in this way would allow anyone whose has estimated system shading losses to be able to quickly approximate power optimizer benefits and determine whether or not to consider their use.

Table 7.3 also shows the shade impact factor (SIF -- Equation 7.3) for each scenario with the module-level power optimizers. It is significantly reduced in all cases (refer to Table 7.1 for SIF without power optimizers), yet is still between 1.5 and 2, rather than a 1:1 relationship between fraction of array shaded and annual energy lost. This indicates that there is still potential for additional energy capture with power optimizers at lower levels in the array, as also noted in Table 7.2.

Table 7.3. Potential annual loss recovery and SIF with module level power optimizers

	Annual % Light Loss	Annual % Loss Recovered	SIF
Denver Heavy	13.7%	33.8%	1.6
Denver Moderate	6.6%	40.7%	1.8
Denver Light	3.8%	38.1%	1.5
Orlando Heavy	9.5%	37.6%	1.7
Orlando Moderate	4.2%	42.2%	2.0
Orlando Light	3.2%	41.2%	1.7

7.3 Shade Modeling Simplifications

It has been shown in literature that for some partially shaded arrays, the commercially-available tool PV*SOL gives annual energy output results similar (prediction within 5%) to those of the more detailed, cell-level tool used in this work (MacAlpine, Brandemuehl, & Erickson, 2012). However, there are still situations in which one might wish to run more detailed or flexible simulations. Unfortunately the speed and computation requirements of a cell-level tool for PV simulation are somewhat impractical. The goal of this section is to determine how much accuracy is sacrificed by simulating at higher levels in the array instead, which would drastically reduce necessary computation time.

7.3.1 Modeled Cases

A typical 5.3kW residential-sized array, made up of twenty- four 220W identical (performance parameters taken from manufacturer's datasheet) monocrystalline modules feeding a 6kW SMA central inverter, is chosen for annual hourly energy simulation. The array, located in Denver, CO, is assumed to be south facing with a 22.6 degree tilt corresponding to a 5:12 roof pitch. To isolate shading losses in the simulations, other losses such as wiring, mismatch, etc. are considered to be negligible. Shaded portions of the array receive the diffuse radiation fraction as calculated by the HDKR anisotropic sky model. The inverter and panel level power optimizers (where employed) are assumed to function ideally such that there are no system AC losses, though system string voltages are constrained by the inverter's input MPPT range. This array is simulated in both moderately (11% of incident light blocked annually) and lightly (5% of incident light blocked annually) shaded sites, shown in Figure 7.9.

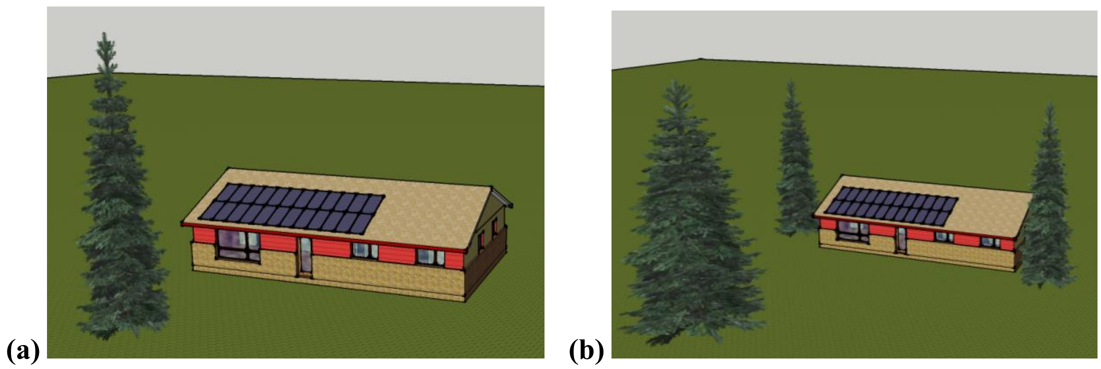


Figure 7.9. (a) Light and (b) moderate shading cases for simulated array in Denver, CO.

7.3.2 Results

To determine how much accuracy is sacrificed by simulating at higher levels in the array instead of at the cell level, the light and moderate shading cases are also run with shading modeled at the sub-module (bypass diode) and module levels shown in Figure 7.10.

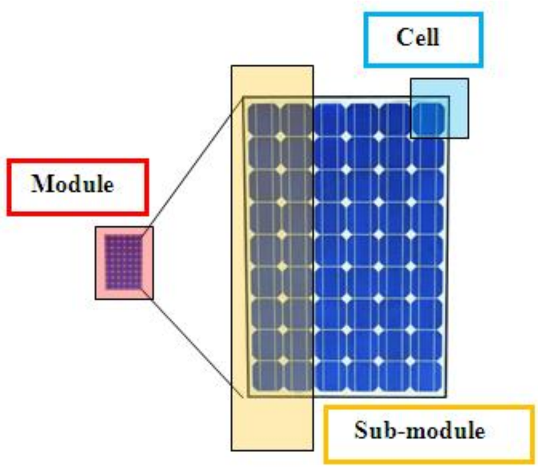


Figure 7.10. Levels to run and compare annual simulations of partially shaded arrays

The sub-module and panel level simulations are each run two ways: 1) averaging the light available over the designated level unit or 2) treating the unit in a binary way such that shade on any part of it equates to uniform shading of the whole unit surface. These simulations examine both power lost to shading and the opportunity for power recovery in an array employing distributed maximum power point tracking (DMPPT) in the form of panel level power optimizers (PO). Results follow in Table 7.4.

Table 7.4. Shading loss and opportunity for recoverable power modeled at different array levels.

Simulation Level	Moderate Shading		Heavy Shading	
	% Loss	PO % Gain	% Loss	PO % Gain
Cell (averaged)	16.1%	9.7%	25.7%	14.4%
Sub-module (averaged)	11.3%	6.3%	19.6%	5.3%
Sub-module (binary)	16.5%	10.3%	26.0%	14.8%
Module (averaged)	11.8%	6.9%	22.6%	13.6%
Module (binary)	18.4%	11.4%	27.6%	15.5%

*(av) indicates that the incident light is averaged over the space while (bin) indicates that the space is given a binary shaded or unshaded designation

These results clearly show that simulations run at the sub-module level with assumed binary shading sacrifice very little in terms of accuracy as compared to cell level modeling, which has also been suggested in (Deline, 2010). The predicted shading losses and resulting increased energy capture available to power optimizers are nearly the same at both of these levels. In cases where very detailed simulations are necessary, modeling at the sub-module level shows good potential to drastically reduce cell level model run times and computational requirements. Module level binary shading loss/gain potential calculations are also reasonable, within 2% of their cell-level counterparts.

7.4 Summary

In conventional grid-tied PV arrays, non-uniform operating conditions can have a disproportionally large impact on system performance, which creates an opportunity for increased energy capture in systems that employ sub-array distributed power conversion and power point tracking (power optimizers). Existing PV modeling tools do not have the level of detail required to accurately model mismatch-related power losses at the system level, making it difficult to estimate the actual potential for power optimizers to boost energy harvest in realistic PV systems. This chapter employs the detailed, flexible simulation environment described in Chapter 5 in an improved methodology for accurate prediction of partial shading and electrical mismatch related losses in PV arrays. The methodology was then used to quantify the device-independent potential for increased annual energy capture in a diverse set of realistic PV installations employing DMPPT at various sub-array levels.

A typical, residential-sized array is chosen for simulation, configured in two parallel strings. The array is modeled based on I-V curve data taken at the bypass diode sub-module level; this work is the first to use an existing array's measured variations in sub-module electrical characteristics as a basis for electrical mismatch in an annual, system-level energy model. Partial shading of the array is simulated for light, moderate, and heavy shading scenarios, created using a survey of shading found in real, installed PV systems.

In all of the simulations with partial shading, annual energy losses were found to be two to three times as large as the amount of light blocked over the year (shade impact factor, or SIF ~2-3), indicating that the current and voltage balancing requirements in a conventional grid-tied array do create an opportunity for power recovery with DMPPT. Modeling partial array shading at different levels in the array (cell, sub-module, and panel) revealed that in both light and moderate shading scenarios, simplifying the simulation by modeling at the sub-module (bypass diode) level gives nearly the same results as cell level modeling, but takes much less time and compute power. Modeling at the panel level changes the results by approximately 2% or less.

All of the simulated cases (unshaded, low, medium, and high shading) are also simulated with power optimizers inserted into the arrays at the string, module, sub-module, and cell levels. The potential for energy gain in unshaded arrays is <1% for all of the cases, agreeing with results found in Chapter 6. In shaded arrays it increased to 3-16% for panel-level DMPPT and 7-30% for cell-level DMPPT, with slightly greater opportunities in climates receiving more sun throughout the year. The panel and cell level power optimizers are found to provide a higher relative increase in performance than their string or sub-module counterparts, each of which provides little gain as compared to power point tracking at the next level up in the array. In each of the simulated cases panel-level power optimization was able to recover 34-42% of the energy lost to partial shading. The SIF with module level power optimizers ranged from 1.5-2 for all simulated cases, indicating that there is still even more potential for power recovery, with power optimizer granularity at a finer level in the array.

CHAPTER 8

PV MODULE MODEL COMPARISON CASE STUDY

Three different single diode models are utilized in this work, the five parameter model (Chapter 6), the seven parameter model (Chapter 7), and the newly-developed DR model (Chapter 4). Each of these models is described in detail in Chapter 4. The following case study is designed to examine the impact, if any, of using each of these different single diode models. A comparison between the three analyzes performance prediction for conventional PV systems, and also power optimizers' potential for increased energy capture in PV arrays with mismatched module electrical characteristics and/or partial shading.

8.1 Annual Performance

Two arrays with data collected using the NREL multitracer are selected to analyze the models' impact on annual performance prediction. Mono 1A and Thin 3A are representative crystalline silicon and thin film arrays, respectively, and were chosen in part because the DR model showed improved accuracy under low and med light conditions for each of them when compared to the 5 and 7 parameter models (Figure 4.19, Figure 4.21). Annual performance simulations are run for each array in Denver with a south-facing latitude tilt, to simulate typical irradiance on ideally oriented array, and a west-facing vertical tilt, to simulate a BIPV situation where much of the array's energy may be generated under lower irradiance conditions. The arrays are assumed to be wired in their actual, installed configurations. Figure 8.1 shows the predicted annual energy output for each array and orientation, using the three different single diode models.

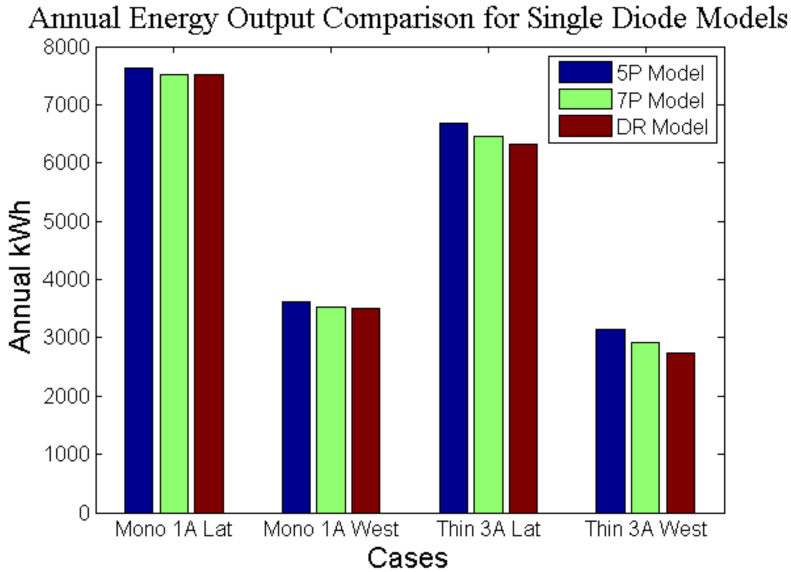


Figure 8.1. Comparison of annual energy predictions for single diode models

For Mono 1A, the predictions of the 7 parameter and DR models are nearly identical, which is expected given that their predictions under low and medium light levels (Figure 4.19, Figure 4.21) are similar. They predict approximately 1.5% and 3% less energy output than the 5 parameter model in the south-facing, latitude tilt and west-facing, vertical tilt cases, respectively. These numbers, while small, represent a significant source of uncertainty in PV modeling. With regard to Thin 3A, the DR model predicts less energy output than the 7 parameter model, by 2-6%, and less than the 5 parameter model, by 5-13%. These results agree well with Figures 4.19 and 4.21, and also with another study (MacAlpine & Brandemuehl, 2011) in which the 5 parameter model tended to significantly over-predict for some thin film technologies. It is clear that a model incorporating low light data, such as the DR model, could significantly improve performance prediction in thin film and even crystalline silicon arrays, particularly in arrays which frequently operate under lower light levels.

8.2 Increased Energy Capture

8.2.1 Electrical Mismatch

Potential for increased energy capture from mismatched electrical characteristics between modules is examined for the cases described in Section 8.1, assuming power optimizers at the module level. Again, the DR and 5 and 7 parameter single diode models are compared to one another, with results found in Figure 8.2.

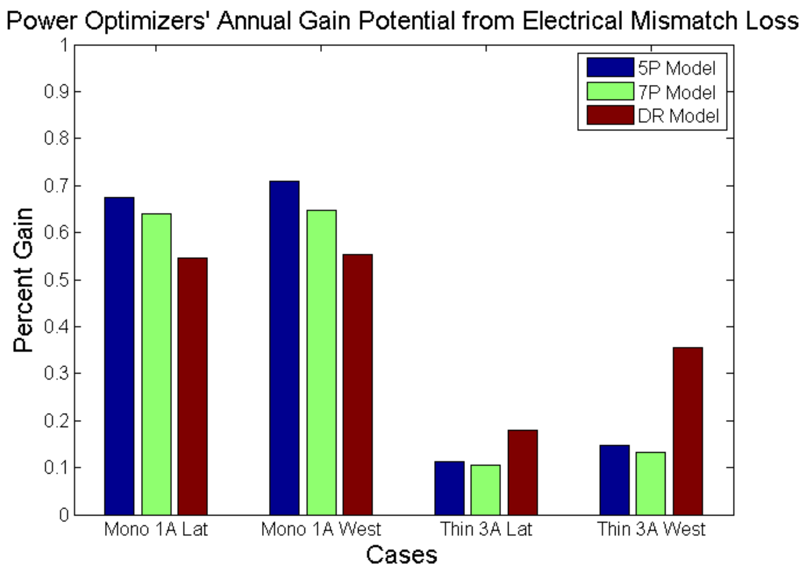


Figure 8.2. Model comparison of predicted gain potential for power optimizers due to electrical mismatch between modules

The DR model predicts less gain potential than the other two models for Mono 1A, but only by 0.1-0.2%. Conversely the DR model suggests that there is more potential than the other two models for Thin 3A, again by just 0.1-0.2%. These small fractions of a percent indicate that use of any of the single diode models to predict mismatch loss, and the resulting gain potential with power optimizers, is justified. Use of a more accurate model does not significantly affect the results or conclusions for either crystalline silicon or thin film arrays.

8.2.2 Partial Array Shading

The three previously-mentioned single diode models are used to simulate the low, medium, and high shading cases described in Section 7.1.2, comparing their predicted annual potential for increased energy capture with power optimizers at the module or cell levels. This is done exclusively for array Mono 1A, as thin film modules are not typically utilized in partially shaded, residential PV installations. As noted in Figure 8.3, the potential percent gain is nearly identical for all three models in all cases. This again indicates that use of any of the single diode models described in this work will give similar results and conclusions with regard to potential for power optimizers in partially shaded arrays.

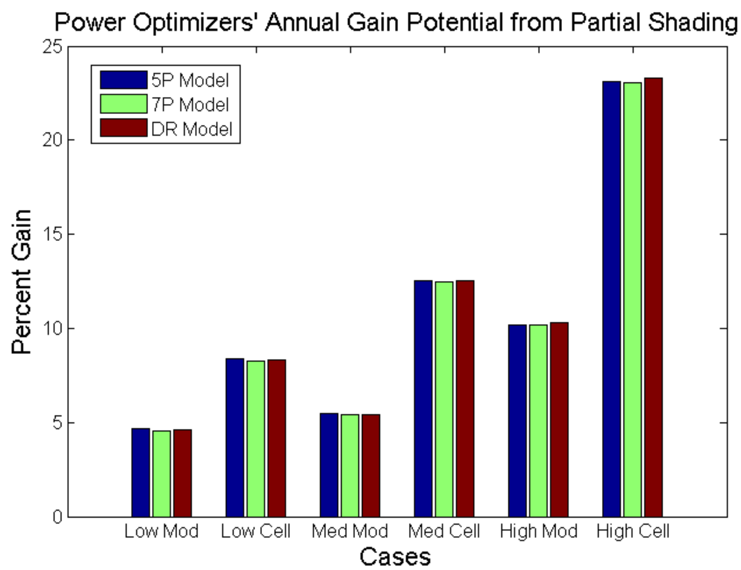


Figure 8.3. Model comparison of predicted gain potential for power optimizers due to partial shading

8.3 Summary

The case study presented in this chapter compares the five parameter, seven parameter, and DR single diode models when used to predict the performance of a conventional PV array, as well as the potential for increased energy capture when using power optimizers. It is found that all three models predict similar gains from use of power optimizers in both unshaded and partially shaded PV arrays. However, the newly-developed DR model, designed to be more accurate under low and medium light conditions, predicts less significantly less output overall on an annual basis for the analyzed crystalline silicon and thin film arrays. This is particularly evident in the comparison between the DR and 5 parameter models' results for the thin film array, where the discrepancy between the two models is 5-13%. These results indicate that thin film array performance prediction in particular would benefit from use of a more detailed single diode model that incorporates low light data to improve accuracy.

CHAPTER 9

CONTRIBUTIONS, CONCLUSIONS AND FUTURE WORK

9.1 Conclusions and Contributions

(1) An extensive dataset of simultaneous module-level I-V curves, collected for 27 installed PV arrays in the Southwest U.S., ranging in age from newly installed to 11 years old.

These arrays are comprised of over 500 modules, representing six different PV technologies including mono- and polycrystalline silicon, hybrid silicon (a combination of mono and amorphous), and thin film including CdTe, CIS/CIGS and amorphous silicon. The data, taken under both high and low (and in some cases, medium as well) light conditions, will be extremely useful to the PV modeling and research communities. Measured module-level I-V curves from the majority of the arrays are planned to be made publicly available on the widely-used PV Performance Modeling Collaborative website pvpmc.org.

(2) Investigation of parameter behavior with varied module operating temperature and incident irradiance for the standard single diode PV generator model, and proposed modeling methodology changes to improve model accuracy over the full range of typical PV operating conditions.

Analysis of existing single diode models' parameters under measured high, medium, and low light conditions indicates that the series and shunt resistance, particularly the former, do not behave in the way that is assumed by the most commonly-used models. Modifications to the way that these resistances are translated from fitted reference models to different operating conditions are proposed, and an additional fitting parameter is also suggested for the model's diode reverse saturation current. In total three new translation parameters are introduced to establish a new improved model, X_{RS}, X_{RSH}, and X_{I0}, requiring only two I-V curves (one high irradiance, one low) to determine their values. Average RMSE in the prediction of modules' maximum power output is reduced to less than 1% for most arrays under low light conditions, and is reduced by approximately half as compared to common, existing single diode models under medium irradiance conditions. This demonstrates that a model using two sets of fitted reference curves (high and low light) is beneficial.

(3) Statistical quantification of each array's performance variation coefficients (average absolute deviation of the module values from their array-level mean) at key I-V curve points.

In each array, the average absolute deviations (AADs) of the modules' key curve points (I_{sc}, V_{oc}, P_{mp}, and its associated current and voltage) from the array mean are presented, along with their respective uncertainties, under high and low light operating conditions. Most arrays show a low level of module-to-module mismatch (AAD <3% for all curve points) though some of the older systems exhibit significant parameter or fill factor variation, and several arrays have one or more bypass diodes that are always conducting. PV modelers may use this information to determine realistic boundaries for running statistical models of PV module performance mismatch and its associated losses.

(4) Illustration of a variety of observed types of module-to-module mismatch found in installed PV arrays, as well as simulation and analysis of their associated annual energy losses.

Module-to-module mismatch in current and voltage characteristics (taken from the measured, module-level I-V curves) is shown and discussed. The mismatch-related energy losses are often less than 1%, even for arrays that have experienced field degradation, demonstrating that the mismatch losses are small compared to the module-to-module performance parameter variation. It is clear from this work that the commonly used "default mismatch derate" of 2% in many modeling tools is overestimating these effects.

(5) Development and validation of detailed, cell-level shading simulation methodology and environment for calculation of annual energy losses due to partial shading on PV arrays.

Simulations are used to assess the impact of shading and array configuration on PV array performance, showing that for a variety of array configurations and degrees of shading, partial shading reduces annual energy output by 2-3 times the percentage of light blocked over the year. The simulated arrays in these cases are made up of typical monocrystalline silicon modules, and results may vary with other technologies. Modeling the array at the bypass diode submodule level instead of cell level, to reduce computation time and resources, has little effect on the system level energy output, suggesting that this is a good solution. Modeling at the module level further reduces complexity, but may change the predicted shading losses by as much as 2%, which may or may not represent an acceptable difference, depending on the application.

(6) Assessment of the potential for use of sub-array power conversion and maximum power point tracking (via power optimizers) in residential PV arrays.

In unshaded PV arrays, module-to-module mismatch usually creates only a modest opportunity for ideal (no efficiency or operating losses) power optimizers to increase annual energy capture, 1% or less. Simulation of numerous different partially shaded arrays showed more potential, with module-level power optimizers recovering 34-42% of the shading losses. It is noted that in the studied residential-sized arrays, power optimizers at the module and cell levels tend to show the most dramatic gains, whereas placing them at the string level has very little impact, and the bypass diode sub-module level showed little gain over the module level.

9.2 Future Work

The following are possible topics for future research that have come out of this work:

(1) Improved PV module model utilizing data from the new required IEC 61853 matrix.

These data, taken indoors or outdoors, will cover a full breadth of module operating conditions with independent variation of irradiance and temperature, which should allow for better understanding of module behavior.

(2) Analysis of temperature and irradiance dependence of PV generator voltage and current temperature coefficients

The behavior of the temperature coefficients for PV cells' voltage and current is not well understood over the breadth of typical PV operating conditions. Uncertainty in the values of these coefficients has the potential to contribute significantly to overall PV model uncertainty, and should be explored.

(3) Examine module-to-module mismatch in larger arrays, with a focus on frequency of bypass diode failure, and degradation in humid climates.

Data in this study were taken on smaller arrays, and only in dry climates. Consideration of larger arrays (larger module sample sets) would allow better understanding of the likelihood of bypass diode failure, which this work has shown is a large driver of mismatch. Additionally, the PV degradation literature suggests that degradation is more prevalent and rapid in humid climates; this may mean that these arrays also have more variable degradation between modules, which could lead to greater mismatch losses.

(4) Continued efforts to simplify the partial array shading model.

The detailed model takes more time than is practical for most commercial tools. While this work presents some simplifications, it would be very useful to PV modelers and researchers alike to have an even simpler tool.

(5) Incorporate converter efficiencies and operating limits into simulations.

This work focuses on the device-independent opportunity for power optimizers, but differences in actual hardware topology and operation would be to model, to develop better understanding of which types of power optimizers may be most useful in different situations.

(6) Potential for power optimizers arising from maximum power point tracking.

There may be added opportunity for power optimizers in cases with quickly changing shade patterns across the array, as a central inverter may not be able to track the maximum power point when the system conditions fluctuate rapidly.

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APPENDIX A

MULTITRACER AND DATA COLLECTION

A.1 Parts List

Company	Part	Qty	Description
NH Research	NHR 4750-3	1	3kW DC Load
MCC-Daq	USB-2416	1	24-bit 1kS/s datalogger
MCC-Daq	AI-EXP32	1	32-ch expansion board
MCC-Daq	ACC-202	2	DIN-rail mounting kit
Digikey	A98091-ND	3	12-pos terminal block
Digikey	486-1261-ND	30	Fuse holder
Digikey	F2986-ND	35	Fuse, 400Vdc
Digikey	1776-C681-ND	30	Decade resistor
Digikey	HLN20H-ND	3	20 Pin header
Digikey	HKR20H-ND	3	20 Pin IDC connector
Digikey	989-1087-ND	3	5mOhm 25A sense resistor
Digikey	609-3929-ND	3	4-position connector for GND, shunt
Digikey	HMM37H-ND	1	DB37M IDC
Digikey	HFU37H-ND	1	DB37F IDC
Win-Solar	---------------	33	MC4 "U" branch
Win-Solar	---------------	30	MC3 "U" branch
Eco Direct	ECO-CABLE-88-3344-F	30	MC3-MC4 adapter
--------------	---------------	~250ft	10 gauge PV wire
--------------	---------------	~600ft	12 gauge insulated stranded wire
Advantech	USB-4718	1	8-Ch Thermocouple/Voltage, USB
PCBoards	Sunstone	3	Custom PCBs
Digikey	HM1003-ND	1	16"x18"x5.25" rack mount enclosure
Digikey	RP785-ND	16	0.156" dia. Snap-in board supports 0.5" spacing
Hardigg	Classic rack 7U 19x32 w/ wheels	2	shipping / rack mount enclosure
Eppley	PSP (SN 24034F3)	1	Precision Spectral Pyranometer
Omega	CO1-T	5	Type T thin file thermocouple

A.2 Colorado Array Run Details

Array	Panels	Age (yrs)	Configuration	Tilt (deg)	Run	Julian Day	Time (MST)	Solar Incidence Angle (deg)	Incident Irradiance (W/m2)	Effective Irradiance (W/m2)	Avg. Panel Temperature (deg. C)
Mono 1A	24	1	multiple strings	10	lo 1	217	6:36	75.3	225.0	185.1	20.8
					med 1	216	15:49	51.8	577.4	533.6	48.1
					hi 1	216	12:31	13.7	1003.7	930.8	61.0
Poly 1A	30	4	multiple strings	32	lo 1	220	7:34	66.6	352.7	313.0	33.0
					lo 2	221	7:25	68.9	313.1	275.8	28.1
					lo 3	220	16:38	66.7	294.1	265.2	44.8
					med 1	220	8:26	54.3	530.5	487.6	45.0
					med 2	220	15:36	51.8	530.5	488.6	56.1
					hi 1	220	11:23	13.5	953.2	883.7	68.8
					hi 2	220	10:32	24.3	879.3	816.0	66.9
					hi 3	220	12:56	14.7	950.4	881.2	70.6
Thin 1A	20	1	multiple strings	0	lo 1	229	7:10	68.9	269.9	240.2	18.0
					lo 2	229	7:17	67.6	288.8	258.1	18.9
					med 1	226	15:51	55.1	609.9	561.1	51.8
					hi 1	230	11:57	26.7	921.4	854.1	51.7
					hi 2	230	11:40	27.2	908.3	841.9	51.5
Thin 2A	24	1	multiple strings	25	lo 1	283	10:12	31.9	267.5	244.8	17.4
					lo 2	283	10:41	26.9	209.8	191.0	17.5
					lo 3	289	10:21	31.6	290.1	266.2	26.3
					med 1	288	15:12	56.1	562.5	527.3	39.8
					hi 2	288	12:22	24.9	953.6	900.2	52.5
					hi 3	288	12:53	28.5	987.2	930.9	56.9
Thin 3A	24	1	multiple strings	25	lo 1	290	7:20	70.0	285.8	247.4	11.7
					lo 2	290	7:29	68.0	326.7	288.8	12.3
					med 1	290	8:21	56.0	555.9	521.6	20.4
					hi 1	290	11:59	24.2	996.2	939.6	43.3
					hi 2	290	11:46	24.0	1001.1	944.2	39.2
Poly 3A	11	1	single string	25	lo 1	291	7:21	69.8	281.9	244.7	7.7
					lo 2	291	7:32	67.3	328.3	292.6	11.6
					lo 3	291	7:34	66.9	336.8	301.2	11.8
					med 1	290	15:16	57.3	542.2	507.2	25.6
					hi 1	290	13:00	30.3	941.3	889.5	35.8
					hi 2	290	12:50	28.7	955.6	902.6	36.6
					hi 3	290	12:53	29.3	951.5	898.9	37.2
Thin 4A	24	1	multiple strings	Tracking	lo 1	291	14:00	75.9	305.9	234.6	33.0
					lo 2	291	14:29	81.3	208.2	155.2	25.1
					hi 1	291	13:41	42.8	776.2	731.4	42.6
					hi 2	291	14:40	37.4	780.5	748.8	35.1
Thin 1B	14	6	multiple strings	40	lo 1	144	11:17	23.0	---	182.5	23.3
					med 1	144	8:23	56.1	---	592.8	33.4
					hi 1	143	13:25	29.9	---	994.6	45.5

A.3 New Mexico Array Run Details

Array	Panels	Age (yrs)	Configuration	Tilt (deg)	Run	Julian Day	Time (MST)	Solar Incidence Angle (deg)	Incident Irradiance (W/m2)	Effective Irradiance (W/m2)	Avg. Panel Temperature (deg. C)
Mono 1B	21	8	single string	35	lo 1	257	8:56	46.5	264.4	255.4	22.7
					med 1	250	8:33	53.1	570.5	557.2	47.2
					hi 1	253	10:02	30.5	894.7	880.5	56.6
Poly 1B	21	7	single string	35	lo 1	254	7:30	68.2	336.1	312.2	30.7
					med 1	254	8:22	55.2	557.0	543.4	43.2
					hi 1	253	11:07	14.8	989.3	970.5	63.2
Mono 2B	21	8	single string	35	lo 1	248	9:24	40.6	209.1	200.1	32.0
					hi 1	249	11:27	11.4	1031.9	1010.9	68.6
Poly 2B	21	7	multiple strings	35	lo 1	248	10:46	20.9	248.1	235.5	34.5
					hi 1	249	13:11	17.9	987.8	968.6	68.3
Hybrid 1A	12	5	single string	35	lo 1	249	8:09	59.0	128.6	125.1	29.9
					hi 1	249	9:30	39.0	845.9	832.2	56.2
Mono 3B	27	8	single string	35	lo 1	253	14:18	34.0	165.7	158.2	34.7
					hi 1	253	12:56	14.3	1089.2	1068.5	63.1
Hybrid 2A	15	3	multiple strings	35	lo 1	253	6:57	76.5	203.4	172.0	20.1
					hi 1	250	13:51	27.4	858.5	842.8	62.9

A.4 Arizona Array Run Details

Array	Panels	Age (yrs)	Configuration	Tilt (deg)	Run	Julian Day	Time (MST)	Solar Incidence Angle (deg)	Incident Irradiance (W/m2)	Effective Irradiance (W/m2)	Avg. Panel Temperature (deg. C)
Poly 3B	18	6	multiple strings	32	lo 1	273	16:52	69.9	288.6	252.4	39.4
					med 1	273	15:37	51.2	607.4	568.5	51.4
					hi 1	273	13:44	22.8	949.5	888.5	61.8
Hybrid 1B	8	9	multiple strings	32	lo 1	273	16:41	67.1	333.3	297.9	44.6
					lo 2	273	7:48	66.4	330.8	297.7	30.4
					med 1	273	8:36	54.2	539.5	503.2	41.2
					hi 1	273	10:13	30.2	862.8	808.6	61.4
Poly 4B	10	9	single string	32	lo 1	276	16:58	71.5	248.3	214.4	39.6
					med 1	276	15:32	50.1	625.8	586.9	51.2
					hi 1	276	13:55	25.9	940.9	881.9	60.6
Thin 2B	32	9	multiple strings	32	lo 1	276	7:23	72.3	298.8	262.9	27.6
					lo 2	276	7:26	71.5	255.7	220.0	25.6
					lo 3	276	7:35	69.2	242.5	206.5	24.9
					lo 4	276	7:41	67.8	353.9	318.5	29.9
					lo 5	276	7:46	66.7	344.5	308.8	29.5
					lo 6	276	7:48	66.0	323.5	287.7	28.8
					med1	276	8:37	53.8	572.7	535.3	41.0
					hi 1	276	11:47	7.3	1056.1	986.0	69.5
					hi 2	276	11:54	6.0	1050.9	981.2	69.4
					hi 3	276	11:58	5.1	1045.5	976.3	68.8
					hi 4	276	11:39	9.0	1028.1	960.6	68.5
					hi 5	276	11:33	10.4	1036.4	968.2	70.0
					hi 6	276	11:29	11.3	1041.0	972.3	70.3
Hybrid 2B	8	9	multiple strings	32	lo 1	273	7:27	71.5	237.7	206.4	24.4
					hi 1	273	11:06	16.9	985.4	920.8	67.3
Thin 3B	27	9	multiple strings	32	lo 1	275	7:27	71.4	255.5	220.6	26.0
					lo 2	275	7:37	68.8	304.3	268.6	27.8
					lo 3	275	16:53	70.2	281.7	245.7	42.5
					med 1	275	8:31	55.5	304.3	268.6	27.8
					hi 1	275	11:23	12.8	1028.4	960.8	67.8
					hi 2	275	11:15	14.7	1017.2	950.7	68.8
					hi 3	275	12:21	4.0	1060.7	990.0	70.6
Mono 4B	20	9	multiple strings	32	lo 1	274	7:20	73.2	298.3	261.6	26.4
					lo 2	274	7:35	69.5	232.8	196.0	23.2
					med 1	274	8:32	55.2	560.4	522.3	39.9
					hi 1	274	11:29	11.4	972.7	910.5	63.9
					hi 2	274	10:42	22.8	1046.2	976.9	67.3
Mono 5B	9	8	single string	32	lo 1	274	17:07	73.7	228.3	190.3	39.8
					med 1	274	15:51	54.6	582.3	543.3	50.1
					hi 1	274	13:57	26.2	968.1	906.9	60.9
Poly 2A	15	5	multiple strings	32	lo 1	272	17:04	72.8	231.7	197.1	37.1
					med 1	272	15:51	54.5	558.3	520.5	49.4
					hi 1	272	12:41	7.2	1055.2	984.5	63.0
Mono 2A	9	3	single string	32	lo 1	272	7:29	71.2	242.3	211.2	25.9
					med 1	272	8:45	52.2	581.3	543.3	40.2
					hi 1	272	10:40	23.5	958.9	897.2	56.8
Mono 6B	18	6	multiple strings	32	lo 1	271	9:40	38.4	283.3	258.9	32.1
					med 1	271	15:45	52.9	555.3	518.3	38.7
					hi 1	271	14:33	34.9	882.0	827.3	48.9
Poly 5B	32	11	multiple strings	32	lo 1	277	7:30	70.5	304.2	260.9	38.6
					lo 2	278	7:33	69.8	207.6	168.7	20.0
					lo 3	278	7:29	70.6	303.0	264.2	24.5
					lo 4	277	7:12	74.9	287.9	248.9	23.8
					lo 5	278	16:54	70.8	308.0	265.6	26.0
					hi 1	277	10:58	18.9	992.5	929.3	63.6
					hi 2	277	11:43	8.3	1008.9	943.5	65.2
					hi 3	277	11:18	14.1	1053.6	984.2	67.8

APPENDIX B

UNCERTAINTY CALCULATIONS

B.1 MCC Panel Voltage Measurements

According to the datasheet for the MCC 2416 USB data acquisition (DAQ) device, the uncertainty of voltage measurements for the +/- 5V range at 36S/s is 0.002%+0.0006%/°C of the reading, and 0.0008% of the range, plus 2μV/°C. There is also an offset uncertainty of 6μV. The test equipment has a nominal temperature of 25°C, and maximum ΔT of 25°C under high and medium irradiance conditions and 10°C under low light conditions. As the DAQ output is multiplied by 100 in the software, the voltage input must be divided by 100. The uncertainty is

$$u_{V,MCC} = \left(\frac{V}{100} * \frac{0.002 + 0.0006 * \Delta T}{100} + \frac{0.0008}{100} * 10 + 2E^{-6} * \Delta T + 6E^{-6}\right) \qquad \textbf{B 1}$$

where V is the measured panel-level voltage value.

B.2 Current Shunt Resistors

The multitracer has three current shunt resistors, one for each string. They are calibrated outdoors under sunny operating conditions with voltage data recorded on the MCC DAQ and current data recorded on a new Agilent 34405 multimeter. The absolute error of the DAQ is 16.122μV and the multimeter error is 0.25% of the measurement + 0.007% of the range. Resistance is calculated by fitting a line to the I-V data using the method detailed in (York, 2004) implemented in Matlab[4]. This method allows for linear regression with uncorrelated errors in both the x and y measurements. Results of the

[4] MATLAB code written by Travis Wiens may be downloaded here: http://www.mathworks.com/matlabcentral/fileexchange/26586-linear-regression-with-errors-in-x-and-y

regression are found below; they indicate that each of the resistors has a value of 0.0053Ω and all may conservatively be assumed to have a standard uncertainty of 0.35%.

Resistor	Value (Ohms)	Standard Uncertainty
1	0.0053	0.31%
2	0.0053	0.30%
3	0.0053	0.33%

B.3 MCC String Current Measurements

According to the datasheet for the MCC 2416 USB data acquisition (DAQ) device, the uncertainty of voltage measurements for the +/- 0.15625V range at 36S/s is 0.006%+0.0006%/°C of the reading, and 0.0005% of the range, plus 1μV/°C. There is also an offset uncertainty of 6μV. The test equipment has a nominal temperature of 25°C, and an assumed maximum ΔT of 25°C under high and medium irradiance conditions and 10°C under low light conditions. Uncertainty is expressed as

$$u_{V,MCC} = \left(V * \frac{0.006 + 0.0006 * \Delta T}{100} + \frac{0.0005}{100} * 0.3125 + 1E^{-6} * \Delta T + 6E^{-6}\right) \qquad \textbf{B 2}$$

where V is the voltage measured across the current shunt resistor.

B.4 Advantech Pyranometer Voltage Measurements

According to the datasheet for the Advantech USB 4718 data acquisition device, the accuracy of voltage measurements for the 0-15mV range is 0.1%. There is also a zero drift of 3μV/°C and a span drift of 25ppm/°C. The test equipment has a nominal temperature of 25°C, and an assumed maximum ΔT of 25°C under high and medium irradiance conditions and 10°C under low light conditions.

$$u_{V,Advantech} = \frac{0.1 * V}{100} + (25E^{-6} * .015 + 3E^{-6}) * \Delta T \qquad \textbf{B 3}$$

where V is the measured voltage from the pyranometer.

B.5 Eppley PSP Calibration (S/N 24034F3) and Uncertainty

Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	AM			PM			Zenith Angle (deg.)	AM			PM		
	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle		R (μV/W/m²)	u(B) ± (%)	Azimuth Angle	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.6146	0.43	94.82	8.7459	0.43	265.01
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.5617	0.44	93.06	8.7310	0.44	266.83
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.5310	0.45	91.33	8.6614	0.45	268.58
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.4712	0.46	89.64	8.6731	0.46	270.23
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.4381	0.47	87.99	8.6540	0.47	271.88
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.3871	0.47	86.38	8.5834	0.48	273.49
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.3718	0.49	84.84	8.5139	0.50	275.07
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.3448	0.50	83.29	8.5131	0.52	276.59
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.2764	0.51	81.76	8.5136	0.55	278.13
18	8.9423	0.37	153.33	8.9557	0.38	206.59	64	8.2811	0.53	80.24	8.4724	0.57	279.67
20	8.9336	0.37	141.05	8.9615	0.38	218.85	66	8.2938	0.55	78.70	8.4377	0.61	281.18
22	8.8993	0.38	133.02	8.9521	0.38	226.90	68	8.2667	0.58	77.20	8.3442	0.65	282.71
24	8.8854	0.38	126.91	8.9455	0.38	233.09	70	8.1867	0.61	75.67	8.2105	0.71	284.25
26	8.8746	0.38	121.99	8.9265	0.38	238.00	72	8.0483	0.67	74.10	8.1356	0.77	285.78
28	8.8599	0.38	117.82	8.9347	0.39	242.14	74	8.0050	0.73	72.56	8.0978	0.87	287.42
30	8.8388	0.39	114.16	8.9114	0.39	245.73	76	7.9681	N/A	70.98	8.0344	N/A	289.00
32	8.8182	0.39	111.05	8.9292	0.39	248.99	78	7.8987	N/A	69.35	7.8733	N/A	290.60
34	8.7867	0.39	108.16	8.8889	0.40	251.84	80	7.8889	N/A	67.74	7.7720	N/A	292.28
36	8.7611	0.40	105.53	8.8863	0.40	254.47	82	7.8475	N/A	66.23	7.6367	N/A	293.98
38	8.7338	0.41	102.98	8.8720	0.40	256.87	84	N/A	N/A	N/A	7.6062	N/A	295.72
40	8.6778	0.42	100.79	8.8547	0.41	259.08	86	N/A	N/A	N/A	7.3461	N/A	297.56
42	8.6671	0.42	98.67	8.8407	0.41	261.15	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.6514	0.43	96.70	8.7927	0.42	263.13	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

The Eppley Precision Spectral Pyranometer (PSP) used in this work (Serial Number 24034F3) was borrowed from the National Renewable Energy Laboratory (NREL). It was calibrated on June 18, 2010, with calibration due again in two years. Though most of the data for this dissertation were taken slightly outside of this timeframe, it was indicated by NREL researchers that a few months would not make a significant difference in instrument response, and that the calibration should still remain valid.

During calibration at NREL, the pyranometer was placed horizontally, oriented with its leads facing north, and its responsivity (Equation B4) was measured throughout the day. AM and PM responses from the calibration report are recorded over a range of solar zenith angles in the table above, along with their associated uncertainties.

$$R = \frac{V - R_{net} * W_{net}}{I} \qquad \textbf{B 4}$$

In Equation B4, R is the pyranometer responsivity ($\mu V/W/m^2$), V is the pyranometer's output voltage in microvolts, R_{net} is the pranometer's net infrared responsivity (estimated in the calibration report to be 0.60

μV/W/m^2), W_{net} is the effective net infrared radiation measured by an onsite pyrgeometer (W/m^2), and I is the incident global irradiance (W/m^2).

As the pyranometer was mounted in the plane of array during data collection, rather than placed horizontally, it was decided that to best represent the device responsivity and associated uncertainty, one should average the device's AM and PM responsivities at each measured solar zenith angle.

$$R_{Z,avg} = \frac{R_{Z,AM} + R_{Z,PM}}{2} \qquad \textbf{B 5}$$

$R_{Z,avg}$ is the average responsivity at each zenith angle Z (two degree increments as seen in the calibration table), and $R_{Z,AM}$ and $R_{Z,PM}$ are the pyranometer's measured AM and PM responsivities at that angle.

The total uncertainty at each two-degree angle increment is then found by adding half the difference between the two responsivities to the highest uncertainty (AM or PM) at that angle. Thus the uncertainty at each solar zenith angle becomes

$$U_{Z,tot} = \frac{\max\left(\frac{U_{Z,AM}}{100} * R_{Z,AM}, \frac{U_{Z,PM}}{100} * R_{Z,PM}\right) + \frac{\left|R_{Z,AM} - R_{Z,PM}\right|}{2}}{R_{Z,avg}/100} \qquad \textbf{B 6}$$

where $U_{Z,,tot}$ is the percent uncertainty at each solar zenith angle, $U_{Z,AM}$ and $U_{Z,PM}$ are the calibrated percent uncertainties of the angle's AM and PM responsivities, respectively, and $R_{Z,avg}$ is given in Equation B5. It is noted that since the pyranometer is orientated horizontally, the solar zenith angle is actually also the incidence angle between the sun and the pyranometer.

Once the zenith angle dependent responsivities and associated uncertainties are calculated, they are fitted to a cubic spline fit in MATLAB so that they can be accurately estimated for all incidence angles between the sun and the pyranometer experienced during data collection. The overall uncertainty associated with pyranometer calibration, $u_{PYR,CAL}$ comes from the cubic spline fit of the collection of values of $U_{Z,tot}$. There are some cases where the incidence angle falls outside of the measured calibrated range, either mid-day or very early/late in the day, and in these scenarios the pyranometer's responsivity and associated uncertainty are taken to be those of the nearest calibrated measurement angle.

B.6 Eppley PSP Directional Response

According to the calibration report, the voltage response of the Eppley PSP is very different in the morning and afternoon, when the incidence angle between the sun and pyranometer falls between 40 and 60 degrees. This may be due to AM/PM spectral differences in Colorado, but also could be impacted by the orientation of the pyranometer and nonuniformities in its dome. During calibration, the leads of the pyranometer were oriented north, but during data collection, this was not controlled. An experiment was designed and carried out to determine the impact of pyranometer orientation on its responsivity.

The pyranometer was placed in the plane of a photovoltaic array (10 degree tilt) on the roof of the University of Colorado Engineering Center with a mostly unobstructed view plane. Incident irradiance was measured on a clear, calm, sunny day with the pyranometer rotated such that its leads pointed North, South, East, and West, all within one minute. As shown in the table below, the pyranometer response was essentially independent of orientation, with measurements at each solar incidence angle falling within 1% of their average. This held true for the range of angles, including those for which the calibration report showed the largest AM/PM variance in responsivity, and indicates that the orientation of the pyranometer during data collection has minimal impact on the associated measurements of incident irradiance. Any contribution of pyranometer orientation to measurement uncertainty is thus assumed accounted for by the averaging of the AM/PM responsivities discussed in Appendix B.5.

Pyranometer measured irradiance with different lead orientation

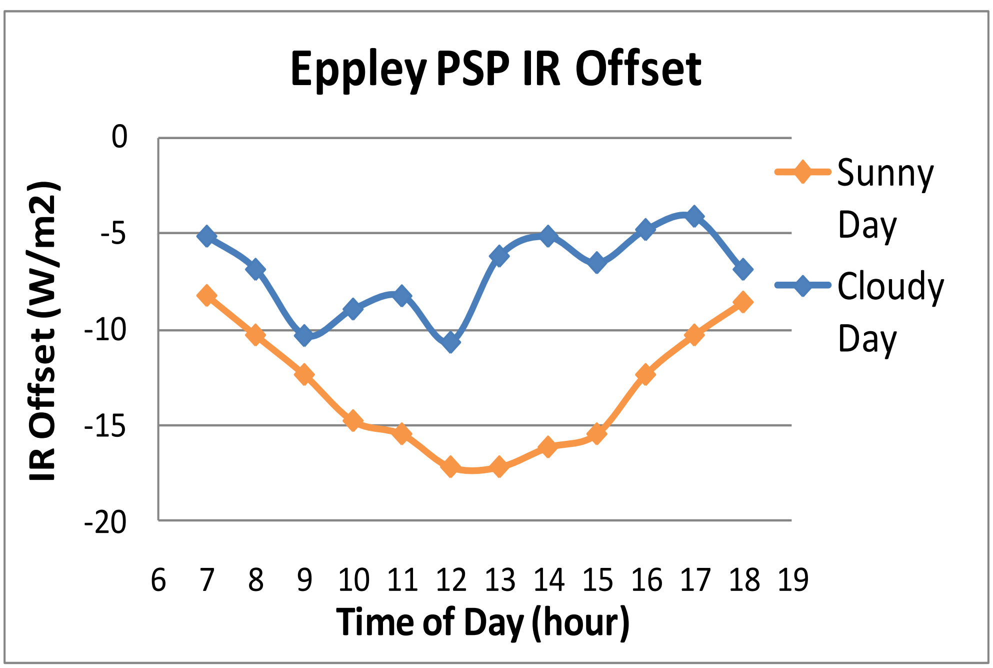
Orientation of Leads	Solar Incidence Angle	
	53 degrees	59 degrees
N	670 W/m2	565 W/m2
E	666 W/m2	563 W/m2
S	663 W/m2	564 W/m2
W	666 W/m2	558 W/m2

B.7 Eppley PSP IR Response

Irradiance measurements taken with a black thermopile-based pyranometer, such as the Eppley PSP, include a negative thermal offset because of the infrared radiation emitted by the instrument (Haeffelin, 2001). Equation B4 has been rearranged below, showing the calculation of irradiance *I* from a measured pyranometer output voltage *V* and calibrated responsivity *R*, with the thermal offset shown in red.

$$I = \frac{V}{R} - \frac{R_{net} * W_{net}}{R} \quad \textbf{B 7}$$

It was not possible to directly measure the net infrared radiation W_{net} during data collection, but R_{net} and R are both found in the calibration report (see Appendix B.5). Using values from the calibration report, as well as infrared radiation measurements taken at NREL on representative sunny and cloudy days (NREL SRRL/BMS database), typical offsets are presented in the figure below. These offsets are similar to those found in other sources (Haeffelin, 2001) (Vignola, 2008), and add some uncertainty to irradiance measurements taken using the Eppley PSP.



APPENDIX C

SOLAR RADIATION CALCULATIONS

C.1 Solar Angles

The following are variable and solar angle definitions used in this work. All are found in Chapters 1 and 2 of (Duffie & Beckman, 2006).

φ Latitude of the PV array location.

δ Declination: Angle between the sun and the plane of the equator at solar noon; North positive.

β Slope of the PV array relative to the horizontal

γ Surface azimuth angle: Angle between due South and the orientation of the array, projected on a horizontal plane; East is negative and West positive.

θ Angle of incidence between the sun's beam radiation and the normal to the PV surface

ω Hour angle: Angular displacement of sun East or West of the local meridian at 15°/hour relative to solar noon, morning negative, afternoon positive.

θ_z Zenith angle: Angle between vertical line and the sun

α_s Solar altitude angle: Angle between horizontal line and the sun

γ_s Solar azimuth angle: Angle between due South and the sun, projected on a horizontal plane; East is negative and West Positive.

n Julian day (one year cycle)

B A day-dependent value used in some solar calculations

All of the solar angle calculations are done using *solar time*, which is based on local clock time, but includes corrections for the specific location longitude and variations in the earth's rotation. Solar time also excludes daylight savings time, where applicable.

$$\text{Solar Time} = \text{Standard Time} + 4 * (L_{st} - L_{loc}) + E \qquad \textbf{C 1}$$

where L_{st} is the standard meridian for the local time zone, L_{loc} is the actual location's longitude, and E is the equation of time, in minutes, given by the following equation.

$$E = 229.2(0.00075 + 0.001868\cos(B) - 0.32077\sin(B) - 0.014615\cos(2B) - 0.04089\sin(2B) \qquad \textbf{C 2}$$

where

$$B = (n-1)\frac{360}{365} \qquad \textbf{C 3}$$

The solar angle calculations are then as follows:

$$\delta = 23.45 * \sin\left(360 * \frac{284+n}{365}\right) \qquad \textbf{C 4}$$

$$\cos(\theta) = \cos(\theta_z) * \cos(\beta) + \sin(\theta_z) * \sin(\beta) * \cos(\gamma_s - \gamma) \qquad \textbf{C 5}$$

$$\cos(\theta_z) = \cos(\varphi) * \cos(\delta) * \cos(\omega) + \sin(\varphi) * \sin(\delta) \qquad \textbf{C 6}$$

$$\gamma_s = \text{sign}(\omega)\left|\cos^{-1}\frac{\cos(\theta_z) * \sin(\varphi) - \sin(\delta)}{\sin(\theta_z) * \cos(\varphi)}\right| \qquad \textbf{C 7}$$

$$\alpha_s = 90 - \theta_z \qquad \textbf{C 8}$$

C.2 Plane-of-Array Irradiance -- HDKR Model

Chapters 6 and 7 of this work include annual hourly simulations of PV system energy production, with hourly weather conditions taken from available TMY3 (NSRDB, 2008) weather data. The weather data include global horizontal and direct normal irradiance values for each hour, and these are used to calculate the total irradiance in the plane of the array, I_T. This is most accurately done using an anisotropic sky model, and the commonly-used HDKR model (Reindl, Beckman, & Duffie, 1990) is chosen for this work. Variables used in this model are defined below; as in the previous appendix section all are found in (Duffie & Beckman, 2006).

G_{sc} Solar constant: Energy per unit time received by a section of the earth perpendicular to the sun's rays, outside the atmospere. In this work it is set to 1367 W/m^2.

I_o Extraterrestrial radiation on a horizontal surface over an hour, with the beginning and end of the hour denoted by hour angles ω_1 and ω_2, respectively.

k_T Hourly clearness index

I_T Total radiation on a tilted surface

I_H Total radiation on a horizontal surface

I_b Direct beam component of the total radiation on a horizontal surface

I_d Diffuse component of the total radiation on a horizontal surface

ρ_g Ground reflectance coefficient, taken to be 0.2 in this work

R_b Ratio of beam radiation on a tilted surface to that on a horizontal surface

A_i Anisotropy index

f Modulating factor for cloudiness

Calculation of the values of these variables is described in the following equations; some use variables defined in Appendix C.1.

$$\mathrm{I_O} = \frac{12 * 3600}{\pi} \mathrm{G_{sc}} \left(1 + 0.033\cos(\frac{360n}{365}\right) * \left[\cos(\varphi)\cos(\delta) * (\sin(\omega_2) - \sin(\omega_1)) + \frac{\pi(\omega_2 - \omega_1)}{180}\sin(\varphi)\sin(\delta)\right] \quad \textbf{C 9}$$

$$k_T = \frac{I_H}{I_O} \tag{C 10}$$

$$R_B = \frac{\cos(\theta)}{\cos(\theta_Z)} \tag{C 11}$$

$$I_d = I_H * \begin{cases} 1.0 - 0.09k_T & k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 \\ -16.638k_T^3 + 12.336k_T^4 & 0.22 < k_T \leq 0.8 \\ 0.165 & k_T > 0.8 \end{cases} \tag{C 12}$$

$$I_b = I_H - I_d \tag{C 13}$$

$$A_i = \frac{I_b}{I_O} \tag{C 14}$$

$$f = \sqrt{\frac{I_b}{I_H}} \tag{C 15}$$

$$I_T = (I_b + I_d A_i)R_B + I_d(1 - A_i)\left(\frac{1 + \cos(\beta)}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + I_H \rho_g \left(\frac{1 - \cos(\beta)}{2}\right) \tag{C 16}$$

In equation C16, the total calculated irradiance on the tilted plane, I_T, is composed of three parts, the beam contribution (shown in blue), the diffuse contribution (shown in green), and the ground-reflected contribution (shown in orange).

C.3 Absorbed Radiation of Photovoltaic Modules

Due to the nature of solar cells and their encapsulants, only a portion of the incident irradiance calculated in Appendix C.2 (Equation C16) is actually converted to energy. This effective absorbed radiation, described in (Duffie & Beckman, 2006), is a sum of a fraction of each of the beam, diffuse, and ground-reflected components of the total incident radiation. It is calculated as

$$S_{Tot} = M(\text{Beam} * (\tau\alpha)_b + \text{Diffuse} * (\tau\alpha)_d + \text{GroundReflected} * (\tau\alpha)_r) \tag{C 17}$$

with *Beam*, *Diffuse*, and *GroundReflected* calculated in Appendix C.2 and the other equation variables defined as follows:

M Air mass modifier from the Sandia array performance model

(King, Boyson, & Kratochvil, Photovoltaic Array Performance Model, 2003)

$(\tau\alpha)_b$ Transmittance-absorptance factor for beam radiation

$(\tau\alpha)_d$ Transmittance-absorptance factor for diffuse radiation

$(\tau\alpha)_r$ Transmittance-absorptance factor for ground-reflected radiation

The air mass modifier *M* depends on the air mass *AM* during the measurement, as well as empirical constants $a_{1\text{-}4}$ which are material-specific. However, it has been reported (De Soto, Klein, & Beckman, 2006) that a set of these constants for crystalline silicon cells provides adequate accuracy, especially at incident angles less than 70°, for most technologies. As indicated in (Duffie & Beckman, 2006), the air mass modifier is calculated as

$$M = \sum_{0}^{4} a_i \, (AM)^i \qquad \textbf{C 18}$$

where

$$AM = \frac{1}{\cos(\theta)} \qquad \textbf{C 19}$$

with solar radiation incidence angle θ defined and calculated in Appendix C.1. The constants $a_{0\text{-}4}$ are

0.935823 0.054289 -0.008677 0.000527 -0.000011

which come from (Fanney A. H., 2002).

The transmittance-absorptance factor $\tau\alpha$ for incident radiation may be calculated with good accuracy for most PV modules assuming a glass-air interface (Duffie & Beckman, 2006). The equation for this calculation is

$$\tau\alpha(\theta) = e^{-8/\cos(\theta_r)}\left[1 - \frac{1}{2}\left(\frac{\sin^2(\theta_r - \theta)}{\sin^2(\theta_r + \theta)} + \frac{\tan^2(\theta_r - \theta)}{\tan^2(\theta_r + \theta)}\right)\right] \qquad \textbf{C 20}$$

In this equation, θ is the irradiance incidence angle, which must be separately calculated for the beam, diffuse, and ground-reflected components of the total incident radiation. For the beam irradiance, *θ(beam)* is calculated as in Appendix C.1 to obtain $(\tau\alpha)_b$. The incident angles of the diffuse and ground-reflected radiation (both isotropic) are determined empirically (Brandemuehl, 1980) as a function of the module tilt β to find $(\tau\alpha)_d$ and $(\tau\alpha)_r$.

$$\theta\ (\text{diffuse}) = 59.7 - 0.1388\beta + 0.001497\beta^2 \qquad \textbf{C 21}$$

$$\theta\ (\text{gndref}) = 90 - 0.5788\beta + 0.002693\beta^2 \qquad \textbf{C 22}$$

Finally, the angle of refraction, θ_r in Equation C 20, is calculated as

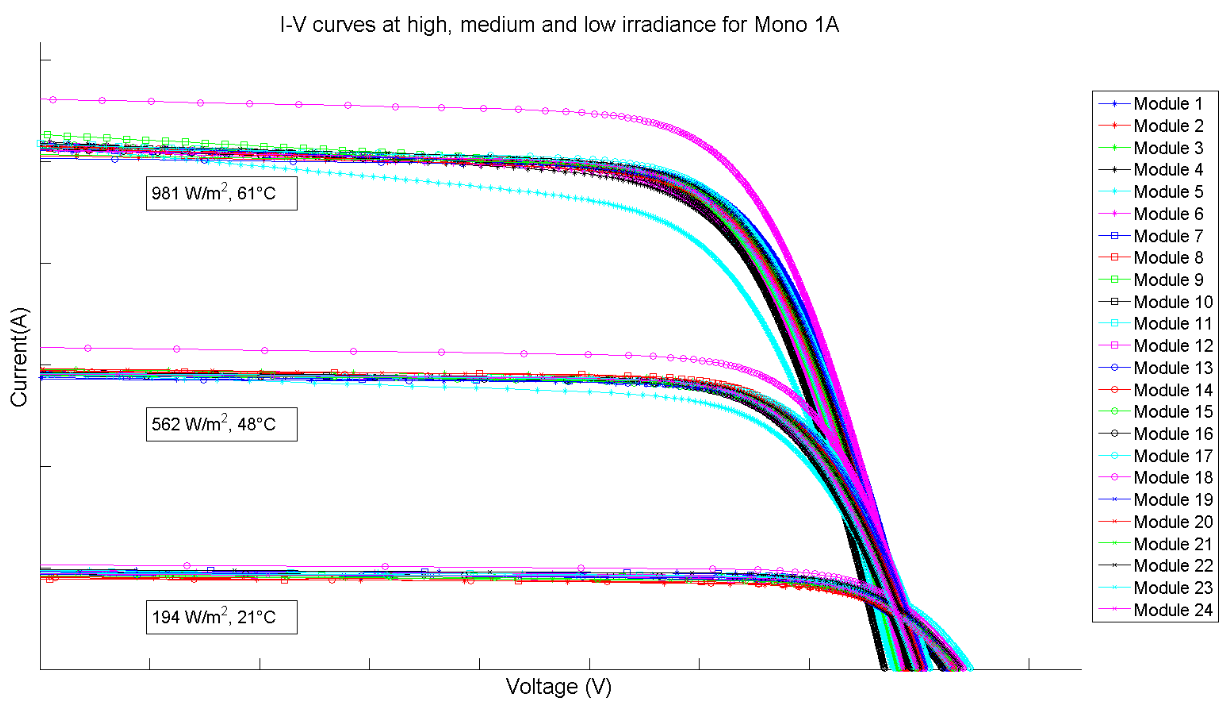
$$\theta_r = \sin^{-1}\left(\frac{\sin(\theta)}{n}\right) \qquad \textbf{C 23}$$

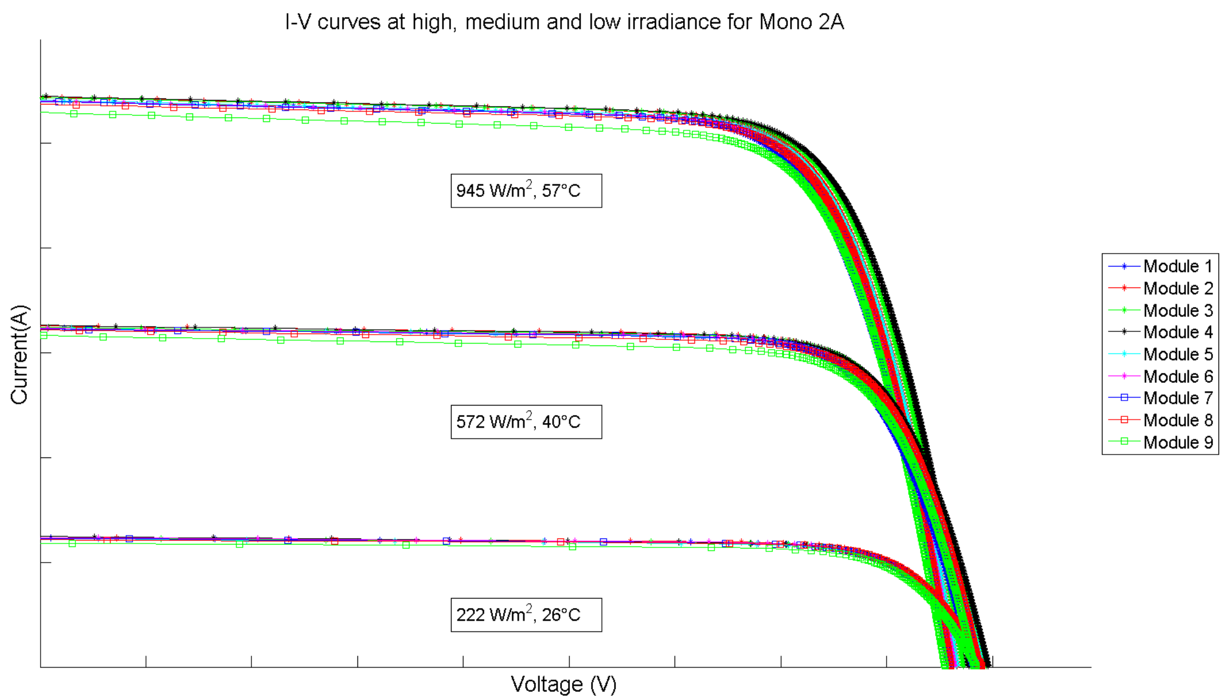
with n=1.526 for glass, which is commonly used as the front sheet cover for PV modules.

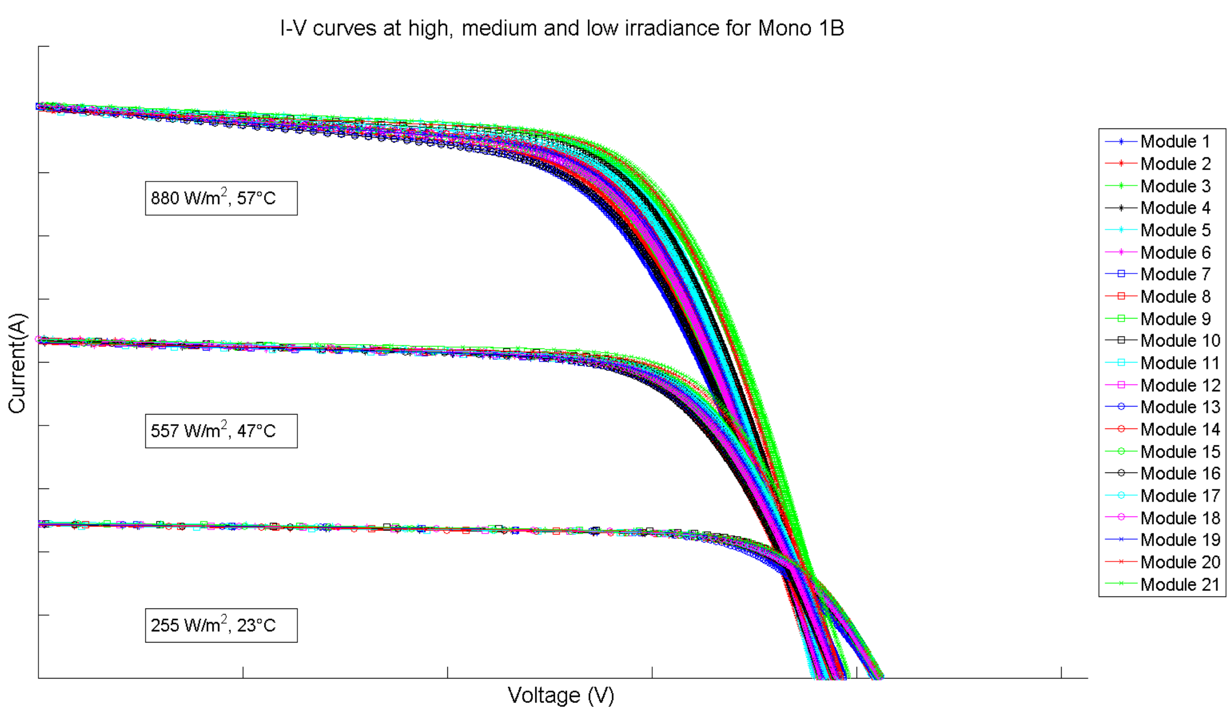
APPENDIX D

MODULE LEVEL I-V CURVES

This appendix includes figures of the module-level I-V curves collected for each array under high, low, and medium (where applicable) operating conditions. The array-level effective irradiance and cell temperatures (with calibrations and calculations found in Sections 3.4.5-3.4.7) are noted in each figure. For arrays with high or low irradiance data collection requiring multiple runs, the curve data for each module in the array are translated using the five parameter single diode model (Duffie & Beckman, 2006) to a common (average of the relevant runs) irradiance and cell temperature.




I-V curves at high, medium and low irradiance for Mono 2A
945 W/m2, 57°C
572 W/m2, 40°C
222 W/m2, 26°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9


I-V curves at high, medium and low irradiance for Mono 1B
880 W/m2, 57°C
557 W/m2, 47°C
255 W/m2, 23°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
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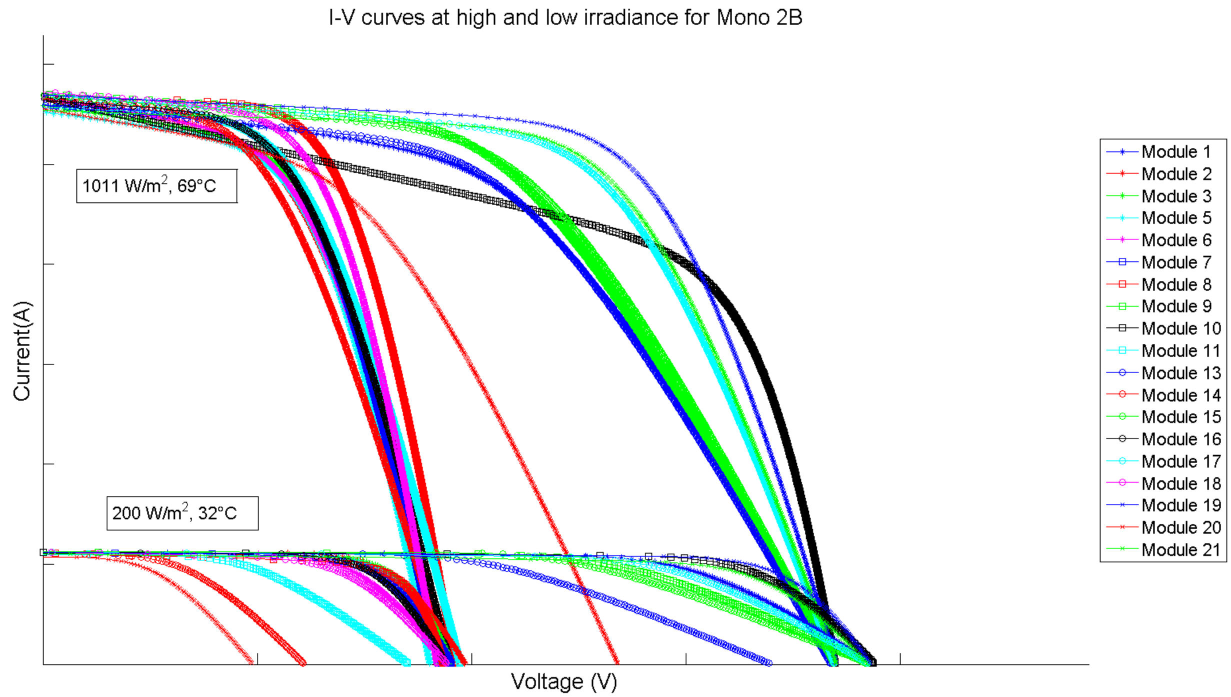
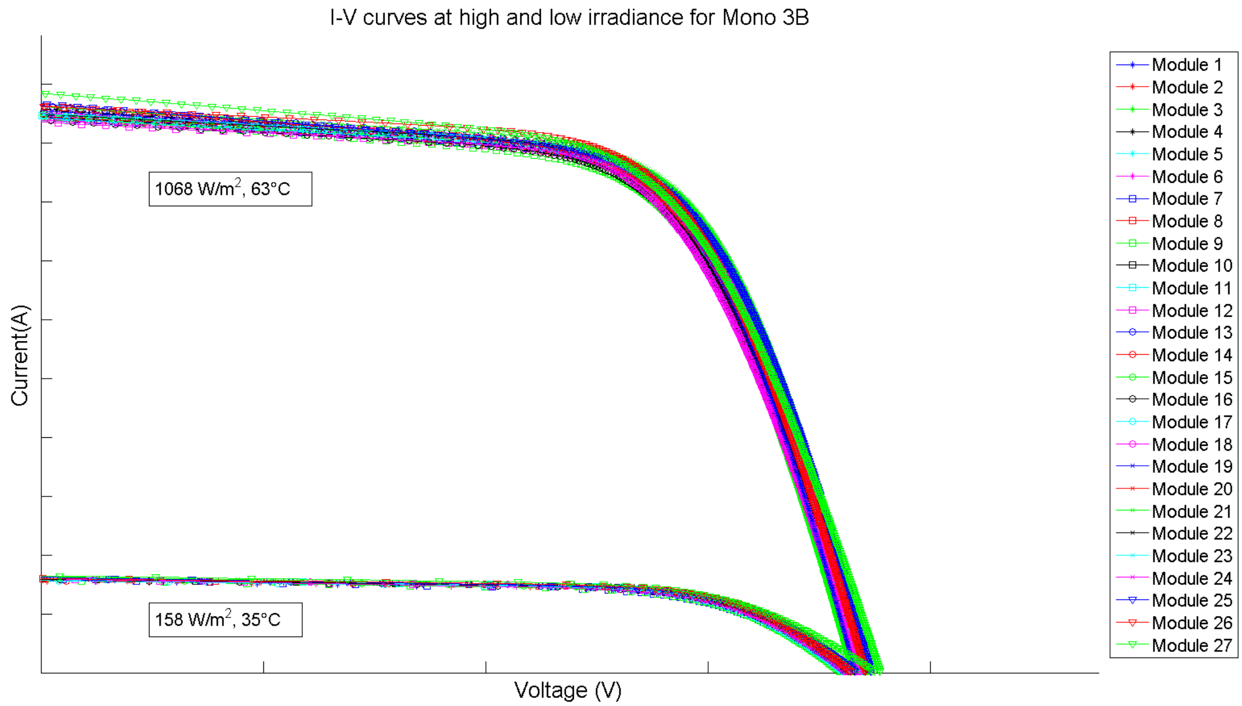
Module 21



I-V curves at high and low irradiance for Mono 2B
Current(A)
Voltage (V)
1011 W/m2, 69°C
200 W/m2, 32°C
Module 1
Module 2
Module 3
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20
Module 21


I-V curves at high and low irradiance for Mono 3B
Current(A)
Voltage (V)
1068 W/m2, 63°C
158 W/m2, 35°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
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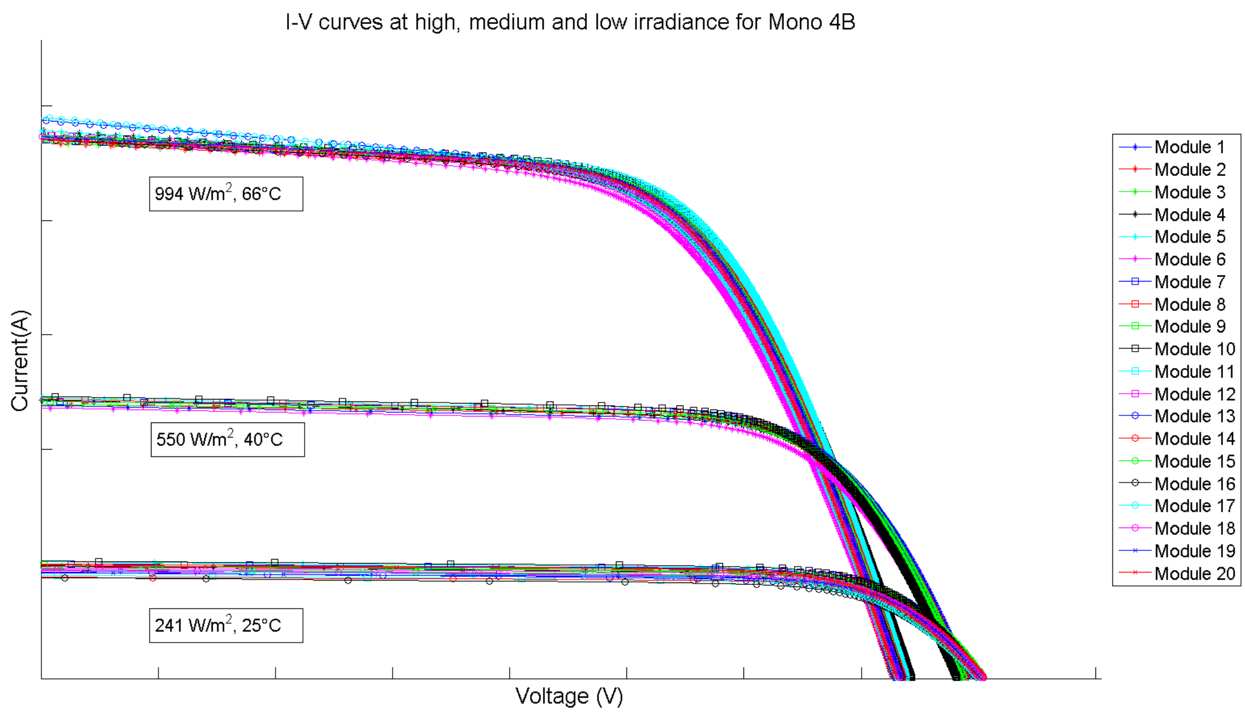
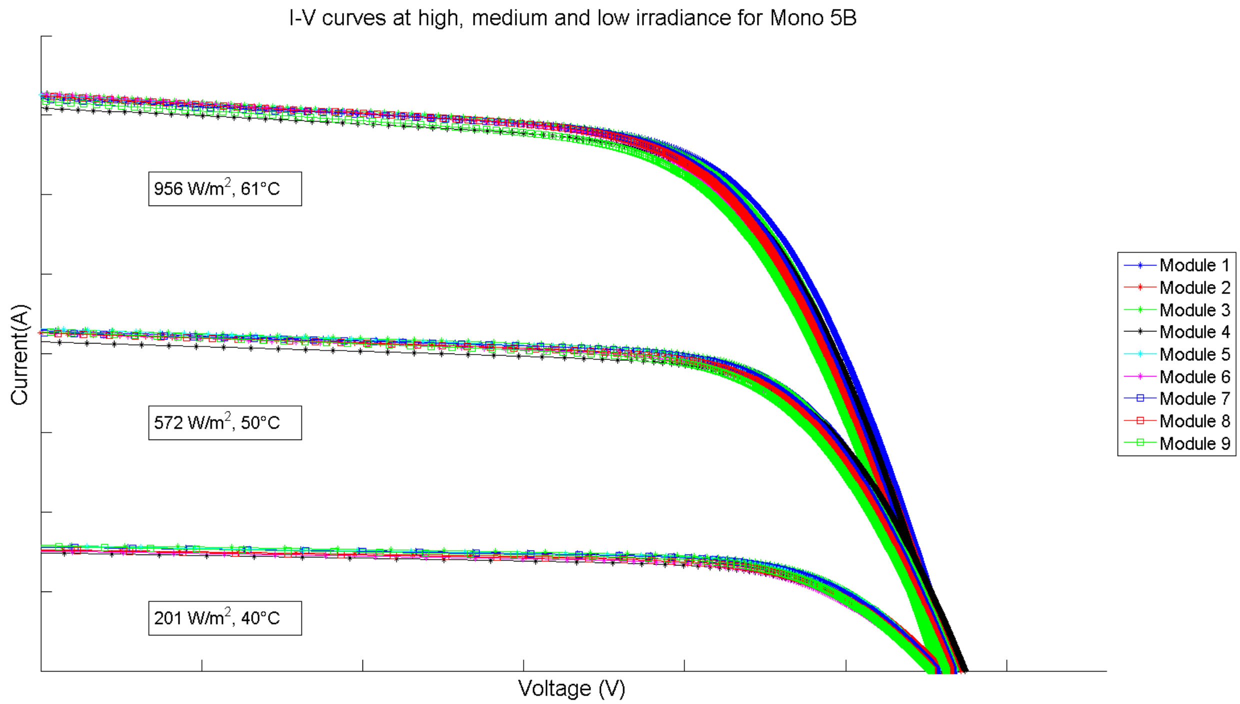
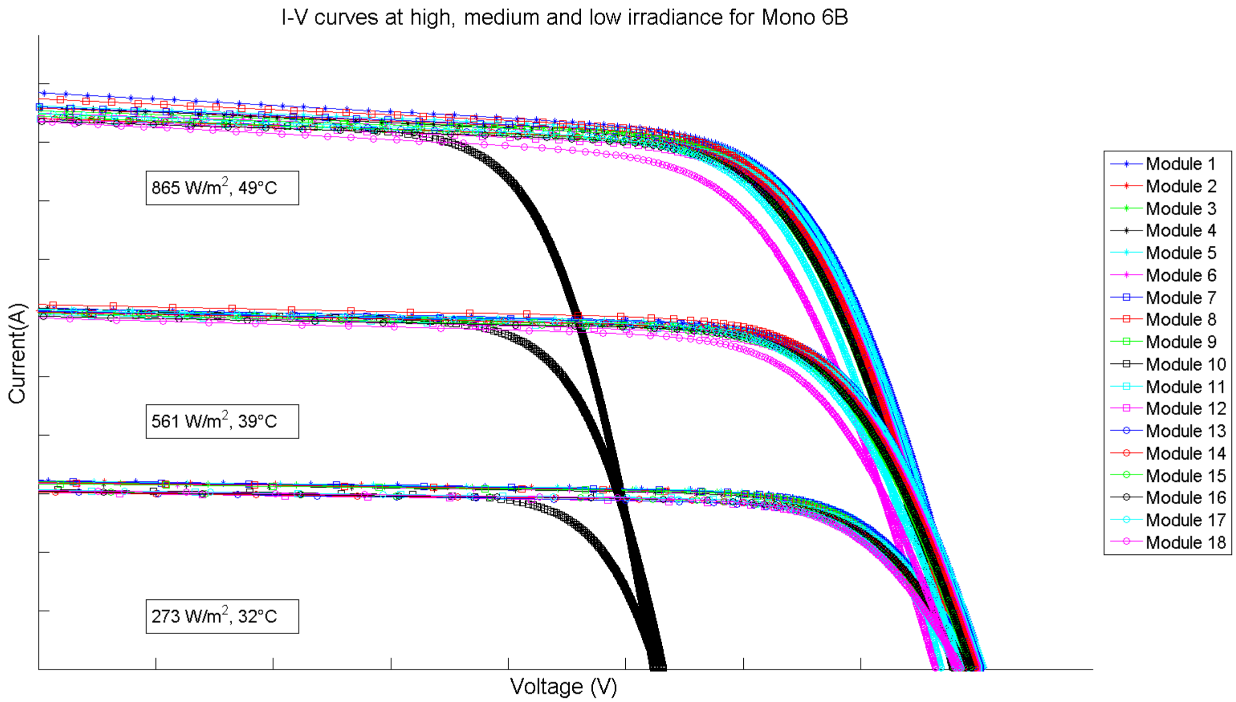
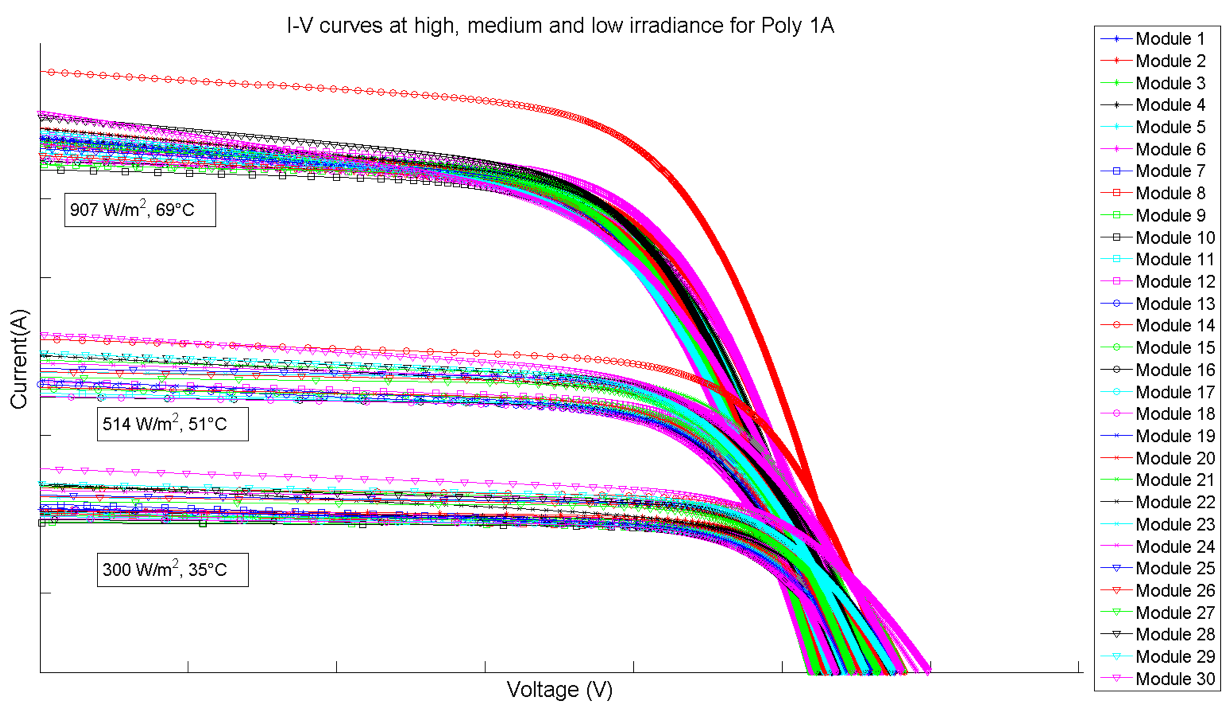
Module 22
Module 23
Module 24
Module 25
Module 26
Module 27


I-V curves at high, medium and low irradiance for Mono 4B
Current(A)
Voltage (V)
994 W/m2, 66°C
550 W/m2, 40°C
241 W/m2, 25°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20


I-V curves at high, medium and low irradiance for Mono 5B
Current(A)
Voltage (V)
956 W/m², 61°C
572 W/m², 50°C
201 W/m², 40°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9


I-V curves at high, medium and low irradiance for Mono 6B
Current(A)
Voltage (V)
865 W/m², 49°C
561 W/m², 39°C
273 W/m², 32°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18


I-V curves at high, medium and low irradiance for Poly 1A
Current(A)
Voltage (V)
907 W/m², 69°C
514 W/m², 51°C
300 W/m², 35°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
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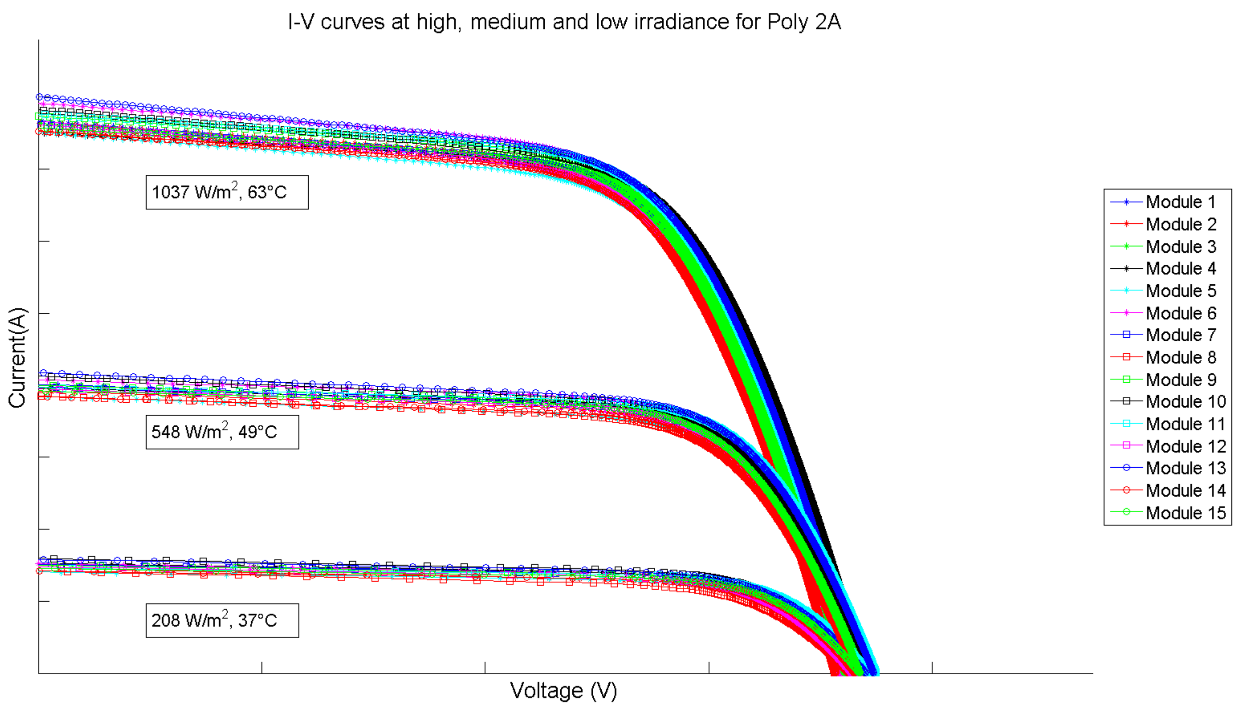
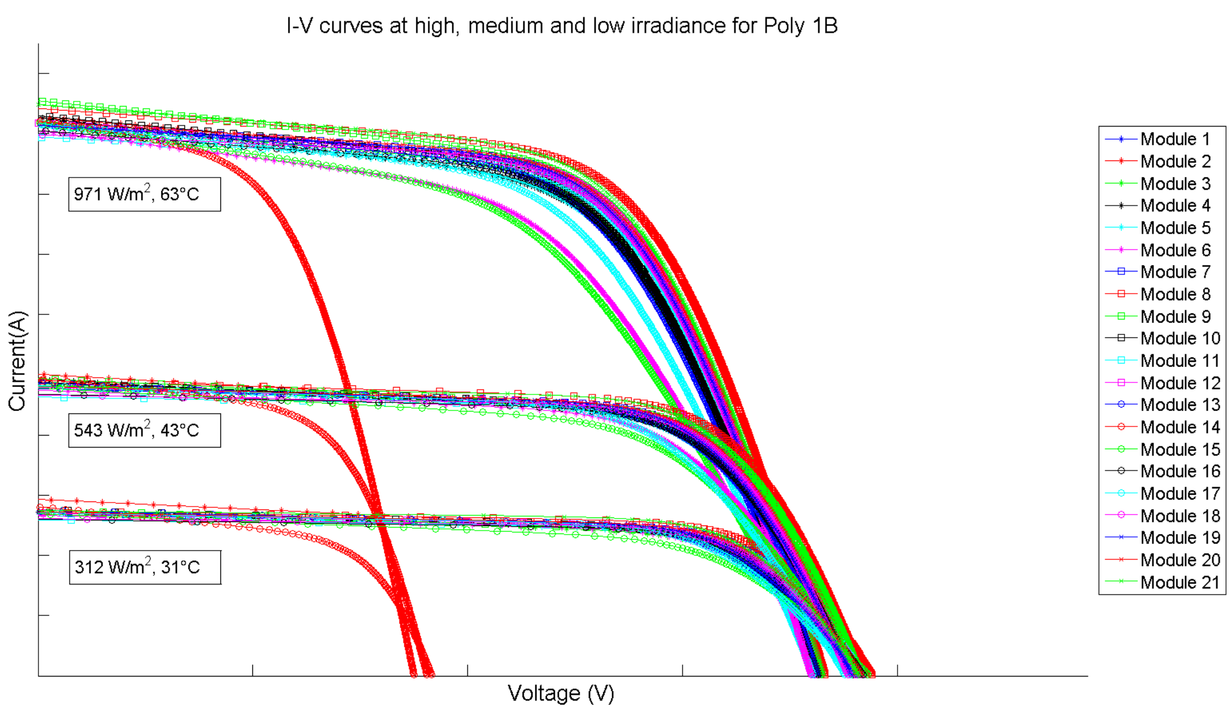
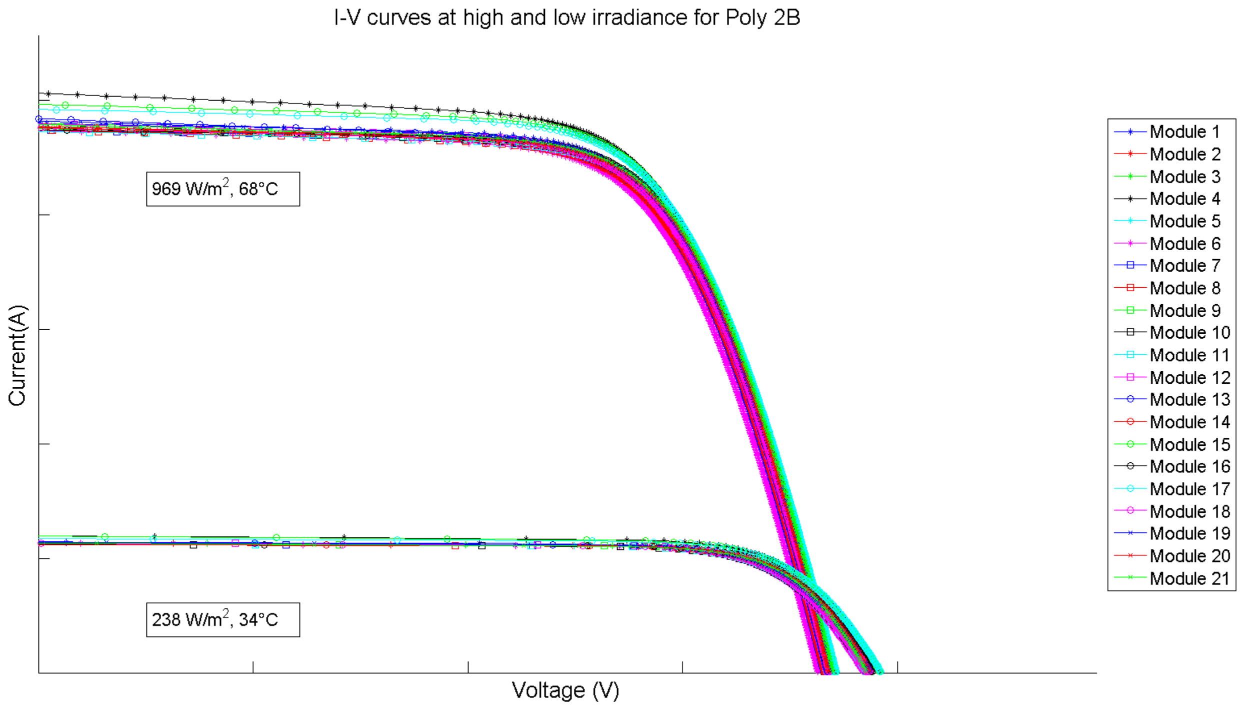
Module 28
Module 29
Module 30


I-V curves at high, medium and low irradiance for Poly 2A
Current(A)
Voltage (V)
1037 W/m2, 63°C
548 W/m2, 49°C
208 W/m2, 37°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15


I-V curves at high, medium and low irradiance for Poly 1B
Current(A)
Voltage (V)
971 W/m2, 63°C
543 W/m2, 43°C
312 W/m2, 31°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20
Module 21


I-V curves at high and low irradiance for Poly 2B
Current(A)
Voltage (V)
969 W/m2, 68°C
238 W/m2, 34°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
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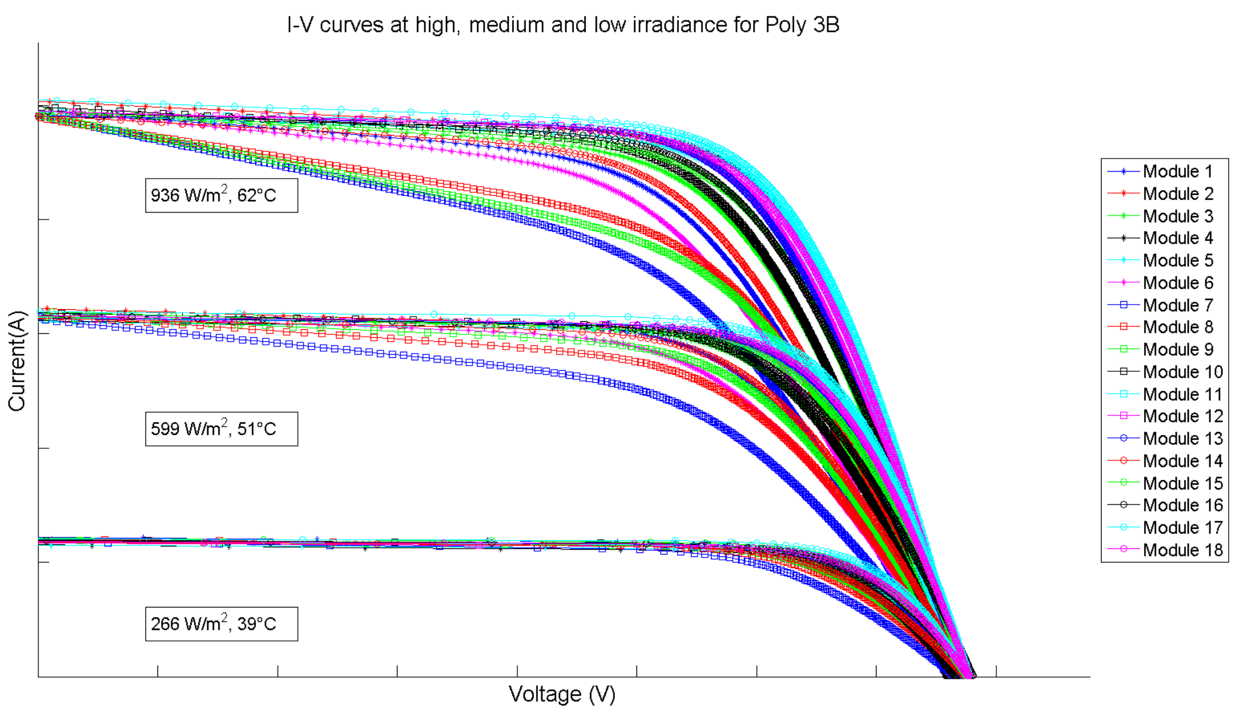
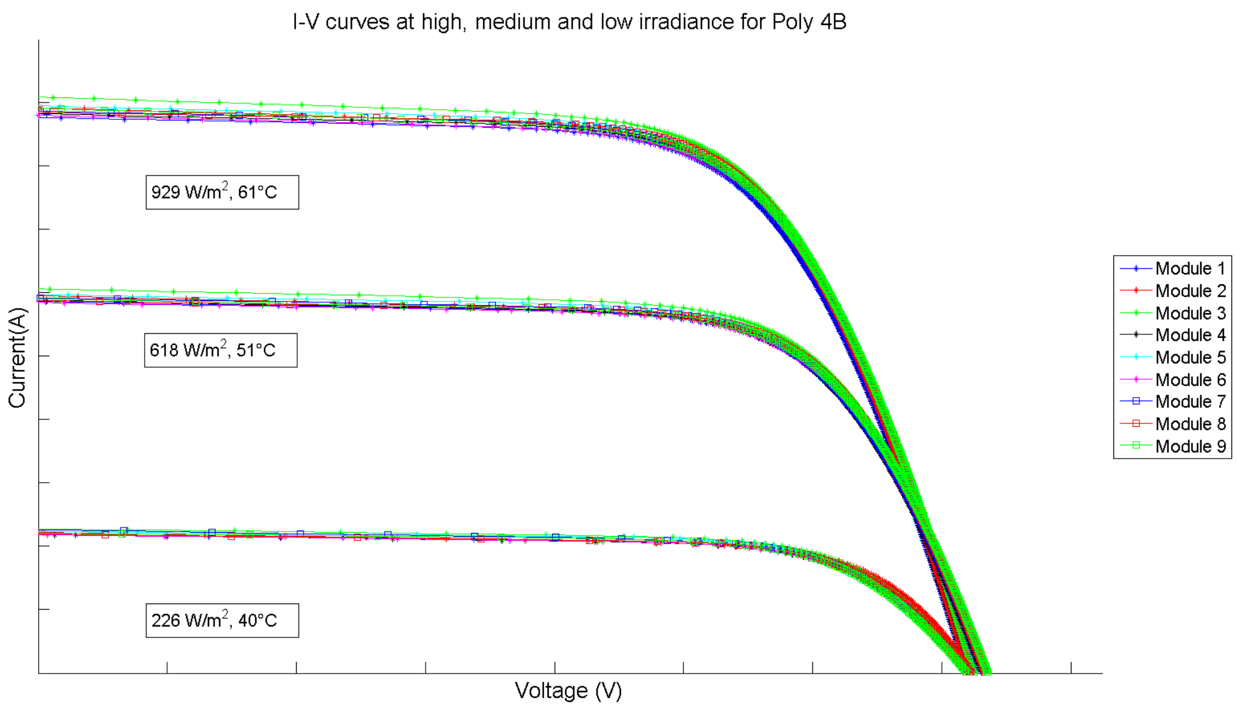
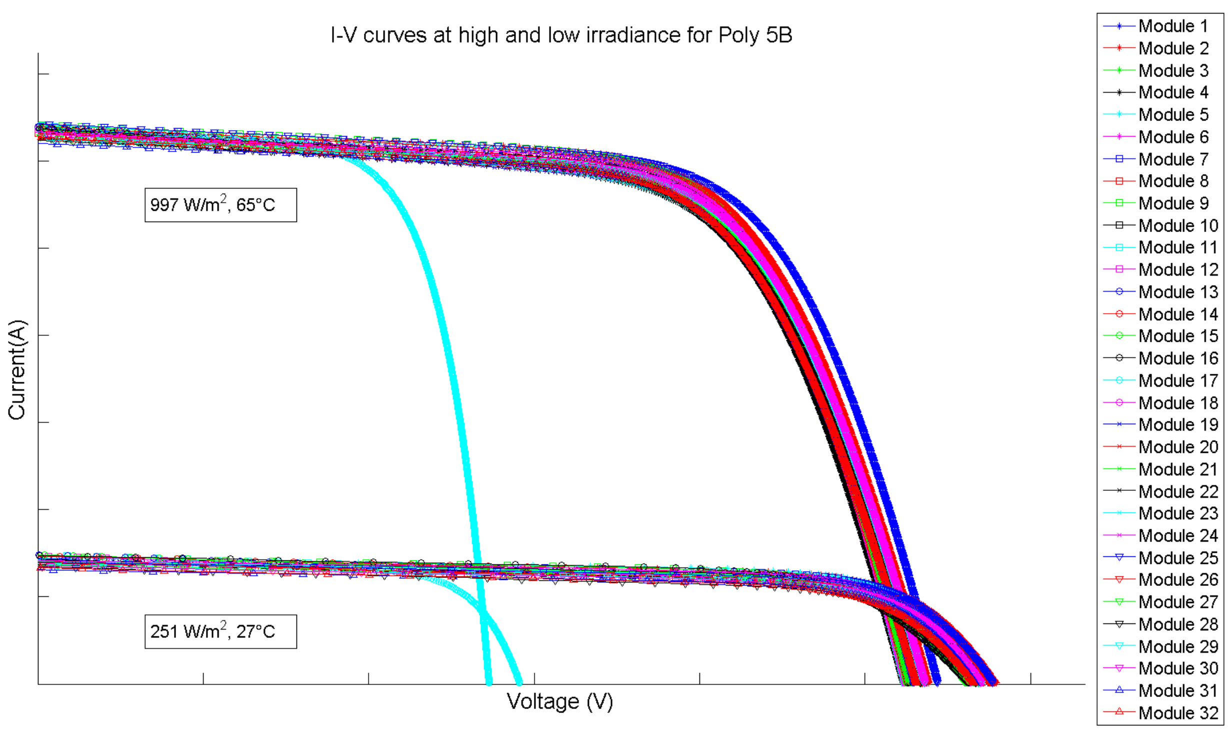
Module 19
Module 20
Module 21


I-V curves at high, medium and low irradiance for Poly 3B
Current(A)
Voltage (V)
936 W/m2, 62°C
599 W/m2, 51°C
266 W/m2, 39°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18


I-V curves at high, medium and low irradiance for Poly 4B
929 W/m2, 61°C
618 W/m2, 51°C
226 W/m2, 40°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9


I-V curves at high and low irradiance for Poly 5B
997 W/m2, 65°C
251 W/m2, 27°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20
Module 21
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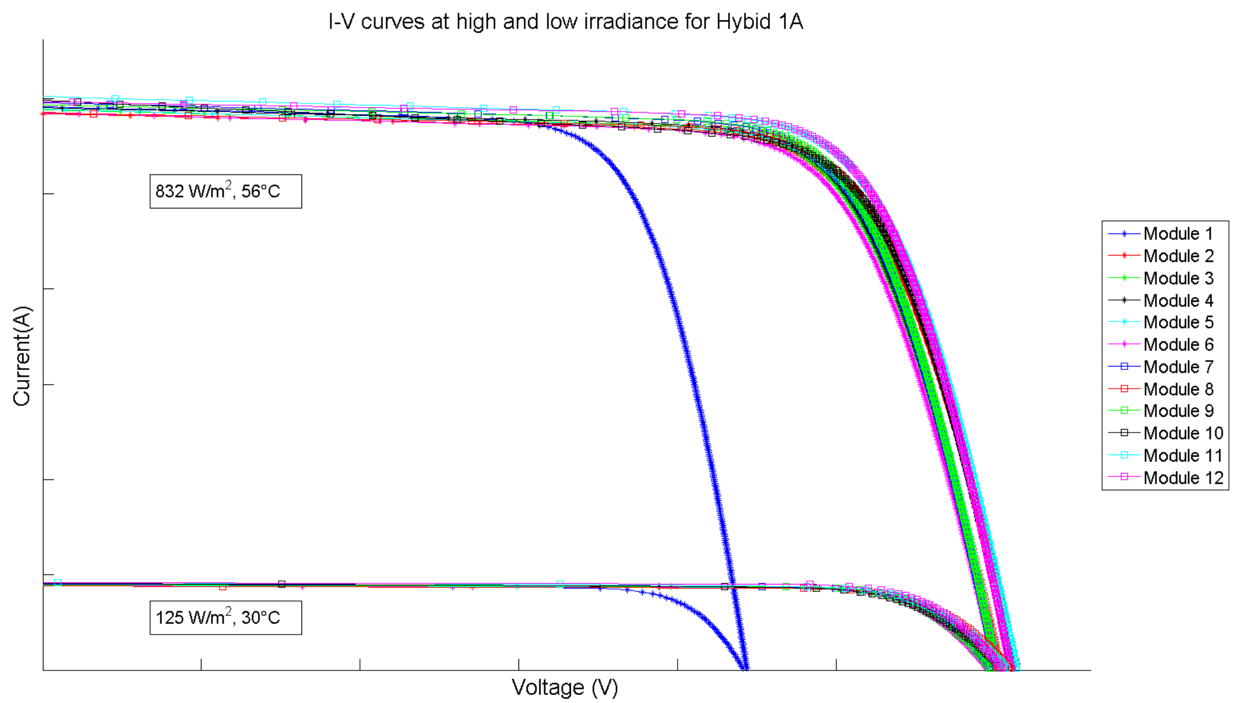
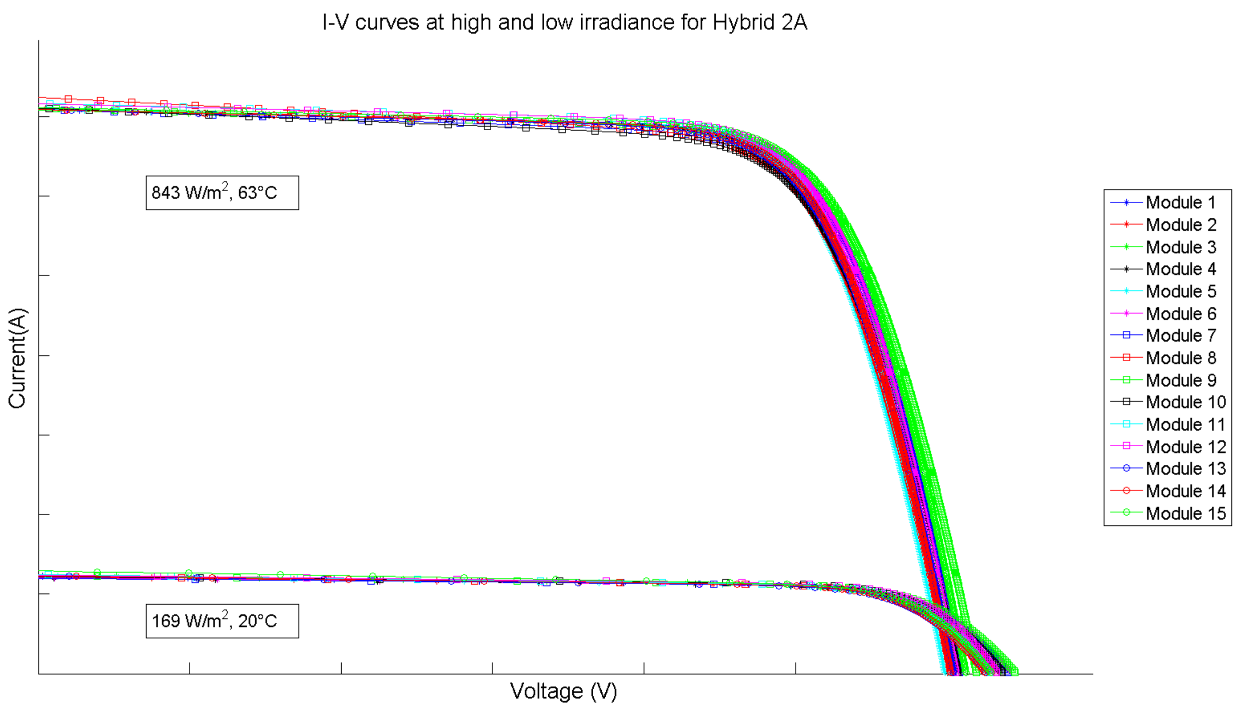
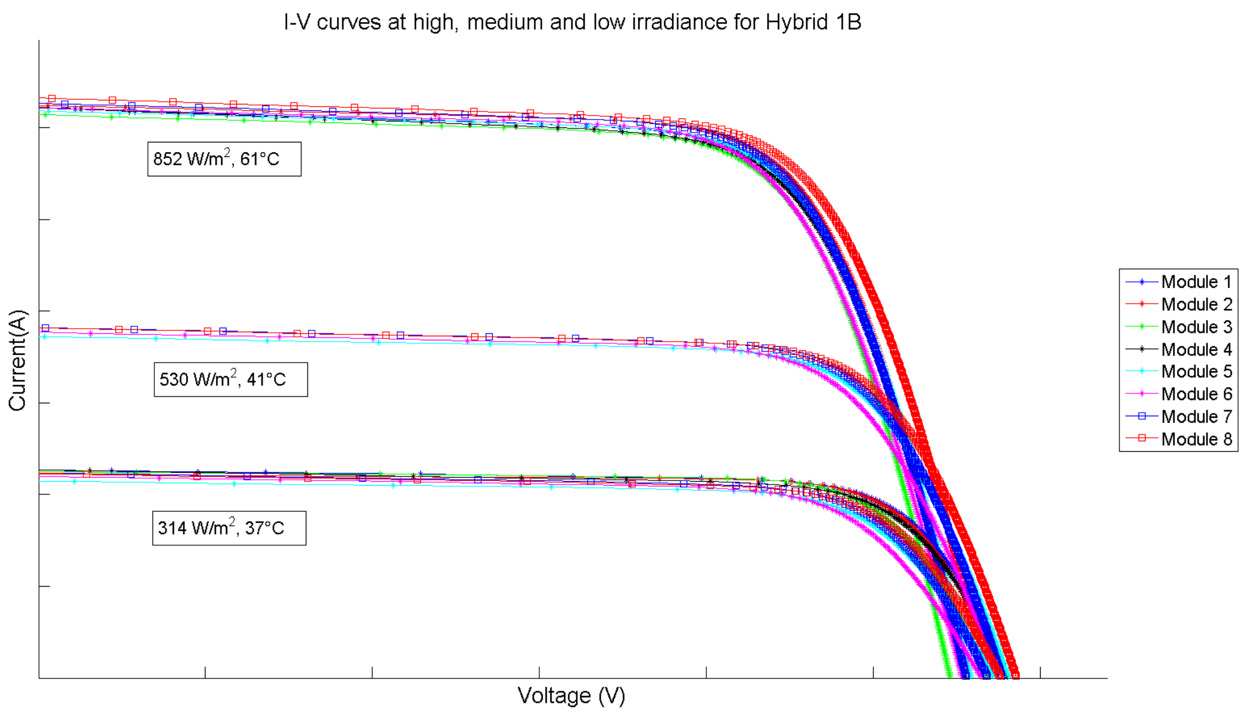
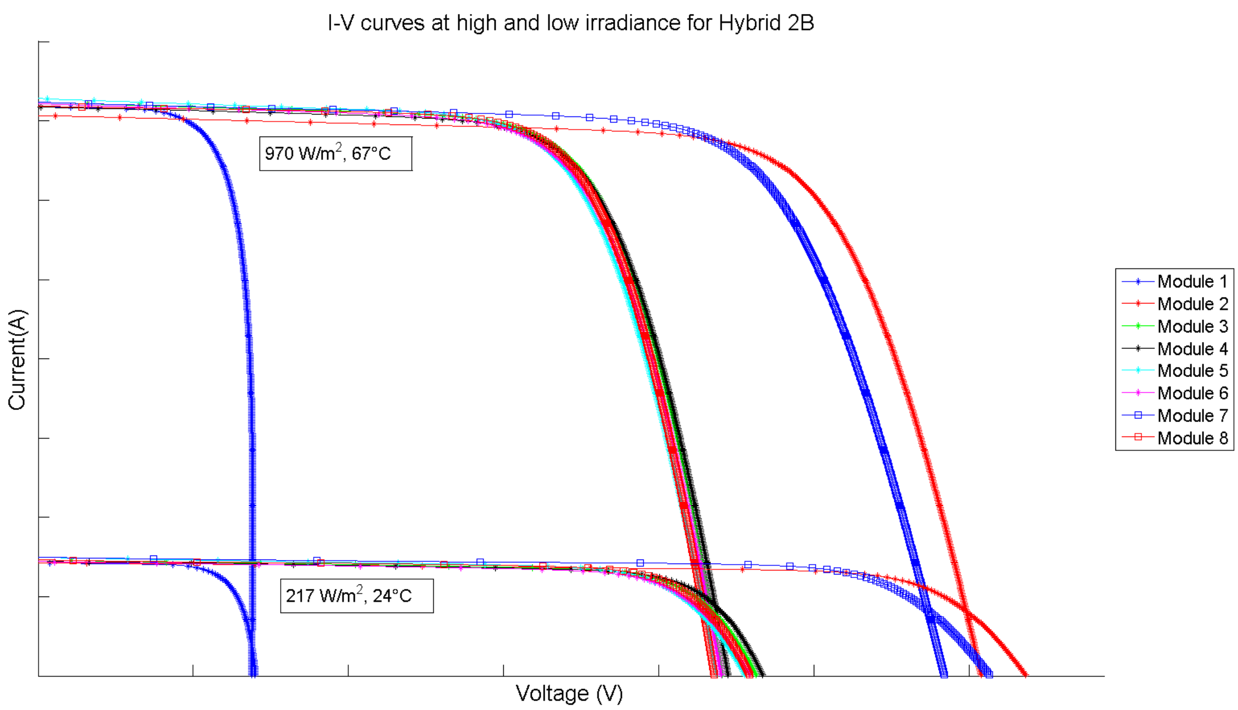
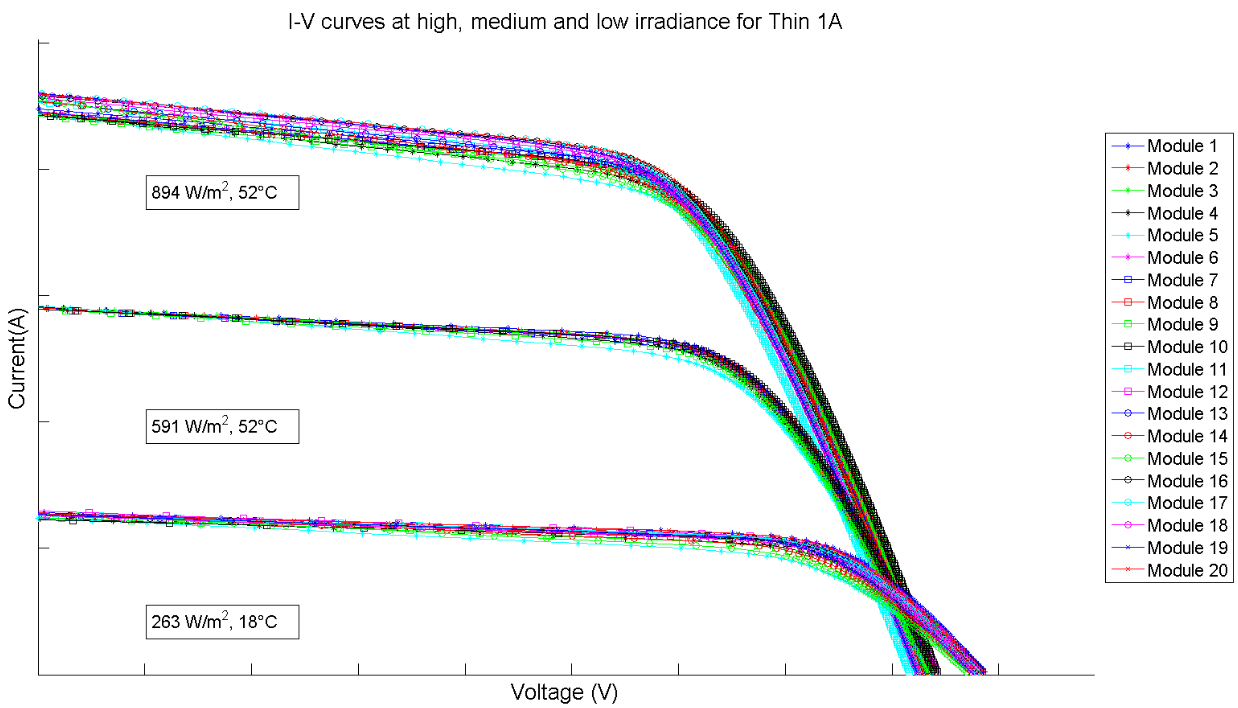
Module 23
Module 24
Module 25
Module 26
Module 27
Module 28
Module 29
Module 30
Module 31
Module 32

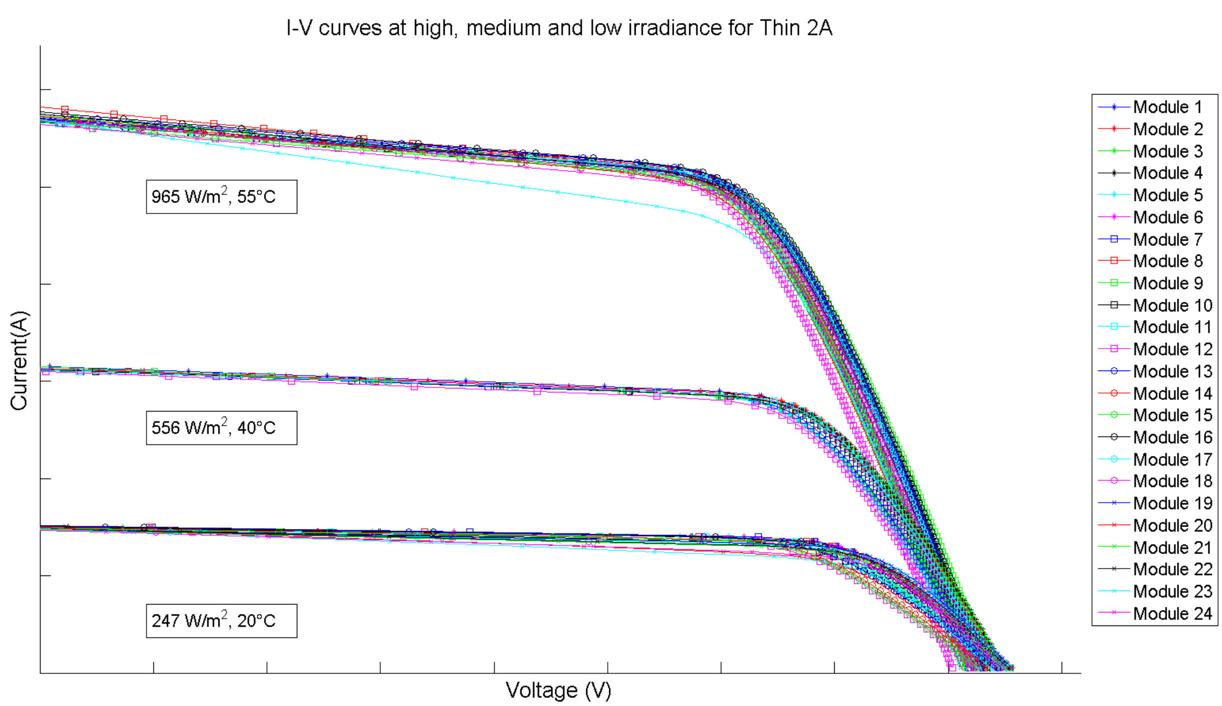

I-V curves at high and low irradiance for Hybid 1A
832 W/m2, 56°C
125 W/m2, 30°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12

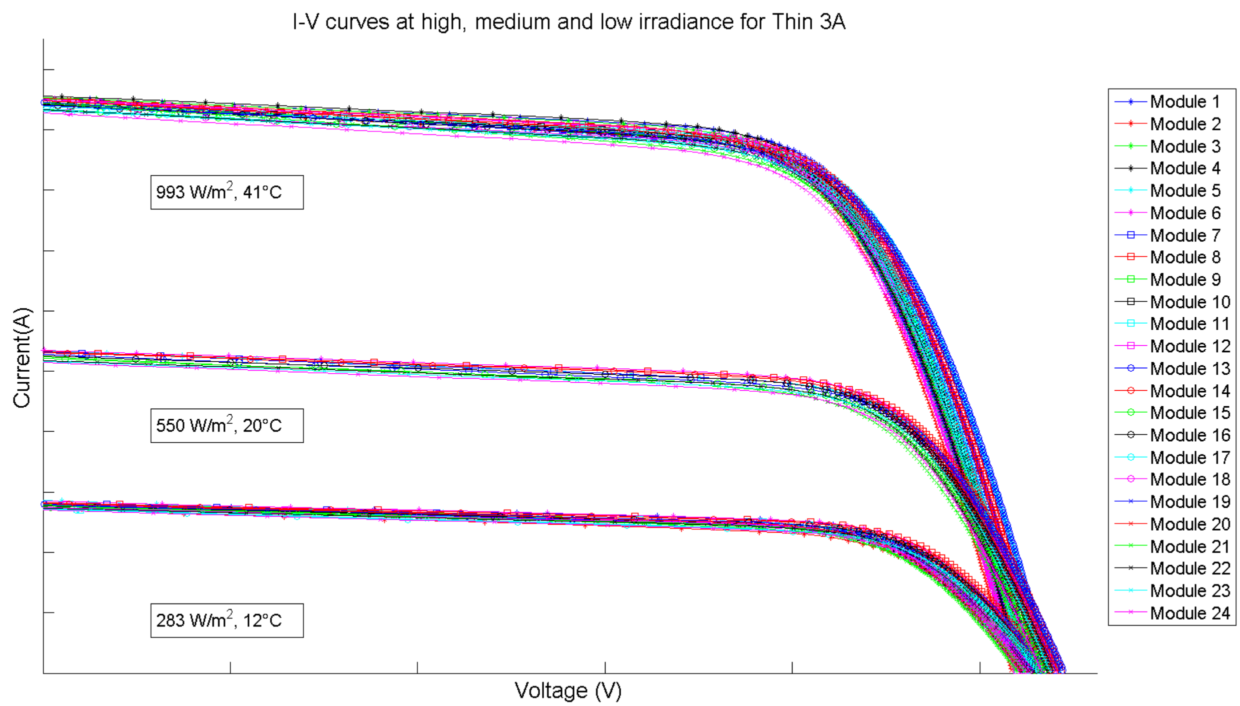

I-V curves at high and low irradiance for Hybrid 2A
843 W/m2, 63°C
169 W/m2, 20°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15

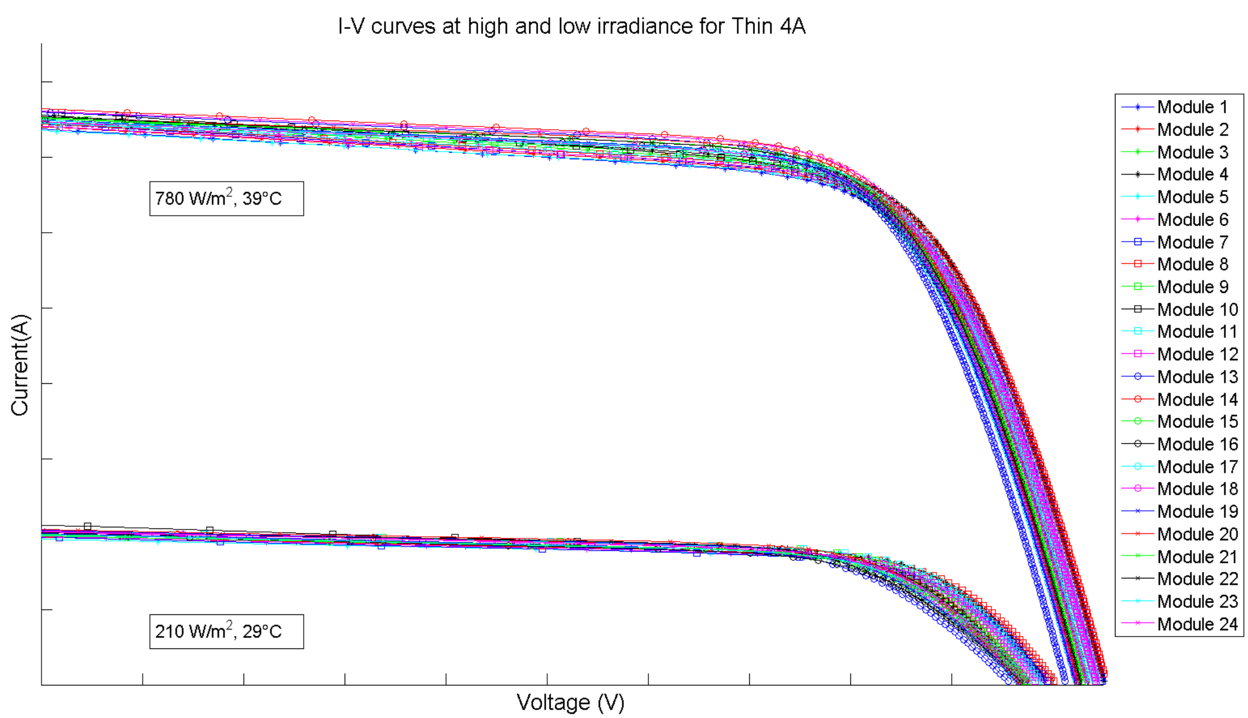

I-V curves at high, medium and low irradiance for Hybrid 1B
852 W/m2, 61°C
530 W/m2, 41°C
314 W/m2, 37°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8


I-V curves at high and low irradiance for Hybrid 2B
970 W/m2, 67°C
217 W/m2, 24°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8


I-V curves at high, medium and low irradiance for Thin 1A
Current(A)
Voltage (V)
894 W/m2, 52°C
591 W/m2, 52°C
263 W/m2, 18°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20


I-V curves at high, medium and low irradiance for Thin 2A
Current(A)
Voltage (V)
965 W/m2, 55°C
556 W/m2, 40°C
247 W/m2, 20°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20
Module 21
Module 22
Module 23
Module 24


I-V curves at high, medium and low irradiance for Thin 3A
Current(A)
Voltage (V)
993 W/m2, 41°C
550 W/m2, 20°C
283 W/m2, 12°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
Module 16
Module 17
Module 18
Module 19
Module 20
Module 21
Module 22
Module 23
Module 24


I-V curves at high and low irradiance for Thin 4A
Current(A)
Voltage (V)
780 W/m2, 39°C
210 W/m2, 29°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
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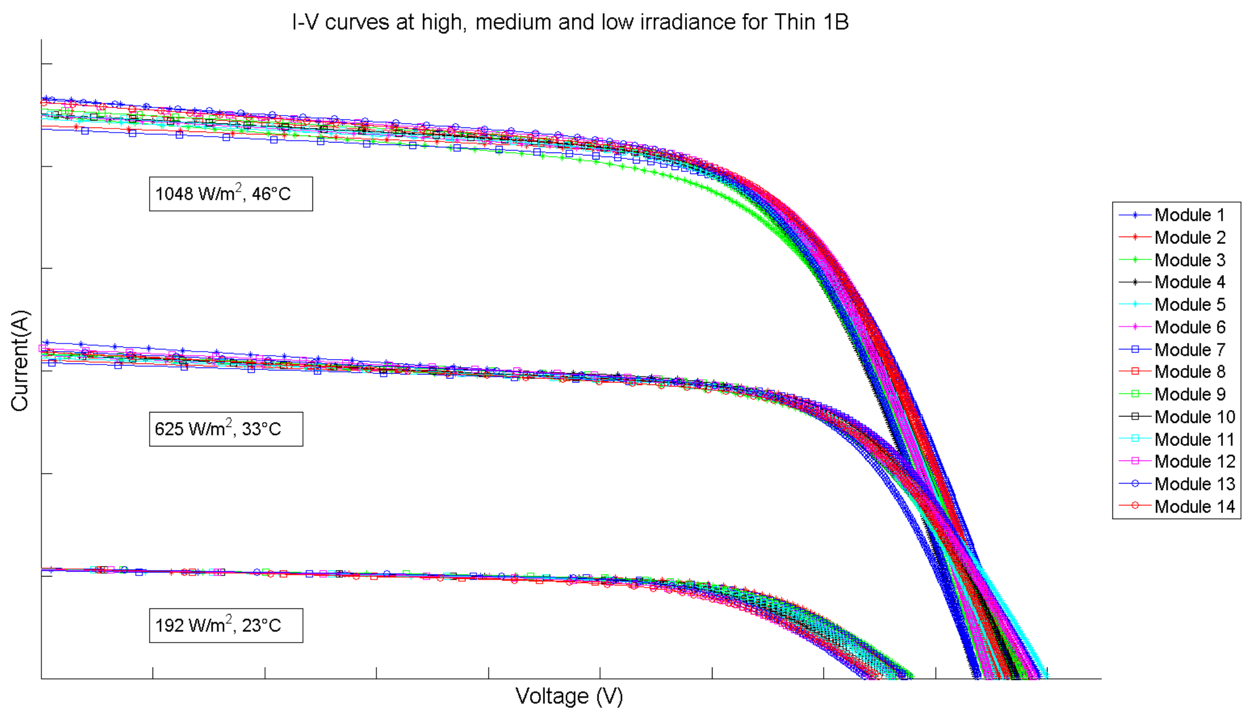
Module 23
Module 24


I-V curves at high, medium and low irradiance for Thin 1B
Current(A)
Voltage (V)
1048 W/m2, 46°C
625 W/m2, 33°C
192 W/m2, 23°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
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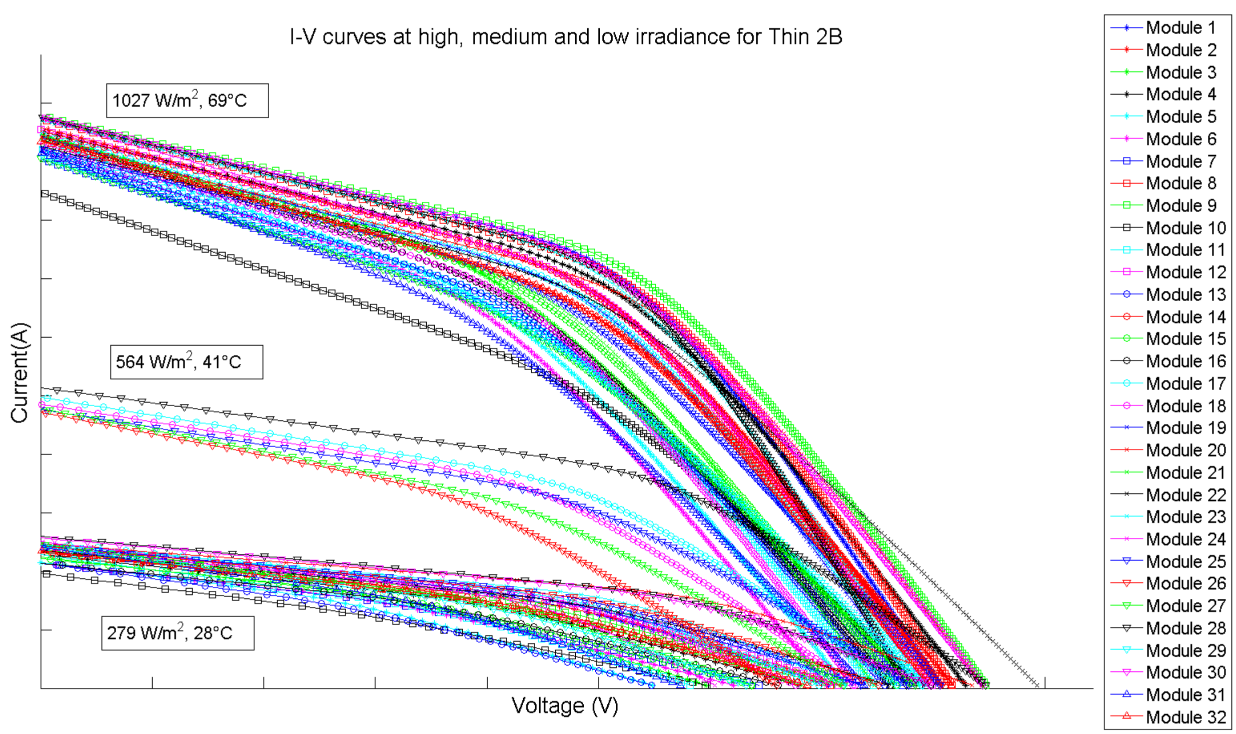
Module 10
Module 11
Module 12
Module 13
Module 14


I-V curves at high, medium and low irradiance for Thin 2B
Current(A)
Voltage (V)
1027 W/m2, 69°C
564 W/m2, 41°C
279 W/m2, 28°C
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
Module 15
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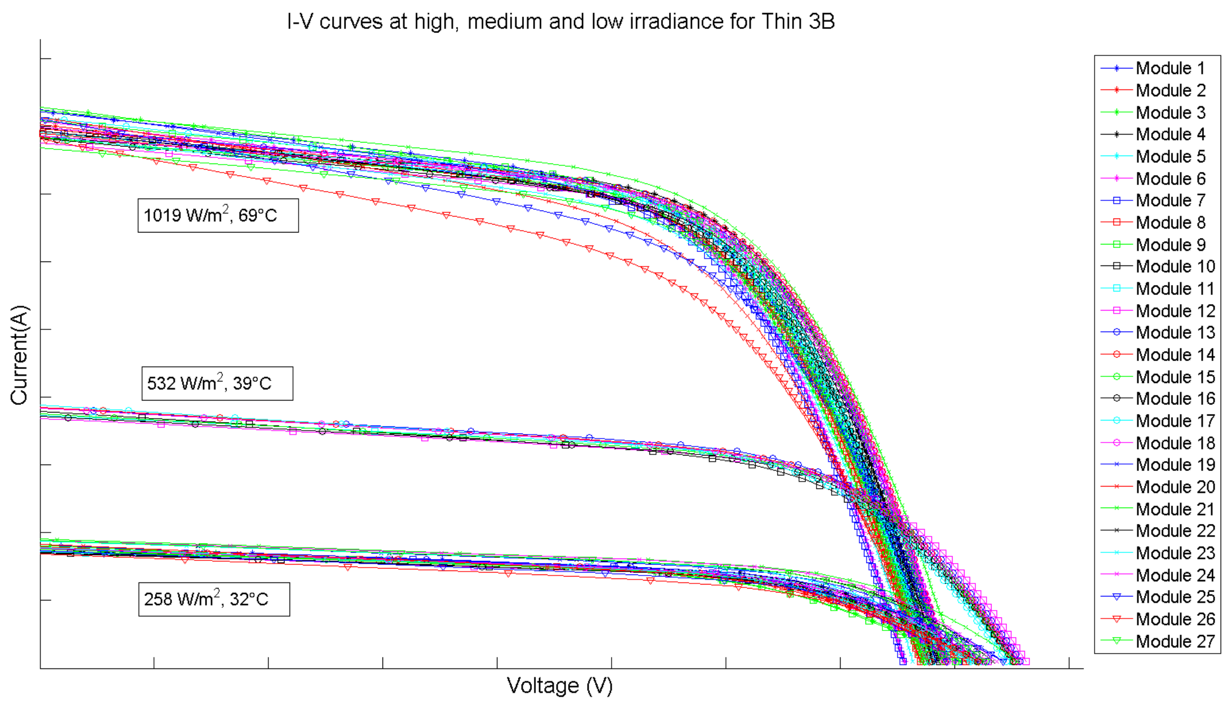
Module 32


I-V curves at high, medium and low irradiance for Thin 3B
1019 W/m2, 69°C
532 W/m2, 39°C
258 W/m2, 32°C
Current(A)
Voltage (V)
Module 1
Module 2
Module 3
Module 4
Module 5
Module 6
Module 7
Module 8
Module 9
Module 10
Module 11
Module 12
Module 13
Module 14
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Module 25
Module 26
Module 27

APPENDIX E

PV GENERATOR MODEL DATA

E.1. Five and Seven Parameter Single Diode Model Translation Accuracy

The following tables show the accuracy of the five parameter single diode model used in this work (Duffie & Beckman, 2006), when the high irradiance reference conditions are used to predict performance under medium (when data are available) and low irradiance. Each table includes the nominal and high and low uncertainty bounds of the module level short circuit current, open circuit voltage, and maximum power points for a single array. Also noted is the percent difference between the measured and modeled values for each parameter, and whether or not the measured and modeled values are in agreement, given the associated uncertainty of each.

Several of the arrays, including Mono 1A, Poly 1A, Hybrid 1B, Thin 2B, and Thin3A, have the same analysis performed using the seven parameter model (Boyd, Klein, Reindl, & Dougherty, 2011). Tables of values for the seven parameter model for each of these arrays are found directly following their individual five parameter results.

Mono 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.8759	0.9732	1.0705	0.9719	0.9739	0.9760	0.07%	yes	41.134	41.175	41.215	42.450	42.738	43.027	3.80%	no	30.771	30.957	31.144	32.664	32.966	33.269	6.49%	no
2	0.8198	0.9109	1.0020	0.9106	0.9125	0.9145	0.18%	yes	41.219	41.267	41.316	42.130	42.419	42.708	2.79%	no	27.861	28.041	28.222	30.521	30.808	31.095	9.87%	no
3	0.8232	0.9147	1.0062	0.9134	0.9153	0.9172	0.06%	yes	41.453	41.501	41.548	42.118	42.408	42.697	2.19%	no	29.044	29.227	29.410	29.826	30.099	30.372	2.98%	no
4	0.8418	0.9353	1.0288	0.9334	0.9353	0.9372	0.00%	yes	41.632	41.678	41.724	41.792	42.082	42.371	0.97%	no	29.739	29.923	30.108	29.247	29.507	29.767	-1.39%	yes
5	0.8761	0.9734	1.0707	0.9713	0.9733	0.9753	-0.01%	yes	41.602	41.645	41.687	41.711	42.000	42.289	0.85%	no	30.047	30.232	30.417	28.393	28.627	28.861	-5.31%	no
6	0.8719	0.9688	1.0657	0.9678	0.9699	0.9719	0.11%	yes	41.680	41.780	41.880	42.402	42.691	42.979	2.18%	no	30.522	30.709	30.897	31.671	31.959	32.248	4.07%	no
7	0.8802	0.9780	1.0758	0.9772	0.9793	0.9813	0.13%	yes	41.350	41.395	41.441	42.780	43.068	43.357	4.04%	no	30.609	30.795	30.981	32.731	33.029	33.327	7.26%	no
8	0.8014	0.8904	0.9794	0.8890	0.8908	0.8927	0.05%	yes	41.428	41.476	41.525	42.144	42.434	42.723	2.31%	no	28.543	28.725	28.908	29.401	29.673	29.946	3.30%	no
9	0.8537	0.9485	1.0434	0.9471	0.9490	0.9510	0.06%	yes	41.713	41.758	41.803	42.015	42.304	42.593	1.31%	no	29.950	30.137	30.324	29.988	30.255	30.521	0.39%	yes
10	0.8509	0.9454	1.0399	0.9443	0.9462	0.9482	0.09%	yes	41.612	41.657	41.703	41.885	42.174	42.463	1.24%	no	30.029	30.215	30.401	30.823	31.108	31.393	2.95%	no
11	0.8676	0.9640	1.0604	0.9627	0.9647	0.9667	0.07%	yes	41.565	41.618	41.670	41.903	42.192	42.481	1.38%	no	30.490	30.677	30.865	30.942	31.224	31.505	1.78%	no
12	0.8507	0.9452	1.0397	0.9448	0.9468	0.9488	0.17%	yes	41.570	41.628	41.685	42.006	42.295	42.584	1.60%	no	29.399	29.583	29.767	30.607	30.886	31.166	4.41%	no
13	0.8409	0.9343	1.0277	0.9335	0.9355	0.9375	0.13%	yes	41.340	41.389	41.438	42.649	42.938	43.227	3.74%	no	29.651	29.836	30.021	31.951	32.250	32.549	8.09%	no
14	0.8110	0.9011	0.9912	0.9001	0.9020	0.9039	0.10%	yes	41.445	41.501	41.557	42.096	42.386	42.675	2.13%	no	28.197	28.378	28.560	29.339	29.607	29.875	4.33%	no
15	0.8493	0.9437	1.0381	0.9429	0.9449	0.9469	0.13%	yes	41.528	41.583	41.637	41.929	42.218	42.507	1.53%	no	29.147	29.331	29.516	30.575	30.855	31.136	5.20%	no
16	0.8545	0.9494	1.0443	0.9480	0.9500	0.9520	0.06%	yes	41.073	41.102	41.131	41.302	41.590	41.879	1.19%	no	29.978	30.163	30.348	30.513	30.799	31.085	2.11%	no
17	0.8532	0.9480	1.0428	0.9469	0.9489	0.9509	0.10%	yes	42.288	42.351	42.413	42.666	42.955	43.244	1.43%	no	30.887	31.079	31.270	32.154	32.453	32.753	4.42%	no
18	0.9247	1.0274	1.1301	1.0267	1.0287	1.0307	0.12%	yes	41.980	42.023	42.067	42.556	42.845	43.134	1.96%	no	32.941	33.136	33.331	34.612	34.930	35.249	5.41%	no
19	0.8681	0.9646	1.0611	0.9633	0.9653	0.9673	0.07%	yes	41.474	41.526	41.577	42.544	42.833	43.122	3.15%	no	29.543	29.729	29.915	31.362	31.641	31.921	6.43%	no
20	0.8174	0.9082	0.9990	0.9069	0.9088	0.9107	0.07%	yes	41.607	41.662	41.716	42.348	42.638	42.927	2.34%	no	28.748	28.930	29.111	29.473	29.739	30.004	2.80%	no
21	0.8257	0.9174	1.0091	0.9168	0.9187	0.9207	0.14%	yes	41.541	41.592	41.643	42.093	42.382	42.671	1.90%	no	29.013	29.196	29.380	30.822	31.113	31.403	6.56%	no
22	0.8798	0.9776	1.0754	0.9763	0.9784	0.9804	0.08%	yes	41.921	41.969	42.016	42.338	42.627	42.915	1.57%	no	31.433	31.623	31.813	32.330	32.626	32.923	3.17%	no
23	0.9361	0.9416	0.9471	0.9397	0.9417	0.9436	0.01%	yes	41.416	41.472	41.528	41.995	42.284	42.573	1.96%	no	30.325	30.511	30.698	30.801	31.086	31.371	1.88%	no
24	0.9336	0.9391	0.9446	0.9380	0.9400	0.9420	0.10%	yes	41.541	41.593	41.645	42.099	42.388	42.676	1.91%	no	29.908	30.093	30.279	31.206	31.498	31.790	4.67%	no

Mono 1A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.5832	2.8702	3.1572	2.8629	2.8691	2.8753	-0.04%	yes	39.804	39.837	39.870	40.115	40.408	40.702	1.43%	no	85.137	85.566	85.996	86.015	86.901	87.788	1.56%	no
2	2.5998	2.8887	3.1776	2.8801	2.8864	2.8927	-0.08%	yes	39.891	39.926	39.961	39.920	40.213	40.506	0.72%	yes	86.029	86.461	86.894	85.879	86.779	87.680	0.37%	yes
3	2.6585	2.9539	3.2493	2.9448	2.9511	2.9573	-0.10%	yes	39.891	39.926	39.961	39.944	40.237	40.530	0.78%	yes	86.309	86.742	87.175	85.894	86.772	87.651	0.03%	yes
4	2.6278	2.9198	3.2118	2.9060	2.9121	2.9182	-0.26%	yes	39.823	39.860	39.896	39.545	39.838	40.131	-0.05%	yes	84.387	84.812	85.237	81.400	82.218	83.036	-3.06%	no
5	2.6141	2.9045	3.1950	2.8902	2.8963	2.9024	-0.28%	yes	39.749	39.877	40.006	39.381	39.674	39.968	-0.51%	yes	79.799	80.207	80.616	75.842	76.563	77.283	-4.54%	no
6	2.6066	2.8962	3.1858	2.8842	2.8904	2.8966	-0.20%	yes	40.015	40.125	40.235	40.089	40.383	40.676	0.64%	yes	84.350	84.775	85.200	83.497	84.355	85.215	-0.49%	yes
7	2.5987	2.8874	3.1761	2.8790	2.8852	2.8914	-0.08%	yes	40.166	40.202	40.238	40.453	40.746	41.039	1.35%	no	85.572	86.003	86.435	86.040	86.916	87.793	1.06%	yes
8	2.6457	2.9397	3.2337	2.9299	2.9362	2.9425	-0.12%	yes	39.983	40.018	40.053	40.010	40.303	40.596	0.71%	yes	87.362	87.800	88.237	86.487	87.379	88.273	-0.48%	yes
9	2.6305	2.9228	3.2151	2.9095	2.9156	2.9216	-0.25%	yes	39.821	39.857	39.893	39.747	40.040	40.333	0.46%	yes	85.346	85.776	86.206	82.563	83.388	84.213	-2.78%	no
10	2.6241	2.9157	3.2073	2.9068	2.9130	2.9192	-0.09%	yes	39.747	39.784	39.820	39.620	39.913	40.206	0.33%	yes	85.187	85.615	86.044	84.464	85.340	86.217	-0.32%	yes
11	2.6061	2.8957	3.1853	2.8837	2.8898	2.8959	-0.20%	yes	39.690	39.799	39.908	39.588	39.881	40.174	0.21%	yes	84.497	84.923	85.349	82.521	83.366	84.213	-1.83%	no
12	2.6346	2.9273	3.2200	2.9180	2.9242	2.9305	-0.10%	yes	39.802	39.906	40.009	39.750	40.043	40.336	0.34%	yes	84.810	85.237	85.664	84.063	84.927	85.792	-0.36%	yes
13	2.5722	2.8580	3.1438	2.8513	2.8576	2.8639	-0.01%	yes	40.085	40.118	40.151	40.387	40.680	40.973	1.40%	no	85.652	86.084	86.516	86.924	87.830	88.736	2.03%	no
14	2.6426	2.9362	3.2298	2.9269	2.9332	2.9394	-0.10%	yes	39.925	39.958	39.991	39.936	40.229	40.522	0.68%	yes	86.222	86.655	87.089	85.263	86.133	87.005	-0.60%	yes
15	2.6348	2.9275	3.2203	2.9204	2.9266	2.9328	-0.03%	yes	39.806	39.839	39.872	39.676	39.969	40.262	0.33%	yes	84.982	85.411	85.840	84.462	85.330	86.198	-0.09%	yes
16	2.6094	2.8993	3.1892	2.8911	2.8973	2.9035	-0.07%	yes	39.641	39.676	39.711	39.006	39.299	39.592	-0.95%	no	84.200	84.624	85.048	82.963	83.832	84.703	-0.94%	yes
17	2.6105	2.9005	3.1906	2.8934	2.8996	2.9059	-0.03%	yes	40.405	40.499	40.593	40.404	40.698	40.991	0.49%	yes	87.417	87.857	88.297	87.211	88.117	89.024	0.30%	yes
18	2.8489	3.1654	3.4819	3.1591	3.1653	3.1715	0.00%	yes	40.155	40.245	40.334	40.306	40.599	40.892	0.88%	yes	94.408	94.871	95.335	94.679	95.654	96.630	0.82%	yes
19	2.6319	2.9243	3.2167	2.9157	2.9218	2.9280	-0.08%	yes	40.286	40.319	40.352	40.262	40.555	40.848	0.59%	yes	86.081	86.516	86.951	85.008	85.858	86.709	-0.76%	yes
20	2.6643	2.9603	3.2563	2.9498	2.9561	2.9624	-0.14%	yes	40.145	40.178	40.211	40.196	40.489	40.782	0.77%	yes	86.884	87.320	87.756	85.827	86.690	87.555	-0.72%	yes
21	2.8833	2.8974	2.9115	2.8914	2.8977	2.9040	0.01%	yes	39.798	39.831	39.864	39.877	40.170	40.463	0.85%	no	86.031	86.464	86.897	86.709	87.617	88.527	1.33%	yes
22	2.9061	2.9203	2.9345	2.9112	2.9174	2.9237	-0.10%	yes	40.031	40.064	40.097	40.025	40.318	40.611	0.63%	yes	86.481	86.915	87.350	85.942	86.824	87.708	-0.10%	yes
23	2.8980	2.9121	2.9262	2.9020	2.9082	2.9144	-0.13%	yes	39.732	39.823	39.914	39.737	40.030	40.323	0.52%	yes	85.393	85.822	86.251	84.610	85.486	86.364	-0.39%	yes
24	2.8909	2.9050	2.9191	2.8969	2.9032	2.9094	-0.06%	yes	39.832	39.923	40.013	39.844	40.138	40.431	0.54%	yes	85.554	85.984	86.414	85.601	86.495	87.392	0.59%	yes

Mono 1A -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.8759	0.9732	1.0705	0.9718	0.9739	0.9760	0.07%	yes	41.134	41.175	41.215	40.028	40.333	40.638	-2.04%	no	30.771	30.957	31.144	30.523	30.836	31.150	-0.39%	yes
2	0.8198	0.9109	1.0020	0.9105	0.9125	0.9145	0.18%	yes	41.219	41.267	41.316	40.928	41.226	41.523	-0.10%	yes	27.861	28.041	28.222	29.474	29.764	30.054	6.14%	no
3	0.8232	0.9147	1.0062	0.9133	0.9152	0.9172	0.06%	yes	41.453	41.501	41.548	40.726	41.025	41.324	-1.15%	no	29.044	29.227	29.410	28.698	28.976	29.255	-0.86%	yes
4	0.8418	0.9353	1.0288	0.9333	0.9352	0.9372	-0.01%	yes	41.632	41.678	41.724	40.538	40.836	41.133	-2.02%	no	29.739	29.923	30.108	28.279	28.545	28.811	-4.61%	no
5	0.8761	0.9734	1.0707	0.9713	0.9733	0.9753	-0.01%	yes	41.602	41.645	41.687	40.345	40.643	40.941	-2.41%	no	30.047	30.232	30.417	27.474	27.717	27.960	-8.32%	no
6	0.8719	0.9688	1.0657	0.9677	0.9698	0.9718	0.10%	yes	41.680	41.780	41.880	40.814	41.114	41.413	-1.59%	no	30.522	30.709	30.897	30.294	30.588	30.883	-0.40%	yes
7	0.8802	0.9780	1.0758	0.9772	0.9792	0.9813	0.13%	yes	41.350	41.395	41.441	40.132	40.439	40.746	-2.31%	no	30.609	30.795	30.981	30.432	30.743	31.054	-0.17%	yes
8	0.8014	0.8904	0.9794	0.8889	0.8908	0.8927	0.04%	yes	41.428	41.476	41.525	40.925	41.223	41.521	-0.61%	yes	28.543	28.725	28.908	28.407	28.683	28.960	-0.15%	yes
9	0.8537	0.9485	1.0434	0.9471	0.9490	0.9509	0.05%	yes	41.713	41.758	41.803	40.994	41.290	41.586	-1.12%	no	29.950	30.137	30.324	29.188	29.459	29.730	-2.25%	no
10	0.8509	0.9454	1.0399	0.9442	0.9462	0.9481	0.08%	yes	41.612	41.657	41.703	40.621	40.919	41.216	-1.77%	no	30.029	30.215	30.401	29.731	30.020	30.309	-0.65%	yes
11	0.8676	0.9640	1.0604	0.9626	0.9646	0.9666	0.06%	yes	41.565	41.618	41.670	40.802	41.099	41.395	-1.25%	no	30.490	30.677	30.865	30.001	30.287	30.572	-1.27%	yes
12	0.8507	0.9452	1.0397	0.9447	0.9467	0.9487	0.16%	yes	41.570	41.628	41.685	40.719	41.017	41.315	-1.47%	no	29.399	29.583	29.767	29.521	29.805	30.089	0.75%	yes
13	0.8409	0.9343	1.0277	0.9334	0.9354	0.9375	0.12%	yes	41.340	41.389	41.438	40.594	40.897	41.200	-1.19%	no	29.651	29.836	30.021	30.139	30.446	30.754	2.05%	no
14	0.8110	0.9011	0.9912	0.9000	0.9019	0.9038	0.09%	yes	41.445	41.501	41.557	40.979	41.276	41.573	-0.54%	yes	28.197	28.378	28.560	28.444	28.716	28.989	1.19%	yes
15	0.8493	0.9437	1.0381	0.9429	0.9448	0.9468	0.12%	yes	41.528	41.583	41.637	41.172	41.467	41.761	-0.28%	yes	29.147	29.331	29.516	29.923	30.205	30.487	2.98%	no
16	0.8545	0.9494	1.0443	0.9479	0.9499	0.9519	0.05%	yes	41.073	41.102	41.131	40.356	40.651	40.946	-1.10%	no	29.978	30.163	30.348	29.672	29.960	30.247	-0.68%	yes
17	0.8532	0.9480	1.0428	0.9469	0.9489	0.9509	0.09%	yes	42.288	42.351	42.413	41.854	42.148	42.442	-0.48%	yes	30.887	31.079	31.270	31.402	31.703	32.003	2.01%	no
18	0.9247	1.0274	1.1301	1.0266	1.0286	1.0306	0.12%	yes	41.980	42.023	42.067	41.071	41.370	41.669	-1.55%	no	32.941	33.136	33.331	33.181	33.504	33.829	1.11%	yes
19	0.8681	0.9646	1.0611	0.9632	0.9652	0.9673	0.07%	yes	41.474	41.526	41.577	41.343	41.640	41.937	0.27%	yes	29.543	29.729	29.915	30.381	30.667	30.952	3.15%	no
20	0.8174	0.9082	0.9990	0.9069	0.9088	0.9107	0.06%	yes	41.607	41.662	41.716	40.400	40.702	41.005	-2.30%	no	28.748	28.930	29.111	27.966	28.240	28.515	-2.38%	no
21	0.8257	0.9174	1.0091	0.9167	0.9187	0.9206	0.14%	yes	41.541	41.592	41.643	40.849	41.147	41.444	-1.07%	no	29.013	29.196	29.380	29.731	30.025	30.320	2.84%	no
22	0.8798	0.9776	1.0754	0.9763	0.9783	0.9804	0.07%	yes	41.921	41.969	42.016	40.881	41.179	41.478	-1.88%	no	31.433	31.623	31.813	31.042	31.344	31.647	-0.88%	yes
23	0.9361	0.9416	0.9471	0.9396	0.9416	0.9436	0.00%	yes	41.416	41.472	41.528	40.566	40.865	41.164	-1.46%	no	30.325	30.511	30.698	29.575	29.864	30.154	-2.12%	no
24	0.9336	0.9391	0.9446	0.9379	0.9399	0.9419	0.09%	yes	41.541	41.593	41.645	40.624	40.923	41.222	-1.61%	no	29.908	30.093	30.279	29.907	30.203	30.499	0.36%	yes

Mono 1A -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.5832	2.8702	3.1572	2.8628	2.8690	2.8752	-0.04%	yes	39.804	39.837	39.870	39.192	39.492	39.793	-0.87%	no	85.137	85.566	85.996	83.575	84.464	85.354	-1.29%	yes
2	2.5998	2.8887	3.1776	2.8799	2.8863	2.8926	-0.08%	yes	39.891	39.926	39.961	39.489	39.786	40.082	-0.35%	yes	86.029	86.461	86.894	84.611	85.492	86.375	-1.12%	yes
3	2.6585	2.9539	3.2493	2.9446	2.9509	2.9572	-0.10%	yes	39.891	39.926	39.961	39.450	39.747	40.044	-0.45%	yes	86.309	86.742	87.175	84.547	85.418	86.290	-1.53%	no
4	2.6278	2.9198	3.2118	2.9057	2.9119	2.9181	-0.27%	yes	39.823	39.860	39.896	39.080	39.377	39.674	-1.21%	no	84.387	84.812	85.237	80.235	81.050	81.866	-4.44%	no
5	2.6141	2.9045	3.1950	2.8904	2.8965	2.9025	-0.28%	yes	39.749	39.877	40.006	38.861	39.159	39.456	-1.80%	no	79.799	80.207	80.616	74.783	75.519	76.254	-5.85%	no
6	2.6066	2.8962	3.1858	2.8838	2.8901	2.8963	-0.21%	yes	40.015	40.125	40.235	39.491	39.789	40.087	-0.84%	yes	84.350	84.775	85.200	81.877	82.723	83.571	-2.42%	no
7	2.5987	2.8874	3.1761	2.8789	2.8851	2.8913	-0.08%	yes	40.166	40.202	40.238	39.444	39.746	40.047	-1.13%	no	85.572	86.003	86.435	83.428	84.311	85.195	-1.97%	no
8	2.6457	2.9397	3.2337	2.9297	2.9360	2.9424	-0.12%	yes	39.983	40.018	40.053	39.584	39.881	40.177	-0.34%	yes	87.362	87.800	88.237	85.273	86.153	87.035	-1.87%	no
9	2.6305	2.9228	3.2151	2.9093	2.9154	2.9215	-0.25%	yes	39.821	39.857	39.893	39.360	39.657	39.953	-0.50%	yes	85.346	85.776	86.206	81.601	82.426	83.251	-3.91%	no
10	2.6241	2.9157	3.2073	2.9065	2.9127	2.9190	-0.10%	yes	39.747	39.784	39.820	39.154	39.451	39.747	-0.84%	yes	85.187	85.615	86.044	83.150	84.011	84.873	-1.87%	no
11	2.6061	2.8957	3.1853	2.8834	2.8895	2.8957	-0.21%	yes	39.690	39.799	39.908	39.168	39.465	39.761	-0.84%	yes	84.497	84.923	85.349	81.384	82.219	83.055	-3.18%	no
12	2.6346	2.9273	3.2200	2.9177	2.9240	2.9303	-0.11%	yes	39.802	39.906	40.009	39.277	39.574	39.871	-0.83%	yes	84.810	85.237	85.664	82.759	83.611	84.463	-1.91%	no
13	2.5722	2.8580	3.1438	2.8512	2.8575	2.8638	-0.02%	yes	40.085	40.118	40.151	39.630	39.929	40.229	-0.47%	yes	85.652	86.084	86.516	84.837	85.736	86.636	-0.40%	yes
14	2.6426	2.9362	3.2298	2.9267	2.9330	2.9393	-0.11%	yes	39.925	39.958	39.991	39.539	39.836	40.132	-0.31%	yes	86.222	86.655	87.089	84.174	85.036	85.899	-1.87%	no
15	2.6348	2.9275	3.2203	2.9201	2.9264	2.9326	-0.04%	yes	39.806	39.839	39.872	39.398	39.694	39.989	-0.37%	yes	84.982	85.411	85.840	83.657	84.511	85.365	-1.05%	yes
16	2.6094	2.8993	3.1892	2.8908	2.8970	2.9033	-0.08%	yes	39.641	39.676	39.711	38.655	38.951	39.247	-1.83%	no	84.200	84.624	85.048	81.928	82.777	83.628	-2.18%	no
17	2.6105	2.9005	3.1906	2.8932	2.8995	2.9058	-0.03%	yes	40.405	40.499	40.593	40.103	40.399	40.694	-0.25%	yes	87.417	87.857	88.297	86.289	87.176	88.065	-0.78%	yes
18	2.8489	3.1654	3.4819	3.1589	3.1651	3.1714	-0.01%	yes	40.155	40.245	40.334	39.757	40.054	40.351	-0.47%	yes	94.408	94.871	95.335	92.973	93.932	94.891	-0.99%	yes
19	2.6319	2.9243	3.2167	2.9156	2.9218	2.9280	-0.09%	yes	40.286	40.319	40.352	39.812	40.109	40.406	-0.52%	yes	86.081	86.516	86.951	83.875	84.729	85.583	-2.07%	no
20	2.6643	2.9603	3.2563	2.9496	2.9559	2.9623	-0.15%	yes	40.145	40.178	40.211	39.512	39.811	40.109	-0.91%	no	86.884	87.320	87.756	84.069	84.937	85.806	-2.73%	no
21	2.8833	2.8974	2.9115	2.8912	2.8975	2.9039	0.00%	yes	39.798	39.831	39.864	39.432	39.728	40.025	-0.26%	yes	86.031	86.464	86.897	85.402	86.294	87.188	-0.20%	yes
22	2.9061	2.9203	2.9345	2.9111	2.9173	2.9235	-0.10%	yes	40.031	40.064	40.097	39.475	39.772	40.070	-0.73%	yes	86.481	86.915	87.350	84.442	85.317	86.194	-1.84%	no
23	2.8980	2.9121	2.9262	2.9018	2.9080	2.9142	-0.14%	yes	39.732	39.823	39.914	39.208	39.506	39.803	-0.80%	yes	85.393	85.822	86.251	83.133	83.996	84.860	-2.13%	no
24	2.8909	2.9050	2.9191	2.8967	2.9030	2.9093	-0.07%	yes	39.832	39.923	40.013	39.304	39.602	39.899	-0.80%	yes	85.554	85.984	86.414	84.050	84.927	85.806	-1.23%	yes

Mono 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.2243	1.2307	1.2371	1.2262	1.2320	1.2378	0.10%	yes	44.377	44.417	44.457	44.411	44.685	44.959	0.60%	yes	42.103	42.332	42.562	43.347	43.779	44.213	3.42%	no
2	1.2280	1.2345	1.2410	1.2298	1.2356	1.2413	0.09%	yes	44.520	44.570	44.619	44.668	44.942	45.215	0.84%	no	42.730	42.962	43.195	43.964	44.399	44.837	3.34%	no
3	1.2209	1.2273	1.2337	1.2228	1.2285	1.2343	0.10%	yes	44.576	44.627	44.678	44.963	45.237	45.511	1.37%	no	42.505	42.737	42.969	44.088	44.523	44.960	4.18%	no
4	1.2381	1.2446	1.2511	1.2407	1.2465	1.2523	0.15%	yes	44.533	44.582	44.631	45.223	45.497	45.771	2.05%	no	42.409	42.640	42.871	44.946	45.387	45.830	6.44%	no
5	1.2175	1.2239	1.2303	1.2196	1.2253	1.2310	0.11%	yes	44.401	44.449	44.497	44.633	44.907	45.181	1.03%	no	42.014	42.244	42.474	43.578	44.011	44.446	4.18%	no
6	1.2273	1.2337	1.2401	1.2292	1.2349	1.2407	0.10%	yes	44.424	44.469	44.514	44.525	44.799	45.072	0.74%	no	42.442	42.673	42.904	43.757	44.192	44.629	3.56%	no
7	1.2192	1.2256	1.2320	1.2210	1.2267	1.2325	0.09%	yes	44.389	44.440	44.491	44.343	44.617	44.891	0.40%	yes	42.231	42.461	42.692	43.245	43.676	44.109	2.86%	no
8	1.2065	1.2129	1.2193	1.2079	1.2136	1.2194	0.06%	yes	44.443	44.490	44.537	44.373	44.647	44.921	0.35%	yes	42.359	42.590	42.821	42.956	43.385	43.816	1.87%	no
9	1.1757	1.1820	1.1883	1.1773	1.1829	1.1886	0.08%	yes	44.194	44.246	44.299	44.085	44.359	44.633	0.26%	yes	40.571	40.796	41.020	41.221	41.633	42.047	2.05%	no

Mono 2A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	3.2174	3.2327	3.2480	3.2156	3.2321	3.2487	-0.02%	yes	43.980	44.047	44.115	44.071	44.388	44.705	0.77%	yes	108.870	109.401	109.931	108.829	110.081	111.338	0.62%	yes
2	3.2412	3.2566	3.2720	3.2406	3.2571	3.2738	0.02%	yes	44.460	44.503	44.547	44.341	44.658	44.975	0.35%	yes	111.150	111.691	112.232	111.513	112.784	114.062	0.98%	yes
3	3.2256	3.2409	3.2562	3.2248	3.2412	3.2579	0.01%	yes	44.665	44.708	44.750	44.643	44.960	45.278	0.57%	yes	111.588	112.132	112.675	112.062	113.334	114.611	1.07%	yes
4	3.2439	3.2595	3.2751	3.2439	3.2605	3.2772	0.03%	yes	44.751	44.793	44.836	44.893	45.210	45.527	0.93%	no	111.814	112.358	112.903	113.197	114.475	115.759	1.88%	no
5	3.2184	3.2337	3.2490	3.2179	3.2344	3.2511	0.02%	yes	44.440	44.482	44.524	44.307	44.625	44.942	0.32%	yes	110.246	110.783	111.321	110.709	111.974	113.245	1.07%	yes
6	3.2154	3.2307	3.2460	3.2143	3.2309	3.2475	0.01%	yes	44.366	44.407	44.448	44.181	44.499	44.816	0.21%	yes	110.032	110.568	111.104	110.009	111.270	112.537	0.63%	yes
7	3.2103	3.2255	3.2407	3.2092	3.2257	3.2423	0.01%	yes	44.265	44.309	44.352	44.005	44.323	44.640	0.03%	yes	109.707	110.242	110.777	109.394	110.649	111.910	0.37%	yes
8	3.2003	3.2155	3.2307	3.1998	3.2164	3.2330	0.03%	yes	44.326	44.367	44.408	44.050	44.367	44.684	0.00%	yes	109.726	110.263	110.799	109.701	110.961	112.227	0.63%	yes
9	3.1456	3.1606	3.1756	3.1451	3.1616	3.1782	0.03%	yes	44.092	44.132	44.172	43.771	44.089	44.406	-0.10%	yes	106.418	106.942	107.466	106.292	107.512	108.738	0.53%	yes

Mono 1B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.2044	1.2107	1.2170	1.2068	1.2096	1.2124	-0.09%	yes	20.456	20.480	20.504	20.491	20.651	20.812	0.84%	yes	18.064	18.164	18.265	17.543	17.724	17.906	-2.42%	no
2	1.1971	1.2034	1.2097	1.1990	1.2018	1.2047	-0.13%	yes	20.405	20.429	20.454	20.418	20.578	20.738	0.73%	yes	17.951	18.051	18.151	17.372	17.553	17.735	-2.76%	no
3	1.1996	1.2059	1.2122	1.2036	1.2064	1.2093	0.04%	yes	20.479	20.502	20.526	20.525	20.686	20.846	0.89%	yes	18.511	18.613	18.715	18.706	18.911	19.117	1.60%	yes
4	1.2043	1.2106	1.2169	1.2079	1.2108	1.2136	0.01%	yes	20.445	20.468	20.492	20.448	20.608	20.768	0.68%	yes	18.137	18.238	18.338	18.045	18.238	18.431	0.00%	yes
5	1.2279	1.2343	1.2407	1.2333	1.2362	1.2392	0.16%	yes	20.369	20.391	20.414	20.388	20.548	20.708	0.77%	yes	18.456	18.558	18.660	18.981	19.189	19.397	3.40%	no
6	1.2130	1.2194	1.2258	1.2162	1.2191	1.2220	-0.03%	yes	20.445	20.469	20.492	20.483	20.643	20.803	0.85%	yes	18.421	18.522	18.624	18.230	18.424	18.620	-0.53%	yes
7	1.2140	1.2204	1.2268	1.2153	1.2181	1.2210	-0.19%	yes	20.456	20.477	20.499	20.595	20.755	20.915	1.36%	no	18.114	18.214	18.314	17.560	17.742	17.924	-2.59%	no
8	1.2086	1.2150	1.2214	1.2119	1.2148	1.2177	-0.02%	yes	20.458	20.481	20.505	20.765	20.925	21.085	2.17%	no	18.136	18.237	18.337	18.175	18.365	18.555	0.70%	yes
9	1.2208	1.2272	1.2336	1.2256	1.2285	1.2314	0.11%	yes	20.520	20.543	20.567	20.937	21.098	21.258	2.70%	no	18.540	18.642	18.744	19.255	19.461	19.667	4.39%	no
10	1.2143	1.2207	1.2271	1.2181	1.2210	1.2239	0.02%	yes	20.507	20.530	20.553	20.683	20.843	21.003	1.52%	no	18.522	18.624	18.726	18.680	18.880	19.080	1.37%	yes
11	1.1975	1.2038	1.2101	1.2012	1.2041	1.2070	0.02%	yes	20.485	20.509	20.532	20.544	20.704	20.865	0.95%	no	18.203	18.304	18.405	18.236	18.433	18.629	0.70%	yes
12	1.2125	1.2189	1.2253	1.2163	1.2192	1.2221	0.02%	yes	20.519	20.543	20.567	20.521	20.681	20.841	0.67%	yes	18.255	18.356	18.457	18.169	18.362	18.556	0.03%	yes
13	1.2122	1.2186	1.2250	1.2176	1.2205	1.2234	0.16%	yes	20.489	20.514	20.539	20.514	20.674	20.834	0.78%	yes	17.814	17.913	18.012	18.135	18.328	18.522	2.32%	no
14	1.2077	1.2141	1.2205	1.2121	1.2150	1.2179	0.07%	yes	20.522	20.547	20.571	20.514	20.675	20.835	0.62%	yes	18.199	18.300	18.401	18.297	18.493	18.690	1.06%	yes
15	1.2184	1.2248	1.2312	1.2224	1.2252	1.2281	0.04%	yes	20.527	20.554	20.581	20.519	20.679	20.839	0.61%	yes	18.106	18.206	18.307	17.966	18.155	18.344	-0.28%	yes
16	1.2070	1.2134	1.2198	1.2082	1.2111	1.2139	-0.19%	yes	20.563	20.591	20.619	20.532	20.693	20.853	0.49%	yes	18.176	18.276	18.377	17.408	17.588	17.767	-3.77%	no
17	1.2150	1.2214	1.2278	1.2199	1.2228	1.2257	0.11%	yes	20.574	20.606	20.637	20.599	20.759	20.920	0.75%	yes	18.292	18.393	18.494	18.528	18.726	18.925	1.81%	no
18	1.2139	1.2203	1.2267	1.2168	1.2197	1.2225	-0.05%	yes	20.538	20.583	20.628	20.544	20.705	20.865	0.59%	yes	18.284	18.385	18.486	17.900	18.087	18.275	-1.62%	no
19	1.2069	1.2133	1.2197	1.2096	1.2125	1.2154	-0.07%	yes	20.613	20.639	20.664	20.594	20.754	20.914	0.56%	yes	18.536	18.639	18.741	18.183	18.376	18.570	-1.41%	yes
20	1.2005	1.2068	1.2131	1.2050	1.2079	1.2108	0.09%	yes	20.591	20.618	20.645	20.700	20.860	21.020	1.17%	no	18.652	18.755	18.857	19.100	19.310	19.520	2.96%	no
21	1.2197	1.2261	1.2325	1.2248	1.2277	1.2306	0.13%	yes	20.609	20.636	20.663	20.957	21.118	21.278	2.33%	no	18.617	18.719	18.822	19.329	19.535	19.741	4.36%	no

Mono 1B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.6663	2.6796	2.6929	2.6651	2.6733	2.6815	-0.24%	yes	19.362	19.387	19.412	19.090	19.350	19.610	-0.19%	yes	34.942	35.126	35.310	33.761	34.388	35.014	-2.10%	yes
2	2.6780	2.6918	2.7056	2.6771	2.6853	2.6936	-0.24%	yes	19.334	19.356	19.379	19.026	19.286	19.546	-0.36%	yes	34.822	35.005	35.188	33.650	34.281	34.913	-2.07%	yes
3	2.6572	2.6705	2.6838	2.6624	2.6708	2.6792	0.01%	yes	19.403	19.426	19.449	19.125	19.385	19.645	-0.21%	yes	36.486	36.677	36.867	35.995	36.690	37.387	0.04%	yes
4	2.6383	2.6515	2.6647	2.6388	2.6470	2.6552	-0.17%	yes	19.351	19.375	19.398	19.035	19.295	19.555	-0.41%	yes	35.337	35.522	35.708	34.201	34.854	35.507	-1.88%	yes
5	2.6700	2.6833	2.6966	2.6767	2.6851	2.6935	0.07%	yes	19.261	19.284	19.307	18.967	19.228	19.488	-0.29%	yes	36.315	36.505	36.695	35.976	36.669	37.364	0.45%	yes
6	2.6266	2.6398	2.6530	2.6246	2.6327	2.6409	-0.27%	yes	19.487	19.511	19.535	19.058	19.319	19.579	-0.99%	yes	35.833	36.021	36.209	34.194	34.844	35.496	-3.27%	no
7	2.6447	2.6580	2.6713	2.6355	2.6436	2.6517	-0.54%	yes	19.659	19.683	19.707	19.179	19.439	19.699	-1.24%	yes	34.948	35.132	35.316	32.825	33.441	34.057	-4.81%	no
8	2.6503	2.6636	2.6769	2.6479	2.6561	2.6643	-0.28%	yes	19.576	19.599	19.621	19.357	19.617	19.878	0.10%	yes	35.740	35.927	36.114	34.553	35.196	35.839	-2.03%	yes
9	2.6559	2.6692	2.6825	2.6590	2.6673	2.6756	-0.07%	yes	19.483	19.506	19.528	19.525	19.785	20.045	1.43%	yes	36.451	36.642	36.832	36.414	37.100	37.787	1.25%	yes
10	2.6580	2.6713	2.6846	2.6597	2.6680	2.6763	-0.12%	yes	19.440	19.462	19.485	19.273	19.533	19.793	0.36%	yes	36.115	36.303	36.492	35.476	36.148	36.822	-0.43%	yes
11	2.6345	2.6477	2.6609	2.6368	2.6450	2.6533	-0.10%	yes	19.410	19.432	19.455	19.137	19.397	19.657	-0.18%	yes	35.572	35.759	35.946	34.774	35.437	36.102	-0.90%	yes
12	2.6553	2.6686	2.6819	2.6562	2.6644	2.6727	-0.16%	yes	19.425	19.448	19.471	19.109	19.369	19.629	-0.41%	yes	35.475	35.661	35.847	34.425	35.078	35.732	-1.63%	yes
13	2.6480	2.6613	2.6746	2.6465	2.6547	2.6629	-0.25%	yes	19.409	19.432	19.454	19.097	19.358	19.618	-0.38%	yes	35.369	35.555	35.740	34.122	34.772	35.422	-2.20%	yes
14	2.6483	2.6616	2.6749	2.6500	2.6583	2.6666	-0.13%	yes	19.408	19.430	19.453	19.103	19.364	19.624	-0.34%	yes	35.705	35.892	36.079	34.752	35.414	36.077	-1.33%	yes
15	2.6458	2.6591	2.6724	2.6406	2.6488	2.6569	-0.39%	yes	19.453	19.477	19.501	19.096	19.357	19.617	-0.62%	yes	35.319	35.504	35.690	33.665	34.299	34.933	-3.39%	no
16	2.6541	2.6674	2.6807	2.6464	2.6545	2.6627	-0.48%	yes	19.472	19.497	19.522	19.124	19.385	19.645	-0.58%	yes	34.716	34.898	35.081	32.992	33.608	34.224	-3.70%	no
17	2.6679	2.6813	2.6947	2.6709	2.6792	2.6876	-0.08%	yes	19.551	19.578	19.604	19.191	19.451	19.711	-0.65%	yes	36.183	36.372	36.562	35.250	35.920	36.591	-1.24%	yes
18	2.6668	2.6802	2.6936	2.6644	2.6726	2.6808	-0.28%	yes	19.496	19.521	19.547	19.136	19.396	19.656	-0.64%	yes	35.453	35.639	35.824	34.013	34.651	35.290	-2.77%	no
19	2.6360	2.6492	2.6624	2.6346	2.6428	2.6511	-0.24%	yes	19.573	19.598	19.624	19.181	19.441	19.701	-0.80%	yes	35.797	35.985	36.173	34.388	35.039	35.691	-2.63%	no
20	2.6320	2.6452	2.6584	2.6358	2.6441	2.6525	-0.04%	yes	19.612	19.635	19.658	19.291	19.551	19.811	-0.43%	yes	37.159	37.353	37.546	36.467	37.167	37.870	-0.50%	yes
21	2.6630	2.6764	2.6898	2.6644	2.6727	2.6810	-0.14%	yes	19.782	19.828	19.873	19.547	19.808	20.068	-0.10%	yes	37.651	37.846	38.042	36.786	37.475	38.165	-0.98%	yes

Mono 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0041	1.1157	1.2273	1.1055	1.1079	1.1104	-0.70%	yes	19.338	19.356	19.374	19.236	19.370	19.504	0.07%	yes	14.479	14.562	14.644	14.024	14.143	14.261	-2.88%	no
2	1.0080	1.1200	1.2320	1.1120	1.1146	1.1171	-0.49%	yes	9.596	9.611	9.626	10.542	10.673	10.805	11.05%	no	7.593	7.637	7.680	7.949	8.076	8.203	5.75%	no
3	1.0028	1.1142	1.2256	1.1080	1.1106	1.1132	-0.32%	yes	9.506	9.521	9.535	10.327	10.459	10.591	9.86%	no	7.658	7.701	7.745	7.780	7.904	8.029	2.64%	no
5	0.9884	1.0982	1.2080	1.0918	1.0944	1.0970	-0.35%	yes	9.433	9.458	9.483	10.156	10.288	10.420	8.77%	no	7.482	7.525	7.568	7.620	7.746	7.872	2.94%	no
6	1.0071	1.1190	1.2309	1.1137	1.1162	1.1188	-0.25%	yes	9.437	9.453	9.469	10.458	10.590	10.722	12.03%	no	6.797	6.836	6.875	7.836	7.960	8.084	16.44%	no
7	1.0055	1.1172	1.2289	1.1165	1.1191	1.1218	0.17%	yes	9.519	9.534	9.549	10.353	10.485	10.617	9.98%	no	7.226	7.268	7.310	8.379	8.524	8.670	17.29%	no
8	1.0020	1.1133	1.2246	1.1109	1.1135	1.1162	0.02%	yes	9.329	9.344	9.359	10.722	10.854	10.985	16.16%	no	7.368	7.411	7.455	9.046	9.200	9.355	24.14%	no
9	1.0102	1.1224	1.2346	1.1222	1.1248	1.1274	0.21%	yes	19.284	19.302	19.320	19.263	19.396	19.530	0.49%	yes	13.149	13.224	13.299	15.601	15.749	15.897	19.09%	no
10	1.0080	1.1200	1.2320	1.1168	1.1194	1.1220	-0.05%	yes	19.382	19.403	19.424	19.304	19.438	19.572	0.18%	yes	15.950	16.040	16.131	12.623	12.699	12.774	-20.83%	no
11	1.0964	1.1024	1.1084	1.1044	1.1071	1.1097	0.42%	yes	8.501	8.539	8.576	10.849	10.981	11.112	28.60%	no	4.719	4.747	4.776	8.760	8.907	9.055	87.63%	no
13	1.1029	1.1089	1.1149	1.1002	1.1027	1.1052	-0.56%	yes	16.984	17.000	17.016	19.185	19.319	19.453	13.64%	no	10.350	10.410	10.470	14.612	14.745	14.878	41.64%	no
14	1.0975	1.1035	1.1095	1.1010	1.1036	1.1061	0.00%	yes	6.027	6.100	6.173	10.518	10.650	10.782	74.60%	no	3.191	3.211	3.230	8.202	8.343	8.484	159.85%	no
15	1.1193	1.1254	1.1315	1.1161	1.1186	1.1212	-0.60%	yes	19.263	19.291	19.319	19.258	19.392	19.526	0.52%	yes	12.484	12.556	12.627	15.212	15.352	15.492	22.27%	no
16	1.1065	1.1125	1.1185	1.1083	1.1109	1.1135	-0.15%	yes	9.400	9.417	9.434	10.613	10.745	10.877	14.10%	no	7.225	7.266	7.307	8.444	8.586	8.729	18.17%	no
17	1.1146	1.1207	1.1268	1.1251	1.1277	1.1303	0.62%	yes	19.267	19.285	19.303	19.281	19.415	19.548	0.67%	yes	13.942	14.022	14.102	15.895	16.041	16.187	14.40%	no
18	1.1157	1.1218	1.1279	1.1316	1.1343	1.1369	1.11%	no	9.418	9.432	9.447	10.323	10.454	10.586	10.84%	no	6.396	6.434	6.471	8.448	8.591	8.734	33.53%	no
19	1.1095	1.1155	1.1215	1.1123	1.1149	1.1175	-0.05%	yes	19.290	19.308	19.326	19.327	19.460	19.594	0.79%	no	16.513	16.607	16.700	16.343	16.496	16.649	-0.67%	yes
20	1.0694	1.0754	1.0814	1.0611	1.0635	1.0658	-1.11%	no	4.701	4.900	5.099	14.349	14.482	14.615	195.55%	no	2.441	2.456	2.472	9.744	9.851	9.959	301.04%	no
21	1.0969	1.1029	1.1089	1.1054	1.1081	1.1108	0.47%	yes	19.221	19.240	19.259	19.339	19.473	19.607	1.21%	no	15.131	15.219	15.307	16.415	16.573	16.731	8.90%	no

Mono 3B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.7817	0.7868	0.7919	0.7928	0.7948	0.7969	1.02%	no	18.257	18.274	18.292	19.025	19.176	19.327	4.93%	no	9.251	9.318	9.386	11.091	11.209	11.326	20.28%	no
2	0.7755	0.7806	0.7857	0.7835	0.7855	0.7875	0.63%	yes	18.051	18.068	18.085	18.856	19.007	19.157	5.20%	no	9.372	9.440	9.508	10.838	10.954	11.070	16.04%	no
3	0.7855	0.7906	0.7957	0.7927	0.7947	0.7967	0.52%	yes	18.138	18.156	18.174	18.856	19.007	19.157	4.69%	no	9.670	9.739	9.808	11.104	11.224	11.345	15.25%	no
4	0.7851	0.7902	0.7953	0.7915	0.7935	0.7955	0.42%	yes	18.161	18.178	18.196	18.890	19.041	19.192	4.75%	no	9.752	9.822	9.891	10.947	11.064	11.180	12.64%	no
5	0.7823	0.7874	0.7925	0.7893	0.7913	0.7933	0.50%	yes	18.171	18.188	18.206	18.845	18.995	19.146	4.44%	no	9.664	9.733	9.802	11.047	11.167	11.287	14.73%	no
6	0.7800	0.7851	0.7902	0.7874	0.7894	0.7914	0.55%	yes	18.192	18.210	18.227	18.908	19.059	19.210	4.66%	no	9.620	9.689	9.759	11.014	11.132	11.250	14.89%	no
7	0.7879	0.7930	0.7981	0.8000	0.8020	0.8040	1.13%	no	18.149	18.166	18.184	18.988	19.139	19.289	5.35%	no	9.178	9.245	9.312	11.176	11.295	11.414	22.17%	no
8	0.7950	0.8002	0.8054	0.8028	0.8048	0.8068	0.58%	yes	18.267	18.285	18.302	18.901	19.052	19.202	4.19%	no	9.715	9.784	9.854	10.964	11.079	11.194	13.23%	no
9	0.7799	0.7850	0.7901	0.7889	0.7909	0.7929	0.75%	yes	17.986	18.004	18.021	18.745	18.895	19.046	4.95%	no	9.229	9.296	9.363	10.664	10.776	10.889	15.92%	no
10	0.7904	0.7955	0.8006	0.7987	0.8007	0.8028	0.66%	yes	18.117	18.135	18.153	18.886	19.036	19.187	4.97%	no	9.572	9.640	9.708	11.115	11.234	11.353	16.54%	no
11	0.7916	0.7967	0.8018	0.7997	0.8018	0.8038	0.64%	yes	18.105	18.129	18.153	18.893	19.044	19.194	5.04%	no	9.614	9.682	9.751	11.221	11.342	11.464	17.15%	no
12	0.7889	0.7940	0.7991	0.7979	0.8000	0.8020	0.75%	yes	18.151	18.174	18.196	18.863	19.013	19.164	4.62%	no	9.498	9.567	9.635	11.177	11.298	11.419	18.09%	no
13	0.7922	0.7973	0.8024	0.8006	0.8026	0.8046	0.66%	yes	18.263	18.287	18.311	19.020	19.171	19.322	4.83%	no	9.663	9.732	9.801	11.078	11.194	11.309	15.02%	no
14	0.7766	0.7817	0.7868	0.7826	0.7845	0.7865	0.36%	yes	18.098	18.120	18.143	18.889	19.040	19.190	5.07%	no	9.706	9.775	9.844	11.032	11.153	11.273	14.10%	no
15	0.7910	0.7961	0.8012	0.8000	0.8020	0.8040	0.74%	yes	18.254	18.278	18.302	19.075	19.225	19.376	5.18%	no	9.608	9.678	9.747	11.327	11.447	11.568	18.29%	no
16	0.7870	0.7921	0.7972	0.7959	0.7980	0.8000	0.74%	yes	18.185	18.208	18.231	18.984	19.134	19.285	5.09%	no	9.470	9.538	9.606	11.106	11.224	11.343	17.68%	no
17	0.7766	0.7817	0.7868	0.7847	0.7867	0.7887	0.64%	yes	18.030	18.054	18.078	18.931	19.082	19.233	5.69%	no	9.389	9.456	9.524	11.010	11.128	11.247	17.68%	no
18	0.7898	0.7949	0.8000	0.7973	0.7993	0.8014	0.56%	yes	18.091	18.110	18.130	18.904	19.055	19.205	5.22%	no	9.613	9.682	9.750	11.082	11.201	11.321	15.70%	no
19	0.7858	0.7909	0.7960	0.7930	0.7950	0.7970	0.52%	yes	18.061	18.102	18.142	18.777	18.927	19.078	4.56%	no	9.613	9.681	9.750	10.901	11.017	11.134	13.80%	no
20	0.8040	0.8092	0.8144	0.8143	0.8163	0.8184	0.88%	yes	18.170	18.187	18.205	19.004	19.155	19.305	5.32%	no	9.503	9.571	9.639	11.129	11.244	11.360	17.49%	no
21	0.8074	0.8126	0.8178	0.8164	0.8185	0.8205	0.72%	yes	18.375	18.393	18.411	19.131	19.281	19.432	4.83%	no	9.867	9.937	10.007	11.500	11.621	11.743	16.95%	no
22	0.7897	0.7948	0.7999	0.7982	0.8003	0.8023	0.69%	yes	18.139	18.157	18.175	19.015	19.165	19.316	5.55%	no	9.551	9.619	9.688	11.244	11.365	11.485	18.14%	no
23	0.8037	0.8089	0.8141	0.8143	0.8163	0.8184	0.92%	no	18.210	18.228	18.246	18.986	19.136	19.287	4.98%	no	9.561	9.629	9.698	11.468	11.591	11.715	20.38%	no
24	0.7915	0.7966	0.8017	0.8035	0.8055	0.8076	1.12%	no	18.163	18.180	18.198	18.973	19.124	19.274	5.19%	no	9.250	9.317	9.385	11.285	11.405	11.526	22.41%	no
25	0.8043	0.8095	0.8147	0.8145	0.8165	0.8186	0.87%	yes	18.327	18.348	18.368	19.133	19.283	19.434	5.10%	no	9.617	9.686	9.755	11.177	11.292	11.406	16.58%	no
26	0.7923	0.7974	0.8025	0.7995	0.8015	0.8035	0.51%	yes	18.208	18.241	18.274	18.993	19.144	19.294	4.95%	no	9.788	9.857	9.926	11.302	11.424	11.546	15.90%	no
27	0.8154	0.8220	0.8286	0.8273	0.8293	0.8313	0.89%	yes	18.690	18.786	18.883	19.321	19.472	19.622	3.65%	no	9.932	10.001	10.071	11.411	11.527	11.643	15.25%	no

Mono 4B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.9751	1.0834	1.1917	1.0810	1.0839	1.0867	0.04%	yes	40.112	40.140	40.168	39.667	39.984	40.302	-0.39%	yes	31.832	32.018	32.205	31.440	31.791	32.142	-0.71%	yes
2	1.0056	1.1173	1.2290	1.1144	1.1174	1.1203	0.01%	yes	40.112	40.140	40.168	39.764	40.081	40.398	-0.15%	yes	33.236	33.426	33.616	32.752	33.121	33.490	-0.91%	yes
3	1.0109	1.1232	1.2355	1.1207	1.1236	1.1266	0.04%	yes	40.188	40.216	40.244	39.824	40.141	40.458	-0.19%	yes	33.672	33.864	34.056	33.474	33.855	34.237	-0.03%	yes
5	1.0135	1.1261	1.2387	1.1234	1.1263	1.1292	0.02%	yes	40.072	40.101	40.129	39.796	40.113	40.430	0.03%	yes	32.830	33.019	33.207	32.222	32.574	32.927	-1.35%	yes
6	1.0483	1.1648	1.2813	1.1618	1.1648	1.1679	0.00%	yes	40.020	40.048	40.076	39.916	40.233	40.550	0.46%	yes	34.204	34.397	34.589	33.675	34.044	34.414	-1.03%	yes
7	0.9671	1.0745	1.1820	1.0709	1.0737	1.0765	-0.07%	yes	40.093	40.144	40.194	39.765	40.083	40.400	-0.15%	yes	31.669	31.853	32.038	30.550	30.884	31.219	-3.04%	no
8	1.0320	1.1467	1.2614	1.1441	1.1471	1.1501	0.03%	yes	40.132	40.175	40.219	39.945	40.262	40.578	0.21%	yes	34.243	34.436	34.630	34.129	34.514	34.901	0.23%	yes
9	1.0293	1.1437	1.2581	1.1411	1.1441	1.1471	0.03%	yes	40.115	40.159	40.203	40.109	40.426	40.743	0.67%	yes	33.794	33.986	34.178	33.698	34.073	34.448	0.26%	yes
10	1.0202	1.1335	1.2469	1.1315	1.1345	1.1375	0.09%	yes	40.135	40.179	40.224	40.212	40.530	40.847	0.87%	yes	33.202	33.392	33.583	33.572	33.944	34.317	1.65%	yes
11	1.0543	1.1714	1.2885	1.1682	1.1712	1.1743	-0.01%	yes	40.040	40.071	40.103	40.564	40.881	41.198	2.02%	no	34.824	35.019	35.213	35.066	35.454	35.843	1.24%	yes
13	0.6934	0.7704	0.8474	0.7700	0.7713	0.7726	0.11%	yes	40.004	40.057	40.110	40.172	40.473	40.773	1.04%	no	22.877	23.039	23.201	23.306	23.535	23.764	2.15%	no
14	0.7413	0.8237	0.9061	0.8225	0.8239	0.8253	0.02%	yes	40.173	40.220	40.268	40.128	40.428	40.728	0.52%	yes	24.492	24.657	24.823	24.181	24.413	24.645	-0.99%	yes
15	0.7155	0.7950	0.8745	0.7942	0.7955	0.7968	0.06%	yes	39.941	39.993	40.045	39.845	40.146	40.447	0.38%	yes	23.148	23.311	23.474	22.546	22.755	22.964	-2.38%	no
16	0.6798	0.7553	0.8308	0.7537	0.7549	0.7562	-0.05%	yes	40.173	40.224	40.276	39.999	40.300	40.601	0.19%	yes	23.249	23.413	23.578	22.536	22.756	22.977	-2.81%	no
17	0.7334	0.8149	0.8964	0.8146	0.8159	0.8173	0.13%	yes	40.049	40.097	40.144	40.079	40.379	40.679	0.70%	yes	24.011	24.174	24.337	24.309	24.546	24.783	1.54%	yes
18	0.6784	0.7538	0.8292	0.7533	0.7546	0.7559	0.11%	yes	39.903	39.956	40.009	39.946	40.247	40.548	0.73%	yes	22.138	22.298	22.458	22.316	22.533	22.751	1.05%	yes
19	0.7306	0.8118	0.8930	0.8112	0.8125	0.8138	0.09%	yes	39.965	40.011	40.057	39.813	40.114	40.414	0.26%	yes	23.383	23.545	23.707	22.647	22.854	23.061	-2.93%	no
20	0.7320	0.8133	0.8946	0.8125	0.8139	0.8153	0.08%	yes	40.046	40.092	40.138	40.001	40.301	40.601	0.52%	yes	24.096	24.262	24.427	24.087	24.322	24.556	0.25%	yes
21	0.7112	0.7902	0.8692	0.7891	0.7904	0.7918	0.03%	yes	40.018	40.063	40.107	40.004	40.305	40.605	0.60%	yes	23.731	23.896	24.061	23.597	23.828	24.060	-0.28%	yes

Mono 4B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.1459	2.3843	2.6227	2.3729	2.3807	2.3885	-0.15%	yes	39.557	39.596	39.634	38.708	39.203	39.697	-0.99%	yes	66.963	67.329	67.695	64.261	65.399	66.539	-2.87%	no
2	2.1549	2.3943	2.6337	2.3828	2.3907	2.3987	-0.15%	yes	39.468	39.507	39.546	38.759	39.254	39.748	-0.64%	yes	67.268	67.633	67.999	64.992	66.157	67.324	-2.18%	yes
3	2.1554	2.3949	2.6344	2.3841	2.3921	2.4001	-0.12%	yes	39.385	39.424	39.463	38.810	39.305	39.799	-0.30%	yes	67.912	68.280	68.648	66.117	67.312	68.510	-1.42%	yes
4	2.1873	2.4303	2.6733	2.4181	2.4259	2.4338	-0.18%	yes	39.278	39.317	39.356	38.804	39.299	39.793	-0.05%	yes	66.622	66.984	67.346	64.521	65.647	66.774	-2.00%	yes
5	2.2054	2.4504	2.6954	2.4372	2.4451	2.4530	-0.22%	yes	39.177	39.214	39.250	38.878	39.373	39.867	0.41%	yes	67.844	68.211	68.577	65.752	66.901	68.052	-1.92%	yes
6	2.1254	2.3615	2.5977	2.3466	2.3543	2.3620	-0.31%	yes	39.232	39.271	39.310	38.805	39.301	39.795	0.08%	yes	64.685	65.040	65.394	62.189	63.275	64.363	-2.71%	no
7	2.1801	2.4223	2.6645	2.4113	2.4193	2.4273	-0.12%	yes	39.184	39.221	39.258	38.916	39.410	39.904	0.48%	yes	68.049	68.417	68.784	66.826	68.024	69.226	-0.57%	yes
8	2.1930	2.4367	2.6804	2.4254	2.4334	2.4415	-0.13%	yes	39.184	39.222	39.261	39.099	39.594	40.088	0.95%	yes	67.390	67.755	68.119	66.510	67.687	68.866	-0.10%	yes
9	2.1794	2.4215	2.6637	2.4108	2.4188	2.4268	-0.11%	yes	39.186	39.223	39.260	39.208	39.703	40.197	1.22%	yes	67.231	67.596	67.960	66.564	67.736	68.910	0.21%	yes
10	2.2157	2.4619	2.7081	2.4503	2.4584	2.4665	-0.14%	yes	39.063	39.096	39.130	39.537	40.031	40.525	2.39%	no	68.127	68.493	68.859	68.258	69.459	70.662	1.41%	yes

Mono 5B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.5575	1.5651	1.5727	1.5677	1.5721	1.5765	0.45%	yes	27.953	27.978	28.004	28.572	28.837	29.103	3.07%	no	30.017	30.169	30.322	32.516	32.926	33.337	9.14%	no
2	1.5163	1.5237	1.5311	1.5264	1.5306	1.5349	0.45%	yes	28.049	28.084	28.119	28.507	28.773	29.039	2.46%	no	29.213	29.364	29.514	31.364	31.760	32.157	8.16%	no
3	1.5781	1.5858	1.5935	1.5883	1.5928	1.5972	0.44%	yes	27.888	27.920	27.951	28.326	28.591	28.857	2.41%	no	30.257	30.411	30.564	32.421	32.831	33.241	7.96%	no
4	1.4777	1.4850	1.4923	1.4917	1.4960	1.5002	0.74%	yes	27.915	27.951	27.987	28.406	28.672	28.938	2.58%	no	27.597	27.741	27.885	30.732	31.123	31.515	12.19%	no
5	1.5609	1.5684	1.5759	1.5705	1.5749	1.5793	0.41%	yes	27.885	27.917	27.948	28.231	28.497	28.762	2.08%	no	29.899	30.051	30.204	31.768	32.171	32.575	7.05%	no
6	1.4990	1.5063	1.5136	1.5118	1.5160	1.5202	0.64%	yes	27.644	27.678	27.712	28.089	28.355	28.621	2.45%	no	27.811	27.956	28.100	30.315	30.700	31.085	9.82%	no
7	1.5485	1.5560	1.5635	1.5590	1.5634	1.5678	0.48%	yes	27.816	27.849	27.881	28.202	28.468	28.734	2.23%	no	29.592	29.743	29.894	31.932	32.342	32.752	8.74%	no
8	1.5095	1.5169	1.5243	1.5208	1.5250	1.5293	0.54%	yes	27.701	27.734	27.766	28.085	28.351	28.617	2.23%	no	28.436	28.583	28.730	30.740	31.133	31.527	8.92%	no
9	1.5566	1.5641	1.5716	1.5692	1.5736	1.5780	0.60%	yes	27.634	27.667	27.700	28.066	28.332	28.598	2.40%	no	28.852	29.000	29.148	31.307	31.704	32.101	9.33%	no

Mono 5B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	4.2665	4.2857	4.3049	4.2771	4.2884	4.2997	0.06%	yes	28.424	28.456	28.488	28.737	28.973	29.208	1.82%	no	82.930	83.314	83.698	84.695	85.690	86.687	2.85%	no
2	4.2412	4.2602	4.2792	4.2515	4.2627	4.2739	0.06%	yes	28.564	28.593	28.622	28.704	28.940	29.175	1.21%	no	81.768	82.147	82.527	82.945	83.925	84.907	2.16%	no
3	4.2871	4.3063	4.3255	4.2953	4.3065	4.3178	0.01%	yes	28.402	28.432	28.463	28.473	28.708	28.944	0.97%	no	83.087	83.471	83.855	83.637	84.623	85.611	1.38%	yes
4	4.1282	4.1468	4.1654	4.1393	4.1504	4.1616	0.09%	yes	28.685	28.712	28.740	28.594	28.829	29.065	0.41%	yes	80.710	81.086	81.462	81.402	82.366	83.331	1.58%	yes
5	4.2905	4.3097	4.3289	4.3004	4.3117	4.3230	0.05%	yes	28.334	28.363	28.391	28.396	28.632	28.867	0.95%	no	81.718	82.097	82.475	82.446	83.427	84.409	1.62%	yes
6	4.2373	4.2563	4.2753	4.2487	4.2598	4.2710	0.08%	yes	28.245	28.274	28.304	28.291	28.526	28.762	0.89%	yes	79.795	80.166	80.537	80.913	81.874	82.837	2.13%	no
7	4.2421	4.2612	4.2803	4.2517	4.2630	4.2743	0.04%	yes	28.315	28.344	28.373	28.359	28.595	28.831	0.89%	yes	81.935	82.314	82.694	82.864	83.856	84.851	1.87%	no
8	4.2376	4.2566	4.2756	4.2483	4.2595	4.2707	0.07%	yes	28.238	28.268	28.297	28.277	28.513	28.748	0.87%	yes	80.792	81.166	81.541	81.743	82.717	83.693	1.91%	no
9	4.2556	4.2747	4.2938	4.2689	4.2802	4.2915	0.13%	yes	28.100	28.135	28.170	28.219	28.454	28.690	1.13%	no	79.333	79.701	80.070	80.803	81.763	82.725	2.59%	no

Mono 5B -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.5575	1.5651	1.5727	1.5671	1.5715	1.5760	0.41%	yes	27.953	27.978	28.004	24.054	24.354	24.653	-12.95%	no	30.017	30.169	30.322	26.555	26.990	27.426	-10.54%	no
2	1.5163	1.5237	1.5311	1.5257	1.5300	1.5343	0.41%	yes	28.049	28.084	28.119	24.172	24.470	24.768	-12.87%	no	29.213	29.364	29.514	25.821	26.240	26.659	-10.64%	no
3	1.5781	1.5858	1.5935	1.5876	1.5921	1.5966	0.40%	yes	27.888	27.920	27.951	24.092	24.389	24.686	-12.64%	no	30.257	30.411	30.564	26.811	27.243	27.676	-10.42%	no
4	1.4777	1.4850	1.4923	1.4911	1.4954	1.4998	0.70%	yes	27.915	27.951	27.987	23.854	24.154	24.454	-13.58%	no	27.597	27.741	27.885	25.021	25.436	25.852	-8.31%	no
5	1.5609	1.5684	1.5759	1.5697	1.5742	1.5786	0.37%	yes	27.885	27.917	27.948	24.167	24.463	24.759	-12.37%	no	29.899	30.051	30.204	26.443	26.866	27.289	-10.60%	no
6	1.4990	1.5063	1.5136	1.5110	1.5153	1.5196	0.60%	yes	27.644	27.678	27.712	23.581	23.880	24.180	-13.72%	no	27.811	27.956	28.100	24.694	25.103	25.512	-10.20%	no
7	1.5485	1.5560	1.5635	1.5583	1.5628	1.5672	0.44%	yes	27.816	27.849	27.881	23.929	24.226	24.524	-13.01%	no	29.592	29.743	29.894	26.266	26.696	27.127	-10.24%	no
8	1.5095	1.5169	1.5243	1.5201	1.5244	1.5287	0.49%	yes	27.701	27.734	27.766	23.804	24.102	24.399	-13.10%	no	28.436	28.583	28.730	25.298	25.712	26.127	-10.04%	no
9	1.5566	1.5641	1.5716	1.5683	1.5728	1.5773	0.55%	yes	27.634	27.667	27.700	23.742	24.040	24.337	-13.11%	no	28.852	29.000	29.148	25.733	26.153	26.573	-9.82%	no

Mono 5B -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	4.2665	4.2857	4.3049	4.2747	4.2863	4.2980	0.01%	yes	28.424	28.456	28.488	27.139	27.389	27.639	-3.75%	no	82.930	83.314	83.698	78.638	79.587	80.537	-4.47%	no
2	4.2412	4.2602	4.2792	4.2488	4.2603	4.2719	0.00%	yes	28.564	28.593	28.622	27.173	27.423	27.672	-4.09%	no	81.768	82.147	82.527	77.163	78.088	79.013	-4.94%	no
3	4.2871	4.3063	4.3255	4.2925	4.3042	4.3159	-0.05%	yes	28.402	28.432	28.463	26.960	27.210	27.459	-4.30%	no	83.087	83.471	83.855	77.903	78.838	79.773	-5.55%	no
4	4.1282	4.1468	4.1654	4.1369	4.1484	4.1599	0.04%	yes	28.685	28.712	28.740	26.972	27.222	27.472	-5.19%	no	80.710	81.086	81.462	75.455	76.373	77.291	-5.81%	no
5	4.2905	4.3097	4.3289	4.2973	4.3090	4.3208	-0.02%	yes	28.334	28.363	28.391	26.961	27.210	27.458	-4.06%	no	81.718	82.097	82.475	76.941	77.858	78.775	-5.16%	no
6	4.2373	4.2563	4.2753	4.2455	4.2571	4.2687	0.02%	yes	28.245	28.274	28.304	26.698	26.948	27.197	-4.69%	no	79.795	80.166	80.537	74.988	75.893	76.798	-5.33%	no
7	4.2421	4.2612	4.2803	4.2491	4.2607	4.2724	-0.01%	yes	28.315	28.344	28.373	26.840	27.090	27.339	-4.43%	no	81.935	82.314	82.694	77.027	77.958	78.889	-5.29%	no
8	4.2376	4.2566	4.2756	4.2454	4.2570	4.2686	0.01%	yes	28.238	28.268	28.297	26.765	27.015	27.264	-4.43%	no	80.792	81.166	81.541	76.033	76.948	77.864	-5.20%	no
9	4.2556	4.2747	4.2938	4.2655	4.2773	4.2891	0.06%	yes	28.100	28.135	28.170	26.691	26.940	27.190	-4.25%	no	79.333	79.701	80.070	75.102	76.005	76.907	-4.64%	no

Mono 6B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.6035	1.6112	1.6189	1.6055	1.6120	1.6184	0.05%	yes	39.742	39.773	39.804	40.010	40.312	40.613	1.35%	no	46.696	46.929	47.162	47.051	47.549	48.048	1.32%	yes
2	1.6000	1.6077	1.6154	1.6034	1.6101	1.6167	0.15%	yes	39.466	39.499	39.531	39.565	39.867	40.167	0.93%	no	46.216	46.447	46.678	47.528	48.050	48.574	3.45%	no
3	1.5917	1.5993	1.6069	1.5952	1.6018	1.6085	0.16%	yes	39.724	39.755	39.786	39.852	40.153	40.454	1.00%	no	46.249	46.480	46.711	47.725	48.250	48.777	3.81%	no
4	1.5803	1.5879	1.5955	1.5833	1.5899	1.5964	0.12%	yes	39.468	39.499	39.530	39.603	39.905	40.206	1.03%	no	45.439	45.667	45.895	46.404	46.908	47.413	2.72%	no
5	1.5983	1.6060	1.6137	1.6015	1.6081	1.6147	0.13%	yes	39.829	39.860	39.891	40.000	40.301	40.602	1.11%	no	46.761	46.994	47.227	48.062	48.587	49.112	3.39%	no
6	1.5765	1.5841	1.5917	1.5795	1.5861	1.5927	0.13%	yes	39.646	39.677	39.707	39.739	40.040	40.341	0.92%	no	45.991	46.222	46.452	47.209	47.730	48.253	3.26%	no
7	1.5963	1.6040	1.6117	1.5995	1.6061	1.6128	0.13%	yes	39.711	39.743	39.774	39.785	40.086	40.387	0.86%	no	46.418	46.650	46.882	47.574	48.095	48.618	3.10%	no
8	1.5866	1.5942	1.6018	1.5894	1.5958	1.6023	0.10%	yes	39.514	39.545	39.576	39.590	39.891	40.193	0.88%	no	45.850	46.079	46.308	46.561	47.066	47.573	2.14%	no
9	1.5745	1.5821	1.5897	1.5772	1.5838	1.5904	0.10%	yes	39.432	39.465	39.498	39.452	39.753	40.054	0.73%	yes	45.923	46.153	46.382	46.948	47.472	47.998	2.86%	no
10	1.5244	1.5320	1.5396	1.5258	1.5322	1.5387	0.01%	yes	26.312	26.334	26.355	26.814	27.113	27.412	2.96%	no	29.395	29.544	29.693	30.083	30.558	31.035	3.43%	no
11	1.5178	1.5252	1.5326	1.5202	1.5266	1.5331	0.09%	yes	39.583	39.611	39.639	39.623	39.925	40.226	0.79%	yes	44.600	44.826	45.052	45.477	45.982	46.487	2.58%	no
12	1.5026	1.5099	1.5172	1.5051	1.5115	1.5178	0.10%	yes	39.380	39.408	39.435	39.566	39.868	40.170	1.17%	no	43.417	43.639	43.861	44.426	44.914	45.403	2.92%	no
13	1.5076	1.5150	1.5224	1.5105	1.5168	1.5232	0.12%	yes	39.221	39.249	39.277	39.387	39.688	39.990	1.12%	no	43.466	43.688	43.909	44.711	45.207	45.705	3.48%	no
14	1.5044	1.5117	1.5190	1.5070	1.5133	1.5197	0.11%	yes	39.380	39.408	39.436	39.477	39.779	40.080	0.94%	no	43.824	44.046	44.269	44.886	45.385	45.886	3.04%	no
15	1.5103	1.5177	1.5251	1.5131	1.5194	1.5258	0.11%	yes	39.308	39.336	39.364	39.248	39.550	39.852	0.54%	yes	43.617	43.839	44.060	44.440	44.934	45.428	2.50%	no
16	1.5092	1.5166	1.5240	1.5118	1.5182	1.5247	0.11%	yes	39.466	39.494	39.522	39.244	39.545	39.847	0.13%	yes	44.088	44.312	44.536	44.750	45.252	45.754	2.12%	no
17	1.5226	1.5300	1.5374	1.5256	1.5320	1.5384	0.13%	yes	39.088	39.116	39.144	38.753	39.054	39.355	-0.16%	yes	43.548	43.769	43.990	44.107	44.601	45.097	1.90%	no
18	1.5192	1.5266	1.5340	1.5212	1.5276	1.5341	0.07%	yes	39.203	39.268	39.333	38.539	38.841	39.142	-1.09%	no	43.345	43.565	43.785	42.729	43.203	43.678	-0.83%	yes

Mono 6B-- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.7743	3.0826	3.3909	3.0646	3.0767	3.0890	-0.19%	yes	40.217	40.246	40.275	40.144	40.438	40.731	0.48%	yes	89.243	89.634	90.024	87.224	88.146	89.071	-1.66%	no
2	2.7542	3.0602	3.3662	3.0492	3.0617	3.0742	0.05%	yes	39.793	39.824	39.856	39.686	39.979	40.272	0.39%	yes	87.150	87.532	87.914	87.626	88.588	89.553	1.21%	yes
3	2.7465	3.0517	3.3569	3.0386	3.0511	3.0637	-0.02%	yes	40.060	40.090	40.120	39.980	40.273	40.566	0.46%	yes	87.851	88.236	88.621	87.884	88.851	89.822	0.70%	yes
4	2.7741	3.0823	3.3905	3.0714	3.0839	3.0965	0.05%	yes	39.856	39.886	39.916	39.763	40.056	40.349	0.43%	yes	86.752	87.133	87.513	87.214	88.161	89.111	1.18%	yes
5	2.7680	3.0755	3.3831	3.0625	3.0750	3.0875	-0.02%	yes	40.216	40.246	40.276	40.137	40.430	40.723	0.46%	yes	89.013	89.403	89.792	89.028	89.998	90.972	0.67%	yes
6	2.7491	3.0546	3.3601	3.0432	3.0557	3.0684	0.04%	yes	39.999	40.030	40.060	39.887	40.180	40.473	0.37%	yes	87.576	87.960	88.344	88.016	88.986	89.960	1.17%	yes
7	2.7495	3.0550	3.3605	3.0398	3.0522	3.0647	-0.09%	yes	40.067	40.098	40.129	39.907	40.200	40.494	0.26%	yes	88.316	88.703	89.090	87.478	88.436	89.397	-0.30%	yes
8	2.8013	3.1125	3.4238	3.0967	3.1092	3.1217	-0.11%	yes	39.909	39.940	39.970	39.758	40.051	40.344	0.28%	yes	88.937	89.326	89.715	87.860	88.813	89.769	-0.57%	yes
9	3.0354	3.0484	3.0614	3.0375	3.0501	3.0628	0.06%	yes	39.708	39.737	39.767	39.594	39.888	40.181	0.38%	yes	86.884	87.265	87.646	87.414	88.390	89.368	1.29%	yes
10	3.0355	3.0486	3.0617	3.0348	3.0475	3.0602	-0.04%	yes	26.573	26.597	26.622	26.837	27.129	27.421	2.00%	no	57.452	57.703	57.955	57.931	58.847	59.766	1.98%	yes
11	3.0166	3.0296	3.0426	3.0186	3.0312	3.0439	0.05%	yes	40.002	40.031	40.059	39.826	40.119	40.412	0.22%	yes	87.115	87.498	87.880	87.590	88.557	89.527	1.21%	yes
12	3.0299	3.0429	3.0559	3.0328	3.0454	3.0582	0.08%	yes	39.930	39.958	39.986	39.797	40.090	40.383	0.33%	yes	86.100	86.478	86.857	86.835	87.784	88.737	1.51%	yes
13	3.0460	3.0591	3.0722	3.0482	3.0608	3.0736	0.06%	yes	39.814	39.842	39.870	39.617	39.910	40.203	0.17%	yes	87.000	87.382	87.763	87.490	88.457	89.427	1.23%	yes
14	3.0356	3.0486	3.0616	3.0371	3.0498	3.0625	0.04%	yes	39.878	39.907	39.935	39.706	40.000	40.293	0.23%	yes	87.241	87.623	88.006	87.700	88.672	89.647	1.20%	yes
15	3.0260	3.0390	3.0520	3.0278	3.0404	3.0530	0.04%	yes	39.670	39.698	39.726	39.461	39.754	40.047	0.14%	yes	85.833	86.210	86.586	86.165	87.119	88.076	1.05%	yes
16	2.9978	3.0107	3.0236	2.9979	3.0105	3.0232	-0.01%	yes	39.707	39.735	39.762	39.439	39.732	40.025	-0.01%	yes	86.260	86.638	87.017	85.998	86.958	87.921	0.37%	yes
17	3.0534	3.0666	3.0798	3.0540	3.0666	3.0793	0.00%	yes	39.248	39.276	39.303	38.959	39.252	39.545	-0.06%	yes	85.781	86.157	86.533	85.503	86.459	87.418	0.35%	yes
18	2.9840	2.9969	3.0098	2.9821	2.9945	3.0071	-0.08%	yes	39.012	39.040	39.067	38.705	38.998	39.291	-0.11%	yes	81.917	82.277	82.638	80.841	81.740	82.642	-0.65%	yes

Poly 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.0332	2.2591	2.4850	2.2578	2.2627	2.2675	0.16%	yes	28.996	29.046	29.096	30.079	30.418	30.758	4.72%	no	45.115	45.322	45.530	47.742	48.442	49.142	6.88%	no
2	2.0376	2.2640	2.4904	2.2572	2.2621	2.2670	-0.08%	yes	29.279	29.325	29.370	30.589	30.929	31.268	5.47%	no	47.106	47.321	47.537	48.317	48.998	49.679	3.54%	no
3	1.9627	2.1808	2.3989	2.1742	2.1789	2.1837	-0.09%	yes	28.987	29.036	29.084	30.077	30.417	30.756	4.76%	no	45.890	46.101	46.312	47.080	47.777	48.474	3.63%	no
4	2.0066	2.2296	2.4526	2.2232	2.2280	2.2328	-0.07%	yes	29.160	29.209	29.257	30.136	30.476	30.816	4.34%	no	46.343	46.556	46.769	47.262	47.953	48.644	3.00%	no
5	1.9994	2.2215	2.4437	2.2200	2.2249	2.2297	0.15%	yes	28.946	29.003	29.059	29.955	30.295	30.635	4.46%	no	44.421	44.627	44.833	46.521	47.190	47.859	5.74%	no
6	1.9565	2.1739	2.3913	2.1704	2.1753	2.1803	0.06%	yes	28.355	28.404	28.452	29.449	29.789	30.128	4.88%	no	44.429	44.635	44.840	46.829	47.550	48.271	6.53%	no
7	2.0992	2.3324	2.5656	2.3432	2.3482	2.3533	0.68%	yes	28.751	28.789	28.828	29.963	30.302	30.641	5.25%	no	43.660	43.862	44.065	49.264	49.984	50.704	13.96%	no
8	1.9895	2.2106	2.4317	2.2062	2.2110	2.2159	0.02%	yes	28.683	28.718	28.752	29.740	30.080	30.419	4.74%	no	44.026	44.231	44.436	46.157	46.831	47.504	5.88%	no
9	1.8762	2.0847	2.2932	2.0799	2.0846	2.0894	0.00%	yes	28.111	28.147	28.183	29.157	29.497	29.837	4.80%	no	43.113	43.314	43.514	45.055	45.763	46.473	5.66%	no
10	1.8656	2.0729	2.2802	2.0674	2.0722	2.0770	-0.04%	yes	28.448	28.484	28.521	29.471	29.811	30.151	4.66%	no	43.292	43.494	43.695	44.903	45.607	46.313	4.86%	no
11	1.7043	1.8937	2.0831	1.8908	1.8970	1.9032	0.17%	yes	29.155	29.216	29.277	30.545	30.971	31.396	6.01%	no	39.076	39.263	39.450	42.002	42.779	43.557	8.96%	no
12	1.7715	1.9683	2.1651	1.9655	1.9717	1.9779	0.17%	yes	29.281	29.335	29.388	30.890	31.316	31.741	6.75%	no	40.404	40.597	40.789	43.547	44.324	45.101	9.18%	no
13	1.7925	1.9917	2.1909	1.9891	1.9953	2.0016	0.18%	yes	29.187	29.243	29.299	30.550	30.975	31.400	5.92%	no	39.223	39.411	39.598	41.215	41.915	42.613	6.35%	no
14	2.0250	2.2500	2.4750	2.2425	2.2488	2.2551	-0.05%	yes	30.102	30.136	30.170	31.366	31.791	32.215	5.49%	no	49.562	49.789	50.017	50.687	51.573	52.460	3.58%	no
15	1.7204	1.9116	2.1028	1.9061	1.9122	1.9183	0.03%	yes	29.157	29.216	29.275	30.376	30.801	31.226	5.43%	no	40.047	40.237	40.428	41.723	42.491	43.259	5.60%	no
16	1.6694	1.8549	2.0404	1.8495	1.8557	1.8619	0.04%	yes	28.427	28.454	28.481	29.817	30.242	30.667	6.28%	no	38.704	38.889	39.074	41.182	41.982	42.783	7.95%	no
17	1.6826	1.8696	2.0566	1.8644	1.8706	1.8768	0.05%	yes	28.699	28.729	28.758	30.042	30.468	30.892	6.05%	no	39.366	39.554	39.742	41.830	42.638	43.448	7.80%	no
18	1.6830	1.8700	2.0570	1.8639	1.8700	1.8762	0.00%	yes	28.437	28.470	28.502	29.642	30.067	30.492	5.61%	no	38.530	38.714	38.898	40.103	40.868	41.635	5.56%	no
19	1.7932	1.9924	2.1916	1.9882	1.9945	2.0007	0.10%	yes	28.769	28.801	28.834	30.104	30.529	30.954	6.00%	no	39.278	39.465	39.652	40.940	41.655	42.368	5.55%	no
20	1.7650	1.9611	2.1572	1.9487	1.9547	1.9607	-0.33%	yes	28.982	29.015	29.047	30.046	30.472	30.898	5.02%	no	41.067	41.261	41.455	39.695	40.388	41.080	-2.12%	yes
21	1.9935	2.2150	2.4365	2.2080	2.2145	2.2210	-0.02%	yes	27.624	27.646	27.668	28.234	28.628	29.021	3.55%	no	42.722	42.920	43.118	43.408	44.218	45.029	3.02%	no
22	2.0264	2.2516	2.4768	2.2799	2.2863	2.2928	1.54%	yes	27.420	27.442	27.465	28.342	28.736	29.130	4.71%	no	36.713	36.887	37.061	43.405	44.173	44.941	19.75%	no
23	1.8826	2.0918	2.3010	2.0828	2.0890	2.0952	-0.13%	yes	27.224	27.246	27.267	27.866	28.260	28.655	3.72%	no	39.830	40.015	40.201	40.481	41.262	42.043	3.11%	no
24	1.9516	2.1684	2.3852	2.1583	2.1646	2.1709	-0.18%	yes	28.047	28.069	28.092	29.023	29.417	29.811	4.80%	no	41.963	42.158	42.352	42.078	42.811	43.544	1.55%	yes
25	1.9017	2.1130	2.3243	2.1049	2.1111	2.1174	-0.09%	yes	27.268	27.289	27.311	27.973	28.367	28.761	3.95%	no	40.422	40.610	40.798	41.047	41.828	42.610	3.00%	no
26	1.8884	2.0982	2.3080	2.0921	2.0984	2.1047	0.01%	yes	27.021	27.043	27.065	27.746	28.141	28.535	4.06%	no	39.775	39.961	40.146	40.948	41.732	42.518	4.43%	no
27	1.8385	2.0428	2.2471	2.0381	2.0444	2.0507	0.08%	yes	26.702	26.732	26.761	27.455	27.849	28.243	4.18%	no	38.828	39.009	39.191	40.905	41.730	42.558	6.97%	no
28	2.0052	2.2280	2.4508	2.2231	2.2293	2.2355	0.06%	yes	27.136	27.166	27.196	27.935	28.329	28.723	4.28%	no	40.704	40.894	41.083	41.631	42.379	43.127	3.63%	no
29	2.0245	2.2494	2.4743	2.2382	2.2446	2.2509	-0.21%	yes	27.193	27.222	27.251	27.933	28.327	28.721	4.06%	no	41.421	41.612	41.803	40.947	41.679	42.411	0.16%	yes
30	2.1825	2.4250	2.6675	2.4133	2.4198	2.4262	-0.22%	yes	28.399	28.430	28.460	29.055	29.449	29.843	3.58%	no	43.990	44.192	44.393	42.545	43.214	43.880	-2.21%	no

Poly 1A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
11	3.1707	3.5230	3.8753	3.5156	3.5199	3.5243	-0.09%	yes	28.470	28.514	28.557	29.402	29.404	29.406	3.12%	no	69.298	69.631	69.965	71.676	71.765	71.853	3.06%	no
12	3.3012	3.6680	4.0348	3.6652	3.6695	3.6739	0.04%	yes	28.604	28.650	28.695	29.756	29.758	29.760	3.87%	no	71.347	71.689	72.031	74.987	75.076	75.166	4.73%	no
13	3.2706	3.6340	3.9974	3.6276	3.6319	3.6362	-0.06%	yes	28.438	28.485	28.532	29.377	29.379	29.381	3.14%	no	67.967	68.296	68.625	69.578	69.661	69.744	2.00%	no
14	3.7800	4.2000	4.6200	4.1960	4.2005	4.2049	0.01%	yes	29.312	29.347	29.382	30.246	30.247	30.249	3.07%	no	84.538	84.931	85.324	87.720	87.814	87.908	3.39%	no
15	3.2193	3.5770	3.9347	3.5676	3.5720	3.5763	-0.14%	yes	28.367	28.414	28.461	29.240	29.242	29.244	2.91%	no	69.980	70.316	70.652	71.734	71.820	71.907	2.14%	no
16	3.1258	3.4731	3.8204	3.4682	3.4726	3.4770	-0.01%	yes	27.674	27.703	27.732	28.677	28.679	28.681	3.52%	no	67.473	67.798	68.123	70.796	70.886	70.976	4.55%	no
17	3.1353	3.4837	3.8321	3.4784	3.4828	3.4872	-0.03%	yes	27.917	27.944	27.971	28.897	28.899	28.901	3.42%	no	68.622	68.952	69.283	71.447	71.537	71.627	3.75%	no
18	3.1323	3.4803	3.8283	3.4714	3.4757	3.4801	-0.13%	yes	27.609	27.636	27.662	28.489	28.491	28.494	3.10%	no	66.561	66.882	67.204	68.348	68.433	68.519	2.32%	no
19	3.3170	3.6855	4.0541	3.6808	3.6852	3.6896	-0.01%	yes	28.000	28.027	28.053	28.950	28.952	28.954	3.30%	no	67.702	68.028	68.355	69.955	70.038	70.121	2.95%	no
20	3.2364	3.5960	3.9556	3.5685	3.5726	3.5768	-0.65%	yes	28.101	28.128	28.155	28.873	28.875	28.877	2.65%	no	69.317	69.650	69.982	66.871	66.948	67.025	-3.88%	no
21	3.5722	3.9691	4.3660	3.9571	3.9621	3.9670	-0.18%	yes	27.414	27.441	27.468	27.879	27.881	27.884	1.60%	no	73.259	73.603	73.948	73.509	73.600	73.692	0.00%	yes
22	3.6266	4.0296	4.4326	4.0340	4.0389	4.0438	0.23%	yes	27.381	27.408	27.435	27.968	27.971	27.973	2.05%	no	69.934	70.265	70.596	72.996	73.084	73.172	4.01%	no
23	3.4382	3.8202	4.2022	3.8005	3.8054	3.8102	-0.39%	yes	27.014	27.048	27.081	27.537	27.539	27.541	1.82%	no	67.590	67.910	68.229	69.219	69.305	69.391	2.05%	no
24	3.5377	3.9308	4.3239	3.9102	3.9150	3.9198	-0.40%	yes	27.949	27.978	28.007	28.698	28.700	28.702	2.58%	no	72.266	72.607	72.948	72.251	72.339	72.428	-0.37%	yes
25	3.4782	3.8647	4.2512	3.8479	3.8527	3.8576	-0.31%	yes	27.095	27.124	27.153	27.648	27.650	27.652	1.94%	no	70.098	70.428	70.759	70.619	70.706	70.794	0.40%	yes
26	3.4414	3.8238	4.2062	3.8121	3.8170	3.8219	-0.18%	yes	26.816	26.843	26.870	27.412	27.414	27.417	2.13%	no	69.692	70.021	70.351	70.664	70.755	70.846	1.05%	no
27	3.3767	3.7519	4.1271	3.7467	3.7517	3.7566	-0.01%	yes	26.514	26.540	26.566	27.130	27.132	27.134	2.23%	no	68.323	68.646	68.970	70.907	71.000	71.093	3.43%	no
28	3.6529	4.0588	4.4647	4.0477	4.0525	4.0572	-0.16%	yes	26.971	26.997	27.024	27.604	27.606	27.608	2.25%	no	71.117	71.451	71.786	71.919	72.003	72.088	0.77%	no
29	3.6525	4.0583	4.4641	4.0378	4.0427	4.0475	-0.38%	yes	26.963	26.989	27.015	27.590	27.592	27.594	2.23%	no	69.502	69.829	70.156	69.551	69.633	69.715	-0.28%	yes
30	3.8700	4.3000	4.7300	4.2784	4.2832	4.2880	-0.39%	yes	28.152	28.196	28.241	28.703	28.705	28.707	1.81%	no	71.641	71.977	72.313	71.134	71.211	71.289	-1.06%	no

Poly 1A -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.0332	2.2591	2.4850	2.2507	2.2560	2.2614	-0.14%	yes	28.996	29.046	29.096	28.866	29.216	29.566	0.59%	yes	45.115	45.322	45.530	44.121	44.719	45.313	-1.33%	yes
2	2.0376	2.2640	2.4904	2.2501	2.2555	2.2609	-0.37%	yes	29.279	29.325	29.370	29.160	29.511	29.863	0.64%	yes	47.106	47.321	47.537	44.594	45.196	45.794	-4.49%	no
3	1.9627	2.1808	2.3989	2.1686	2.1738	2.1790	-0.32%	yes	28.987	29.036	29.084	29.069	29.418	29.766	1.32%	yes	45.890	46.101	46.312	43.894	44.483	45.068	-3.51%	no
4	2.0066	2.2296	2.4526	2.2165	2.2217	2.2270	-0.35%	yes	29.160	29.209	29.257	29.352	29.699	30.045	1.68%	no	46.343	46.556	46.769	44.506	45.092	45.675	-3.14%	no
5	1.9994	2.2215	2.4437	2.2124	2.2178	2.2231	-0.17%	yes	28.946	29.003	29.059	29.022	29.370	29.718	1.27%	yes	44.421	44.627	44.833	43.625	44.198	44.766	-0.96%	yes
6	1.9565	2.1739	2.3913	2.1655	2.1708	2.1761	-0.14%	yes	28.355	28.404	28.452	28.693	29.039	29.385	2.24%	no	44.429	44.635	44.840	43.762	44.337	44.906	-0.67%	yes
7	2.0992	2.3324	2.5656	2.3350	2.3407	2.3464	0.36%	yes	28.751	28.789	28.828	28.704	29.054	29.404	0.92%	yes	43.660	43.862	44.065	45.386	45.995	46.598	4.86%	no
8	1.9895	2.2106	2.4317	2.1987	2.2041	2.2094	-0.30%	yes	28.683	28.718	28.752	29.266	29.610	29.953	3.11%	no	44.026	44.231	44.436	43.988	44.550	45.108	0.72%	yes
9	1.8762	2.0847	2.2932	2.0763	2.0813	2.0864	-0.16%	yes	28.111	28.147	28.183	28.485	28.830	29.176	2.43%	no	43.113	43.314	43.514	42.149	42.703	43.251	-1.41%	yes
10	1.8656	2.0729	2.2802	2.0640	2.0691	2.0741	-0.19%	yes	28.448	28.484	28.521	28.887	29.232	29.577	2.62%	no	43.292	43.494	43.695	42.247	42.813	43.374	-1.57%	yes
11	1.7043	1.8937	2.0831	1.8861	1.8926	1.8992	-0.06%	yes	29.155	29.216	29.277	29.050	29.492	29.934	0.95%	yes	39.076	39.263	39.450	38.458	39.131	39.800	-0.33%	yes
12	1.7715	1.9683	2.1651	1.9599	1.9666	1.9733	-0.09%	yes	29.281	29.335	29.388	29.301	29.744	30.186	1.40%	yes	40.404	40.597	40.789	39.963	40.654	41.340	0.14%	yes
13	1.7925	1.9917	2.1909	1.9807	1.9877	1.9946	-0.20%	yes	29.187	29.243	29.299	29.143	29.584	30.024	1.17%	yes	39.223	39.411	39.598	38.291	38.927	39.558	-1.23%	yes
14	2.0250	2.2500	2.4750	2.2366	2.2434	2.2502	-0.29%	yes	30.102	30.136	30.170	30.159	30.596	31.034	1.53%	yes	49.562	49.789	50.017	47.299	48.083	48.861	-3.43%	no
15	1.7204	1.9116	2.1028	1.9007	1.9072	1.9138	-0.23%	yes	29.157	29.216	29.275	29.127	29.566	30.005	1.20%	yes	40.047	40.237	40.428	38.605	39.269	39.927	-2.41%	no
16	1.6694	1.8549	2.0404	1.8460	1.8525	1.8590	-0.13%	yes	28.427	28.454	28.481	28.680	29.118	29.555	2.33%	no	38.704	38.889	39.074	37.901	38.551	39.193	-0.87%	yes
17	1.6826	1.8696	2.0566	1.8611	1.8676	1.8741	-0.11%	yes	28.699	28.729	28.758	29.238	29.672	30.106	3.28%	no	39.366	39.554	39.742	39.095	39.755	40.408	0.51%	yes
18	1.6830	1.8700	2.0570	1.8585	1.8651	1.8717	-0.26%	yes	28.437	28.470	28.502	28.786	29.220	29.655	2.64%	no	38.530	38.714	38.898	37.425	38.056	38.680	-1.70%	yes
19	1.7932	1.9924	2.1916	1.9794	1.9864	1.9934	-0.30%	yes	28.769	28.801	28.834	28.791	29.230	29.670	1.49%	yes	39.278	39.465	39.652	37.977	38.610	39.238	-2.17%	no
20	1.7650	1.9611	2.1572	1.9399	1.9466	1.9533	-0.74%	yes	28.982	29.015	29.047	29.028	29.465	29.901	1.55%	yes	41.067	41.261	41.455	37.252	37.864	38.472	-8.23%	no
21	1.9935	2.2150	2.4365	2.2031	2.2101	2.2171	-0.22%	yes	27.624	27.646	27.668	27.805	28.204	28.601	2.02%	no	42.722	42.920	43.118	41.767	42.463	43.154	-1.06%	yes
22	2.0264	2.2516	2.4768	2.2733	2.2804	2.2876	1.28%	yes	27.420	27.442	27.465	26.534	26.945	27.357	-1.81%	no	36.713	36.887	37.061	39.602	40.306	41.005	9.27%	no
23	1.8826	2.0918	2.3010	2.0785	2.0852	2.0919	-0.32%	yes	27.224	27.246	27.267	26.890	27.294	27.698	0.18%	yes	39.830	40.015	40.201	37.920	38.594	39.264	-3.55%	no
24	1.9516	2.1684	2.3852	2.1528	2.1596	2.1665	-0.40%	yes	28.047	28.069	28.092	27.445	27.855	28.265	-0.76%	yes	41.963	42.158	42.352	38.897	39.576	40.251	-6.12%	no
25	1.9017	2.1130	2.3243	2.1005	2.1072	2.1139	-0.28%	yes	27.268	27.289	27.311	27.073	27.476	27.879	0.68%	yes	40.422	40.610	40.798	38.647	39.324	39.998	-3.17%	no
26	1.8884	2.0982	2.3080	2.0879	2.0946	2.1014	-0.17%	yes	27.021	27.043	27.065	26.743	27.147	27.551	0.38%	yes	39.775	39.961	40.146	38.347	39.023	39.694	-2.35%	no
27	1.8385	2.0428	2.2471	2.0362	2.0427	2.0492	-0.01%	yes	26.702	26.732	26.761	26.587	26.989	27.392	0.96%	yes	38.828	39.009	39.191	38.318	39.005	39.686	-0.01%	yes
28	2.0052	2.2280	2.4508	2.2165	2.2233	2.2302	-0.21%	yes	27.136	27.166	27.196	26.971	27.375	27.779	0.77%	yes	40.704	40.894	41.083	39.300	39.967	40.629	-2.27%	no
29	2.0245	2.2494	2.4743	2.2303	2.2375	2.2446	-0.53%	yes	27.193	27.222	27.251	26.911	27.315	27.719	0.34%	yes	41.421	41.612	41.803	38.514	39.165	39.811	-5.88%	no
30	2.1825	2.4250	2.6675	2.4033	2.4107	2.4181	-0.59%	yes	28.399	28.430	28.460	27.659	28.067	28.474	-1.28%	yes	43.990	44.192	44.393	39.864	40.495	41.121	-8.36%	no

Poly 1A -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
11	3.1707	3.5230	3.8753	3.5083	3.5126	3.5170	-0.29%	yes	28.470	28.514	28.557	28.649	28.653	28.656	0.49%	no	69.298	69.631	69.965	67.277	67.362	67.447	-3.26%	no
12	3.3012	3.6680	4.0348	3.6565	3.6609	3.6653	-0.19%	yes	28.604	28.650	28.695	28.964	28.968	28.971	1.11%	no	71.347	71.689	72.031	70.636	70.723	70.810	-1.35%	no
13	3.2706	3.6340	3.9974	3.6150	3.6193	3.6236	-0.41%	yes	28.438	28.485	28.532	28.658	28.662	28.665	0.62%	no	67.967	68.296	68.625	66.007	66.088	66.168	-3.23%	no
14	3.7800	4.2000	4.6200	4.1868	4.1912	4.1957	-0.21%	yes	29.312	29.347	29.382	29.658	29.661	29.664	1.07%	no	84.538	84.931	85.324	83.457	83.548	83.639	-1.63%	no
15	3.2193	3.5770	3.9347	3.5593	3.5636	3.5679	-0.38%	yes	28.367	28.414	28.461	28.611	28.615	28.618	0.70%	no	69.980	70.316	70.652	67.705	67.788	67.871	-3.60%	no
16	3.1258	3.4731	3.8204	3.4630	3.4674	3.4718	-0.16%	yes	27.674	27.703	27.732	28.110	28.114	28.117	1.48%	no	67.473	67.798	68.123	66.477	66.562	66.647	-1.82%	no
17	3.1353	3.4837	3.8321	3.4735	3.4779	3.4823	-0.17%	yes	27.917	27.944	27.971	28.494	28.497	28.500	1.98%	no	68.622	68.952	69.283	67.660	67.745	67.829	-1.75%	no
18	3.1323	3.4803	3.8283	3.4632	3.4676	3.4719	-0.37%	yes	27.609	27.636	27.662	28.058	28.061	28.064	1.54%	no	66.561	66.882	67.204	64.653	64.733	64.814	-3.21%	no
19	3.3170	3.6855	4.0541	3.6673	3.6717	3.6760	-0.38%	yes	28.000	28.027	28.053	28.296	28.299	28.303	0.97%	no	67.702	68.028	68.355	66.222	66.302	66.382	-2.54%	no
20	3.2364	3.5960	3.9556	3.5551	3.5592	3.5633	-1.02%	yes	28.101	28.128	28.155	28.338	28.341	28.344	0.76%	no	69.317	69.650	69.982	63.621	63.695	63.769	-8.55%	no
21	3.5722	3.9691	4.3660	3.9500	3.9549	3.9599	-0.36%	yes	27.414	27.441	27.468	27.666	27.668	27.671	0.83%	no	73.259	73.603	73.948	71.208	71.295	71.384	-3.14%	no
22	3.6266	4.0296	4.4326	4.0246	4.0295	4.0343	0.00%	yes	27.381	27.408	27.435	27.046	27.050	27.054	-1.30%	no	69.934	70.265	70.596	68.879	68.967	69.054	-1.85%	no
23	3.4382	3.8202	4.2022	3.7941	3.7989	3.8037	-0.56%	yes	27.014	27.048	27.081	27.046	27.050	27.053	0.01%	yes	67.590	67.910	68.229	65.988	66.071	66.155	-2.71%	no
24	3.5377	3.9308	4.3239	3.9018	3.9066	3.9114	-0.62%	yes	27.949	27.978	28.007	27.908	27.912	27.916	-0.24%	no	72.266	72.607	72.948	68.701	68.789	68.877	-5.26%	no
25	3.4782	3.8647	4.2512	3.8411	3.8459	3.8508	-0.49%	yes	27.095	27.124	27.153	27.198	27.201	27.204	0.29%	no	70.098	70.428	70.759	67.565	67.649	67.734	-3.95%	no
26	3.4414	3.8238	4.2062	3.8058	3.8107	3.8156	-0.34%	yes	26.816	26.843	26.870	26.911	26.914	26.918	0.26%	no	69.692	70.021	70.351	67.449	67.537	67.625	-3.55%	no
27	3.3767	3.7519	4.1271	3.7438	3.7488	3.7537	-0.08%	yes	26.514	26.540	26.566	26.701	26.704	26.707	0.62%	no	68.323	68.646	68.970	67.560	67.650	67.739	-1.45%	no
28	3.6529	4.0588	4.4647	4.0376	4.0424	4.0472	-0.40%	yes	26.971	26.997	27.024	27.117	27.120	27.123	0.45%	no	71.117	71.451	71.786	69.027	69.109	69.192	-3.28%	no
29	3.6525	4.0583	4.4641	4.0259	4.0307	4.0356	-0.68%	yes	26.963	26.989	27.015	27.081	27.084	27.087	0.35%	no	69.502	69.829	70.156	66.575	66.655	66.734	-4.55%	no
30	3.8700	4.3000	4.7300	4.2633	4.2681	4.2729	-0.74%	yes	28.152	28.196	28.241	28.011	28.014	28.018	-0.65%	no	71.641	71.977	72.313	68.128	68.204	68.281	-5.24%	no

Poly 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.3700	1.5222	1.6744	1.5104	1.5235	1.5368	0.09%	yes	17.546	18.200	18.854	18.358	18.482	18.607	1.55%	yes	19.287	19.386	19.486	19.749	19.965	20.183	2.99%	no
2	1.3099	1.4554	1.6009	1.4506	1.4634	1.4763	0.55%	yes	18.212	18.253	18.293	18.126	18.251	18.376	-0.01%	yes	17.773	17.867	17.961	19.186	19.405	19.626	8.61%	no
3	1.3566	1.5073	1.6580	1.4966	1.5097	1.5230	0.16%	yes	18.307	18.386	18.464	18.274	18.398	18.523	0.07%	yes	19.382	19.482	19.583	19.933	20.157	20.382	3.46%	no
4	1.3730	1.5256	1.6782	1.5165	1.5302	1.5440	0.30%	yes	18.240	18.263	18.285	18.139	18.264	18.388	0.01%	yes	19.391	19.491	19.591	20.480	20.719	20.960	6.30%	no
5	1.2637	1.4041	1.5445	1.3936	1.4061	1.4187	0.14%	yes	18.221	18.240	18.259	18.078	18.203	18.328	-0.20%	yes	17.998	18.093	18.189	18.160	18.364	18.570	1.50%	yes
6	1.3682	1.5202	1.6722	1.5127	1.5255	1.5384	0.35%	yes	18.388	18.442	18.497	18.288	18.412	18.537	-0.16%	yes	19.151	19.250	19.349	20.011	20.233	20.456	5.11%	no
7	1.3638	1.5153	1.6668	1.5088	1.5222	1.5357	0.45%	yes	18.249	18.338	18.426	18.156	18.281	18.405	-0.31%	yes	18.924	19.023	19.121	20.031	20.258	20.487	6.50%	no
8	1.2767	1.4185	1.5604	1.4166	1.4293	1.4421	0.76%	yes	18.035	18.153	18.272	17.940	18.065	18.190	-0.49%	yes	16.882	16.973	17.063	18.588	18.802	19.017	10.78%	no
9	1.3533	1.5037	1.6541	1.4967	1.5097	1.5228	0.40%	yes	18.290	18.392	18.493	18.258	18.383	18.508	-0.05%	yes	18.988	19.086	19.184	20.064	20.291	20.520	6.32%	no
10	1.4349	1.5943	1.7537	1.5878	1.6013	1.6151	0.44%	yes	18.447	18.548	18.649	18.661	18.785	18.910	1.28%	no	19.953	20.055	20.156	21.224	21.453	21.683	6.97%	no
11	1.3088	1.4542	1.5996	1.4420	1.4545	1.4671	0.02%	yes	18.557	18.576	18.594	18.415	18.540	18.664	-0.19%	yes	19.592	19.693	19.794	19.525	19.744	19.965	0.26%	yes
12	1.3316	1.4795	1.6275	1.4716	1.4845	1.4976	0.34%	yes	18.197	18.215	18.232	18.091	18.216	18.340	0.01%	yes	18.449	18.546	18.642	19.270	19.487	19.706	5.08%	no
13	1.4233	1.5814	1.7395	1.5741	1.5872	1.6005	0.37%	yes	18.490	18.508	18.526	18.486	18.611	18.735	0.55%	yes	19.769	19.870	19.971	20.565	20.784	21.003	4.60%	no
14	1.4132	1.4202	1.4272	1.4094	1.4220	1.4347	0.12%	yes	18.236	18.254	18.272	17.973	18.098	18.222	-0.86%	no	18.296	18.392	18.489	18.467	18.679	18.891	1.56%	yes
15	1.4459	1.4530	1.4601	1.4436	1.4564	1.4694	0.24%	yes	18.348	18.366	18.384	18.167	18.292	18.417	-0.40%	yes	18.730	18.827	18.925	19.424	19.649	19.875	4.36%	no

Poly 2A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	3.6077	4.0085	4.4094	3.9600	3.9942	4.0288	-0.36%	yes	18.259	18.316	18.373	18.365	18.488	18.612	0.94%	yes	49.588	49.821	50.054	48.990	49.542	50.096	-0.56%	yes
2	3.5239	3.9154	4.3069	3.8774	3.9112	3.9455	-0.11%	yes	18.338	18.361	18.383	18.143	18.267	18.390	-0.51%	yes	48.696	48.926	49.155	48.476	49.041	49.609	0.24%	yes
3	3.5779	3.9754	4.3729	3.9338	3.9682	4.0030	-0.18%	yes	18.454	18.477	18.499	18.279	18.403	18.527	-0.40%	yes	50.704	50.942	51.181	49.947	50.519	51.094	-0.83%	yes
4	3.5681	3.9645	4.3610	3.9269	3.9621	3.9977	-0.06%	yes	18.275	18.297	18.319	18.130	18.253	18.377	-0.24%	yes	50.210	50.446	50.682	50.281	50.878	51.480	0.86%	yes
5	3.4602	3.8447	4.2292	3.8033	3.8371	3.8713	-0.20%	yes	18.316	18.338	18.360	18.110	18.234	18.358	-0.57%	yes	48.303	48.532	48.762	47.365	47.907	48.452	-1.29%	yes
6	3.6664	4.0738	4.4812	4.0315	4.0654	4.0997	-0.21%	yes	18.489	18.551	18.614	18.306	18.430	18.553	-0.66%	yes	51.226	51.465	51.704	50.528	51.101	51.677	-0.71%	yes
7	3.5798	3.9776	4.3754	3.9405	3.9752	4.0103	-0.06%	yes	18.338	18.417	18.497	18.154	18.278	18.402	-0.76%	yes	50.073	50.309	50.544	49.861	50.438	51.018	0.26%	yes
8	3.4664	3.8515	4.2367	3.8194	3.8533	3.8877	0.05%	yes	18.170	18.273	18.375	17.959	18.083	18.207	-1.04%	yes	47.686	47.913	48.139	47.833	48.392	48.955	1.00%	yes
9	3.5960	3.9956	4.3952	3.9575	3.9918	4.0264	-0.10%	yes	18.369	18.458	18.547	18.269	18.392	18.516	-0.35%	yes	50.455	50.692	50.928	50.424	51.006	51.591	0.62%	yes
10	3.7147	4.1274	4.5401	4.0908	4.1256	4.1608	-0.04%	yes	18.559	18.645	18.732	18.660	18.783	18.906	0.74%	yes	51.489	51.730	51.971	52.094	52.667	53.244	1.81%	no
11	3.5702	3.9669	4.3636	3.9208	3.9546	3.9888	-0.31%	yes	18.716	18.742	18.768	18.451	18.575	18.699	-0.89%	no	52.097	52.341	52.585	50.516	51.094	51.675	-2.38%	no
12	3.5543	3.9492	4.3441	3.9087	3.9429	3.9776	-0.16%	yes	18.335	18.358	18.381	18.102	18.225	18.349	-0.72%	yes	49.379	49.612	49.845	48.678	49.238	49.802	-0.75%	yes
13	3.7557	4.1730	4.5903	4.1311	4.1653	4.1999	-0.18%	yes	18.658	18.681	18.705	18.497	18.620	18.744	-0.33%	yes	52.216	52.460	52.704	51.461	52.020	52.582	-0.84%	yes
14	3.8262	3.8437	3.8612	3.8050	3.8388	3.8730	-0.13%	yes	18.246	18.269	18.291	17.993	18.117	18.241	-0.83%	no	48.159	48.387	48.615	47.529	48.083	48.641	-0.63%	yes
15	3.9048	3.9226	3.9404	3.8830	3.9174	3.9522	-0.13%	yes	18.359	18.381	18.404	18.189	18.313	18.437	-0.37%	yes	49.940	50.175	50.410	49.617	50.201	50.788	0.05%	yes

Poly 3A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.1380	2.1476	2.1572	2.1383	2.1507	2.1632	0.15%	yes	36.278	36.480	36.682	36.022	36.259	36.495	-0.61%	yes	60.214	60.492	60.771	61.815	62.502	63.193	3.32%	no
2	2.0614	2.0707	2.0800	2.0609	2.0732	2.0857	0.12%	yes	36.353	36.400	36.447	35.793	36.030	36.266	-1.02%	no	57.893	58.163	58.433	59.583	60.257	60.935	3.60%	no
3	2.1358	2.1454	2.1550	2.1374	2.1499	2.1626	0.21%	yes	36.450	36.480	36.509	36.266	36.503	36.739	0.06%	yes	59.318	59.593	59.868	62.446	63.141	63.841	5.95%	no
4	2.5239	2.5350	2.5461	2.5194	2.5373	2.5554	0.09%	yes	36.431	36.458	36.484	35.849	36.134	36.420	-0.89%	no	71.827	72.149	72.471	72.398	73.393	74.397	1.72%	yes
5	2.5768	2.5882	2.5996	2.5731	2.5913	2.6097	0.12%	yes	36.460	36.486	36.513	35.862	36.147	36.432	-0.93%	no	73.064	73.390	73.717	73.980	74.996	76.021	2.19%	no
6	2.5157	2.5268	2.5379	2.5103	2.5278	2.5456	0.04%	yes	25.037	25.058	25.079	25.999	26.282	26.565	4.89%	no	47.888	48.103	48.318	50.274	51.147	52.026	6.33%	no
7	2.6511	2.6629	2.6747	2.6507	2.6696	2.6887	0.25%	yes	36.370	36.396	36.422	35.811	36.095	36.380	-0.83%	yes	72.875	73.200	73.526	76.412	77.468	78.532	5.83%	no
8	2.6697	2.6813	2.6929	2.6669	2.6835	2.7003	0.08%	yes	36.336	36.362	36.388	35.892	36.156	36.419	-0.57%	yes	75.732	76.069	76.405	76.334	77.274	78.220	1.58%	yes
9	2.6832	2.6949	2.7066	2.6816	2.6983	2.7152	0.13%	yes	36.393	36.420	36.446	35.922	36.185	36.449	-0.64%	yes	75.168	75.503	75.837	77.017	77.967	78.923	3.26%	no
10	2.7331	2.7452	2.7573	2.7335	2.7507	2.7679	0.20%	yes	36.498	36.524	36.550	36.053	36.316	36.580	-0.57%	yes	76.501	76.841	77.180	79.406	80.391	81.382	4.62%	no
11	2.6934	2.7051	2.7168	2.6921	2.7093	2.7267	0.16%	yes	36.137	36.163	36.189	35.699	35.962	36.226	-0.55%	yes	73.834	74.164	74.494	77.094	78.057	79.027	5.25%	no

Poly 3A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	4.3223	4.3419	4.3615	4.3159	4.3436	4.3715	0.04%	yes	35.134	35.177	35.221	34.725	35.014	35.302	-0.47%	yes	116.522	117.055	117.589	115.970	117.541	119.121	0.41%	yes
2	4.2026	4.2215	4.2404	4.1965	4.2244	4.2525	0.07%	yes	34.930	34.961	34.992	34.505	34.794	35.082	-0.48%	yes	112.759	113.278	113.796	112.851	114.404	115.966	0.99%	yes
3	4.2807	4.2999	4.3191	4.2746	4.3024	4.3305	0.06%	yes	35.315	35.346	35.376	34.959	35.248	35.536	-0.28%	yes	115.918	116.449	116.981	116.043	117.616	119.200	1.00%	yes

Poly 1B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.2044	1.3382	1.4720	1.3385	1.3408	1.3430	0.19%	yes	19.081	19.101	19.122	19.401	19.546	19.691	2.33%	no	17.788	17.883	17.978	18.540	18.719	18.899	4.68%	no
2	1.3187	1.4652	1.6117	1.4813	1.4838	1.4862	1.27%	yes	19.176	19.199	19.221	19.565	19.709	19.854	2.66%	no	17.474	17.568	17.663	20.230	20.418	20.607	16.22%	no
3	1.2268	1.3631	1.4994	1.3709	1.3732	1.3755	0.74%	yes	19.081	19.103	19.126	19.399	19.543	19.688	2.30%	no	17.018	17.110	17.203	18.548	18.724	18.900	9.43%	no
4	1.2242	1.3602	1.4962	1.3600	1.3623	1.3645	0.15%	yes	19.215	19.236	19.256	19.426	19.571	19.716	1.74%	no	17.652	17.747	17.843	17.677	17.835	17.994	0.50%	yes
5	1.2182	1.3536	1.4890	1.3571	1.3594	1.3617	0.43%	yes	19.099	19.120	19.140	19.371	19.516	19.661	2.08%	no	17.297	17.391	17.485	18.114	18.284	18.453	5.13%	no
6	1.1979	1.3310	1.4641	1.3267	1.3289	1.3311	-0.16%	yes	19.196	19.217	19.238	19.419	19.564	19.709	1.81%	no	16.957	17.049	17.141	16.620	16.769	16.918	-1.64%	no
7	1.2199	1.3554	1.4909	1.3573	1.3596	1.3619	0.31%	yes	19.189	19.208	19.228	19.500	19.644	19.789	2.27%	no	18.075	18.172	18.269	19.101	19.287	19.474	6.14%	no
8	1.2340	1.3711	1.5082	1.3709	1.3732	1.3755	0.15%	yes	19.393	19.411	19.429	19.613	19.758	19.903	1.79%	no	18.815	18.914	19.014	19.280	19.463	19.646	2.90%	no
9	1.2393	1.3770	1.5147	1.3819	1.3842	1.3864	0.52%	yes	19.182	19.200	19.218	19.475	19.621	19.766	2.19%	no	17.474	17.569	17.663	18.424	18.591	18.759	5.82%	no
10	1.2389	1.3765	1.5142	1.3821	1.3844	1.3867	0.57%	yes	19.001	19.019	19.037	19.405	19.550	19.695	2.79%	no	17.310	17.403	17.496	18.489	18.663	18.836	7.24%	no
11	1.1634	1.2927	1.4220	1.2912	1.2934	1.2957	0.06%	yes	19.182	19.200	19.217	19.452	19.597	19.742	2.07%	no	17.817	17.913	18.009	18.363	18.545	18.727	3.53%	no
12	1.2156	1.3507	1.4858	1.3530	1.3553	1.3576	0.34%	yes	19.164	19.182	19.200	19.433	19.578	19.723	2.07%	no	17.819	17.915	18.010	18.689	18.869	19.048	5.33%	no
13	1.2376	1.3751	1.5126	1.3821	1.3844	1.3867	0.68%	yes	19.049	19.067	19.085	19.381	19.526	19.671	2.41%	no	17.266	17.359	17.451	18.686	18.865	19.044	8.67%	no
14	1.2617	1.4019	1.5421	1.4136	1.4160	1.4184	1.01%	yes	9.146	9.164	9.181	10.325	10.469	10.612	14.24%	no	7.434	7.475	7.516	9.569	9.740	9.910	30.29%	no
15	1.2095	1.3439	1.4783	1.3526	1.3548	1.3569	0.81%	yes	19.319	19.342	19.364	19.532	19.677	19.822	1.74%	no	15.846	15.934	16.022	16.494	16.637	16.779	4.41%	no
16	1.1688	1.2987	1.4286	1.2972	1.2994	1.3017	0.06%	yes	19.188	19.209	19.229	19.455	19.601	19.746	2.04%	no	17.470	17.565	17.659	17.797	17.968	18.139	2.30%	no
17	1.2184	1.3538	1.4892	1.3532	1.3555	1.3577	0.12%	yes	18.914	18.936	18.957	19.349	19.494	19.639	2.95%	no	17.198	17.290	17.382	17.728	17.894	18.061	3.49%	no
18	1.1742	1.3047	1.4352	1.3052	1.3074	1.3097	0.21%	yes	19.028	19.048	19.067	19.296	19.441	19.586	2.07%	no	17.725	17.820	17.915	18.711	18.900	19.088	6.06%	no
19	1.2241	1.3601	1.4961	1.3636	1.3659	1.3683	0.43%	yes	19.017	19.038	19.058	19.495	19.640	19.785	3.16%	no	17.773	17.868	17.963	19.242	19.430	19.619	8.74%	no
20	1.2222	1.3580	1.4938	1.3590	1.3613	1.3636	0.24%	yes	19.167	19.186	19.204	19.620	19.765	19.909	3.02%	no	18.196	18.293	18.390	19.182	19.367	19.552	5.87%	no
21	1.2338	1.3709	1.5080	1.3678	1.3700	1.3722	-0.07%	yes	19.098	19.122	19.145	19.577	19.722	19.867	3.14%	no	18.710	18.808	18.907	18.997	19.178	19.358	1.96%	no

Poly 1B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.1457	2.3841	2.6225	2.3786	2.3827	2.3867	-0.06%	yes	18.851	18.873	18.895	18.908	19.055	19.201	0.96%	no	30.320	30.486	30.652	30.670	30.992	31.313	1.66%	no
2	2.2526	2.5029	2.7532	2.5108	2.5151	2.5193	0.49%	yes	18.956	18.979	19.001	19.031	19.177	19.323	1.05%	no	30.556	30.725	30.893	32.042	32.366	32.691	5.34%	no
3	2.1800	2.4222	2.6644	2.4216	2.4257	2.4298	0.14%	yes	18.866	18.888	18.911	18.901	19.047	19.193	0.84%	yes	29.968	30.134	30.299	30.466	30.781	31.096	2.15%	no
4	2.2093	2.4548	2.7003	2.4495	2.4535	2.4576	-0.05%	yes	18.948	18.971	18.993	18.948	19.094	19.240	0.65%	yes	29.999	30.165	30.331	29.767	30.059	30.351	-0.35%	yes
5	2.1595	2.3994	2.6393	2.3938	2.3979	2.4020	-0.06%	yes	18.846	18.868	18.890	18.872	19.019	19.165	0.80%	yes	29.788	29.952	30.117	29.769	30.073	30.376	0.40%	yes
6	2.1318	2.3687	2.6056	2.3408	2.3447	2.3486	-1.01%	yes	18.940	18.962	18.985	18.923	19.070	19.216	0.57%	yes	28.598	28.757	28.916	27.019	27.290	27.561	-5.10%	no
7	2.1678	2.4087	2.6496	2.4063	2.4104	2.4145	0.07%	yes	18.948	18.970	18.993	19.006	19.152	19.298	0.96%	no	31.007	31.177	31.347	31.502	31.833	32.166	2.11%	no
8	2.2060	2.4511	2.6962	2.4453	2.4493	2.4534	-0.07%	yes	19.187	19.210	19.233	19.125	19.272	19.418	0.32%	yes	32.412	32.588	32.764	32.200	32.529	32.859	-0.18%	yes
9	2.2199	2.4665	2.7132	2.4624	2.4664	2.4704	-0.01%	yes	19.124	19.147	19.169	18.986	19.133	19.279	-0.07%	yes	31.136	31.307	31.479	30.770	31.074	31.378	-0.75%	yes
10	2.1935	2.4372	2.6809	2.4336	2.4377	2.4418	0.02%	yes	18.957	18.981	19.004	18.905	19.051	19.197	0.37%	yes	30.198	30.364	30.530	30.301	30.610	30.920	0.81%	yes
11	2.0819	2.3132	2.5445	2.3054	2.3094	2.3135	-0.16%	yes	18.928	18.951	18.973	18.963	19.110	19.256	0.84%	yes	30.494	30.662	30.830	30.498	30.823	31.149	0.53%	yes
12	2.1595	2.3994	2.6393	2.3950	2.3991	2.4032	-0.01%	yes	18.926	18.949	18.972	18.937	19.083	19.230	0.71%	yes	30.686	30.855	31.023	30.874	31.194	31.514	1.10%	yes
13	2.1884	2.4315	2.6747	2.4304	2.4345	2.4386	0.12%	yes	18.822	18.859	18.895	18.880	19.026	19.172	0.89%	yes	29.960	30.126	30.291	30.457	30.775	31.093	2.15%	no
14	2.2176	2.4640	2.7104	2.4674	2.4715	2.4757	0.31%	yes	9.033	9.054	9.074	9.715	9.860	10.005	8.91%	no	13.268	13.342	13.417	14.796	15.098	15.399	13.16%	no
15	2.1506	2.3896	2.6286	2.3716	2.3754	2.3792	-0.59%	yes	19.097	19.120	19.142	19.034	19.181	19.327	0.32%	yes	27.459	27.614	27.768	26.601	26.863	27.123	-2.72%	no
16	2.1054	2.3393	2.5732	2.3298	2.3338	2.3379	-0.23%	yes	18.954	18.977	18.999	18.973	19.119	19.266	0.75%	yes	29.973	30.139	30.304	29.677	29.987	30.297	-0.50%	yes
17	2.1665	2.4072	2.6479	2.3983	2.4023	2.4063	-0.20%	yes	18.767	18.789	18.812	18.855	19.001	19.147	1.13%	no	28.615	28.773	28.930	29.008	29.309	29.609	1.86%	no
18	2.0951	2.3279	2.5607	2.3229	2.3270	2.3311	-0.04%	yes	18.830	18.852	18.875	18.802	18.949	19.095	0.51%	yes	30.803	30.972	31.141	31.055	31.390	31.726	1.35%	yes
19	2.1630	2.4033	2.6436	2.4011	2.4052	2.4094	0.08%	yes	18.901	18.923	18.945	18.995	19.141	19.287	1.15%	no	30.730	30.898	31.066	31.495	31.829	32.162	3.01%	no
20	2.1629	2.4032	2.6435	2.3983	2.4024	2.4065	-0.03%	yes	19.043	19.066	19.088	19.123	19.269	19.415	1.07%	no	31.226	31.396	31.567	31.513	31.842	32.171	1.42%	yes
21	2.1623	2.4025	2.6428	2.3875	2.3914	2.3953	-0.46%	yes	19.025	19.054	19.083	19.069	19.215	19.361	0.84%	yes	32.012	32.186	32.359	30.961	31.279	31.597	-2.82%	no

Poly 1B -- low irradiance (7P)

Module	Measured Isc (A) Low Bound	Measured Isc (A) Value	Measured Isc (A) High Bound	Modeled Isc (A) Low Bound	Modeled Isc (A) Value	Modeled Isc (A) High Bound	% Diff (Mod vs. Meas)	Isc in Agreement?	Measured Voc (V) Low Bound	Measured Voc (V) Value	Measured Voc (V) High Bound	Modeled Voc (V) Low Bound	Modeled Voc (V) Value	Modeled Voc (V) High Bound	% Diff (Mod vs. Meas)	Voc in Agreement?	Measured Pmax (W) Low Bound	Measured Pmax (W) Value	Measured Pmax (W) High Bound	Modeled Pmax (W) Low Bound	Modeled Pmax (W) Value	Modeled Pmax (W) High Bound	% Diff (Mod vs. Meas)	Pmax in Agreement?
1	1.2044	1.3382	1.4720	1.3363	1.3387	1.3411	0.03%	yes	19.081	19.101	19.122	18.560	18.711	18.861	-2.04%	no	17.788	17.883	17.978	17.362	17.529	17.696	-1.98%	no
2	1.3187	1.4652	1.6117	1.4783	1.4810	1.4836	1.08%	yes	19.176	19.199	19.221	18.800	18.949	19.099	-1.30%	no	17.474	17.568	17.663	19.080	19.256	19.432	9.61%	no
3	1.2268	1.3631	1.4994	1.3681	1.3705	1.3730	0.55%	yes	19.081	19.103	19.126	18.736	18.886	19.035	-1.14%	no	17.018	17.110	17.203	17.574	17.737	17.900	3.66%	no
4	1.2242	1.3602	1.4962	1.3568	1.3592	1.3616	-0.07%	yes	19.215	19.236	19.256	18.897	19.045	19.194	-0.99%	no	17.652	17.747	17.843	16.959	17.108	17.257	-3.60%	no
5	1.2182	1.3536	1.4890	1.3541	1.3566	1.3590	0.22%	yes	19.099	19.120	19.140	18.760	18.909	19.058	-1.10%	no	17.297	17.391	17.485	17.238	17.395	17.552	0.02%	yes
6	1.1979	1.3310	1.4641	1.3223	1.3247	1.3272	-0.47%	yes	19.196	19.217	19.238	18.830	18.979	19.128	-1.24%	no	16.957	17.049	17.141	15.836	15.974	16.111	-6.31%	no
7	1.2199	1.3554	1.4909	1.3552	1.3577	1.3601	0.17%	yes	19.189	19.208	19.228	19.032	19.180	19.328	-0.15%	yes	18.075	18.172	18.269	18.289	18.459	18.629	1.58%	no
8	1.2340	1.3711	1.5082	1.3689	1.3712	1.3736	0.01%	yes	19.393	19.411	19.429	19.040	19.189	19.338	-1.14%	no	18.815	18.914	19.014	18.402	18.572	18.742	-1.81%	no
9	1.2393	1.3770	1.5147	1.3791	1.3815	1.3838	0.32%	yes	19.182	19.200	19.218	18.834	18.984	19.133	-1.13%	no	17.474	17.569	17.663	17.559	17.718	17.876	0.85%	yes
10	1.2389	1.3765	1.5142	1.3791	1.3815	1.3840	0.36%	yes	19.001	19.019	19.037	18.425	18.576	18.727	-2.33%	no	17.310	17.403	17.496	17.207	17.370	17.534	-0.19%	yes
11	1.1634	1.2927	1.4220	1.2896	1.2919	1.2943	-0.06%	yes	19.182	19.200	19.217	18.824	18.973	19.122	-1.18%	no	17.817	17.913	18.009	17.400	17.567	17.734	-1.93%	no
12	1.2156	1.3507	1.4858	1.3507	1.3531	1.3555	0.18%	yes	19.164	19.182	19.200	18.730	18.880	19.029	-1.57%	no	17.819	17.915	18.010	17.671	17.838	18.004	-0.43%	yes
13	1.2376	1.3751	1.5126	1.3792	1.3817	1.3842	0.48%	yes	19.049	19.067	19.085	18.374	18.525	18.677	-2.84%	no	17.266	17.359	17.451	17.311	17.479	17.646	0.69%	yes
14	1.2617	1.4019	1.5421	1.3808	1.3863	1.3916	-1.11%	yes	9.146	9.164	9.181	10.253	10.397	10.541	13.46%	no	7.434	7.475	7.516	7.772	7.813	7.840	4.52%	no
15	1.2095	1.3439	1.4783	1.3473	1.3497	1.3522	0.44%	yes	19.319	19.342	19.364	18.715	18.866	19.016	-2.46%	no	15.846	15.934	16.022	15.534	15.668	15.802	-1.67%	no
16	1.1688	1.2987	1.4286	1.2949	1.2972	1.2996	-0.11%	yes	19.188	19.209	19.229	18.815	18.964	19.113	-1.27%	no	17.470	17.565	17.659	16.881	17.040	17.198	-2.99%	no
17	1.2184	1.3538	1.4892	1.3497	1.3522	1.3546	-0.12%	yes	18.914	18.936	18.957	18.372	18.523	18.675	-2.18%	no	17.198	17.290	17.382	16.469	16.625	16.781	-3.85%	no
18	1.1742	1.3047	1.4352	1.3038	1.3061	1.3085	0.11%	yes	19.028	19.048	19.067	18.618	18.767	18.917	-1.47%	no	17.725	17.820	17.915	17.650	17.822	17.993	0.01%	yes
19	1.2241	1.3601	1.4961	1.3616	1.3641	1.3665	0.29%	yes	19.017	19.038	19.058	18.535	18.687	18.838	-1.84%	no	17.773	17.868	17.963	17.862	18.038	18.212	0.95%	yes
20	1.2222	1.3580	1.4938	1.3569	1.3593	1.3618	0.10%	yes	19.167	19.186	19.204	18.870	19.020	19.169	-0.87%	yes	18.196	18.293	18.390	18.073	18.245	18.417	-0.26%	yes
21	1.2338	1.3709	1.5080	1.3655	1.3679	1.3702	-0.22%	yes	19.098	19.122	19.145	18.702	18.853	19.003	-1.41%	no	18.710	18.808	18.907	17.798	17.968	18.137	-4.47%	no

Poly 1B -- med irradiance (7P)

Module	Measured Isc (A) Low Bound	Measured Isc (A) Value	Measured Isc (A) High Bound	Modeled Isc (A) Low Bound	Modeled Isc (A) Value	Modeled Isc (A) High Bound	% Diff (Mod vs. Meas)	Isc in Agreement?	Measured Voc (V) Low Bound	Measured Voc (V) Value	Measured Voc (V) High Bound	Modeled Voc (V) Low Bound	Modeled Voc (V) Value	Modeled Voc (V) High Bound	% Diff (Mod vs. Meas)	Voc in Agreement?	Measured Pmax (W) Low Bound	Measured Pmax (W) Value	Measured Pmax (W) High Bound	Modeled Pmax (W) Low Bound	Modeled Pmax (W) Value	Modeled Pmax (W) High Bound	% Diff (Mod vs. Meas)	Pmax in Agreement?
1	2.1457	2.3841	2.6225	2.3744	2.3788	2.3833	-0.22%	yes	18.851	18.873	18.895	18.441	18.591	18.740	-1.50%	no	30.320	30.486	30.652	29.287	29.562	29.835	-3.03%	no
2	2.2526	2.5029	2.7532	2.5057	2.5104	2.5151	0.30%	yes	18.956	18.979	19.001	18.602	18.752	18.901	-1.20%	no	30.556	30.725	30.893	30.752	31.033	31.313	1.00%	yes
3	2.1800	2.4222	2.6644	2.4163	2.4209	2.4255	-0.05%	yes	18.866	18.888	18.911	18.536	18.685	18.834	-1.08%	no	29.968	30.134	30.299	29.296	29.564	29.830	-1.89%	no
4	2.2093	2.4548	2.7003	2.4431	2.4477	2.4523	-0.29%	yes	18.948	18.971	18.993	18.660	18.809	18.957	-0.85%	yes	29.999	30.165	30.331	28.868	29.122	29.376	-3.46%	no
5	2.1595	2.3994	2.6393	2.3883	2.3928	2.3974	-0.27%	yes	18.846	18.868	18.890	18.534	18.683	18.831	-0.98%	no	29.788	29.952	30.117	28.706	28.966	29.225	-3.29%	no
6	2.1318	2.3687	2.6056	2.3324	2.3370	2.3416	-1.34%	yes	18.940	18.962	18.985	18.592	18.741	18.890	-1.17%	no	28.598	28.757	28.916	26.022	26.250	26.478	-8.72%	no
7	2.1678	2.4087	2.6496	2.4025	2.4069	2.4114	-0.07%	yes	18.948	18.970	18.993	18.748	18.896	19.044	-0.39%	yes	31.007	31.177	31.347	30.481	30.760	31.038	-1.34%	yes
8	2.2060	2.4511	2.6962	2.4413	2.4458	2.4502	-0.22%	yes	19.187	19.210	19.233	18.809	18.957	19.106	-1.32%	no	32.412	32.588	32.764	31.129	31.414	31.698	-3.60%	no
9	2.2199	2.4665	2.7132	2.4569	2.4614	2.4659	-0.21%	yes	19.124	19.147	19.169	18.629	18.778	18.927	-1.92%	no	31.136	31.307	31.479	29.724	29.991	30.257	-4.20%	no
10	2.1935	2.4372	2.6809	2.4280	2.4325	2.4371	-0.19%	yes	18.957	18.981	19.004	18.359	18.509	18.660	-2.48%	no	30.198	30.364	30.530	28.828	29.096	29.362	-4.18%	no
11	2.0819	2.3132	2.5445	2.3023	2.3066	2.3109	-0.29%	yes	18.928	18.951	18.973	18.615	18.763	18.912	-0.99%	no	30.494	30.662	30.830	29.322	29.597	29.870	-3.47%	no
12	2.1595	2.3994	2.6393	2.3907	2.3951	2.3996	-0.18%	yes	18.926	18.949	18.972	18.547	18.696	18.845	-1.33%	no	30.686	30.855	31.023	29.663	29.937	30.211	-2.97%	no
13	2.1884	2.4315	2.6747	2.4250	2.4296	2.4342	-0.08%	yes	18.822	18.859	18.895	18.323	18.474	18.624	-2.04%	no	29.960	30.126	30.291	28.887	29.158	29.427	-3.21%	no
14	2.2176	2.4640	2.7104	2.4229	2.4325	2.4417	-1.28%	yes	9.033	9.054	9.074	9.675	9.821	9.966	8.47%	no	13.268	13.342	13.417	12.574	12.635	12.672	-5.30%	no
15	2.1506	2.3896	2.6286	2.3616	2.3663	2.3709	-0.98%	yes	19.097	19.120	19.142	18.571	18.721	18.871	-2.08%	no	27.459	27.614	27.768	25.420	25.641	25.861	-7.14%	no
16	2.1054	2.3393	2.5732	2.3253	2.3297	2.3341	-0.41%	yes	18.954	18.977	18.999	18.618	18.767	18.916	-1.10%	no	29.973	30.139	30.304	28.548	28.811	29.073	-4.41%	no
17	2.1665	2.4072	2.6479	2.3917	2.3963	2.4009	-0.45%	yes	18.767	18.789	18.812	18.313	18.464	18.614	-1.73%	no	28.615	28.773	28.930	27.534	27.789	28.042	-3.42%	no
18	2.0951	2.3279	2.5607	2.3203	2.3246	2.3289	-0.14%	yes	18.830	18.852	18.875	18.426	18.575	18.724	-1.47%	no	30.803	30.972	31.141	29.779	30.060	30.341	-2.94%	no
19	2.1630	2.4033	2.6436	2.3975	2.4019	2.4064	-0.06%	yes	18.901	18.923	18.945	18.463	18.613	18.763	-1.64%	no	30.730	30.898	31.066	29.921	30.205	30.487	-2.24%	no
20	2.1629	2.4032	2.6435	2.3945	2.3990	2.4034	-0.18%	yes	19.043	19.066	19.088	18.705	18.855	19.004	-1.11%	no	31.226	31.396	31.567	30.208	30.489	30.769	-2.89%	no
21	2.1623	2.4025	2.6428	2.3833	2.3876	2.3919	-0.62%	yes	19.025	19.054	19.083	18.565	18.715	18.865	-1.78%	no	32.012	32.186	32.359	29.568	29.845	30.121	-7.27%	no

Poly 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0266	1.1407	1.2548	1.1360	1.1406	1.1452	-0.01%	yes	19.319	19.337	19.355	19.579	19.728	19.878	2.02%	no	16.803	16.897	16.992	17.181	17.378	17.576	2.84%	no
2	1.0226	1.1362	1.2498	1.1319	1.1365	1.1411	0.03%	yes	19.242	19.260	19.278	19.486	19.635	19.784	1.95%	no	16.395	16.487	16.580	16.787	16.978	17.169	2.98%	no
3	1.0229	1.1365	1.2502	1.1325	1.1371	1.1417	0.06%	yes	19.307	19.325	19.343	19.537	19.687	19.836	1.87%	no	16.496	16.589	16.682	17.096	17.293	17.490	4.24%	no
4	1.0765	1.1961	1.3157	1.1917	1.1962	1.2008	0.01%	yes	19.573	19.591	19.609	19.717	19.867	20.016	1.41%	no	17.513	17.610	17.706	17.696	17.891	18.087	1.60%	yes
5	1.0132	1.1258	1.2384	1.1211	1.1257	1.1302	-0.01%	yes	19.266	19.284	19.302	19.500	19.649	19.798	1.89%	no	16.534	16.627	16.720	16.796	16.988	17.181	2.17%	no
6	1.0187	1.1319	1.2451	1.1278	1.1324	1.1370	0.04%	yes	19.183	19.201	19.219	19.384	19.533	19.683	1.73%	no	16.290	16.383	16.475	16.727	16.919	17.112	3.27%	no
7	1.0166	1.1295	1.2425	1.1254	1.1300	1.1346	0.05%	yes	19.286	19.304	19.322	19.524	19.673	19.823	1.91%	no	16.510	16.603	16.696	17.020	17.216	17.413	3.69%	no
8	1.0068	1.1187	1.2306	1.1138	1.1183	1.1229	-0.03%	yes	19.321	19.339	19.357	19.527	19.677	19.826	1.74%	no	16.550	16.643	16.736	16.692	16.883	17.074	1.44%	yes
9	1.0148	1.1276	1.2404	1.1230	1.1275	1.1321	-0.01%	yes	19.353	19.371	19.389	19.628	19.777	19.926	2.10%	no	16.603	16.696	16.790	16.984	17.177	17.372	2.88%	no
10	1.0128	1.1253	1.2378	1.1210	1.1255	1.1301	0.02%	yes	19.302	19.320	19.337	19.677	19.826	19.976	2.62%	no	16.388	16.481	16.573	16.943	17.136	17.328	3.97%	no
11	1.0147	1.1274	1.2401	1.1232	1.1278	1.1324	0.03%	yes	19.294	19.312	19.330	19.758	19.907	20.057	3.08%	no	16.450	16.543	16.636	17.140	17.335	17.530	4.79%	no
12	1.0225	1.1361	1.2497	1.1316	1.1361	1.1407	0.00%	yes	19.307	19.325	19.343	19.589	19.739	19.888	2.14%	no	16.585	16.678	16.771	16.976	17.169	17.362	2.94%	no
13	1.0229	1.1366	1.2503	1.1316	1.1361	1.1406	-0.04%	yes	19.348	19.366	19.384	19.580	19.730	19.879	1.88%	no	16.657	16.751	16.844	16.771	16.959	17.147	1.24%	yes
14	1.0157	1.1285	1.2414	1.1240	1.1286	1.1331	0.01%	yes	19.356	19.374	19.392	19.620	19.769	19.919	2.04%	no	16.602	16.695	16.789	16.971	17.164	17.358	2.81%	no
15	1.0745	1.1939	1.3133	1.1903	1.1949	1.1995	0.08%	yes	19.580	19.608	19.636	19.787	19.936	20.085	1.67%	no	17.397	17.493	17.589	17.997	18.199	18.401	4.03%	no
16	1.1196	1.1257	1.1318	1.1213	1.1259	1.1305	0.01%	yes	19.386	19.412	19.438	19.630	19.779	19.928	1.89%	no	16.694	16.788	16.882	17.135	17.332	17.530	3.24%	no
17	1.1685	1.1747	1.1809	1.1705	1.1751	1.1797	0.04%	yes	19.595	19.622	19.648	19.792	19.941	20.090	1.63%	no	17.347	17.443	17.540	17.789	17.989	18.190	3.13%	no
18	1.1240	1.1301	1.1362	1.1258	1.1303	1.1349	0.02%	yes	19.327	19.353	19.378	19.635	19.785	19.934	2.23%	no	16.481	16.574	16.667	16.982	17.175	17.369	3.63%	no
19	1.1372	1.1433	1.1494	1.1394	1.1439	1.1485	0.05%	yes	19.370	19.400	19.429	19.661	19.811	19.960	2.12%	no	16.565	16.658	16.751	17.123	17.316	17.510	3.95%	no
20	1.1127	1.1188	1.1249	1.1137	1.1182	1.1228	-0.05%	yes	19.345	19.373	19.400	19.611	19.760	19.910	2.00%	no	16.721	16.815	16.909	16.827	17.019	17.211	1.21%	yes
21	1.1266	1.1327	1.1388	1.1283	1.1328	1.1374	0.01%	yes	19.221	19.287	19.352	19.715	19.864	20.014	3.00%	no	16.567	16.660	16.754	17.054	17.246	17.439	3.52%	no

Poly 3B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0945	1.2161	1.3377	1.2068	1.2121	1.2174	-0.33%	yes	38.385	38.502	38.619	38.705	39.023	39.342	1.35%	no	33.580	33.765	33.950	32.197	32.577	32.958	-3.52%	no
2	1.0813	1.2014	1.3215	1.1969	1.2021	1.2074	0.06%	yes	38.377	38.495	38.614	38.555	38.873	39.192	0.98%	yes	33.616	33.804	33.992	33.944	34.359	34.775	1.64%	yes
3	1.0637	1.1819	1.3001	1.1743	1.1796	1.1848	-0.20%	yes	38.486	38.607	38.728	38.744	39.063	39.381	1.18%	no	33.580	33.767	33.953	32.577	32.971	33.366	-2.36%	no
4	1.0386	1.1540	1.2694	1.1506	1.1558	1.1611	0.16%	yes	38.569	38.690	38.810	38.902	39.221	39.540	1.37%	no	32.747	32.933	33.118	34.252	34.684	35.118	5.32%	no
5	1.0355	1.1505	1.2656	1.1453	1.1505	1.1557	0.00%	yes	38.282	38.404	38.525	38.595	38.913	39.232	1.33%	no	33.057	33.243	33.428	33.187	33.602	34.018	1.08%	yes
6	1.0707	1.1897	1.3087	1.1776	1.1826	1.1878	-0.59%	yes	38.290	38.435	38.580	38.623	38.942	39.261	1.32%	no	32.445	32.625	32.805	30.337	30.686	31.035	-5.94%	no
7	1.0587	1.1763	1.2939	1.1583	1.1631	1.1679	-1.12%	yes	38.150	38.310	38.469	38.443	38.762	39.081	1.18%	yes	29.844	30.013	30.182	24.782	24.998	25.213	-16.71%	no
8	1.0853	1.2059	1.3265	1.1938	1.1989	1.2041	-0.58%	yes	38.538	38.672	38.807	38.881	39.200	39.519	1.37%	no	31.707	31.884	32.061	28.037	28.311	28.584	-11.21%	no
9	1.0736	1.1929	1.3122	1.1762	1.1812	1.1862	-0.98%	yes	38.544	38.667	38.790	38.952	39.272	39.590	1.56%	no	32.344	32.524	32.705	26.267	26.501	26.733	-18.52%	no
10	1.0751	1.1945	1.3140	1.1878	1.1931	1.1984	-0.12%	yes	38.291	38.325	38.359	38.532	38.850	39.169	1.37%	no	33.433	33.618	33.803	33.086	33.490	33.896	-0.38%	yes
11	1.0666	1.1851	1.3036	1.1805	1.1859	1.1912	0.06%	yes	38.763	38.794	38.826	38.882	39.200	39.519	1.05%	no	34.409	34.600	34.791	35.111	35.553	35.998	2.75%	no
12	1.0499	1.1666	1.2833	1.1616	1.1669	1.1721	0.02%	yes	38.756	38.789	38.822	38.962	39.281	39.599	1.27%	no	33.773	33.961	34.149	34.267	34.698	35.131	2.17%	no
13	1.0703	1.1892	1.3081	1.1848	1.1902	1.1956	0.09%	yes	38.602	38.635	38.667	38.814	39.133	39.451	1.29%	no	34.161	34.350	34.540	35.185	35.634	36.085	3.74%	no
14	1.0616	1.1795	1.2975	1.1733	1.1785	1.1838	-0.08%	yes	38.664	38.699	38.734	38.894	39.213	39.532	1.33%	no	32.448	32.629	32.810	32.479	32.874	33.270	0.75%	yes
15	1.0888	1.2098	1.3308	1.2031	1.2084	1.2138	-0.11%	yes	38.741	38.774	38.807	38.997	39.316	39.634	1.40%	no	34.739	34.930	35.121	34.112	34.525	34.939	-1.16%	yes
16	1.1841	1.1904	1.1967	1.1848	1.1901	1.1955	-0.02%	yes	38.868	38.901	38.934	39.300	39.619	39.938	1.85%	no	33.950	34.138	34.326	34.407	34.830	35.254	2.03%	no
17	1.1981	1.2044	1.2107	1.1980	1.2033	1.2086	-0.09%	yes	38.779	38.809	38.838	39.125	39.444	39.762	1.64%	no	35.955	36.151	36.348	35.327	35.762	36.199	-1.08%	yes
18	1.1807	1.1870	1.1933	1.1820	1.1873	1.1926	0.02%	yes	38.807	38.840	38.873	39.196	39.514	39.833	1.74%	no	34.284	34.473	34.663	34.964	35.398	35.834	2.68%	no

Poly 3B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	3.1653	3.1809	3.1965	3.1372	3.1540	3.1708	-0.85%	yes	38.392	38.586	38.779	38.454	38.900	39.345	0.82%	yes	78.183	78.570	78.958	76.360	77.666	78.974	-1.15%	yes
2	3.2071	3.2223	3.2375	3.2054	3.2227	3.2401	0.01%	yes	38.346	38.504	38.662	38.349	38.795	39.240	0.76%	yes	85.880	86.305	86.729	85.737	87.200	88.668	1.04%	yes
3	3.1374	3.1524	3.1674	3.1223	3.1392	3.1563	-0.42%	yes	38.473	38.636	38.798	38.532	38.978	39.423	0.89%	yes	81.580	81.984	82.388	80.214	81.589	82.969	-0.48%	yes
4	3.1000	3.1148	3.1296	3.0987	3.1160	3.1334	0.04%	yes	38.615	38.767	38.920	38.712	39.158	39.603	1.01%	yes	86.442	86.870	87.298	87.204	88.727	90.258	2.14%	yes
5	3.0890	3.1038	3.1186	3.0825	3.0996	3.1168	-0.13%	yes	38.303	38.461	38.618	38.398	38.844	39.289	1.00%	yes	85.181	85.603	86.025	84.315	85.779	87.250	0.21%	yes
6	3.1531	3.1681	3.1831	3.1314	3.1478	3.1644	-0.64%	yes	38.300	38.523	38.745	38.424	38.869	39.314	0.90%	yes	73.737	74.106	74.476	73.179	74.412	75.646	0.41%	yes
7	3.1115	3.1264	3.1413	3.1228	3.1382	3.1537	0.38%	yes	38.189	38.447	38.706	38.293	38.739	39.184	0.76%	yes	63.467	63.799	64.131	62.663	63.494	64.317	-0.48%	yes
8	3.1476	3.1626	3.1776	3.1370	3.1534	3.1698	-0.29%	yes	38.506	38.695	38.884	38.669	39.115	39.560	1.09%	yes	71.216	71.578	71.941	69.260	70.247	71.228	-1.86%	yes
9	3.1386	3.1536	3.1686	3.0720	3.0878	3.1036	-2.09%	no	38.496	38.669	38.842	38.730	39.176	39.622	1.31%	yes	75.562	75.941	76.321	65.246	66.093	66.931	-12.97%	no
10	3.1689	3.1840	3.1991	3.1587	3.1758	3.1930	-0.26%	yes	38.358	38.391	38.424	38.315	38.760	39.205	0.96%	yes	82.262	82.669	83.075	81.685	83.096	84.513	0.52%	yes
11	3.1263	3.1412	3.1561	3.1219	3.1392	3.1566	-0.06%	yes	38.750	38.784	38.818	38.655	39.101	39.546	0.82%	yes	88.209	88.644	89.078	87.616	89.149	90.690	0.57%	yes
12	3.1202	3.1351	3.1500	3.1147	3.1319	3.1492	-0.10%	yes	38.835	38.868	38.900	38.765	39.211	39.656	0.88%	yes	86.244	86.670	87.095	85.834	87.342	88.858	0.78%	yes
13	3.1205	3.1354	3.1503	3.1177	3.1351	3.1526	-0.01%	yes	38.658	38.692	38.725	38.577	39.022	39.467	0.85%	yes	86.329	86.755	87.180	86.367	87.908	89.456	1.33%	yes
14	3.1201	3.1350	3.1499	3.1070	3.1239	3.1410	-0.35%	yes	38.721	38.755	38.789	38.680	39.126	39.571	0.96%	yes	78.369	78.758	79.148	78.400	79.768	81.141	1.28%	yes
15	3.1783	3.1934	3.2085	3.1739	3.1912	3.2086	-0.07%	yes	38.778	38.812	38.847	38.773	39.219	39.664	1.05%	yes	84.476	84.895	85.313	84.101	85.531	86.966	0.75%	yes
16	3.1494	3.1644	3.1794	3.1454	3.1627	3.1800	-0.06%	yes	39.012	39.047	39.082	39.094	39.540	39.985	1.26%	no	83.265	83.677	84.088	84.638	86.104	87.576	2.90%	no
17	3.1748	3.1901	3.2054	3.1653	3.1824	3.1996	-0.24%	yes	38.856	38.889	38.922	38.903	39.348	39.793	1.18%	yes	90.251	90.693	91.135	88.261	89.771	91.287	-1.02%	yes
18	3.1439	3.1589	3.1739	3.1387	3.1560	3.1734	-0.09%	yes	38.833	38.869	38.905	38.985	39.431	39.876	1.44%	no	87.158	87.588	88.017	87.199	88.707	90.223	1.28%	yes

Poly 4B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0868	1.0928	1.0988	1.0929	1.0956	1.0982	0.25%	yes	35.930	35.968	36.005	36.679	37.040	37.400	2.98%	no	27.715	27.877	28.039	29.875	30.293	30.712	8.67%	no
2	1.1046	1.1106	1.1166	1.1110	1.1136	1.1162	0.27%	yes	36.164	36.202	36.240	36.795	37.156	37.517	2.64%	no	27.918	28.082	28.246	30.119	30.533	30.948	8.73%	no
3	1.1322	1.1384	1.1446	1.1392	1.1418	1.1444	0.30%	yes	36.071	36.108	36.144	36.817	37.178	37.538	2.96%	no	28.652	28.817	28.982	30.872	31.295	31.719	8.60%	no
4	1.0854	1.0914	1.0974	1.0925	1.0951	1.0978	0.34%	yes	35.936	35.975	36.013	36.708	37.070	37.430	3.04%	no	27.363	27.523	27.684	29.866	30.283	30.701	10.03%	no
5	1.1110	1.1171	1.1232	1.1173	1.1199	1.1226	0.25%	yes	36.052	36.086	36.119	36.963	37.324	37.685	3.43%	no	28.302	28.465	28.629	30.634	31.058	31.483	9.11%	no
6	1.0848	1.0908	1.0968	1.0918	1.0944	1.0971	0.33%	yes	36.013	36.051	36.088	36.955	37.316	37.677	3.51%	no	27.353	27.514	27.674	29.930	30.344	30.760	10.29%	no
7	1.1236	1.1297	1.1358	1.1323	1.1350	1.1377	0.47%	yes	35.979	36.012	36.045	36.884	37.245	37.605	3.42%	no	27.881	28.044	28.206	31.105	31.538	31.973	12.46%	no
8	1.0894	1.0954	1.1014	1.0959	1.0985	1.1011	0.28%	yes	35.969	36.002	36.036	36.780	37.141	37.502	3.16%	no	27.803	27.965	28.128	30.305	30.731	31.158	9.89%	no
9	1.1005	1.1065	1.1125	1.1070	1.1096	1.1123	0.28%	yes	35.938	35.982	36.025	36.954	37.315	37.676	3.71%	no	27.776	27.937	28.099	30.128	30.540	30.954	9.32%	no

Poly 4B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.9168	2.9310	2.9452	2.9252	2.9336	2.9420	0.09%	yes	36.502	36.533	36.564	36.364	36.863	37.362	0.90%	yes	73.701	74.075	74.448	74.332	75.817	77.308	2.35%	yes
2	2.9629	2.9773	2.9917	2.9720	2.9804	2.9887	0.10%	yes	36.662	36.694	36.725	36.483	36.982	37.481	0.79%	yes	74.607	74.984	75.362	75.069	76.545	78.026	2.08%	yes
3	3.0165	3.0318	3.0471	3.0249	3.0332	3.0416	0.05%	yes	36.663	36.694	36.726	36.489	36.988	37.487	0.80%	yes	76.095	76.477	76.859	76.424	77.922	79.424	1.89%	yes
4	2.9270	2.9412	2.9554	2.9363	2.9447	2.9531	0.12%	yes	36.544	36.576	36.607	36.403	36.902	37.401	0.89%	yes	73.651	74.024	74.396	74.587	76.076	77.570	2.77%	no
5	2.9694	2.9838	2.9982	2.9771	2.9855	2.9939	0.06%	yes	36.703	36.735	36.766	36.645	37.144	37.643	1.12%	yes	74.819	75.195	75.572	75.657	77.157	78.662	2.61%	no
6	2.9092	2.9234	2.9376	2.9170	2.9254	2.9337	0.07%	yes	36.776	36.808	36.840	36.643	37.142	37.641	0.91%	yes	73.565	73.938	74.311	74.294	75.764	77.239	2.47%	yes
7	2.9459	2.9602	2.9745	2.9550	2.9633	2.9718	0.11%	yes	36.674	36.705	36.736	36.520	37.020	37.519	0.86%	yes	74.394	74.769	75.145	75.246	76.747	78.254	2.65%	no
8	2.9223	2.9365	2.9507	2.9310	2.9393	2.9477	0.10%	yes	36.658	36.690	36.721	36.465	36.965	37.464	0.75%	yes	74.747	75.125	75.502	75.392	76.902	78.418	2.37%	yes
9	2.9384	2.9527	2.9670	2.9447	2.9530	2.9614	0.01%	yes	36.748	36.779	36.811	36.632	37.132	37.631	0.96%	yes	74.438	74.815	75.191	74.670	76.132	77.598	1.76%	yes

Poly 5B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.5989	1.6066	1.6143	1.5952	1.6101	1.6251	0.22%	yes	55.330	55.388	55.446	55.855	56.373	56.891	1.78%	no	62.943	63.260	63.578	66.154	67.238	68.334	6.29%	no
2	1.6187	1.6265	1.6343	1.6150	1.6299	1.6451	0.21%	yes	55.421	55.474	55.526	55.986	56.504	57.021	1.86%	no	64.177	64.499	64.821	67.624	68.737	69.862	6.57%	no
3	1.5856	1.5932	1.6008	1.5818	1.5965	1.6114	0.21%	yes	54.998	55.060	55.123	55.473	55.992	56.510	1.69%	no	60.649	60.958	61.268	64.247	65.292	66.348	7.11%	no
4	1.5982	1.6059	1.6136	1.5930	1.6080	1.6231	0.13%	yes	53.949	54.000	54.050	54.479	54.997	55.514	1.85%	no	58.183	58.482	58.782	62.668	63.690	64.722	8.90%	no
5	1.6509	1.6588	1.6667	1.6474	1.6626	1.6780	0.23%	yes	54.953	55.007	55.062	55.455	55.972	56.489	1.75%	no	64.367	64.688	65.010	67.673	68.783	69.904	6.33%	no
6	1.5990	1.6067	1.6144	1.5952	1.6100	1.6250	0.20%	yes	54.326	54.387	54.448	54.706	55.224	55.742	1.54%	no	60.276	60.583	60.890	62.612	63.616	64.630	5.01%	no
7	1.6198	1.6276	1.6354	1.6162	1.6313	1.6466	0.23%	yes	55.087	55.162	55.236	55.607	56.124	56.642	1.75%	no	63.418	63.736	64.055	67.090	68.201	69.324	7.01%	no
8	1.5927	1.6004	1.6081	1.5876	1.6023	1.6172	0.12%	yes	55.056	55.172	55.288	55.629	56.147	56.665	1.77%	no	59.227	59.532	59.838	63.854	64.876	65.908	8.98%	no
9	0.9824	0.9881	0.9938	0.9851	0.9928	1.0006	0.48%	yes	57.306	57.378	57.449	58.223	58.691	59.158	2.29%	no	39.085	39.333	39.581	43.440	44.028	44.619	11.94%	no
10	0.9633	0.9689	0.9745	0.9649	0.9724	0.9800	0.36%	yes	57.006	57.087	57.169	58.021	58.489	58.956	2.45%	no	35.834	36.075	36.315	40.496	41.020	41.547	13.71%	no
11	0.9951	1.0008	1.0065	0.9947	1.0025	1.0103	0.17%	yes	57.048	57.122	57.197	58.031	58.498	58.965	2.41%	no	37.325	37.571	37.816	42.130	42.679	43.233	13.60%	no
12	0.9843	0.9900	0.9957	0.9848	0.9925	1.0002	0.25%	yes	56.973	57.041	57.109	58.063	58.531	58.998	2.61%	no	36.332	36.574	36.815	41.492	42.032	42.574	14.92%	no
13	0.9974	1.0031	1.0088	1.0006	1.0084	1.0163	0.53%	yes	56.953	57.026	57.099	58.537	59.005	59.472	3.47%	no	36.558	36.799	37.040	42.618	43.169	43.723	17.31%	no
14	0.9863	0.9920	0.9977	0.9885	0.9962	1.0040	0.42%	yes	57.856	57.929	58.002	59.120	59.588	60.055	2.86%	no	38.815	39.065	39.315	43.957	44.542	45.131	14.02%	no
15	0.9986	1.0043	1.0100	1.0017	1.0096	1.0175	0.53%	yes	56.880	56.954	57.029	58.171	58.639	59.106	2.96%	no	36.603	36.844	37.085	42.625	43.182	43.743	17.20%	no
16	0.9902	0.9959	1.0016	0.9934	1.0011	1.0090	0.53%	yes	57.010	57.075	57.139	58.220	58.687	59.154	2.83%	no	39.065	39.312	39.558	42.653	43.215	43.781	9.93%	no
17	1.4978	1.5051	1.5124	1.4946	1.5058	1.5171	0.04%	yes	29.993	30.016	30.039	33.577	34.065	34.553	13.49%	no	32.597	32.763	32.930	38.291	39.142	40.001	19.47%	no
18	1.5374	1.5449	1.5524	1.5377	1.5491	1.5606	0.27%	yes	57.965	58.003	58.041	59.066	59.560	60.055	2.68%	no	63.293	63.618	63.943	68.620	69.555	70.497	9.33%	no
19	1.5734	1.5810	1.5886	1.5685	1.5802	1.5920	-0.05%	yes	57.361	57.398	57.436	58.406	58.900	59.394	2.62%	no	57.478	57.785	58.091	66.410	67.280	68.156	16.43%	no
20	1.5557	1.5632	1.5707	1.5537	1.5652	1.5769	0.13%	yes	57.206	57.244	57.282	58.214	58.708	59.202	2.56%	no	58.101	58.409	58.716	65.876	66.749	67.628	14.28%	no
21	1.4467	1.4538	1.4609	1.4500	1.4598	1.4697	0.41%	yes	57.292	57.343	57.394	58.287	58.780	59.273	2.51%	no	57.699	58.003	58.308	63.001	63.802	64.606	10.00%	no
22	1.4646	1.4718	1.4790	1.4681	1.4779	1.4878	0.42%	yes	57.990	58.054	58.117	59.118	59.610	60.103	2.68%	no	58.639	58.948	59.257	64.745	65.559	66.376	11.22%	no
23	1.4577	1.4649	1.4721	1.4593	1.4690	1.4788	0.28%	yes	58.077	58.136	58.196	59.047	59.541	60.033	2.42%	no	57.855	58.162	58.469	61.810	62.556	63.304	7.56%	no
24	1.4556	1.4628	1.4700	1.4585	1.4682	1.4781	0.37%	yes	57.989	58.040	58.092	58.947	59.440	59.933	2.41%	no	59.453	59.764	60.075	63.717	64.515	65.317	7.95%	no
25	1.5478	1.5553	1.5628	1.5501	1.5600	1.5701	0.31%	yes	58.252	58.313	58.374	59.571	60.028	60.486	2.94%	no	62.610	62.934	63.257	68.800	69.612	70.427	10.61%	no
26	1.5309	1.5383	1.5457	1.5358	1.5458	1.5559	0.49%	yes	57.517	57.588	57.659	58.726	59.184	59.641	2.77%	no	59.895	60.206	60.518	66.892	67.695	68.501	12.44%	no
27	1.5086	1.5160	1.5234	1.5136	1.5236	1.5336	0.50%	yes	57.433	57.504	57.574	58.577	59.034	59.492	2.66%	no	58.586	58.893	59.200	66.008	66.806	67.608	13.44%	no
28	1.4826	1.4899	1.4972	1.4831	1.4929	1.5028	0.20%	yes	57.223	57.307	57.392	58.582	59.040	59.498	3.02%	no	56.232	56.533	56.834	64.215	64.988	65.764	14.96%	no
29	1.4967	1.5040	1.5113	1.5010	1.5110	1.5210	0.46%	yes	57.390	57.428	57.467	58.782	59.240	59.698	3.15%	no	58.970	59.279	59.587	66.345	67.153	67.966	13.28%	no
30	1.4956	1.5029	1.5102	1.4973	1.5071	1.5170	0.28%	yes	57.548	57.585	57.623	58.782	59.240	59.697	2.87%	no	59.266	59.577	59.888	65.309	66.091	66.877	10.93%	no
31	1.4512	1.4584	1.4656	1.4530	1.4627	1.4725	0.29%	yes	57.257	57.296	57.335	58.287	58.745	59.203	2.53%	no	57.919	58.225	58.531	63.706	64.490	65.279	10.76%	no
32	1.4706	1.4778	1.4850	1.4748	1.4845	1.4943	0.45%	yes	57.167	57.204	57.241	58.287	58.745	59.203	2.69%	no	56.706	57.007	57.308	63.569	64.335	65.106	12.86%	no

Hybrid 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.6056	0.6103	0.6150	0.6102	0.6127	0.6153	0.40%	yes	63.496	63.587	63.678	64.381	64.753	65.125	1.83%	no	28.324	28.565	28.807	31.662	31.955	32.249	11.87%	no
2	0.6032	0.6079	0.6126	0.6080	0.6105	0.6130	0.43%	yes	63.084	63.176	63.268	63.922	64.295	64.667	1.77%	no	27.920	28.159	28.398	31.177	31.466	31.756	11.75%	no
3	0.6107	0.6154	0.6201	0.6150	0.6175	0.6201	0.35%	yes	63.513	63.605	63.697	64.290	64.662	65.034	1.66%	no	28.693	28.936	29.179	31.897	32.193	32.490	11.26%	no
4	0.5964	0.6010	0.6056	0.6005	0.6030	0.6055	0.33%	yes	63.407	63.496	63.584	64.039	64.412	64.784	1.44%	no	28.112	28.353	28.595	30.788	31.073	31.358	9.59%	no
5	0.6068	0.6115	0.6162	0.6115	0.6140	0.6165	0.41%	yes	62.581	62.668	62.755	63.400	63.772	64.144	1.76%	no	27.793	28.031	28.268	31.075	31.365	31.656	11.90%	no
6	0.5964	0.6010	0.6056	0.6006	0.6031	0.6056	0.35%	yes	64.216	64.332	64.449	64.348	64.721	65.093	0.60%	yes	28.480	28.724	28.968	31.044	31.331	31.618	9.07%	no
7	0.5943	0.5989	0.6035	0.5984	0.6009	0.6034	0.33%	yes	63.957	64.078	64.200	64.289	64.662	65.034	0.91%	no	28.366	28.609	28.852	30.488	30.766	31.045	7.54%	no
8	0.6051	0.6098	0.6145	0.6095	0.6120	0.6144	0.35%	yes	63.186	63.302	63.418	63.739	64.112	64.484	1.28%	no	28.119	28.359	28.599	29.950	30.217	30.484	6.55%	no
9	0.6095	0.6142	0.6189	0.6145	0.6170	0.6196	0.46%	yes	64.482	64.599	64.715	65.434	65.807	66.179	1.87%	no	28.709	28.953	29.198	32.124	32.415	32.707	11.96%	no
10	0.6043	0.6090	0.6137	0.6082	0.6107	0.6133	0.29%	yes	63.629	63.743	63.857	64.208	64.580	64.953	1.31%	no	28.785	29.028	29.270	30.540	30.816	31.092	6.16%	no
11	0.6161	0.6208	0.6255	0.6204	0.6230	0.6255	0.35%	yes	62.855	62.909	62.963	63.812	64.184	64.556	2.03%	no	28.279	28.519	28.760	31.782	32.077	32.372	12.47%	no
12	0.6132	0.6179	0.6226	0.6171	0.6196	0.6222	0.28%	yes	63.300	63.342	63.384	64.082	64.455	64.827	1.76%	no	28.950	29.194	29.438	31.826	32.121	32.417	10.03%	no
13	0.6077	0.6124	0.6171	0.6125	0.6151	0.6176	0.43%	yes	62.597	62.638	62.678	63.937	64.310	64.682	2.67%	no	27.660	27.897	28.135	31.351	31.641	31.933	13.42%	no
14	0.6081	0.6128	0.6175	0.6127	0.6152	0.6178	0.39%	yes	62.559	62.600	62.641	63.772	64.144	64.516	2.47%	no	27.889	28.127	28.366	31.410	31.702	31.996	12.71%	no
15	0.6413	0.6464	0.6515	0.6478	0.6504	0.6531	0.62%	yes	62.950	62.992	63.033	64.873	65.244	65.616	3.58%	no	28.306	28.546	28.786	33.940	34.252	34.566	19.99%	no

Hybrid 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4039	0.4488	0.4937	0.4481	0.4489	0.4497	0.03%	yes	44.112	44.165	44.217	44.654	44.993	45.332	1.88%	no	15.341	15.501	15.661	15.801	15.963	16.126	2.99%	no
2	0.4007	0.4452	0.4897	0.4446	0.4454	0.4462	0.04%	yes	59.981	60.027	60.073	60.128	60.471	60.813	0.74%	no	21.061	21.280	21.498	21.410	21.579	21.748	1.40%	yes
3	0.4019	0.4466	0.4913	0.4459	0.4467	0.4475	0.02%	yes	59.521	59.566	59.611	59.742	60.085	60.427	0.87%	no	20.973	21.190	21.406	21.319	21.488	21.657	1.41%	yes
4	0.4034	0.4482	0.4930	0.4476	0.4484	0.4492	0.04%	yes	59.619	59.664	59.709	59.750	60.093	60.435	0.72%	no	21.108	21.326	21.545	21.354	21.522	21.691	0.92%	yes
5	0.4027	0.4474	0.4921	0.4468	0.4476	0.4484	0.04%	yes	59.699	59.743	59.788	59.948	60.291	60.633	0.92%	no	20.973	21.191	21.409	21.350	21.518	21.686	1.54%	yes
6	0.3980	0.4422	0.4864	0.4413	0.4421	0.4429	-0.01%	yes	59.470	59.514	59.558	59.728	60.070	60.413	0.94%	no	20.903	21.120	21.337	20.989	21.155	21.321	0.17%	yes
7	0.4042	0.4491	0.4940	0.4483	0.4491	0.4499	-0.01%	yes	59.751	59.799	59.848	59.730	60.073	60.415	0.46%	yes	21.404	21.623	21.843	21.361	21.529	21.697	-0.44%	yes
8	0.3977	0.4419	0.4861	0.4413	0.4421	0.4429	0.04%	yes	60.952	61.011	61.069	61.022	61.365	61.708	0.58%	yes	21.207	21.428	21.649	21.637	21.806	21.975	1.76%	yes
9	0.4036	0.4484	0.4932	0.4476	0.4484	0.4492	0.00%	yes	59.742	59.795	59.847	59.794	60.136	60.479	0.57%	yes	21.378	21.597	21.816	21.500	21.670	21.841	0.34%	yes
10	0.4095	0.4550	0.5005	0.4548	0.4556	0.4564	0.13%	yes	60.495	60.550	60.604	60.744	61.087	61.429	0.89%	no	20.990	21.206	21.423	21.411	21.572	21.733	1.72%	yes
11	0.4143	0.4603	0.5063	0.4601	0.4609	0.4617	0.12%	yes	60.784	60.839	60.893	61.018	61.361	61.703	0.86%	no	21.567	21.787	22.007	22.410	22.582	22.756	3.65%	no
12	0.4135	0.4594	0.5053	0.4586	0.4594	0.4603	0.01%	yes	60.449	60.509	60.570	60.694	61.037	61.379	0.87%	no	22.163	22.385	22.607	22.519	22.695	22.872	1.39%	yes

Hybrid 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.7052	0.7101	0.7150	0.7083	0.7101	0.7118	-0.01%	yes	13.771	14.000	14.229	18.929	19.283	19.637	37.74%	no	7.261	7.314	7.367	10.071	10.326	10.581	41.18%	no
2	0.7080	0.7129	0.7178	0.7131	0.7149	0.7166	0.27%	yes	63.620	63.661	63.702	64.479	64.842	65.204	1.85%	no	33.832	34.086	34.339	36.567	36.863	37.160	8.15%	no
3	0.7286	0.7336	0.7386	0.7341	0.7358	0.7376	0.30%	yes	46.291	46.325	46.358	48.359	48.718	49.078	5.17%	no	24.481	24.664	24.847	27.774	28.061	28.349	13.78%	no
4	0.7201	0.7250	0.7299	0.7247	0.7264	0.7282	0.20%	yes	46.675	46.707	46.739	48.693	49.053	49.412	5.02%	no	24.741	24.927	25.113	27.683	27.970	28.257	12.21%	no
5	0.7447	0.7498	0.7549	0.7513	0.7530	0.7548	0.43%	yes	45.565	45.603	45.641	48.026	48.385	48.744	6.10%	no	24.296	24.475	24.654	28.036	28.328	28.620	15.74%	no
6	0.7167	0.7216	0.7265	0.7223	0.7240	0.7258	0.34%	yes	45.850	45.885	45.919	48.252	48.612	48.971	5.94%	no	23.810	23.989	24.169	27.184	27.467	27.750	14.50%	no
7	0.7421	0.7471	0.7521	0.7478	0.7496	0.7514	0.34%	yes	61.247	61.338	61.428	62.223	62.584	62.946	2.03%	no	33.795	34.040	34.285	36.803	37.110	37.418	9.02%	no
8	0.7278	0.7328	0.7378	0.7328	0.7346	0.7364	0.25%	yes	45.858	45.912	45.965	47.860	48.219	48.578	5.03%	no	24.748	24.931	25.113	27.797	28.091	28.386	12.68%	no

Hybrid 1B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.1363	1.1426	1.1489	1.1415	1.1436	1.1456	0.08%	yes	56.728	56.787	56.846	56.143	56.496	56.850	-0.51%	yes	48.138	48.411	48.683	48.503	48.924	49.346	1.06%	yes
2	1.1114	1.1176	1.1238	1.1156	1.1176	1.1196	0.00%	yes	56.299	56.360	56.421	55.759	56.113	56.466	-0.44%	yes	47.990	48.262	48.534	47.741	48.162	48.583	-0.21%	yes
3	1.1257	1.1318	1.1379	1.1302	1.1322	1.1343	0.04%	yes	55.505	55.565	55.626	54.988	55.341	55.694	-0.40%	yes	47.136	47.402	47.669	47.307	47.727	48.147	0.68%	yes
4	1.1364	1.1425	1.1486	1.1429	1.1450	1.1470	0.22%	yes	56.605	56.669	56.734	55.878	56.231	56.584	-0.77%	no	46.873	47.141	47.408	47.919	48.332	48.746	2.53%	no
5	1.0586	1.0645	1.0704	1.0652	1.0672	1.0691	0.25%	yes	58.580	58.634	58.688	58.948	59.301	59.653	1.14%	no	45.799	46.067	46.336	48.596	48.998	49.399	6.36%	no
6	1.0862	1.0922	1.0982	1.0943	1.0963	1.0983	0.38%	yes	57.812	57.860	57.909	58.482	58.834	59.186	1.68%	no	45.525	45.790	46.055	49.274	49.685	50.096	8.51%	no
7	1.1034	1.1102	1.1170	1.1112	1.1132	1.1152	0.27%	yes	58.217	58.255	58.293	58.725	59.077	59.428	1.41%	no	47.384	47.658	47.932	50.394	50.810	51.226	6.61%	no
8	1.1006	1.1066	1.1126	1.1081	1.1100	1.1120	0.31%	yes	58.991	59.033	59.074	59.851	60.203	60.555	1.98%	no	47.521	47.796	48.072	51.044	51.456	51.868	7.66%	no

Hybrid 1B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
5	1.8498	1.8605	1.8712	1.8616	1.8628	1.8640	0.13%	yes	58.076	58.129	58.181	58.514	58.515	58.517	0.67%	no	78.468	78.945	79.421	81.665	81.717	81.770	3.51%	no
6	1.8748	1.8855	1.8962	1.8880	1.8892	1.8904	0.20%	yes	57.449	57.501	57.552	58.011	58.013	58.014	0.89%	no	77.431	77.900	78.368	81.464	81.515	81.567	4.64%	no
7	1.9000	1.9108	1.9216	1.9123	1.9135	1.9148	0.14%	yes	57.683	57.733	57.783	58.250	58.252	58.253	0.90%	no	80.116	80.598	81.079	83.397	83.449	83.502	3.54%	no
8	1.8982	1.9090	1.9198	1.9103	1.9115	1.9128	0.13%	yes	58.525	58.580	58.634	59.393	59.395	59.396	1.39%	no	81.094	81.582	82.070	84.689	84.743	84.796	3.87%	no

Hybrid 1B -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.1363	1.1426	1.1489	1.1411	1.1432	1.1453	0.05%	yes	56.728	56.787	56.846	56.070	56.424	56.778	-0.64%	yes	48.138	48.411	48.683	48.140	48.524	48.909	0.23%	yes
2	1.1114	1.1176	1.1238	1.1153	1.1173	1.1193	-0.03%	yes	56.299	56.360	56.421	55.654	56.009	56.363	-0.62%	yes	47.990	48.262	48.534	47.350	47.734	48.118	-1.09%	yes
3	1.1257	1.1318	1.1379	1.1298	1.1319	1.1340	0.01%	yes	55.505	55.565	55.626	54.563	54.919	55.275	-1.16%	no	47.136	47.402	47.669	46.576	46.958	47.341	-0.94%	yes
4	1.1364	1.1425	1.1486	1.1425	1.1446	1.1467	0.18%	yes	56.605	56.669	56.734	55.645	56.000	56.354	-1.18%	no	46.873	47.141	47.408	47.419	47.799	48.179	1.40%	no
5	1.0586	1.0645	1.0704	1.0647	1.0666	1.0686	0.20%	yes	58.580	58.634	58.688	57.092	57.457	57.822	-2.01%	no	45.799	46.067	46.336	46.304	46.678	47.051	1.32%	yes
6	1.0862	1.0922	1.0982	1.0937	1.0957	1.0977	0.32%	yes	57.812	57.860	57.909	56.395	56.761	57.127	-1.90%	no	45.525	45.790	46.055	46.644	47.024	47.404	2.70%	no
7	1.1034	1.1102	1.1170	1.1106	1.1126	1.1146	0.22%	yes	58.217	58.255	58.293	57.426	57.787	58.148	-0.80%	no	47.384	47.658	47.932	48.531	48.913	49.295	2.63%	no
8	1.1006	1.1066	1.1126	1.1074	1.1094	1.1114	0.26%	yes	58.991	59.033	59.074	57.956	58.321	58.686	-1.21%	no	47.521	47.796	48.072	48.694	49.081	49.469	2.69%	no

Hybrid 1B -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
5	1.8498	1.8605	1.8712	1.8606	1.8618	1.8630	0.07%	yes	58.076	58.129	58.181	57.606	57.608	57.611	-0.90%	no	78.468	78.945	79.421	79.089	79.141	79.193	0.25%	yes
6	1.8748	1.8855	1.8962	1.8869	1.8881	1.8893	0.14%	yes	57.449	57.501	57.552	56.987	56.990	56.993	-0.89%	no	77.431	77.900	78.368	78.570	78.621	78.672	0.93%	no
7	1.9000	1.9108	1.9216	1.9112	1.9124	1.9137	0.09%	yes	57.683	57.733	57.783	57.614	57.617	57.619	-0.20%	no	80.116	80.598	81.079	81.186	81.238	81.290	0.79%	no
8	1.8982	1.9090	1.9198	1.9093	1.9105	1.9117	0.08%	yes	58.525	58.580	58.634	58.457	58.460	58.462	-0.20%	no	81.094	81.582	82.070	82.124	82.176	82.229	0.73%	no

Thin 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.6128	0.6176	0.6224	0.6217	0.6247	0.6277	1.15%	yes	44.242	44.444	44.646	44.586	44.905	45.224	1.04%	yes	18.316	18.476	18.636	20.011	20.221	20.431	9.44%	no
2	0.6092	0.6139	0.6186	0.6186	0.6216	0.6246	1.26%	no	44.238	44.272	44.305	44.610	44.929	45.248	1.49%	no	17.954	18.112	18.271	19.824	20.031	20.239	10.59%	no
3	0.6023	0.6070	0.6117	0.6117	0.6147	0.6176	1.26%	no	44.187	44.337	44.487	44.650	44.969	45.288	1.42%	no	17.775	17.933	18.092	19.587	19.790	19.995	10.35%	no
4	0.5936	0.5982	0.6028	0.6058	0.6087	0.6116	1.75%	no	44.072	44.132	44.192	44.775	45.094	45.413	2.18%	no	16.839	16.994	17.149	19.155	19.350	19.546	13.86%	no
5	0.5938	0.5984	0.6030	0.6151	0.6181	0.6210	3.29%	no	43.854	43.887	43.920	44.911	45.231	45.549	3.06%	no	15.408	15.557	15.707	18.903	19.087	19.273	22.69%	no
6	0.6099	0.6146	0.6193	0.6219	0.6249	0.6279	1.67%	no	44.178	44.310	44.442	44.829	45.148	45.467	1.89%	no	17.557	17.714	17.872	19.994	20.202	20.409	14.04%	no
7	0.6102	0.6149	0.6196	0.6211	0.6241	0.6271	1.50%	no	44.206	44.355	44.504	44.817	45.136	45.454	1.76%	no	17.779	17.937	18.095	20.045	20.254	20.463	12.92%	no
8	0.6032	0.6079	0.6126	0.6141	0.6171	0.6201	1.51%	no	44.247	44.278	44.310	44.889	45.208	45.527	2.10%	no	17.544	17.702	17.859	19.934	20.143	20.352	13.79%	no
9	0.5966	0.6012	0.6058	0.6118	0.6148	0.6178	2.26%	no	43.993	44.054	44.116	44.977	45.296	45.615	2.82%	no	16.583	16.736	16.889	19.688	19.892	20.096	18.85%	no
10	0.5869	0.5915	0.5961	0.5956	0.5985	0.6014	1.18%	yes	44.101	44.253	44.405	45.080	45.399	45.718	2.59%	no	17.507	17.664	17.821	19.529	19.733	19.939	11.72%	no
11	0.6559	0.6607	0.6655	0.6674	0.6698	0.6721	1.37%	no	43.933	43.969	44.004	43.796	44.101	44.405	0.30%	yes	18.959	19.118	19.277	20.847	21.037	21.228	10.04%	no
12	0.6648	0.6697	0.6746	0.6770	0.6794	0.6818	1.45%	no	44.068	44.111	44.154	44.229	44.533	44.837	0.96%	no	19.170	19.330	19.489	21.254	21.445	21.635	10.94%	no
13	0.6535	0.6583	0.6631	0.6659	0.6682	0.6706	1.50%	no	44.003	44.037	44.071	44.190	44.494	44.798	1.04%	no	18.766	18.924	19.083	20.840	21.026	21.212	11.11%	no
14	0.6530	0.6578	0.6626	0.6711	0.6735	0.6758	2.38%	no	43.782	43.818	43.854	44.290	44.594	44.898	1.77%	no	17.675	17.829	17.983	20.546	20.724	20.901	16.23%	no
15	0.6552	0.6600	0.6648	0.6782	0.6806	0.6830	3.12%	no	43.560	43.596	43.631	44.256	44.560	44.864	2.21%	no	16.885	17.037	17.188	20.195	20.363	20.530	19.52%	no
16	0.6517	0.6565	0.6613	0.6637	0.6661	0.6684	1.46%	no	43.951	43.985	44.019	44.222	44.526	44.830	1.23%	no	18.845	19.004	19.162	21.074	21.264	21.455	11.90%	no
17	0.6476	0.6524	0.6572	0.6579	0.6602	0.6625	1.20%	no	44.005	44.039	44.073	44.149	44.453	44.758	0.94%	no	19.008	19.167	19.325	20.772	20.959	21.147	9.35%	no
18	0.6490	0.6538	0.6586	0.6629	0.6652	0.6675	1.74%	no	43.901	43.938	43.974	44.135	44.440	44.744	1.14%	no	18.358	18.514	18.671	20.766	20.952	21.138	13.16%	no
19	0.6521	0.6569	0.6617	0.6647	0.6670	0.6693	1.54%	no	43.748	43.784	43.820	44.097	44.401	44.705	1.41%	no	18.593	18.749	18.905	20.764	20.949	21.135	11.74%	no
20	0.6553	0.6601	0.6649	0.6647	0.6670	0.6693	1.04%	yes	44.087	44.120	44.153	44.381	44.685	44.989	1.28%	no	19.490	19.651	19.811	21.146	21.336	21.526	8.58%	no

Thin 1A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.4424	1.4519	1.4614	1.4371	1.4497	1.4623	-0.15%	yes	41.783	41.822	41.860	39.982	40.918	41.852	-2.16%	yes	39.923	40.210	40.497	38.048	39.262	40.476	-2.36%	yes
2	1.4421	1.4516	1.4611	1.4380	1.4506	1.4633	-0.07%	yes	41.681	41.723	41.765	40.015	40.951	41.885	-1.85%	yes	39.509	39.795	40.080	37.905	39.111	40.317	-1.72%	yes
3	1.4456	1.4551	1.4646	1.4419	1.4546	1.4674	-0.03%	yes	41.651	41.693	41.734	40.075	41.011	41.945	-1.64%	yes	39.407	39.692	39.977	38.000	39.205	40.409	-1.23%	yes
4	1.4462	1.4557	1.4652	1.4443	1.4570	1.4697	0.09%	yes	41.700	41.743	41.785	40.219	41.154	42.088	-1.41%	yes	38.858	39.141	39.425	37.754	38.930	40.103	-0.54%	yes
5	1.4500	1.4595	1.4690	1.4522	1.4648	1.4775	0.36%	yes	41.742	41.785	41.828	40.347	41.282	42.216	-1.20%	yes	37.759	38.040	38.321	37.229	38.349	39.464	0.81%	yes
6	1.4360	1.4455	1.4550	1.4339	1.4464	1.4591	0.07%	yes	42.099	42.181	42.263	40.224	41.160	42.095	-2.42%	no	39.375	39.661	39.946	38.043	39.242	40.440	-1.06%	yes
7	1.4369	1.4464	1.4559	1.4341	1.4467	1.4594	0.02%	yes	41.807	41.850	41.894	40.214	41.150	42.084	-1.67%	yes	39.440	39.726	40.013	38.108	39.316	40.524	-1.03%	yes
8	1.4379	1.4474	1.4569	1.4344	1.4471	1.4599	-0.02%	yes	41.858	41.898	41.938	40.304	41.239	42.174	-1.57%	yes	39.620	39.906	40.193	38.268	39.485	40.702	-1.06%	yes
9	1.4366	1.4461	1.4556	1.4368	1.4495	1.4623	0.24%	yes	41.810	41.852	41.894	40.402	41.338	42.272	-1.23%	yes	38.784	39.068	39.352	38.138	39.335	40.531	0.68%	yes
10	1.4376	1.4471	1.4566	1.4352	1.4479	1.4608	0.06%	yes	42.013	42.055	42.097	40.539	41.475	42.409	-1.38%	yes	39.749	40.037	40.325	38.670	39.896	41.124	-0.35%	yes

Thin 1A -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.6128	0.6176	0.6224	0.6199	0.6230	0.6262	0.88%	yes	44.242	44.444	44.646	42.631	42.969	43.307	-3.32%	no	18.316	18.476	18.636	18.779	18.971	19.163	2.68%	no
2	0.6092	0.6139	0.6186	0.6168	0.6199	0.6230	0.98%	yes	44.238	44.272	44.305	42.654	42.992	43.330	-2.89%	no	17.954	18.112	18.271	18.611	18.801	18.991	3.80%	no
3	0.6023	0.6070	0.6117	0.6099	0.6130	0.6161	0.98%	yes	44.187	44.337	44.487	42.424	42.765	43.105	-3.55%	no	17.775	17.933	18.092	18.278	18.466	18.655	2.97%	no
4	0.5936	0.5982	0.6028	0.6039	0.6069	0.6100	1.46%	no	44.072	44.132	44.192	42.468	42.810	43.152	-3.00%	no	16.839	16.994	17.149	17.881	18.063	18.246	6.29%	no
5	0.5938	0.5984	0.6030	0.6130	0.6161	0.6192	2.95%	no	43.854	43.887	43.920	41.956	42.304	42.652	-3.61%	no	15.408	15.557	15.707	17.444	17.622	17.800	13.27%	no
6	0.6099	0.6146	0.6193	0.6200	0.6232	0.6263	1.39%	no	44.178	44.310	44.442	41.042	41.398	41.754	-6.57%	no	17.557	17.714	17.872	17.946	18.144	18.343	2.43%	no
7	0.6102	0.6149	0.6196	0.6193	0.6224	0.6255	1.22%	yes	44.206	44.355	44.504	42.252	42.596	42.940	-3.96%	no	17.779	17.937	18.095	18.543	18.737	18.931	4.46%	no
8	0.6032	0.6079	0.6126	0.6124	0.6155	0.6186	1.25%	yes	44.247	44.278	44.310	42.377	42.721	43.065	-3.52%	no	17.544	17.702	17.859	18.461	18.655	18.849	5.39%	no
9	0.5966	0.6012	0.6058	0.6100	0.6131	0.6162	1.98%	no	43.993	44.054	44.116	42.359	42.704	43.049	-3.06%	no	16.583	16.736	16.889	18.216	18.407	18.597	9.98%	no
10	0.5869	0.5915	0.5961	0.5940	0.5970	0.6000	0.93%	yes	44.101	44.253	44.405	41.445	41.800	42.155	-5.54%	no	17.507	17.664	17.821	17.593	17.789	17.984	0.71%	yes
11	0.6559	0.6607	0.6655	0.6652	0.6677	0.6702	1.06%	yes	43.933	43.969	44.004	42.319	42.636	42.953	-3.03%	no	18.959	19.118	19.277	19.734	19.902	20.070	4.10%	no
12	0.6648	0.6697	0.6746	0.6748	0.6773	0.6798	1.13%	no	44.068	44.111	44.154	42.188	42.510	42.831	-3.63%	no	19.170	19.330	19.489	19.872	20.044	20.216	3.70%	no
13	0.6535	0.6583	0.6631	0.6637	0.6662	0.6687	1.19%	no	44.003	44.037	44.071	42.117	42.440	42.762	-3.63%	no	18.766	18.924	19.083	19.493	19.662	19.830	3.90%	no
14	0.6530	0.6578	0.6626	0.6687	0.6712	0.6737	2.03%	no	43.782	43.818	43.854	42.078	42.402	42.725	-3.23%	no	17.675	17.829	17.983	19.195	19.359	19.522	8.58%	no
15	0.6552	0.6600	0.6648	0.6756	0.6781	0.6806	2.74%	no	43.560	43.596	43.631	41.225	41.556	41.886	-4.68%	no	16.885	17.037	17.188	18.577	18.737	18.897	9.98%	no
16	0.6517	0.6565	0.6613	0.6617	0.6642	0.6666	1.17%	no	43.951	43.985	44.019	40.931	41.264	41.596	-6.19%	no	18.845	19.004	19.162	19.085	19.263	19.441	1.36%	yes
17	0.6476	0.6524	0.6572	0.6559	0.6583	0.6608	0.91%	yes	44.005	44.039	44.073	42.086	42.408	42.730	-3.70%	no	19.008	19.167	19.325	19.411	19.580	19.750	2.16%	no
18	0.6490	0.6538	0.6586	0.6607	0.6632	0.6656	1.43%	no	43.901	43.938	43.974	42.017	42.339	42.662	-3.64%	no	18.358	18.514	18.671	19.386	19.554	19.723	5.62%	no
19	0.6521	0.6569	0.6617	0.6625	0.6649	0.6674	1.22%	no	43.748	43.784	43.820	41.755	42.080	42.404	-3.89%	no	18.593	18.749	18.905	19.277	19.447	19.616	3.72%	no
20	0.6553	0.6601	0.6649	0.6627	0.6651	0.6675	0.76%	yes	44.087	44.120	44.153	41.453	41.783	42.112	-5.30%	no	19.490	19.651	19.811	19.347	19.523	19.699	-0.65%	yes

Thin 1A -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.4424	1.4519	1.4614	1.4357	1.4497	1.4637	-0.15%	yes	41.783	41.822	41.860	39.198	40.158	41.116	-3.98%	no	39.923	40.210	40.497	37.479	38.421	39.344	-4.45%	no
2	1.4421	1.4516	1.4611	1.4366	1.4506	1.4648	-0.07%	yes	41.681	41.723	41.765	39.243	40.202	41.160	-3.64%	no	39.509	39.795	40.080	37.352	38.287	39.203	-3.79%	no
3	1.4456	1.4551	1.4646	1.4405	1.4546	1.4689	-0.03%	yes	41.651	41.693	41.734	39.210	40.173	41.133	-3.65%	no	39.407	39.692	39.977	37.344	38.282	39.202	-3.55%	no
4	1.4462	1.4557	1.4652	1.4428	1.4570	1.4713	0.09%	yes	41.700	41.743	41.785	39.336	40.299	41.260	-3.46%	no	38.858	39.141	39.425	37.087	38.011	38.917	-2.89%	yes
5	1.4500	1.4595	1.4690	1.4504	1.4648	1.4793	0.36%	yes	41.742	41.785	41.828	39.214	40.185	41.154	-3.83%	no	37.759	38.040	38.321	36.320	37.223	38.109	-2.15%	yes
6	1.4360	1.4455	1.4550	1.4325	1.4465	1.4606	0.07%	yes	42.099	42.181	42.263	38.711	39.693	40.674	-5.90%	no	39.375	39.661	39.946	36.666	37.629	38.575	-5.12%	no
7	1.4369	1.4464	1.4559	1.4327	1.4467	1.4608	0.02%	yes	41.807	41.850	41.894	39.191	40.159	41.125	-4.04%	no	39.440	39.726	40.013	37.273	38.222	39.152	-3.79%	no
8	1.4379	1.4474	1.4569	1.4331	1.4471	1.4612	-0.02%	yes	41.858	41.898	41.938	39.317	40.284	41.248	-3.85%	no	39.620	39.906	40.193	37.469	38.422	39.356	-3.72%	no
9	1.4366	1.4461	1.4556	1.4354	1.4496	1.4638	0.24%	yes	41.810	41.852	41.894	39.386	40.353	41.319	-3.58%	no	38.784	39.068	39.352	37.315	38.258	39.184	-2.07%	yes
10	1.4376	1.4471	1.4566	1.4339	1.4479	1.4621	0.06%	yes	42.013	42.055	42.097	39.151	40.130	41.107	-4.58%	no	39.749	40.037	40.325	37.410	38.386	39.345	-4.12%	no

Thin 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.2817	0.3130	0.3443	0.3134	0.3152	0.3170	0.71%	yes	86.011	86.089	86.166	86.112	86.616	87.120	0.61%	yes	18.899	19.179	19.459	20.283	20.481	20.679	6.79%	no
2	0.2817	0.3130	0.3443	0.3135	0.3153	0.3171	0.74%	yes	86.383	86.458	86.533	86.411	86.915	87.418	0.53%	yes	18.946	19.228	19.509	20.353	20.551	20.750	6.88%	no
3	0.2817	0.3130	0.3443	0.3134	0.3152	0.3170	0.70%	yes	85.099	85.172	85.245	85.418	85.922	86.425	0.88%	no	18.467	18.741	19.016	19.735	19.925	20.115	6.31%	no
4	0.2818	0.3131	0.3444	0.3135	0.3153	0.3171	0.69%	yes	86.299	86.373	86.448	86.434	86.938	87.441	0.65%	yes	18.948	19.229	19.511	20.191	20.385	20.581	6.01%	no
5	0.2835	0.3150	0.3465	0.3155	0.3173	0.3191	0.72%	yes	84.624	84.969	85.313	84.837	85.341	85.844	0.44%	yes	18.585	18.859	19.133	19.920	20.114	20.309	6.65%	no
6	0.2844	0.3160	0.3476	0.3167	0.3185	0.3203	0.80%	yes	86.324	86.649	86.974	86.013	86.516	87.019	-0.15%	yes	19.005	19.286	19.566	20.335	20.532	20.730	6.46%	no
7	0.2843	0.3159	0.3475	0.3163	0.3181	0.3200	0.70%	yes	85.595	85.925	86.255	85.040	85.544	86.047	-0.44%	yes	18.961	19.240	19.518	20.161	20.359	20.558	5.82%	no
8	0.2847	0.3163	0.3479	0.3171	0.3188	0.3206	0.80%	yes	86.122	86.461	86.799	85.759	86.263	86.766	-0.23%	yes	18.769	19.048	19.327	19.658	19.840	20.024	4.16%	no
9	0.2180	0.2422	0.2664	0.2427	0.2440	0.2454	0.76%	yes	86.033	86.088	86.143	86.339	86.848	87.357	0.88%	no	14.546	14.821	15.096	15.561	15.709	15.857	5.99%	no
10	0.2169	0.2410	0.2651	0.2418	0.2432	0.2446	0.91%	yes	85.107	85.163	85.218	85.290	85.799	86.307	0.75%	no	14.319	14.593	14.868	15.636	15.790	15.944	8.20%	no
11	0.2178	0.2420	0.2662	0.2419	0.2433	0.2448	0.56%	yes	85.319	85.375	85.430	85.299	85.808	86.316	0.51%	yes	14.804	15.080	15.356	15.731	15.886	16.042	5.35%	no
12	0.2169	0.2410	0.2651	0.2421	0.2435	0.2449	1.03%	yes	82.994	83.048	83.102	83.125	83.634	84.142	0.71%	no	13.797	14.063	14.330	15.132	15.282	15.433	8.66%	no
13	0.2214	0.2460	0.2706	0.2470	0.2479	0.2489	0.78%	yes	84.866	84.920	84.974	85.709	86.078	86.446	1.36%	no	14.614	14.887	15.159	15.883	15.991	16.100	7.42%	no
14	0.2194	0.2438	0.2682	0.2451	0.2461	0.2470	0.93%	yes	83.902	83.965	84.028	84.823	85.191	85.560	1.46%	no	14.194	14.462	14.730	15.650	15.759	15.868	8.97%	no
15	0.2189	0.2432	0.2675	0.2446	0.2455	0.2465	0.97%	yes	83.163	83.236	83.309	84.361	84.730	85.098	1.79%	no	14.019	14.286	14.553	15.487	15.595	15.703	9.17%	no
16	0.2225	0.2472	0.2719	0.2481	0.2491	0.2500	0.75%	yes	85.845	85.913	85.981	86.177	86.546	86.915	0.74%	no	14.909	15.187	15.465	15.972	16.080	16.188	5.88%	no
17	0.3340	0.3381	0.3422	0.3400	0.3413	0.3427	0.96%	yes	84.933	84.989	85.045	84.521	84.886	85.251	-0.12%	yes	19.706	19.984	20.263	21.288	21.436	21.585	7.27%	no
18	0.3339	0.3380	0.3421	0.3411	0.3424	0.3437	1.30%	yes	84.266	84.322	84.379	83.907	84.272	84.637	-0.06%	yes	19.080	19.353	19.627	21.047	21.194	21.341	9.51%	no
19	0.3352	0.3393	0.3434	0.3412	0.3425	0.3438	0.94%	yes	85.272	85.327	85.382	85.049	85.414	85.779	0.10%	yes	19.850	20.130	20.409	21.383	21.531	21.679	6.96%	no
20	0.3366	0.3408	0.3450	0.3482	0.3496	0.3509	2.57%	no	83.005	83.061	83.116	83.185	83.550	83.915	0.59%	no	17.642	17.908	18.174	20.877	21.020	21.163	17.38%	no
21	0.3329	0.3370	0.3411	0.3400	0.3413	0.3426	1.28%	yes	84.481	84.535	84.588	83.531	83.896	84.261	-0.76%	no	19.124	19.400	19.675	20.896	21.042	21.188	8.46%	no
22	0.3353	0.3395	0.3437	0.3425	0.3438	0.3451	1.27%	yes	84.956	85.009	85.062	84.341	84.706	85.071	-0.36%	yes	19.327	19.604	19.881	21.025	21.168	21.312	7.98%	no
23	0.3346	0.3387	0.3428	0.3447	0.3460	0.3473	2.15%	no	83.289	83.341	83.393	83.054	83.419	83.784	0.09%	yes	17.516	17.787	18.057	19.204	19.323	19.443	8.64%	no
24	0.3322	0.3363	0.3404	0.3415	0.3429	0.3442	1.95%	no	84.610	84.663	84.716	84.273	84.639	85.003	-0.03%	yes	18.330	18.606	18.881	20.960	21.104	21.248	13.43%	no

Thin 2A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.5676	0.6307	0.6938	0.6284	0.6330	0.6377	0.37%	yes	84.044	84.718	85.391	83.389	84.232	85.074	-0.57%	yes	36.073	36.572	37.071	37.271	37.842	38.415	3.47%	no
2	0.6197	0.6274	0.6351	0.6247	0.6294	0.6340	0.31%	yes	84.601	84.955	85.309	83.678	84.521	85.362	-0.51%	yes	36.127	36.629	37.131	37.176	37.745	38.315	3.05%	no
3	0.6192	0.6269	0.6346	0.6250	0.6296	0.6342	0.43%	yes	83.508	83.884	84.261	82.678	83.521	84.362	-0.43%	yes	34.828	35.317	35.807	36.051	36.599	37.148	3.63%	no
4	0.6177	0.6254	0.6331	0.6233	0.6279	0.6326	0.40%	yes	84.892	85.228	85.563	83.697	84.540	85.382	-0.81%	yes	35.804	36.307	36.809	36.851	37.410	37.970	3.04%	no
5	0.6175	0.6252	0.6329	0.6229	0.6275	0.6321	0.36%	yes	82.896	82.956	83.016	82.070	82.913	83.755	-0.05%	yes	34.820	35.308	35.796	36.028	36.584	37.141	3.61%	no
6	0.6198	0.6275	0.6352	0.6250	0.6296	0.6343	0.34%	yes	84.273	84.334	84.395	83.256	84.099	84.941	-0.28%	yes	35.670	36.168	36.665	36.771	37.333	37.897	3.22%	no
7	0.6153	0.6230	0.6307	0.6206	0.6252	0.6299	0.36%	yes	83.345	83.403	83.461	82.261	83.105	83.946	-0.36%	yes	35.084	35.576	36.068	36.241	36.802	37.366	3.45%	no
8	0.6195	0.6272	0.6349	0.6237	0.6282	0.6327	0.16%	yes	84.687	84.753	84.818	82.991	83.835	84.677	-1.08%	no	35.501	36.000	36.499	35.631	36.156	36.681	0.43%	yes
9	0.6221	0.6298	0.6375	0.6280	0.6326	0.6372	0.44%	yes	84.892	84.980	85.068	84.173	85.016	85.858	0.04%	yes	35.568	36.068	36.569	36.856	37.404	37.954	3.70%	no
10	0.6165	0.6242	0.6319	0.6219	0.6265	0.6312	0.37%	yes	84.125	84.183	84.242	83.094	83.938	84.779	-0.29%	yes	35.566	36.065	36.564	36.749	37.313	37.879	3.46%	no
11	0.6150	0.6227	0.6304	0.6198	0.6244	0.6291	0.28%	yes	84.252	84.310	84.369	83.095	83.938	84.780	-0.44%	yes	35.823	36.323	36.823	36.796	37.364	37.934	2.87%	yes
12	0.6128	0.6205	0.6282	0.6187	0.6233	0.6280	0.45%	yes	82.482	82.539	82.596	80.888	81.730	82.572	-0.98%	yes	34.288	34.775	35.262	35.277	35.827	36.380	3.03%	no

Thin 3A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.5155	0.5200	0.5245	0.5238	0.5242	0.5246	0.81%	yes	106.226	106.309	106.392	109.583	110.172	110.760	3.63%	no	38.019	38.391	38.763	43.598	43.906	44.214	14.37%	no
2	0.4982	0.5026	0.5070	0.5078	0.5082	0.5085	1.11%	no	104.936	105.016	105.095	108.690	109.279	109.868	4.06%	no	34.730	35.094	35.459	41.298	41.587	41.876	18.50%	no
3	0.5021	0.5065	0.5109	0.5104	0.5108	0.5111	0.84%	yes	103.930	104.003	104.076	107.066	107.655	108.243	3.51%	no	35.822	36.186	36.549	41.409	41.707	42.005	15.26%	no
4	0.5087	0.5132	0.5177	0.5173	0.5177	0.5181	0.88%	yes	104.345	104.418	104.491	107.738	108.327	108.915	3.74%	no	36.404	36.770	37.136	42.404	42.709	43.013	16.15%	no
5	0.6108	0.6155	0.6202	0.6219	0.6225	0.6230	1.13%	no	106.986	107.080	107.173	111.035	111.698	112.359	4.31%	no	43.246	43.632	44.018	51.368	51.770	52.171	18.65%	no
6	0.6081	0.6128	0.6175	0.6171	0.6177	0.6182	0.80%	yes	106.851	106.937	107.023	110.061	110.723	111.384	3.54%	no	44.762	45.151	45.539	50.916	51.320	51.725	13.67%	no
7	0.6043	0.6090	0.6137	0.6147	0.6152	0.6158	1.03%	no	106.691	106.780	106.869	109.836	110.499	111.160	3.48%	no	43.279	43.662	44.046	49.916	50.308	50.699	15.22%	no
8	0.6046	0.6093	0.6140	0.6135	0.6141	0.6146	0.78%	yes	107.367	107.453	107.539	110.214	110.877	111.538	3.19%	no	44.701	45.091	45.481	50.658	51.059	51.461	13.24%	no
9	0.5073	0.5118	0.5163	0.5162	0.5166	0.5170	0.93%	yes	105.564	105.640	105.716	108.300	108.888	109.476	3.07%	no	36.369	36.738	37.106	41.794	42.088	42.381	14.56%	no
10	0.5035	0.5079	0.5123	0.5121	0.5124	0.5128	0.89%	yes	105.287	105.363	105.439	108.128	108.716	109.304	3.18%	no	36.204	36.572	36.941	41.899	42.197	42.495	15.38%	no
11	0.4960	0.5004	0.5048	0.5027	0.5031	0.5034	0.53%	yes	104.950	105.025	105.101	107.190	107.779	108.367	2.62%	no	37.200	37.570	37.939	41.271	41.571	41.872	10.65%	no
12	0.5146	0.5191	0.5236	0.5237	0.5241	0.5245	0.97%	no	104.554	104.629	104.705	107.208	107.796	108.383	3.03%	no	36.478	36.845	37.212	42.552	42.858	43.164	16.32%	no
13	0.5982	0.6028	0.6074	0.6094	0.6100	0.6105	1.19%	no	107.406	107.486	107.566	111.061	111.723	112.385	3.94%	no	42.617	43.000	43.383	50.034	50.422	50.810	17.26%	no
14	0.6003	0.6050	0.6097	0.6091	0.6097	0.6102	0.77%	yes	106.529	106.604	106.679	109.173	109.836	110.497	3.03%	no	44.102	44.488	44.874	49.730	50.127	50.525	12.68%	no
15	0.5880	0.5926	0.5972	0.5980	0.5985	0.5991	1.00%	no	105.699	105.778	105.857	108.171	108.833	109.495	2.89%	no	42.030	42.408	42.785	48.188	48.575	48.961	14.54%	no
16	0.5915	0.5961	0.6007	0.6001	0.6006	0.6011	0.75%	yes	106.435	106.511	106.587	108.504	109.166	109.828	2.49%	no	43.536	43.921	44.306	48.668	49.059	49.450	11.70%	no
17	0.4972	0.5016	0.5060	0.5063	0.5066	0.5070	1.00%	no	106.143	106.277	106.412	108.580	109.169	109.757	2.72%	no	35.572	35.942	36.312	41.255	41.544	41.834	15.59%	no
18	0.5023	0.5067	0.5111	0.5104	0.5107	0.5111	0.80%	yes	105.172	105.299	105.426	107.713	108.302	108.889	2.85%	no	36.478	36.847	37.215	41.613	41.910	42.208	13.74%	no
19	0.5099	0.5144	0.5189	0.5185	0.5189	0.5193	0.87%	yes	105.440	105.562	105.684	107.732	108.320	108.908	2.61%	no	36.958	37.326	37.694	42.129	42.430	42.730	13.67%	no
20	0.5153	0.5198	0.5243	0.5242	0.5246	0.5250	0.93%	yes	104.258	104.377	104.495	106.624	107.212	107.800	2.72%	no	36.501	36.866	37.232	42.184	42.488	42.792	15.25%	no
21	0.5928	0.5977	0.6026	0.6051	0.6056	0.6062	1.33%	no	105.085	105.185	105.284	108.360	109.022	109.684	3.65%	no	40.800	41.171	41.541	47.632	48.003	48.373	16.59%	no
22	0.5837	0.5883	0.5929	0.5927	0.5933	0.5938	0.84%	yes	105.500	105.592	105.683	107.945	108.607	109.269	2.86%	no	42.089	42.469	42.848	47.819	48.205	48.590	13.51%	no
23	0.5812	0.5858	0.5904	0.5910	0.5915	0.5920	0.97%	no	106.425	106.516	106.607	108.527	109.190	109.852	2.51%	no	41.684	42.065	42.446	47.828	48.211	48.593	14.61%	no
24	0.5763	0.5809	0.5855	0.5859	0.5865	0.5870	0.96%	no	105.608	105.697	105.785	107.434	108.097	108.759	2.27%	no	41.019	41.396	41.773	46.623	46.997	47.372	13.53%	no

Thin 3A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
5	1.0600	1.0685	1.0770	1.0738	1.0743	1.0748	0.54%	yes	108.535	108.620	108.705	111.455	111.457	111.459	2.61%	no	78.969	79.686	80.404	86.650	86.687	86.724	8.79%	no
6	1.0615	1.0701	1.0787	1.0739	1.0744	1.0748	0.40%	yes	108.233	108.312	108.392	110.503	110.505	110.507	2.02%	no	80.279	80.997	81.714	86.513	86.550	86.587	6.86%	no
7	1.0565	1.0650	1.0735	1.0698	1.0703	1.0707	0.49%	yes	108.158	108.242	108.326	110.277	110.279	110.281	1.88%	no	78.494	79.207	79.919	84.872	84.908	84.944	7.20%	no
8	1.0575	1.0660	1.0745	1.0698	1.0703	1.0707	0.40%	yes	108.706	108.792	108.879	110.667	110.669	110.671	1.73%	no	80.285	81.005	81.725	86.266	86.303	86.340	6.54%	no
13	1.0472	1.0557	1.0642	1.0611	1.0616	1.0620	0.55%	yes	108.933	109.011	109.090	111.518	111.520	111.522	2.30%	no	77.983	78.698	79.413	85.171	85.207	85.244	8.27%	no
14	1.0542	1.0627	1.0712	1.0665	1.0669	1.0674	0.40%	yes	107.707	107.784	107.861	109.632	109.634	109.636	1.72%	no	79.191	79.903	80.615	85.017	85.054	85.090	6.45%	no
15	1.0341	1.0426	1.0511	1.0470	1.0475	1.0479	0.47%	yes	106.927	107.002	107.077	108.617	108.619	108.621	1.51%	no	76.484	77.187	77.890	82.431	82.467	82.502	6.84%	no
16	1.0414	1.0499	1.0584	1.0533	1.0537	1.0542	0.37%	yes	107.534	107.611	107.688	108.965	108.967	108.969	1.26%	no	78.325	79.035	79.745	83.426	83.461	83.497	5.60%	no
21	1.0389	1.0474	1.0559	1.0530	1.0534	1.0539	0.57%	yes	106.450	106.535	106.620	108.782	108.784	108.786	2.11%	no	74.774	75.467	76.160	81.093	81.128	81.163	7.50%	no
22	1.0275	1.0360	1.0445	1.0398	1.0402	1.0407	0.41%	yes	106.579	106.661	106.743	108.397	108.399	108.401	1.63%	no	76.372	77.074	77.775	81.989	82.025	82.060	6.42%	no
23	1.0247	1.0332	1.0417	1.0375	1.0379	1.0384	0.46%	yes	107.489	107.573	107.657	108.990	108.992	108.994	1.32%	no	76.362	77.069	77.776	82.076	82.111	82.147	6.54%	no
24	1.0204	1.0289	1.0374	1.0333	1.0338	1.0342	0.47%	yes	106.579	106.661	106.743	107.904	107.906	107.908	1.17%	no	74.959	75.658	76.356	80.363	80.398	80.433	6.27%	no

Thin 3A -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.5155	0.5200	0.5245	0.5235	0.5239	0.5243	0.75%	yes	106.226	106.309	106.392	102.419	103.054	103.689	-3.06%	no	38.019	38.391	38.763	40.077	40.381	40.685	5.18%	no
2	0.4982	0.5026	0.5070	0.5074	0.5078	0.5082	1.03%	no	104.936	105.016	105.095	101.671	102.306	102.940	-2.58%	no	34.730	35.094	35.459	38.081	38.367	38.654	9.33%	no
3	0.5021	0.5065	0.5109	0.5100	0.5104	0.5108	0.77%	yes	103.930	104.003	104.076	100.857	101.487	102.115	-2.42%	no	35.822	36.186	36.549	38.385	38.675	38.965	6.88%	no
4	0.5087	0.5132	0.5177	0.5170	0.5174	0.5177	0.81%	yes	104.345	104.418	104.491	101.274	101.905	102.535	-2.41%	no	36.404	36.770	37.136	39.209	39.505	39.802	7.44%	no
5	0.6108	0.6155	0.6202	0.6215	0.6220	0.6226	1.06%	no	106.986	107.080	107.173	103.861	104.577	105.292	-2.34%	no	43.246	43.632	44.018	47.403	47.801	48.200	9.56%	no
6	0.6081	0.6128	0.6175	0.6167	0.6173	0.6178	0.73%	yes	106.851	106.937	107.023	103.536	104.247	104.957	-2.52%	no	44.762	45.151	45.539	47.224	47.621	48.017	5.47%	no
7	0.6043	0.6090	0.6137	0.6142	0.6148	0.6154	0.95%	no	106.691	106.780	106.869	102.923	103.637	104.351	-2.94%	no	43.279	43.662	44.046	46.164	46.552	46.940	6.62%	no
8	0.6046	0.6093	0.6140	0.6131	0.6137	0.6142	0.72%	yes	107.367	107.453	107.539	103.997	104.706	105.414	-2.56%	no	44.701	45.091	45.481	47.156	47.549	47.942	5.45%	no
9	0.5073	0.5118	0.5163	0.5158	0.5162	0.5166	0.86%	yes	105.564	105.640	105.716	102.038	102.667	103.296	-2.81%	no	36.369	36.738	37.106	38.822	39.111	39.398	6.46%	no
10	0.5035	0.5079	0.5123	0.5117	0.5121	0.5125	0.82%	yes	105.287	105.363	105.439	101.991	102.620	103.248	-2.60%	no	36.204	36.572	36.941	38.922	39.213	39.504	7.22%	no
11	0.4960	0.5004	0.5048	0.5024	0.5028	0.5031	0.47%	yes	104.950	105.025	105.101	101.628	102.253	102.878	-2.64%	no	37.200	37.570	37.939	38.503	38.792	39.081	3.25%	no
12	0.5146	0.5191	0.5236	0.5233	0.5237	0.5241	0.89%	yes	104.554	104.629	104.705	101.553	102.178	102.802	-2.34%	no	36.478	36.845	37.212	39.678	39.973	40.268	8.49%	no
13	0.5982	0.6028	0.6074	0.6090	0.6096	0.6101	1.12%	no	107.406	107.486	107.566	103.168	103.890	104.611	-3.35%	no	42.617	43.000	43.383	45.869	46.260	46.650	7.58%	no
14	0.6003	0.6050	0.6097	0.6087	0.6092	0.6098	0.70%	yes	106.529	106.604	106.679	103.242	103.949	104.655	-2.49%	no	44.102	44.488	44.874	46.393	46.780	47.166	5.15%	no
15	0.5880	0.5926	0.5972	0.5975	0.5981	0.5987	0.93%	no	105.699	105.778	105.857	101.845	102.555	103.264	-3.05%	no	42.030	42.408	42.785	44.741	45.119	45.497	6.39%	no
16	0.5915	0.5961	0.6007	0.5996	0.6002	0.6007	0.68%	yes	106.435	106.511	106.587	103.127	103.830	104.532	-2.52%	no	43.536	43.921	44.306	45.652	46.030	46.408	4.80%	no
17	0.4972	0.5016	0.5060	0.5059	0.5062	0.5066	0.93%	yes	106.143	106.277	106.412	102.830	103.456	104.082	-2.65%	no	35.572	35.942	36.312	38.551	38.834	39.117	8.05%	no
18	0.5023	0.5067	0.5111	0.5100	0.5104	0.5108	0.73%	yes	105.172	105.299	105.426	101.891	102.518	103.144	-2.64%	no	36.478	36.847	37.215	38.771	39.059	39.347	6.00%	no
19	0.5099	0.5144	0.5189	0.5181	0.5185	0.5189	0.80%	yes	105.440	105.562	105.684	101.696	102.324	102.951	-3.07%	no	36.958	37.326	37.694	39.147	39.439	39.731	5.66%	no
20	0.5153	0.5198	0.5243	0.5238	0.5242	0.5246	0.85%	yes	104.258	104.377	104.495	101.237	101.860	102.482	-2.41%	no	36.501	36.866	37.232	39.432	39.724	40.016	7.75%	no
21	0.5928	0.5977	0.6026	0.6046	0.6051	0.6057	1.24%	no	105.085	105.185	105.284	100.385	101.107	101.829	-3.88%	no	40.800	41.171	41.541	43.584	43.958	44.331	6.77%	no
22	0.5837	0.5883	0.5929	0.5923	0.5928	0.5934	0.77%	yes	105.500	105.592	105.683	102.239	102.944	103.648	-2.51%	no	42.089	42.469	42.848	44.685	45.058	45.432	6.10%	no
23	0.5812	0.5858	0.5904	0.5905	0.5911	0.5916	0.90%	no	106.425	106.516	106.607	103.141	103.845	104.547	-2.51%	no	41.684	42.065	42.446	44.885	45.256	45.627	7.59%	no
24	0.5763	0.5809	0.5855	0.5859	0.5865	0.5870	0.96%	no	105.608	105.697	105.785	107.434	108.097	108.759	2.27%	no	41.019	41.396	41.773	46.623	46.997	47.372	13.53%	no

Thin 3A -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
5	1.0600	1.0685	1.0770	1.0730	1.0735	1.0739	0.46%	yes	108.535	108.620	108.705	107.702	107.706	107.711	-0.84%	no	78.969	79.686	80.404	82.625	82.662	82.700	3.73%	no
6	1.0615	1.0701	1.0787	1.0731	1.0736	1.0740	0.32%	yes	108.233	108.312	108.392	107.110	107.115	107.119	-1.11%	no	80.279	80.997	81.714	82.686	82.723	82.760	2.13%	no
7	1.0565	1.0650	1.0735	1.0689	1.0694	1.0698	0.41%	yes	108.158	108.242	108.326	106.678	106.683	106.688	-1.44%	no	78.494	79.207	79.919	81.019	81.056	81.092	2.33%	no
8	1.0575	1.0660	1.0745	1.0690	1.0694	1.0699	0.32%	yes	108.706	108.792	108.879	107.435	107.440	107.444	-1.24%	no	80.285	81.005	81.725	82.614	82.651	82.688	2.03%	no
13	1.0472	1.0557	1.0642	1.0602	1.0607	1.0612	0.47%	yes	108.933	109.011	109.090	107.394	107.399	107.404	-1.48%	no	77.983	78.698	79.413	80.966	81.003	81.040	2.93%	no
14	1.0542	1.0627	1.0712	1.0656	1.0661	1.0666	0.32%	yes	107.707	107.784	107.861	106.555	106.559	106.563	-1.14%	no	79.191	79.903	80.615	81.491	81.527	81.563	2.03%	no
15	1.0341	1.0426	1.0511	1.0461	1.0466	1.0470	0.38%	yes	106.927	107.002	107.077	105.322	105.327	105.331	-1.57%	no	76.484	77.187	77.890	78.801	78.837	78.873	2.14%	no
16	1.0414	1.0499	1.0584	1.0524	1.0529	1.0533	0.28%	yes	107.534	107.611	107.688	106.169	106.173	106.177	-1.34%	no	78.325	79.035	79.745	80.176	80.212	80.248	1.49%	no
21	1.0389	1.0474	1.0559	1.0519	1.0524	1.0528	0.47%	yes	106.450	106.535	106.620	104.587	104.592	104.597	-1.82%	no	74.774	75.467	76.160	76.975	77.010	77.045	2.04%	no
22	1.0275	1.0360	1.0445	1.0389	1.0394	1.0398	0.32%	yes	106.579	106.661	106.743	105.416	105.420	105.424	-1.16%	no	76.372	77.074	77.775	78.629	78.664	78.700	2.06%	no
23	1.0247	1.0332	1.0417	1.0366	1.0371	1.0375	0.38%	yes	107.489	107.573	107.657	106.175	106.179	106.183	-1.30%	no	76.362	77.069	77.776	78.905	78.941	78.977	2.43%	no
24	1.0204	1.0289	1.0374	1.0324	1.0328	1.0333	0.38%	yes	106.579	106.661	106.743	105.198	105.202	105.206	-1.37%	no	74.959	75.658	76.356	77.316	77.351	77.386	2.24%	no

Thin 4A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4789	0.4833	0.4877	0.4869	0.4875	0.4882	0.88%	yes	97.313	97.384	97.455	99.102	100.319	101.534	3.01%	no	31.127	31.458	31.789	34.985	35.528	36.069	12.94%	no
2	0.4781	0.4825	0.4869	0.4858	0.4865	0.4872	0.83%	yes	97.378	97.449	97.519	99.145	100.363	101.578	2.99%	no	31.267	31.598	31.929	34.979	35.522	36.064	12.42%	no
3	0.4846	0.4890	0.4934	0.4924	0.4930	0.4937	0.83%	yes	96.562	96.632	96.703	98.302	99.519	100.734	2.99%	no	31.398	31.728	32.057	35.137	35.687	36.237	12.48%	no
4	0.4955	0.4999	0.5043	0.5029	0.5035	0.5042	0.73%	yes	99.054	99.124	99.193	100.684	101.901	103.116	2.80%	no	33.092	33.435	33.777	36.717	37.278	37.838	11.50%	no
5	0.4681	0.4725	0.4769	0.4756	0.4763	0.4769	0.80%	yes	98.212	98.735	99.258	99.511	100.729	101.946	2.02%	no	31.172	31.507	31.842	34.513	35.050	35.585	11.24%	no
6	0.4775	0.4819	0.4863	0.4858	0.4865	0.4872	0.95%	yes	98.485	99.034	99.583	99.980	101.199	102.415	2.19%	no	31.319	31.656	31.992	35.192	35.733	36.274	12.88%	no
7	0.4741	0.4785	0.4829	0.4819	0.4826	0.4832	0.85%	yes	98.852	99.439	100.026	100.430	101.648	102.865	2.22%	no	31.340	31.679	32.018	34.993	35.527	36.060	12.15%	no
8	0.4856	0.4900	0.4944	0.4931	0.4938	0.4945	0.78%	yes	99.499	99.999	100.499	100.860	102.078	103.293	2.08%	no	32.553	32.897	33.241	36.143	36.696	37.248	11.55%	no
9	0.4962	0.5006	0.5050	0.5033	0.5039	0.5046	0.66%	yes	97.229	97.298	97.367	98.560	99.776	100.990	2.55%	no	32.771	33.107	33.442	35.964	36.527	37.090	10.33%	no
10	0.5134	0.5179	0.5224	0.5234	0.5240	0.5247	1.19%	no	96.547	96.614	96.681	98.323	99.538	100.751	3.03%	no	31.909	32.239	32.569	36.765	37.332	37.897	15.80%	no
11	0.4966	0.5010	0.5054	0.5038	0.5045	0.5051	0.69%	yes	98.494	98.564	98.633	100.068	101.284	102.498	2.76%	no	33.143	33.484	33.824	36.618	37.182	37.746	11.05%	no
12	0.4863	0.4907	0.4951	0.4939	0.4945	0.4952	0.78%	yes	98.092	98.160	98.229	99.921	101.138	102.353	3.03%	no	32.127	32.463	32.800	35.902	36.457	37.011	12.30%	no
13	0.3082	0.3123	0.3164	0.3150	0.3153	0.3156	0.96%	yes	95.657	96.119	96.582	97.772	98.732	99.692	2.72%	no	19.958	20.270	20.581	23.148	23.440	23.731	15.64%	no
14	0.3118	0.3159	0.3200	0.3179	0.3182	0.3186	0.73%	yes	96.851	97.296	97.742	98.964	99.924	100.884	2.70%	no	20.899	21.218	21.537	23.744	24.040	24.337	13.30%	no
15	0.3018	0.3059	0.3100	0.3078	0.3082	0.3085	0.74%	yes	97.020	97.476	97.933	98.932	99.894	100.854	2.48%	no	20.325	20.645	20.964	23.065	23.354	23.644	13.12%	no
16	0.3062	0.3103	0.3144	0.3131	0.3135	0.3138	1.02%	yes	96.787	97.254	97.722	98.980	99.940	100.900	2.76%	no	19.869	20.185	20.501	23.267	23.555	23.844	16.70%	no
17	0.3121	0.3162	0.3203	0.3182	0.3185	0.3188	0.73%	yes	96.971	97.043	97.115	98.931	99.891	100.850	2.93%	no	20.751	21.070	21.389	23.721	24.017	24.313	13.99%	no
18	0.3129	0.3170	0.3211	0.3192	0.3195	0.3198	0.79%	yes	97.085	97.159	97.233	99.036	99.995	100.954	2.92%	no	20.744	21.064	21.384	23.816	24.112	24.408	14.47%	no
19	0.3142	0.3183	0.3224	0.3205	0.3209	0.3212	0.81%	yes	96.729	96.804	96.879	98.875	99.834	100.793	3.13%	no	20.807	21.125	21.442	23.848	24.145	24.442	14.30%	no
20	0.3154	0.3195	0.3236	0.3211	0.3215	0.3218	0.61%	yes	97.059	97.136	97.212	99.134	100.094	101.052	3.05%	no	21.386	21.707	22.029	24.173	24.476	24.779	12.75%	no
21	0.3051	0.3092	0.3133	0.3112	0.3115	0.3119	0.75%	yes	97.590	97.666	97.742	99.457	100.418	101.378	2.82%	no	20.469	20.790	21.111	23.366	23.657	23.947	13.79%	no
22	0.3092	0.3133	0.3174	0.3153	0.3156	0.3159	0.73%	yes	97.317	97.384	97.451	99.276	100.236	101.196	2.93%	no	20.803	21.117	21.431	23.554	23.846	24.138	12.92%	no
23	0.3051	0.3092	0.3133	0.3114	0.3117	0.3121	0.81%	yes	98.255	98.324	98.393	100.021	100.982	101.942	2.70%	no	20.461	20.783	21.106	23.458	23.747	24.036	14.26%	no
24	0.3114	0.3155	0.3196	0.3177	0.3180	0.3183	0.80%	yes	97.792	97.864	97.936	99.804	100.765	101.725	2.96%	no	20.800	21.123	21.445	23.942	24.238	24.535	14.75%	no

Thin 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4785	0.4829	0.4873	0.6414	0.6422	0.6430	32.99%	no	35.654	35.692	35.729	41.865	41.996	42.128	17.66%	no	6.472	6.563	6.653	14.632	14.676	14.720	123.63%	no
2	0.4608	0.4652	0.4696	0.6031	0.6038	0.6046	29.79%	no	36.218	36.244	36.271	41.824	41.956	42.088	15.76%	no	6.404	6.496	6.589	12.953	12.987	13.021	99.91%	no
3	0.3896	0.3938	0.3980	0.5203	0.5208	0.5214	32.26%	no	30.194	30.221	30.248	40.378	40.510	40.642	34.05%	no	4.401	4.474	4.547	10.608	10.634	10.661	137.68%	no
4	0.3980	0.4022	0.4064	0.5451	0.5457	0.5463	35.67%	no	34.356	34.381	34.407	42.915	43.047	43.179	25.21%	no	5.084	5.169	5.255	12.404	12.436	12.467	140.56%	no
5	0.3618	0.3660	0.3702	0.5057	0.5064	0.5070	38.36%	no	27.807	27.844	27.882	37.595	37.728	37.862	35.50%	no	3.616	3.682	3.748	8.808	8.826	8.845	139.71%	no
6	0.3568	0.3610	0.3652	0.4938	0.4945	0.4951	36.97%	no	31.443	31.494	31.545	36.766	36.899	37.032	17.16%	no	4.091	4.165	4.240	8.641	8.662	8.683	107.96%	no
7	0.3616	0.3658	0.3700	0.5215	0.5221	0.5228	42.74%	no	32.411	32.676	32.942	40.171	40.304	40.437	23.34%	no	4.150	4.227	4.304	9.420	9.437	9.453	123.26%	no
8	0.3905	0.3947	0.3989	0.5541	0.5550	0.5558	40.60%	no	35.563	35.837	36.111	42.392	42.525	42.658	18.66%	no	5.093	5.181	5.269	12.491	12.527	12.563	141.79%	no
9	0.4102	0.4145	0.4188	0.5453	0.5459	0.5465	31.71%	no	36.085	36.111	36.138	43.785	43.917	44.049	21.62%	no	5.695	5.785	5.875	12.957	12.991	13.025	124.58%	no
10	0.3525	0.3567	0.3609	0.5901	0.5907	0.5913	65.60%	no	30.303	30.333	30.363	41.017	41.148	41.279	35.65%	no	3.392	3.460	3.528	9.350	9.359	9.367	170.47%	no
11	0.4493	0.4536	0.4579	0.6521	0.6529	0.6537	43.94%	no	29.475	29.498	29.521	38.947	39.078	39.209	32.48%	no	4.590	4.661	4.732	11.840	11.866	11.892	154.58%	no
12	0.4785	0.4830	0.4875	0.6031	0.6039	0.6047	25.03%	no	36.089	36.115	36.141	41.409	41.541	41.672	15.02%	no	6.899	6.992	7.084	12.998	13.034	13.070	86.43%	no
13	0.3797	0.3839	0.3881	0.5934	0.5940	0.5946	54.73%	no	27.788	27.811	27.833	39.487	39.618	39.749	42.46%	no	3.516	3.580	3.644	10.988	11.010	11.031	207.53%	no
14	0.4020	0.4063	0.4106	0.5290	0.5296	0.5302	30.34%	no	34.757	34.782	34.808	41.781	41.913	42.045	20.50%	no	5.387	5.473	5.560	11.543	11.572	11.600	111.41%	no
15	0.3701	0.3743	0.3785	0.5007	0.5014	0.5021	33.96%	no	32.231	32.312	32.394	39.818	39.951	40.085	23.64%	no	4.459	4.536	4.613	9.800	9.824	9.848	116.60%	no
16	0.3583	0.3625	0.3667	0.4938	0.4944	0.4951	36.40%	no	33.458	33.530	33.601	39.529	39.663	39.797	18.29%	no	4.396	4.476	4.557	9.149	9.169	9.188	104.82%	no
17	0.5716	0.5762	0.5808	0.7247	0.7255	0.7264	25.92%	no	35.179	35.206	35.232	41.016	41.149	41.281	16.88%	no	7.855	7.946	8.037	14.963	15.003	15.042	88.81%	no
18	0.5503	0.5548	0.5593	0.6770	0.6777	0.6785	22.16%	no	34.157	34.185	34.212	38.000	38.133	38.266	11.55%	no	7.505	7.594	7.683	12.567	12.600	12.632	65.92%	no
19	0.5457	0.5502	0.5547	0.7738	0.7749	0.7760	40.84%	no	37.190	37.320	37.451	40.752	40.880	41.008	9.54%	no	7.278	7.368	7.458	15.914	15.960	16.006	116.61%	no
20	0.5551	0.5597	0.5643	0.6675	0.6685	0.6694	19.43%	no	42.024	42.140	42.256	43.602	43.731	43.860	3.78%	no	9.792	9.905	10.018	14.852	14.892	14.931	50.35%	no
21	0.4961	0.5005	0.5049	0.7069	0.7078	0.7087	41.42%	no	34.335	34.538	34.741	38.961	39.089	39.218	13.18%	no	6.091	6.174	6.256	13.489	13.523	13.557	119.05%	no
22	0.4960	0.5004	0.5048	0.6588	0.6596	0.6604	31.82%	no	38.386	38.421	38.456	46.056	46.186	46.316	20.21%	no	7.082	7.178	7.273	14.636	14.669	14.702	104.38%	no
23	0.5226	0.5271	0.5316	0.6242	0.6250	0.6258	18.58%	no	36.232	36.384	36.535	41.092	41.221	41.351	13.30%	no	8.084	8.183	8.283	13.859	13.900	13.941	69.86%	no
24	0.5313	0.5358	0.5403	0.6354	0.6362	0.6370	18.74%	no	30.305	30.457	30.608	41.129	41.258	41.388	35.47%	no	6.618	6.703	6.787	13.102	13.134	13.166	95.95%	no
25	0.5442	0.5487	0.5532	0.6865	0.6875	0.6884	25.29%	no	37.103	37.132	37.160	41.795	41.924	42.052	12.91%	no	7.866	7.959	8.052	14.325	14.366	14.406	80.49%	no
26	0.5405	0.5450	0.5495	0.6859	0.6868	0.6877	26.02%	no	37.890	37.919	37.949	41.361	41.490	41.619	9.42%	no	7.969	8.066	8.163	13.554	13.586	13.618	68.44%	no
27	0.5509	0.5554	0.5599	0.7777	0.7785	0.7793	40.18%	no	32.174	32.220	32.267	40.815	40.947	41.079	27.08%	no	6.108	6.186	6.265	13.731	13.756	13.779	122.35%	no
28	0.5962	0.6008	0.6054	0.7428	0.7437	0.7446	23.78%	no	40.198	40.262	40.326	40.346	40.478	40.610	0.54%	no	9.751	9.860	9.968	16.105	16.153	16.200	63.82%	no
29	0.5306	0.5351	0.5396	0.7516	0.7525	0.7535	40.64%	no	31.973	31.998	32.022	41.100	41.229	41.357	28.85%	no	5.847	5.925	6.002	13.544	13.571	13.598	129.06%	no
30	0.5764	0.5810	0.5856	0.7108	0.7117	0.7127	22.50%	no	40.220	40.248	40.277	43.678	43.807	43.936	8.84%	no	9.376	9.484	9.592	16.269	16.318	16.366	72.05%	no
31	0.5041	0.5086	0.5131	0.7109	0.7117	0.7124	39.93%	no	29.016	29.039	29.062	38.498	38.627	38.756	33.02%	no	5.028	5.096	5.165	11.574	11.593	11.611	127.47%	no
32	0.4937	0.4981	0.5025	0.6880	0.6889	0.6897	38.30%	no	34.702	34.728	34.753	42.346	42.475	42.604	22.31%	no	6.148	6.234	6.319	14.086	14.119	14.152	126.50%	no

Thin 2B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
17	0.9854	0.9938	1.0022	1.1157	1.1163	1.1168	12.32%	no	38.472	38.588	38.704	40.878	40.879	40.879	5.94%	no	15.990	16.178	16.366	22.140	22.150	22.161	36.92%	no
18	0.9623	0.9706	0.9789	1.0719	1.0724	1.0730	10.49%	no	36.556	36.587	36.618	37.874	37.875	37.875	3.52%	no	14.767	14.942	15.117	19.104	19.113	19.122	27.92%	no
25	0.9448	0.9531	0.9614	1.0956	1.0964	1.0973	15.04%	no	39.096	39.129	39.162	41.678	41.679	41.680	6.52%	no	14.858	15.042	15.226	21.754	21.768	21.783	44.72%	no
26	0.9352	0.9435	0.9518	1.1282	1.1290	1.1298	19.66%	no	33.139	33.170	33.200	41.276	41.277	41.278	24.44%	no	11.882	12.033	12.183	21.505	21.519	21.534	78.84%	no
27	0.9477	0.9560	0.9643	1.1007	1.1012	1.1016	15.18%	no	36.144	36.185	36.227	40.597	40.598	40.599	12.19%	no	13.016	13.183	13.350	18.875	18.883	18.891	43.23%	no
28	1.0192	1.0277	1.0362	1.1473	1.1480	1.1486	11.70%	no	42.504	42.540	42.577	40.195	40.196	40.196	-5.51%	no	19.210	19.425	19.640	23.981	23.993	24.005	23.52%	no

Thin 2B -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4785	0.4829	0.4873	0.6479	0.6486	0.6493	34.31%	no	35.654	35.692	35.729	32.377	32.571	32.766	-8.74%	no	6.472	6.563	6.653	12.216	12.310	12.402	87.57%	no
2	0.4608	0.4652	0.4696	0.6097	0.6103	0.6110	31.19%	no	36.218	36.244	36.271	31.736	31.934	32.132	-11.89%	no	6.404	6.496	6.589	10.808	10.891	10.972	67.64%	no
3	0.3896	0.3938	0.3980	0.5244	0.5248	0.5252	33.27%	no	30.194	30.221	30.248	28.712	28.918	29.124	-4.31%	no	4.401	4.474	4.547	8.244	8.316	8.388	85.87%	no
4	0.3980	0.4022	0.4064	0.5505	0.5510	0.5514	36.99%	no	34.356	34.381	34.407	32.416	32.616	32.815	-5.14%	no	5.084	5.169	5.255	10.257	10.332	10.407	99.87%	no
5	0.3618	0.3660	0.3702	0.5110	0.5116	0.5121	39.77%	no	27.807	27.844	27.882	27.680	27.879	28.078	0.12%	yes	3.616	3.682	3.748	7.435	7.493	7.550	103.50%	no
6	0.3568	0.3610	0.3652	0.4982	0.4988	0.4993	38.17%	no	31.443	31.494	31.545	26.791	26.990	27.190	-14.30%	no	4.091	4.165	4.240	7.118	7.178	7.237	72.32%	no
7	0.3616	0.3658	0.3700	0.5282	0.5289	0.5295	44.59%	no	32.411	32.676	32.942	29.965	30.166	30.367	-7.68%	no	4.150	4.227	4.304	8.149	8.208	8.267	94.19%	no
8	0.3905	0.3947	0.3989	0.5601	0.5608	0.5615	42.09%	no	35.563	35.837	36.111	32.970	33.167	33.363	-7.45%	no	5.093	5.181	5.269	10.673	10.749	10.825	107.47%	no
9	0.4102	0.4145	0.4188	0.5506	0.5510	0.5515	32.93%	no	36.085	36.111	36.138	33.275	33.475	33.674	-7.30%	no	5.695	5.785	5.875	10.728	10.806	10.882	86.79%	no
10	0.3525	0.3567	0.3609	0.6045	0.6052	0.6060	69.68%	no	30.303	30.333	30.363	35.387	35.555	35.723	17.22%	no	3.392	3.460	3.528	9.322	9.351	9.380	170.27%	no
11	0.4493	0.4536	0.4579	0.6609	0.6616	0.6624	45.86%	no	29.475	29.498	29.521	29.492	29.686	29.879	0.64%	yes	4.590	4.661	4.732	10.081	10.159	10.237	117.97%	no
12	0.4785	0.4830	0.4875	0.6095	0.6102	0.6108	26.33%	no	36.089	36.115	36.141	31.434	31.631	31.829	-12.41%	no	6.899	6.992	7.084	10.798	10.881	10.964	55.63%	no
13	0.3797	0.3839	0.3881	0.6009	0.6014	0.6020	56.66%	no	27.788	27.811	27.833	29.700	29.894	30.088	7.49%	no	3.516	3.580	3.644	9.328	9.397	9.465	162.48%	no
14	0.4020	0.4063	0.4106	0.5342	0.5346	0.5350	31.58%	no	34.757	34.782	34.808	30.147	30.353	30.560	-12.73%	no	5.387	5.473	5.560	9.206	9.282	9.357	69.58%	no
15	0.3701	0.3743	0.3785	0.5058	0.5064	0.5069	35.28%	no	32.231	32.312	32.394	29.504	29.707	29.908	-8.06%	no	4.459	4.536	4.613	8.170	8.233	8.297	81.53%	no
16	0.3583	0.3625	0.3667	0.4989	0.4995	0.5001	37.79%	no	33.458	33.530	33.601	29.020	29.224	29.427	-12.84%	no	4.396	4.476	4.557	7.692	7.751	7.810	73.15%	no
17	0.5716	0.5762	0.5808	0.7343	0.7351	0.7359	27.57%	no	35.179	35.206	35.232	31.951	32.144	32.337	-8.70%	no	7.855	7.946	8.037	12.748	12.847	12.944	61.67%	no
18	0.5503	0.5548	0.5593	0.6849	0.6856	0.6863	23.58%	no	34.157	34.185	34.212	29.075	29.267	29.459	-14.39%	no	7.505	7.594	7.683	10.561	10.646	10.731	40.19%	no
19	0.5457	0.5502	0.5547	0.7849	0.7860	0.7871	42.86%	no	37.190	37.320	37.451	31.821	32.010	32.200	-14.23%	no	7.278	7.368	7.458	13.573	13.681	13.788	85.69%	no
20	0.5551	0.5597	0.5643	0.6768	0.6777	0.6786	21.09%	no	42.024	42.140	42.256	34.192	34.384	34.577	-18.40%	no	9.792	9.905	10.018	12.845	12.937	13.029	30.61%	no
21	0.4961	0.5005	0.5049	0.7168	0.7176	0.7185	43.38%	no	34.335	34.538	34.741	30.195	30.382	30.568	-12.03%	no	6.091	6.174	6.256	11.586	11.673	11.759	89.08%	no
22	0.4960	0.5004	0.5048	0.6679	0.6686	0.6694	33.62%	no	38.386	38.421	38.456	34.321	34.527	34.734	-10.13%	no	7.082	7.178	7.273	12.085	12.180	12.275	69.70%	no
23	0.5226	0.5271	0.5316	0.6306	0.6313	0.6320	19.77%	no	36.232	36.384	36.535	31.807	31.998	32.188	-12.05%	no	8.084	8.183	8.283	11.616	11.703	11.790	43.02%	no
24	0.5313	0.5358	0.5403	0.6434	0.6441	0.6448	20.22%	no	30.305	30.457	30.608	31.700	31.891	32.082	4.71%	no	6.618	6.703	6.787	11.209	11.289	11.369	68.42%	no
25	0.5442	0.5487	0.5532	0.6948	0.6956	0.6965	26.78%	no	37.103	37.132	37.160	31.504	31.702	31.900	-14.62%	no	7.866	7.959	8.052	11.739	11.838	11.937	48.74%	no
26	0.5405	0.5450	0.5495	0.6963	0.6972	0.6982	27.93%	no	37.890	37.919	37.949	32.018	32.209	32.401	-15.06%	no	7.969	8.066	8.163	11.766	11.852	11.938	46.94%	no
27	0.5509	0.5554	0.5599	0.7917	0.7927	0.7937	42.72%	no	32.174	32.220	32.267	31.392	31.587	31.782	-1.97%	no	6.108	6.186	6.265	11.936	12.030	12.122	94.45%	no
28	0.5962	0.6008	0.6054	0.7520	0.7528	0.7536	25.30%	no	40.198	40.262	40.326	32.446	32.631	32.817	-18.95%	no	9.751	9.860	9.968	14.015	14.117	14.218	43.18%	no
29	0.5306	0.5351	0.5396	0.7643	0.7653	0.7664	43.02%	no	31.973	31.998	32.022	31.129	31.325	31.520	-2.10%	no	5.847	5.925	6.002	11.561	11.655	11.748	96.73%	no
30	0.5764	0.5810	0.5856	0.7190	0.7199	0.7208	23.90%	no	40.220	40.248	40.277	33.325	33.524	33.722	-16.71%	no	9.376	9.484	9.592	13.400	13.509	13.617	42.43%	no
31	0.5041	0.5086	0.5131	0.7218	0.7226	0.7234	42.07%	no	29.016	29.039	29.062	28.734	28.926	29.119	-0.39%	yes	5.028	5.096	5.165	9.877	9.956	10.034	95.35%	no
32	0.4937	0.4981	0.5025	0.6978	0.6987	0.6995	40.26%	no	34.702	34.728	34.753	32.279	32.474	32.669	-6.49%	no	6.148	6.234	6.319	11.931	12.022	12.112	92.86%	no

Thin 2B -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
17	0.9854	0.9938	1.0022	1.1323	1.1329	1.1335	13.99%	no	38.472	38.588	38.704	35.668	35.674	35.680	-7.55%	no	15.990	16.178	16.366	20.399	20.412	20.424	26.17%	no
18	0.9623	0.9706	0.9789	1.0863	1.0868	1.0874	11.98%	no	36.556	36.587	36.618	32.756	32.761	32.766	-10.46%	no	14.767	14.942	15.117	17.401	17.411	17.422	16.53%	no
25	0.9448	0.9531	0.9614	1.1109	1.1117	1.1126	16.64%	no	39.096	39.129	39.162	35.943	35.952	35.962	-8.12%	no	14.858	15.042	15.226	19.618	19.635	19.653	30.54%	no
26	0.9352	0.9435	0.9518	1.1490	1.1499	1.1507	21.87%	no	33.139	33.170	33.200	36.254	36.262	36.270	9.32%	no	11.882	12.033	12.183	20.196	20.213	20.230	67.98%	no
27	0.9477	0.9560	0.9643	1.1213	1.1218	1.1223	17.34%	no	36.144	36.185	36.227	34.730	34.735	34.741	-4.01%	no	13.016	13.183	13.350	17.319	17.328	17.337	31.44%	no
28	1.0192	1.0277	1.0362	1.1635	1.1641	1.1648	13.27%	no	42.504	42.540	42.577	35.696	35.702	35.707	-16.08%	no	19.210	19.425	19.640	22.469	22.483	22.497	15.74%	no

Thin 3B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.1438	0.1598	0.1758	0.1635	0.1645	0.1655	2.93%	yes	85.205	85.267	85.328	89.249	90.120	90.990	5.69%	no	7.402	7.656	7.910	9.467	9.589	9.710	25.24%	no
2	0.1422	0.1580	0.1738	0.1630	0.1640	0.1650	3.81%	yes	84.355	84.416	84.476	88.975	89.846	90.717	6.43%	no	7.006	7.254	7.501	9.441	9.564	9.686	31.84%	no
3	0.1436	0.1596	0.1756	0.1660	0.1669	0.1679	4.59%	yes	83.980	84.043	84.105	88.642	89.513	90.383	6.51%	no	6.859	7.102	7.345	9.281	9.397	9.512	32.32%	no
4	0.1373	0.1526	0.1679	0.1547	0.1557	0.1567	2.02%	yes	85.557	85.611	85.666	89.640	90.512	91.383	5.72%	no	7.618	7.876	8.135	9.731	9.869	10.006	25.30%	no
5	0.1372	0.1524	0.1676	0.1555	0.1565	0.1575	2.69%	yes	84.551	84.605	84.660	89.288	90.160	91.032	6.57%	no	7.236	7.488	7.740	9.481	9.611	9.742	28.35%	no
6	0.1400	0.1555	0.1711	0.1583	0.1592	0.1602	2.39%	yes	83.210	83.271	83.332	87.188	88.060	88.930	5.75%	no	7.274	7.523	7.773	9.027	9.147	9.267	21.58%	no
7	0.1398	0.1553	0.1708	0.1582	0.1591	0.1601	2.47%	yes	83.501	83.601	83.701	87.147	88.018	88.888	5.28%	no	7.334	7.583	7.832	9.172	9.297	9.422	22.60%	no
8	0.1393	0.1548	0.1703	0.1586	0.1595	0.1605	3.07%	yes	84.223	84.333	84.443	88.651	89.522	90.393	6.15%	no	7.125	7.374	7.623	9.341	9.466	9.591	28.37%	no
9	0.1394	0.1549	0.1704	0.1598	0.1608	0.1617	3.78%	yes	83.364	83.479	83.595	89.062	89.934	90.804	7.73%	no	6.927	7.170	7.413	9.504	9.631	9.758	34.32%	no
10	0.1661	0.1846	0.2031	0.1899	0.1909	0.1919	3.41%	yes	85.849	85.964	86.079	90.253	91.112	91.970	5.99%	no	8.611	8.863	9.116	11.095	11.229	11.362	26.69%	no
11	0.1666	0.1851	0.2036	0.1885	0.1896	0.1906	2.41%	yes	85.353	85.450	85.546	89.650	90.508	91.366	5.92%	no	9.095	9.350	9.605	11.563	11.713	11.863	25.27%	no
12	0.1643	0.1826	0.2009	0.1865	0.1876	0.1886	2.73%	yes	86.132	86.237	86.342	90.742	91.601	92.459	6.22%	no	8.792	9.050	9.308	11.424	11.567	11.711	27.81%	no
13	0.1722	0.1913	0.2104	0.1952	0.1962	0.1973	2.56%	yes	86.028	86.088	86.147	90.872	91.730	92.588	6.55%	no	9.274	9.532	9.789	11.932	12.081	12.231	26.75%	no
14	0.1733	0.1925	0.2118	0.1991	0.2002	0.2012	3.98%	yes	85.319	85.379	85.439	90.987	91.844	92.701	7.57%	no	8.780	9.029	9.278	12.176	12.327	12.478	36.52%	no
15	0.1685	0.1872	0.2059	0.1922	0.1932	0.1943	3.22%	yes	85.393	85.452	85.512	90.694	91.553	92.410	7.14%	no	8.757	9.010	9.262	11.786	11.934	12.083	32.46%	no
16	0.1645	0.1828	0.2011	0.1868	0.1878	0.1888	2.74%	yes	85.224	85.320	85.417	89.629	90.487	91.345	6.06%	no	8.708	8.962	9.217	11.214	11.355	11.497	26.70%	no
17	0.1728	0.1920	0.2112	0.1978	0.1988	0.1999	3.55%	yes	84.715	84.809	84.903	89.369	90.226	91.083	6.39%	no	8.749	8.998	9.247	11.473	11.611	11.750	29.05%	no
18	0.1716	0.1907	0.2098	0.1956	0.1966	0.1977	3.11%	yes	85.787	85.885	85.983	91.075	91.933	92.791	7.04%	no	8.987	9.241	9.495	11.849	11.995	12.141	29.80%	no
19	0.1762	0.1958	0.2154	0.2000	0.2015	0.2031	2.92%	yes	80.357	80.407	80.458	82.591	83.844	85.095	4.27%	no	8.516	8.749	8.982	10.265	10.464	10.663	19.60%	no
20	0.1708	0.1898	0.2088	0.1959	0.1975	0.1990	4.04%	yes	77.857	77.919	77.982	81.161	82.414	83.666	5.77%	no	7.572	7.793	8.015	9.511	9.689	9.867	24.33%	no
21	0.1783	0.1981	0.2179	0.2011	0.2027	0.2043	2.30%	yes	81.508	81.568	81.628	84.267	85.520	86.772	4.84%	no	9.083	9.324	9.565	11.152	11.378	11.605	22.03%	no
22	0.1759	0.1954	0.2149	0.1978	0.1995	0.2011	2.08%	yes	79.224	79.343	79.462	82.853	84.106	85.357	6.00%	no	8.741	8.978	9.215	10.717	10.937	11.157	21.82%	no
23	0.1750	0.1944	0.2138	0.1967	0.1983	0.1999	2.00%	yes	77.423	77.517	77.610	80.757	82.009	83.260	5.80%	no	8.555	8.784	9.014	10.254	10.467	10.681	19.16%	no
24	0.1766	0.1962	0.2158	0.1984	0.2000	0.2017	1.96%	yes	79.575	79.650	79.724	83.500	84.752	86.003	6.41%	no	8.982	9.220	9.458	11.217	11.454	11.693	24.23%	no
25	0.1627	0.1808	0.1989	0.1859	0.1873	0.1888	3.60%	yes	80.478	80.544	80.609	83.158	84.414	85.668	4.80%	no	7.539	7.770	8.002	8.844	8.995	9.144	15.76%	no
26	0.1584	0.1760	0.1936	0.1811	0.1826	0.1840	3.74%	yes	78.325	78.396	78.467	81.715	82.971	84.226	5.84%	no	7.009	7.233	7.457	8.277	8.416	8.554	16.36%	no
27	0.1760	0.1955	0.2151	0.1976	0.1993	0.2010	1.95%	yes	78.638	78.696	78.753	81.855	83.106	84.357	5.61%	no	8.745	8.980	9.216	10.693	10.919	11.146	21.59%	no

Thin 3B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
10	0.3713	0.3795	0.3877	0.3860	0.3869	0.3878	1.95%	yes	85.677	85.791	85.906	89.018	89.029	89.040	3.77%	no	18.255	18.790	19.325	21.682	21.732	21.783	15.66%	no
11	0.3658	0.3738	0.3818	0.3778	0.3786	0.3795	1.29%	yes	85.374	85.470	85.567	88.332	88.343	88.355	3.36%	no	19.017	19.550	20.083	22.224	22.278	22.331	13.95%	no
12	0.3612	0.3692	0.3772	0.3730	0.3739	0.3747	1.26%	yes	86.521	86.626	86.731	89.425	89.437	89.449	3.25%	no	18.970	19.528	20.085	22.000	22.054	22.108	12.94%	no
13	0.3762	0.3842	0.3922	0.3890	0.3899	0.3908	1.48%	yes	86.083	86.143	86.202	89.548	89.560	89.571	3.97%	no	19.379	19.917	20.455	22.824	22.877	22.931	14.86%	no
14	0.3774	0.3854	0.3934	0.3906	0.3915	0.3924	1.58%	yes	85.596	85.656	85.716	89.586	89.597	89.609	4.60%	no	19.167	19.711	20.256	22.974	23.028	23.082	16.82%	no
15	0.3680	0.3760	0.3840	0.3801	0.3810	0.3819	1.34%	yes	85.425	85.484	85.544	89.327	89.339	89.350	4.51%	no	18.920	19.465	20.010	22.424	22.478	22.533	15.48%	no
16	0.3640	0.3721	0.3802	0.3765	0.3773	0.3782	1.41%	yes	85.432	85.528	85.625	88.337	88.348	88.360	3.30%	no	18.679	19.224	19.770	21.746	21.798	21.851	13.39%	no
17	0.3802	0.3883	0.3964	0.3942	0.3951	0.3960	1.75%	yes	84.841	84.936	85.030	88.025	88.036	88.047	3.65%	no	18.699	19.231	19.764	21.983	22.033	22.083	14.57%	no
18	0.3759	0.3839	0.3919	0.3893	0.3902	0.3911	1.64%	yes	85.913	86.011	86.109	89.748	89.759	89.771	4.36%	no	19.044	19.583	20.122	22.646	22.699	22.752	15.91%	no

Thin 3B -- low irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.1438	0.1598	0.1758	0.1632	0.1642	0.1652	2.76%	yes	85.205	85.267	85.328	79.764	80.717	81.669	-5.34%	no	7.402	7.656	7.910	8.406	8.535	8.664	11.48%	no
2	0.1422	0.1580	0.1738	0.1628	0.1637	0.1647	3.64%	yes	84.355	84.416	84.476	79.937	80.887	81.836	-4.18%	no	7.006	7.254	7.501	8.424	8.554	8.684	17.93%	no
3	0.1436	0.1596	0.1756	0.1656	0.1666	0.1675	4.36%	yes	83.980	84.043	84.105	80.533	81.473	82.413	-3.06%	no	6.859	7.102	7.345	8.393	8.515	8.636	19.89%	no
4	0.1373	0.1526	0.1679	0.1546	0.1556	0.1565	1.93%	yes	85.557	85.611	85.666	81.097	82.044	82.990	-4.17%	no	7.618	7.876	8.135	8.685	8.827	8.969	12.07%	no
5	0.1372	0.1524	0.1676	0.1554	0.1564	0.1573	2.60%	yes	84.551	84.605	84.660	78.405	79.372	80.338	-6.19%	no	7.236	7.488	7.740	8.233	8.372	8.511	11.80%	no
6	0.1400	0.1555	0.1711	0.1581	0.1590	0.1600	2.26%	yes	83.210	83.271	83.332	77.365	78.322	79.277	-5.94%	no	7.274	7.523	7.773	7.960	8.088	8.216	7.50%	no
7	0.1398	0.1553	0.1708	0.1580	0.1590	0.1599	2.35%	yes	83.501	83.601	83.701	76.867	77.828	78.788	-6.91%	no	7.334	7.583	7.832	8.013	8.146	8.280	7.43%	no
8	0.1393	0.1548	0.1703	0.1584	0.1594	0.1603	2.94%	yes	84.223	84.333	84.443	79.417	80.370	81.321	-4.70%	no	7.125	7.374	7.623	8.301	8.433	8.566	14.37%	no
9	0.1394	0.1549	0.1704	0.1596	0.1605	0.1615	3.64%	yes	83.364	83.479	83.595	80.759	81.702	82.645	-2.13%	no	6.927	7.170	7.413	8.541	8.673	8.806	20.97%	no
10	0.1661	0.1846	0.2031	0.1895	0.1905	0.1915	3.19%	yes	85.849	85.964	86.079	83.042	83.962	84.882	-2.33%	no	8.611	8.863	9.116	10.117	10.255	10.392	15.70%	no
11	0.1666	0.1851	0.2036	0.1882	0.1893	0.1903	2.25%	yes	85.353	85.450	85.546	83.254	84.168	85.081	-1.50%	no	9.095	9.350	9.605	10.590	10.742	10.894	14.89%	no
12	0.1643	0.1826	0.2009	0.1863	0.1873	0.1884	2.58%	yes	86.132	86.237	86.342	84.050	84.967	85.883	-1.47%	no	8.792	9.050	9.308	10.474	10.621	10.769	17.36%	no
13	0.1722	0.1913	0.2104	0.1949	0.1960	0.1970	2.44%	yes	86.028	86.088	86.147	80.615	81.561	82.506	-5.26%	no	9.274	9.532	9.789	10.456	10.615	10.775	11.37%	no
14	0.1733	0.1925	0.2118	0.1988	0.1999	0.2010	3.84%	yes	85.319	85.379	85.439	83.361	84.284	85.206	-1.28%	no	8.780	9.029	9.278	11.047	11.204	11.362	24.09%	no
15	0.1685	0.1872	0.2059	0.1919	0.1930	0.1941	3.09%	yes	85.393	85.452	85.512	82.459	83.389	84.317	-2.42%	no	8.757	9.010	9.262	10.599	10.754	10.909	19.36%	no
16	0.1645	0.1828	0.2011	0.1865	0.1876	0.1886	2.60%	yes	85.224	85.320	85.417	82.547	83.467	84.386	-2.17%	no	8.708	8.962	9.217	10.231	10.377	10.523	15.78%	no
17	0.1728	0.1920	0.2112	0.1974	0.1984	0.1995	3.34%	yes	84.715	84.809	84.903	82.783	83.697	84.610	-1.31%	no	8.749	8.998	9.247	10.538	10.681	10.824	18.71%	no
18	0.1716	0.1907	0.2098	0.1952	0.1963	0.1973	2.92%	yes	85.787	85.885	85.983	84.308	85.224	86.139	-0.77%	yes	8.987	9.241	9.495	10.844	10.993	11.142	18.96%	no
19	0.1762	0.1958	0.2154	0.1996	0.2011	0.2027	2.73%	yes	80.357	80.407	80.458	74.826	76.172	77.516	-5.27%	no	8.516	8.749	8.982	9.222	9.429	9.636	7.78%	no
20	0.1708	0.1898	0.2088	0.1954	0.1970	0.1986	3.80%	yes	77.857	77.919	77.982	74.188	75.525	76.860	-3.07%	no	7.572	7.793	8.015	8.655	8.841	9.027	13.45%	no
21	0.1783	0.1981	0.2179	0.2009	0.2025	0.2041	2.20%	yes	81.508	81.568	81.628	72.801	74.192	75.582	-9.04%	no	9.083	9.324	9.565	9.479	9.721	9.963	4.26%	yes
22	0.1759	0.1954	0.2149	0.1976	0.1992	0.2009	1.97%	yes	79.224	79.343	79.462	74.873	76.224	77.573	-3.93%	no	8.741	8.978	9.215	9.582	9.811	10.040	9.28%	no
23	0.1750	0.1944	0.2138	0.1964	0.1981	0.1997	1.88%	yes	77.423	77.517	77.610	73.343	74.686	76.029	-3.65%	no	8.555	8.784	9.014	9.224	9.445	9.667	7.52%	no
24	0.1766	0.1962	0.2158	0.1982	0.1999	0.2016	1.88%	yes	79.575	79.650	79.724	76.297	77.639	78.979	-2.52%	no	8.982	9.220	9.458	10.113	10.357	10.602	12.33%	no
25	0.1627	0.1808	0.1989	0.1859	0.1873	0.1888	3.60%	yes	80.478	80.544	80.609	83.158	84.414	85.668	4.80%	no	7.539	7.770	8.002	8.844	8.995	9.144	15.76%	no
26	0.1584	0.1760	0.1936	0.1811	0.1826	0.1840	3.74%	yes	78.325	78.396	78.467	81.715	82.971	84.226	5.84%	no	7.009	7.233	7.457	8.277	8.416	8.554	16.36%	no
27	0.1760	0.1955	0.2151	0.1976	0.1993	0.2010	1.95%	yes	78.638	78.696	78.753	81.855	83.106	84.357	5.61%	no	8.745	8.980	9.216	10.693	10.919	11.146	21.59%	no

Thin 3B -- med irradiance (7P)

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
10	0.3713	0.3795	0.3877	0.3849	0.3857	0.3866	1.65%	yes	85.677	85.791	85.906	85.320	85.343	85.367	-0.52%	no	18.255	18.790	19.325	20.453	20.503	20.553	9.12%	no
11	0.3658	0.3738	0.3818	0.3770	0.3779	0.3788	1.09%	yes	85.374	85.470	85.567	85.016	85.039	85.062	-0.50%	no	19.017	19.550	20.083	21.013	21.066	21.120	7.76%	no
12	0.3612	0.3692	0.3772	0.3723	0.3731	0.3740	1.07%	yes	86.521	86.626	86.731	85.941	85.964	85.988	-0.76%	no	18.970	19.528	20.085	20.848	20.902	20.955	7.04%	no
13	0.3762	0.3842	0.3922	0.3883	0.3892	0.3901	1.31%	yes	86.083	86.143	86.202	84.242	84.271	84.300	-2.17%	no	19.379	19.917	20.455	21.148	21.202	21.256	6.45%	no
14	0.3774	0.3854	0.3934	0.3899	0.3908	0.3917	1.40%	yes	85.596	85.656	85.716	85.613	85.638	85.663	-0.02%	yes	19.167	19.711	20.256	21.666	21.721	21.775	10.19%	no
15	0.3680	0.3760	0.3840	0.3795	0.3804	0.3813	1.16%	yes	85.425	85.484	85.544	85.035	85.061	85.088	-0.50%	no	18.920	19.465	20.010	21.048	21.103	21.157	8.41%	no
16	0.3640	0.3721	0.3802	0.3758	0.3766	0.3775	1.22%	yes	85.432	85.528	85.625	84.674	84.698	84.722	-0.97%	no	18.679	19.224	19.770	20.567	20.619	20.671	7.25%	no
17	0.3802	0.3883	0.3964	0.3932	0.3941	0.3949	1.48%	yes	84.841	84.936	85.030	84.603	84.625	84.647	-0.37%	no	18.699	19.231	19.764	20.826	20.876	20.926	8.55%	no
18	0.3759	0.3839	0.3919	0.3883	0.3892	0.3901	1.39%	yes	85.913	86.011	86.109	86.243	86.266	86.290	0.30%	no	19.044	19.583	20.122	21.402	21.454	21.507	9.55%	no

E.2. Proposed Improved Single Diode Model Translation Accuracy

The following tables show the accuracy of the improved single diode model proposed in this work, with the high and low irradiance reference conditions used to predict performance under medium (when data are available) and low irradiance. Each table includes the nominal and high and low uncertainty bounds of the module level short circuit current, open circuit voltage, and maximum power points for a single array. Also noted is the percent difference between the measured and modeled values for each parameter, and whether or not the measured and modeled values are in agreement, given the associated uncertainty of each.

Mono 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.8759	0.9732	1.0705	0.9711	0.9732	0.9752	0.00%	yes	41.134	41.175	41.215	40.951	41.175	41.398	0.00%	yes	30.771	30.957	31.144	30.547	30.794	31.043	-0.53%	yes
2	0.8198	0.9109	1.0020	0.9090	0.9109	0.9129	0.00%	yes	41.219	41.267	41.316	41.020	41.267	41.514	0.00%	yes	27.861	28.041	28.222	27.707	27.932	28.157	-0.39%	yes
3	0.8232	0.9147	1.0062	0.9128	0.9147	0.9166	0.00%	yes	41.453	41.501	41.548	41.250	41.501	41.752	0.00%	yes	29.044	29.227	29.410	28.857	29.105	29.354	-0.42%	yes
4	0.8418	0.9353	1.0288	0.9333	0.9353	0.9372	0.00%	yes	41.632	41.678	41.724	41.409	41.678	41.946	0.00%	yes	29.739	29.923	30.108	29.544	29.816	30.089	-0.36%	yes
5	0.8761	0.9734	1.0707	0.9714	0.9734	0.9754	0.00%	yes	41.602	41.645	41.687	41.378	41.645	41.911	0.00%	yes	30.047	30.232	30.417	29.853	30.123	30.393	-0.36%	yes
6	0.8719	0.9688	1.0657	0.9667	0.9688	0.9708	0.00%	yes	41.680	41.780	41.880	41.529	41.780	42.030	0.00%	yes	30.522	30.709	30.897	30.325	30.585	30.846	-0.40%	yes
7	0.8802	0.9780	1.0758	0.9759	0.9780	0.9801	0.00%	yes	41.350	41.395	41.441	41.176	41.395	41.615	0.00%	yes	30.609	30.795	30.981	30.389	30.630	30.871	-0.54%	yes
8	0.8014	0.8904	0.9794	0.8885	0.8904	0.8923	0.00%	yes	41.428	41.476	41.525	41.227	41.476	41.726	0.00%	yes	28.543	28.725	28.908	28.363	28.605	28.847	-0.42%	yes
9	0.8537	0.9485	1.0434	0.9465	0.9485	0.9504	0.00%	yes	41.713	41.758	41.803	41.494	41.758	42.023	0.00%	yes	29.950	30.137	30.324	29.767	30.029	30.290	-0.36%	yes
10	0.8509	0.9454	1.0399	0.9434	0.9454	0.9474	0.00%	yes	41.612	41.657	41.703	41.390	41.657	41.924	0.00%	yes	30.029	30.215	30.401	29.838	30.110	30.383	-0.35%	yes
11	0.8676	0.9640	1.0604	0.9620	0.9640	0.9660	0.00%	yes	41.565	41.618	41.670	41.354	41.618	41.881	0.00%	yes	30.490	30.677	30.865	30.298	30.568	30.839	-0.36%	yes
12	0.8507	0.9452	1.0397	0.9433	0.9452	0.9472	0.01%	yes	41.570	41.628	41.685	41.366	41.628	41.890	0.00%	yes	29.399	29.583	29.767	29.223	29.479	29.736	-0.35%	yes
13	0.8409	0.9343	1.0277	0.9323	0.9343	0.9364	0.00%	yes	41.340	41.389	41.438	41.162	41.389	41.616	0.00%	yes	29.651	29.836	30.021	29.452	29.688	29.925	-0.50%	yes
14	0.8110	0.9011	0.9912	0.8992	0.9011	0.9030	0.00%	yes	41.445	41.501	41.557	41.247	41.501	41.755	0.00%	yes	28.197	28.378	28.560	28.031	28.267	28.504	-0.39%	yes
15	0.8493	0.9437	1.0381	0.9417	0.9437	0.9457	0.00%	yes	41.528	41.583	41.637	41.317	41.583	41.848	0.00%	yes	29.147	29.331	29.516	28.988	29.235	29.482	-0.33%	yes
16	0.8545	0.9494	1.0443	0.9474	0.9494	0.9514	0.00%	yes	41.073	41.102	41.131	40.834	41.102	41.370	0.00%	yes	29.978	30.163	30.348	29.788	30.061	30.335	-0.34%	yes
17	0.8532	0.9480	1.0428	0.9460	0.9480	0.9500	0.00%	yes	42.288	42.351	42.413	42.085	42.351	42.616	0.00%	yes	30.887	31.079	31.270	30.707	30.975	31.245	-0.33%	yes
18	0.9247	1.0274	1.1301	1.0254	1.0274	1.0294	0.00%	yes	41.980	42.023	42.067	41.768	42.023	42.279	0.00%	yes	32.941	33.136	33.331	32.722	33.005	33.288	-0.40%	yes
19	0.8681	0.9646	1.0611	0.9626	0.9646	0.9666	0.00%	yes	41.474	41.526	41.577	41.288	41.526	41.763	0.00%	yes	29.543	29.729	29.915	29.377	29.602	29.826	-0.43%	yes
20	0.8174	0.9082	0.9990	0.9063	0.9082	0.9101	0.00%	yes	41.607	41.662	41.716	41.415	41.662	41.909	0.00%	yes	28.748	28.930	29.111	28.555	28.802	29.049	-0.44%	yes
21	0.8257	0.9174	1.0091	0.9154	0.9174	0.9193	0.00%	yes	41.541	41.592	41.643	41.333	41.592	41.851	0.00%	yes	29.013	29.196	29.380	28.837	29.089	29.341	-0.37%	yes
22	0.8798	0.9776	1.0754	0.9756	0.9776	0.9797	0.00%	yes	41.921	41.969	42.016	41.708	41.969	42.229	0.00%	yes	31.433	31.623	31.813	31.229	31.508	31.788	-0.36%	yes
23	0.9361	0.9416	0.9471	0.9396	0.9416	0.9436	0.00%	yes	41.416	41.472	41.528	41.218	41.472	41.726	0.00%	yes	30.325	30.511	30.698	30.119	30.386	30.654	-0.41%	yes
24	0.9336	0.9391	0.9446	0.9371	0.9391	0.9411	0.00%	yes	41.541	41.593	41.645	41.337	41.593	41.850	0.00%	yes	29.908	30.093	30.279	29.713	29.977	30.241	-0.39%	yes

Mono 1A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.5832	2.8702	3.1572	2.8637	2.8699	2.8761	-0.01%	yes	39.804	39.837	39.870	39.680	39.898	40.116	0.15%	yes	85.137	85.566	85.996	84.963	85.667	86.372	0.12%	yes
2	2.5998	2.8887	3.1776	2.8777	2.8840	2.8903	-0.16%	yes	39.891	39.926	39.961	39.597	39.841	40.085	-0.21%	yes	86.029	86.461	86.894	83.954	84.711	85.470	-2.02%	no
3	2.6585	2.9539	3.2493	2.9469	2.9531	2.9594	-0.03%	yes	39.891	39.926	39.961	39.707	39.956	40.205	0.08%	yes	86.309	86.742	87.175	86.042	86.826	87.612	0.10%	yes
4	2.6278	2.9198	3.2118	2.9141	2.9202	2.9264	0.02%	yes	39.823	39.860	39.896	39.502	39.771	40.040	-0.22%	yes	84.387	84.812	85.237	84.299	85.126	85.956	0.37%	yes
5	2.6141	2.9045	3.1950	2.9063	2.9124	2.9185	0.27%	yes	39.749	39.877	40.006	39.413	39.680	39.948	-0.49%	yes	79.799	80.207	80.616	81.381	82.165	82.950	2.44%	no
6	2.6066	2.8962	3.1858	2.8859	2.8921	2.8983	-0.14%	yes	40.015	40.125	40.235	39.849	40.098	40.347	-0.07%	yes	84.350	84.775	85.200	83.275	84.039	84.804	-0.87%	yes
7	2.5987	2.8874	3.1761	2.8798	2.8860	2.8922	-0.05%	yes	40.166	40.202	40.238	39.988	40.201	40.415	0.00%	yes	85.572	86.003	86.435	84.907	85.590	86.275	-0.48%	yes
8	2.6457	2.9397	3.2337	2.9310	2.9373	2.9437	-0.08%	yes	39.983	40.018	40.053	39.750	39.998	40.245	-0.05%	yes	87.362	87.800	88.237	86.188	86.972	87.757	-0.94%	yes
9	2.6305	2.9228	3.2151	2.9136	2.9197	2.9258	-0.11%	yes	39.821	39.857	39.893	39.635	39.900	40.165	0.11%	yes	85.346	85.776	86.206	84.039	84.834	85.631	-1.10%	yes
10	2.6241	2.9157	3.2073	2.9084	2.9146	2.9208	-0.04%	yes	39.747	39.784	39.820	39.492	39.760	40.028	-0.06%	yes	85.187	85.615	86.044	84.577	85.405	86.235	-0.25%	yes
11	2.6061	2.8957	3.1853	2.8864	2.8925	2.8986	-0.11%	yes	39.690	39.799	39.908	39.452	39.717	39.982	-0.21%	yes	84.497	84.923	85.349	83.145	83.945	84.747	-1.15%	yes
12	2.6346	2.9273	3.2200	2.9185	2.9247	2.9309	-0.09%	yes	39.802	39.906	40.009	39.574	39.836	40.098	-0.18%	yes	84.810	85.237	85.664	83.666	84.461	85.257	-0.91%	yes
13	2.5722	2.8580	3.1438	2.8503	2.8565	2.8628	-0.05%	yes	40.085	40.118	40.151	39.943	40.164	40.386	0.12%	yes	85.652	86.084	86.516	85.052	85.764	86.478	-0.37%	yes
14	2.6426	2.9362	3.2298	2.9272	2.9334	2.9397	-0.09%	yes	39.925	39.958	39.991	39.696	39.948	40.200	-0.03%	yes	86.222	86.655	87.089	84.715	85.487	86.260	-1.35%	yes
15	2.6348	2.9275	3.2203	2.9193	2.9255	2.9318	-0.07%	yes	39.806	39.839	39.872	39.501	39.767	40.033	-0.18%	yes	84.982	85.411	85.840	83.557	84.350	85.145	-1.24%	yes
16	2.6094	2.8993	3.1892	2.8926	2.8988	2.9051	-0.02%	yes	39.641	39.676	39.711	38.886	39.155	39.424	-1.31%	no	84.200	84.624	85.048	83.195	84.020	84.847	-0.71%	yes
17	2.6105	2.9005	3.1906	2.8924	2.8986	2.9049	-0.06%	yes	40.405	40.499	40.593	40.233	40.499	40.766	0.00%	yes	87.417	87.857	88.297	86.241	87.071	87.903	-0.89%	yes
18	2.8489	3.1654	3.4819	3.1586	3.1648	3.1711	-0.02%	yes	40.155	40.245	40.334	40.076	40.330	40.585	0.21%	yes	94.408	94.871	95.335	93.562	94.428	95.297	-0.47%	yes
19	2.6319	2.9243	3.2167	2.9149	2.9210	2.9272	-0.11%	yes	40.286	40.319	40.352	39.896	40.130	40.364	-0.47%	yes	86.081	86.516	86.951	83.759	84.460	85.162	-2.38%	no
20	2.6643	2.9603	3.2563	2.9540	2.9603	2.9666	0.00%	yes	40.145	40.178	40.211	39.958	40.202	40.446	0.06%	yes	86.884	87.320	87.756	86.778	87.554	88.333	0.27%	yes
21	2.8833	2.8974	2.9115	2.8900	2.8963	2.9027	-0.04%	yes	39.798	39.831	39.864	39.653	39.911	40.169	0.20%	yes	86.031	86.464	86.897	85.330	86.139	86.949	-0.38%	yes
22	2.9061	2.9203	2.9345	2.9129	2.9192	2.9254	-0.04%	yes	40.031	40.064	40.097	39.857	40.118	40.378	0.13%	yes	86.481	86.915	87.350	86.003	86.821	87.641	-0.11%	yes
23	2.8980	2.9121	2.9262	2.9057	2.9119	2.9181	-0.01%	yes	39.732	39.823	39.914	39.538	39.790	40.042	-0.08%	yes	85.393	85.822	86.251	85.345	86.148	86.952	0.38%	yes
24	2.8909	2.9050	2.9191	2.8972	2.9034	2.9097	-0.05%	yes	39.832	39.923	40.013	39.625	39.881	40.136	-0.10%	yes	85.554	85.984	86.414	84.885	85.688	86.492	-0.34%	yes

Mono 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.2243	1.2307	1.2371	1.2249	1.2306	1.2364	-0.01%	yes	44.377	44.417	44.457	44.158	44.417	44.676	0.00%	yes	42.103	42.332	42.562	41.832	42.247	42.664	-0.20%	yes
2	1.2280	1.2345	1.2410	1.2287	1.2344	1.2402	0.00%	yes	44.520	44.570	44.619	44.316	44.570	44.823	0.00%	yes	42.730	42.962	43.195	42.455	42.866	43.280	-0.22%	yes
3	1.2209	1.2273	1.2337	1.2216	1.2273	1.2331	0.00%	yes	44.576	44.627	44.678	44.387	44.627	44.867	0.00%	yes	42.505	42.737	42.969	42.235	42.629	43.025	-0.25%	yes
4	1.2381	1.2446	1.2511	1.2388	1.2446	1.2504	0.00%	yes	44.533	44.582	44.631	44.357	44.582	44.807	0.00%	yes	42.409	42.640	42.871	42.144	42.516	42.891	-0.29%	yes
5	1.2175	1.2239	1.2303	1.2182	1.2239	1.2297	0.00%	yes	44.401	44.449	44.497	44.200	44.449	44.698	0.00%	yes	42.014	42.244	42.474	41.751	42.150	42.551	-0.22%	yes
6	1.2273	1.2337	1.2401	1.2279	1.2337	1.2395	0.00%	yes	44.424	44.469	44.514	44.213	44.469	44.725	0.00%	yes	42.442	42.673	42.904	42.172	42.584	42.998	-0.21%	yes
7	1.2192	1.2256	1.2320	1.2199	1.2256	1.2314	0.00%	yes	44.389	44.440	44.491	44.176	44.440	44.705	0.00%	yes	42.231	42.461	42.692	41.967	42.385	42.806	-0.18%	yes
8	1.2065	1.2129	1.2193	1.2072	1.2130	1.2187	0.01%	yes	44.443	44.490	44.537	44.226	44.490	44.755	0.00%	yes	42.359	42.590	42.821	42.086	42.510	42.936	-0.19%	yes
9	1.1757	1.1820	1.1883	1.1763	1.1819	1.1876	-0.01%	yes	44.194	44.246	44.299	43.978	44.246	44.514	0.00%	yes	40.571	40.796	41.020	40.316	40.725	41.136	-0.17%	yes

Mono 2A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	3.2174	3.2327	3.2480	3.2153	3.2318	3.2484	-0.03%	yes	43.980	44.047	44.115	43.951	44.250	44.549	0.46%	yes	108.870	109.401	109.931	108.089	109.295	110.506	-0.10%	yes
2	3.2412	3.2566	3.2720	3.2403	3.2568	3.2735	0.01%	yes	44.460	44.503	44.547	44.171	44.463	44.754	-0.09%	yes	111.150	111.691	112.232	110.661	111.863	113.070	0.15%	yes
3	3.2256	3.2409	3.2562	3.2243	3.2408	3.2574	0.00%	yes	44.665	44.708	44.750	44.360	44.634	44.909	-0.16%	yes	111.588	112.132	112.675	110.739	111.888	113.044	-0.22%	yes
4	3.2439	3.2595	3.2751	3.2426	3.2592	3.2759	-0.01%	yes	44.751	44.793	44.836	44.467	44.722	44.977	-0.16%	yes	111.814	112.358	112.903	110.870	111.960	113.055	-0.35%	yes
5	3.2184	3.2337	3.2490	3.2172	3.2337	3.2504	0.00%	yes	44.440	44.482	44.524	44.097	44.384	44.670	-0.22%	yes	110.246	110.783	111.321	109.455	110.630	111.811	-0.14%	yes
6	3.2154	3.2307	3.2460	3.2138	3.2304	3.2470	-0.01%	yes	44.366	44.407	44.448	44.032	44.327	44.622	-0.18%	yes	110.032	110.568	111.104	109.076	110.275	111.480	-0.27%	yes
7	3.2103	3.2255	3.2407	3.2088	3.2253	3.2419	-0.01%	yes	44.265	44.309	44.352	43.929	44.235	44.541	-0.17%	yes	109.707	110.242	110.777	108.797	110.023	111.256	-0.20%	yes
8	3.2003	3.2155	3.2307	3.2001	3.2166	3.2333	0.04%	yes	44.326	44.367	44.408	43.984	44.289	44.595	-0.17%	yes	109.726	110.263	110.799	109.621	110.861	112.107	0.54%	yes
9	3.1456	3.1606	3.1756	3.1452	3.1617	3.1783	0.03%	yes	44.092	44.132	44.172	43.728	44.037	44.347	-0.21%	yes	106.418	106.942	107.466	106.255	107.466	108.682	0.49%	yes

Mono 1B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.2044	1.2107	1.2170	1.2079	1.2108	1.2136	0.00%	yes	20.456	20.480	20.504	20.337	20.485	20.634	0.03%	yes	18.064	18.164	18.265	17.929	18.120	18.312	-0.24%	yes
2	1.1971	1.2034	1.2097	1.2006	1.2034	1.2063	0.00%	yes	20.405	20.429	20.454	20.285	20.434	20.584	0.02%	yes	17.951	18.051	18.151	17.791	17.985	18.179	-0.37%	yes
3	1.1996	1.2059	1.2122	1.2030	1.2059	1.2088	0.00%	yes	20.479	20.502	20.526	20.355	20.505	20.655	0.01%	yes	18.511	18.613	18.715	18.342	18.542	18.742	-0.38%	yes
4	1.2043	1.2106	1.2169	1.2078	1.2107	1.2136	0.01%	yes	20.445	20.468	20.492	20.321	20.473	20.625	0.02%	yes	18.137	18.238	18.338	18.018	18.212	18.407	-0.14%	yes
5	1.2279	1.2343	1.2407	1.2314	1.2343	1.2372	0.00%	yes	20.369	20.391	20.414	20.242	20.394	20.547	0.02%	yes	18.456	18.558	18.660	18.325	18.522	18.719	-0.20%	yes
6	1.2130	1.2194	1.2258	1.2166	1.2195	1.2224	0.00%	yes	20.445	20.469	20.492	20.322	20.472	20.622	0.02%	yes	18.421	18.522	18.624	18.273	18.470	18.668	-0.28%	yes
7	1.2140	1.2204	1.2268	1.2177	1.2206	1.2234	0.01%	yes	20.456	20.477	20.499	20.339	20.482	20.625	0.02%	yes	18.114	18.214	18.314	17.991	18.178	18.364	-0.20%	yes
8	1.2086	1.2150	1.2214	1.2122	1.2151	1.2179	0.00%	yes	20.458	20.481	20.505	20.351	20.486	20.622	0.02%	yes	18.136	18.237	18.337	17.998	18.176	18.355	-0.33%	yes
9	1.2208	1.2272	1.2336	1.2243	1.2272	1.2302	0.00%	yes	20.520	20.543	20.567	20.415	20.546	20.678	0.02%	yes	18.540	18.642	18.744	18.402	18.578	18.755	-0.34%	yes
10	1.2143	1.2207	1.2271	1.2178	1.2207	1.2236	0.00%	yes	20.507	20.530	20.553	20.391	20.533	20.676	0.02%	yes	18.522	18.624	18.726	18.369	18.560	18.751	-0.35%	yes
11	1.1975	1.2038	1.2101	1.2009	1.2038	1.2067	0.00%	yes	20.485	20.509	20.532	20.363	20.512	20.661	0.02%	yes	18.203	18.304	18.405	18.045	18.239	18.434	-0.35%	yes
12	1.2125	1.2189	1.2253	1.2161	1.2190	1.2219	0.01%	yes	20.519	20.543	20.567	20.395	20.547	20.699	0.02%	yes	18.255	18.356	18.457	18.128	18.323	18.519	-0.18%	yes
13	1.2122	1.2186	1.2250	1.2156	1.2185	1.2213	-0.01%	yes	20.489	20.514	20.539	20.367	20.518	20.668	0.02%	yes	17.814	17.913	18.012	17.582	17.778	17.974	-0.75%	yes
14	1.2077	1.2141	1.2205	1.2112	1.2141	1.2170	0.00%	yes	20.522	20.547	20.571	20.398	20.551	20.704	0.02%	yes	18.199	18.300	18.401	18.063	18.258	18.455	-0.23%	yes
15	1.2184	1.2248	1.2312	1.2220	1.2248	1.2277	0.00%	yes	20.527	20.554	20.581	20.407	20.559	20.711	0.02%	yes	18.106	18.206	18.307	17.967	18.162	18.357	-0.25%	yes
16	1.2070	1.2134	1.2198	1.2106	1.2135	1.2163	0.01%	yes	20.563	20.591	20.619	20.444	20.596	20.747	0.02%	yes	18.176	18.276	18.377	18.015	18.212	18.410	-0.35%	yes
17	1.2150	1.2214	1.2278	1.2185	1.2214	1.2243	0.00%	yes	20.574	20.606	20.637	20.458	20.610	20.762	0.02%	yes	18.292	18.393	18.494	18.152	18.347	18.542	-0.25%	yes
18	1.2139	1.2203	1.2267	1.2175	1.2204	1.2233	0.01%	yes	20.538	20.583	20.628	20.436	20.588	20.739	0.02%	yes	18.284	18.385	18.486	18.134	18.331	18.528	-0.29%	yes
19	1.2069	1.2133	1.2197	1.2104	1.2133	1.2162	0.00%	yes	20.613	20.639	20.664	20.490	20.642	20.794	0.02%	yes	18.536	18.639	18.741	18.379	18.580	18.781	-0.31%	yes
20	1.2005	1.2068	1.2131	1.2039	1.2068	1.2097	0.00%	yes	20.591	20.618	20.645	20.473	20.620	20.768	0.01%	yes	18.652	18.755	18.857	18.476	18.673	18.872	-0.43%	yes
21	1.2197	1.2261	1.2325	1.2231	1.2261	1.2290	0.00%	yes	20.609	20.636	20.663	20.504	20.639	20.774	0.02%	yes	18.617	18.719	18.822	18.453	18.635	18.818	-0.45%	yes

Mono 1B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.6663	2.6796	2.6929	2.6766	2.6849	2.6931	0.20%	yes	19.362	19.387	19.412	19.100	19.340	19.579	-0.24%	yes	34.942	35.126	35.310	34.970	35.604	36.239	1.36%	yes
2	2.6780	2.6918	2.7056	2.6906	2.6989	2.7072	0.26%	yes	19.334	19.356	19.379	19.044	19.285	19.526	-0.37%	yes	34.822	35.005	35.188	34.945	35.591	36.239	1.67%	yes
3	2.6572	2.6705	2.6838	2.6646	2.6729	2.6813	0.09%	yes	19.403	19.426	19.449	19.101	19.343	19.585	-0.43%	yes	36.486	36.677	36.867	36.097	36.764	37.434	0.24%	yes
4	2.6383	2.6515	2.6647	2.6438	2.6520	2.6603	0.02%	yes	19.351	19.375	19.398	19.029	19.274	19.519	-0.52%	yes	35.337	35.522	35.708	34.683	35.328	35.975	-0.55%	yes
5	2.6700	2.6833	2.6966	2.6760	2.6844	2.6928	0.04%	yes	19.261	19.284	19.307	18.940	19.187	19.433	-0.51%	yes	36.315	36.505	36.695	35.736	36.399	37.064	-0.29%	yes
6	2.6266	2.6398	2.6530	2.6309	2.6391	2.6473	-0.03%	yes	19.487	19.511	19.535	19.051	19.292	19.533	-1.12%	yes	35.833	36.021	36.209	34.837	35.477	36.120	-1.51%	yes
7	2.6447	2.6580	2.6713	2.6507	2.6588	2.6670	0.03%	yes	19.659	19.683	19.707	19.172	19.400	19.629	-1.44%	no	34.948	35.132	35.316	34.065	34.667	35.271	-1.32%	yes
8	2.6503	2.6636	2.6769	2.6553	2.6636	2.6718	0.00%	yes	19.576	19.599	19.621	19.301	19.516	19.732	-0.42%	yes	35.740	35.927	36.114	35.184	35.763	36.343	-0.46%	yes
9	2.6559	2.6692	2.6825	2.6597	2.6680	2.6764	-0.04%	yes	19.483	19.506	19.528	19.425	19.633	19.841	0.65%	yes	36.451	36.642	36.832	36.198	36.772	37.348	0.36%	yes
10	2.6580	2.6713	2.6846	2.6638	2.6721	2.6804	0.03%	yes	19.440	19.462	19.485	19.231	19.460	19.689	-0.01%	yes	36.115	36.303	36.492	35.777	36.401	37.028	0.27%	yes
11	2.6345	2.6477	2.6609	2.6414	2.6497	2.6580	0.07%	yes	19.410	19.432	19.455	19.120	19.359	19.599	-0.37%	yes	35.572	35.759	35.946	35.165	35.808	36.453	0.14%	yes
12	2.6553	2.6686	2.6819	2.6615	2.6697	2.6780	0.04%	yes	19.425	19.448	19.471	19.105	19.350	19.595	-0.51%	yes	35.475	35.661	35.847	34.925	35.572	36.221	-0.25%	yes
13	2.6480	2.6613	2.6746	2.6518	2.6600	2.6683	-0.05%	yes	19.409	19.432	19.454	19.092	19.335	19.577	-0.50%	yes	35.369	35.555	35.740	34.401	35.044	35.689	-1.44%	yes
14	2.6483	2.6616	2.6749	2.6533	2.6616	2.6699	0.00%	yes	19.408	19.430	19.453	19.095	19.342	19.589	-0.45%	yes	35.705	35.892	36.079	35.023	35.676	36.330	-0.60%	yes
15	2.6458	2.6591	2.6724	2.6477	2.6559	2.6641	-0.12%	yes	19.453	19.477	19.501	19.102	19.347	19.593	-0.66%	yes	35.319	35.504	35.690	34.316	34.953	35.592	-1.55%	yes
16	2.6541	2.6674	2.6807	2.6630	2.6712	2.6795	0.14%	yes	19.472	19.497	19.522	19.158	19.403	19.647	-0.48%	yes	34.716	34.898	35.081	34.491	35.138	35.786	0.69%	yes
17	2.6679	2.6813	2.6947	2.6734	2.6817	2.6900	0.01%	yes	19.551	19.578	19.604	19.175	19.420	19.665	-0.80%	yes	36.183	36.372	36.562	35.396	36.049	36.702	-0.89%	yes
18	2.6668	2.6802	2.6936	2.6743	2.6825	2.6908	0.09%	yes	19.496	19.521	19.547	19.149	19.394	19.638	-0.65%	yes	35.453	35.639	35.824	34.971	35.621	36.272	-0.05%	yes
19	2.6360	2.6492	2.6624	2.6427	2.6509	2.6592	0.06%	yes	19.573	19.598	19.624	19.189	19.435	19.681	-0.83%	yes	35.797	35.985	36.173	35.213	35.871	36.531	-0.32%	yes
20	2.6320	2.6452	2.6584	2.6364	2.6447	2.6531	-0.02%	yes	19.612	19.635	19.658	19.250	19.488	19.725	-0.75%	yes	37.159	37.353	37.546	36.311	36.966	37.623	-1.04%	yes
21	2.6630	2.6764	2.6898	2.6651	2.6734	2.6818	-0.11%	yes	19.782	19.828	19.873	19.463	19.677	19.892	-0.76%	yes	37.651	37.846	38.042	36.579	37.173	37.769	-1.78%	yes

Mono 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0041	1.1157	1.2273	1.1132	1.1157	1.1182	0.00%	yes	19.338	19.356	19.374	19.230	19.356	19.482	0.00%	yes	14.479	14.562	14.644	14.352	14.506	14.661	-0.38%	yes
2	1.0080	1.1200	1.2320	1.1174	1.1200	1.1226	0.00%	yes	9.596	9.611	9.626	9.538	9.611	9.684	0.00%	yes	7.593	7.637	7.680	7.215	7.305	7.395	-4.35%	no
3	1.0028	1.1142	1.2256	1.1116	1.1142	1.1169	0.00%	yes	9.506	9.521	9.535	9.441	9.521	9.601	0.00%	yes	7.658	7.701	7.745	7.498	7.593	7.688	-1.41%	yes
5	0.9884	1.0982	1.2080	1.0956	1.0982	1.1008	0.00%	yes	9.433	9.458	9.483	9.373	9.458	9.544	0.00%	yes	7.482	7.525	7.568	7.343	7.444	7.546	-1.08%	yes
6	1.0071	1.1190	1.2309	1.1164	1.1189	1.1215	-0.01%	yes	9.437	9.453	9.469	9.384	9.453	9.523	0.00%	yes	6.797	6.836	6.875	6.663	6.747	6.831	-1.31%	yes
7	1.0055	1.1172	1.2289	1.1146	1.1172	1.1199	0.00%	yes	9.519	9.534	9.549	9.452	9.534	9.616	0.00%	yes	7.226	7.268	7.310	7.097	7.193	7.289	-1.03%	yes
8	1.0020	1.1133	1.2246	1.1107	1.1133	1.1160	0.00%	yes	9.329	9.344	9.359	9.288	9.344	9.401	0.00%	yes	7.368	7.411	7.455	7.249	7.319	7.389	-1.25%	yes
9	1.0102	1.1224	1.2346	1.1199	1.1224	1.1250	0.00%	yes	19.284	19.302	19.320	19.176	19.302	19.428	0.00%	yes	13.149	13.224	13.299	13.022	13.178	13.334	-0.35%	yes
10	1.0080	1.1200	1.2320	1.1174	1.1200	1.1226	0.00%	yes	19.382	19.403	19.424	19.286	19.403	19.520	0.00%	yes	15.950	16.040	16.131	15.816	15.964	16.113	-0.48%	yes
11	1.0964	1.1024	1.1084	1.0997	1.1024	1.1050	0.00%	yes	8.501	8.539	8.576	8.535	8.539	8.543	0.00%	yes	4.719	4.747	4.776	4.630	4.648	4.667	-2.09%	no
13	1.1029	1.1089	1.1149	1.1064	1.1089	1.1115	0.00%	yes	16.984	17.000	17.016	16.993	17.000	17.008	0.00%	yes	10.350	10.410	10.470	10.237	10.271	10.305	-1.34%	no
14	1.0975	1.1035	1.1095	1.0996	1.1024	1.1052	-0.10%	yes	6.027	6.100	6.173	5.992	6.100	6.210	0.00%	yes	3.191	3.211	3.230	2.977	3.070	3.165	-4.38%	no
15	1.1193	1.1254	1.1315	1.1229	1.1254	1.1280	0.00%	yes	19.263	19.291	19.319	19.167	19.291	19.415	0.00%	yes	12.484	12.556	12.627	12.352	12.508	12.665	-0.38%	yes
16	1.1065	1.1125	1.1185	1.1098	1.1125	1.1151	0.00%	yes	9.400	9.417	9.434	9.356	9.417	9.479	0.00%	yes	7.225	7.266	7.307	7.089	7.166	7.244	-1.37%	yes
17	1.1146	1.1207	1.1268	1.1181	1.1207	1.1233	0.00%	yes	19.267	19.285	19.303	19.160	19.285	19.410	0.00%	yes	13.942	14.022	14.102	13.821	13.974	14.126	-0.34%	yes
18	1.1157	1.1218	1.1279	1.1191	1.1218	1.1244	0.00%	yes	9.418	9.432	9.447	9.354	9.432	9.512	0.00%	yes	6.396	6.434	6.471	6.278	6.366	6.455	-1.05%	yes
19	1.1095	1.1155	1.1215	1.1128	1.1154	1.1181	-0.01%	yes	19.290	19.308	19.326	19.184	19.308	19.432	0.00%	yes	16.513	16.607	16.700	16.394	16.548	16.702	-0.35%	yes
20	1.0694	1.0754	1.0814	1.0602	1.0680	1.0737	-0.69%	yes	4.701	4.900	5.099	4.526	4.900	5.278	0.00%	yes	2.441	2.456	2.472	1.939	2.219	2.514	-9.66%	yes
21	1.0969	1.1029	1.1089	1.1003	1.1030	1.1056	0.01%	yes	19.221	19.240	19.259	19.117	19.240	19.363	0.00%	yes	15.131	15.219	15.307	15.029	15.170	15.310	-0.32%	yes

Mono 3B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.7817	0.7868	0.7919	0.7848	0.7868	0.7888	0.00%	yes	18.257	18.274	18.292	18.174	18.274	18.375	0.00%	yes	9.251	9.318	9.386	9.400	9.481	9.561	1.74%	no
2	0.7755	0.7806	0.7857	0.7786	0.7806	0.7826	0.00%	yes	18.051	18.068	18.085	17.972	18.068	18.164	0.00%	yes	9.372	9.440	9.508	9.523	9.604	9.684	1.73%	no
3	0.7855	0.7906	0.7957	0.7886	0.7906	0.7926	0.00%	yes	18.138	18.156	18.174	18.054	18.156	18.258	0.00%	yes	9.670	9.739	9.808	9.826	9.912	9.998	1.78%	no
4	0.7851	0.7902	0.7953	0.7882	0.7902	0.7922	0.00%	yes	18.161	18.178	18.196	18.079	18.178	18.278	0.00%	yes	9.752	9.822	9.891	9.908	9.993	10.079	1.75%	no
5	0.7823	0.7874	0.7925	0.7853	0.7874	0.7894	-0.01%	yes	18.171	18.188	18.206	18.084	18.188	18.293	0.00%	yes	9.664	9.733	9.802	9.819	9.907	9.995	1.78%	no
6	0.7800	0.7851	0.7902	0.7831	0.7851	0.7871	0.00%	yes	18.192	18.210	18.227	18.108	18.210	18.311	0.00%	yes	9.620	9.689	9.759	9.776	9.861	9.946	1.77%	no
7	0.7879	0.7930	0.7981	0.7910	0.7930	0.7950	0.00%	yes	18.149	18.166	18.184	18.070	18.166	18.263	0.00%	yes	9.178	9.245	9.312	9.327	9.405	9.482	1.72%	no
8	0.7950	0.8002	0.8054	0.7982	0.8002	0.8022	0.00%	yes	18.267	18.285	18.302	18.178	18.285	18.391	0.00%	yes	9.715	9.784	9.854	9.871	9.957	10.043	1.76%	no
9	0.7799	0.7850	0.7901	0.7830	0.7850	0.7870	-0.01%	yes	17.986	18.004	18.021	17.905	18.004	18.103	0.00%	yes	9.229	9.296	9.363	9.378	9.457	9.537	1.74%	no
10	0.7904	0.7955	0.8006	0.7935	0.7955	0.7975	0.00%	yes	18.117	18.135	18.153	18.036	18.135	18.234	0.00%	yes	9.572	9.640	9.708	9.725	9.808	9.892	1.75%	no
11	0.7916	0.7967	0.8018	0.7947	0.7967	0.7988	0.00%	yes	18.105	18.129	18.153	18.031	18.129	18.228	0.00%	yes	9.614	9.682	9.751	9.769	9.852	9.936	1.75%	no
12	0.7889	0.7940	0.7991	0.7919	0.7940	0.7961	0.00%	yes	18.151	18.174	18.196	18.070	18.174	18.278	0.00%	yes	9.498	9.567	9.635	9.652	9.737	9.821	1.78%	no
13	0.7922	0.7973	0.8024	0.7953	0.7973	0.7993	0.00%	yes	18.263	18.287	18.311	18.188	18.287	18.387	0.00%	yes	9.663	9.732	9.801	9.818	9.900	9.983	1.73%	no
14	0.7766	0.7817	0.7868	0.7797	0.7817	0.7837	0.00%	yes	18.098	18.120	18.143	18.024	18.120	18.218	0.00%	yes	9.706	9.775	9.844	9.862	9.947	10.031	1.76%	no
15	0.7910	0.7961	0.8012	0.7941	0.7961	0.7982	0.00%	yes	18.254	18.278	18.302	18.181	18.278	18.375	0.00%	yes	9.608	9.678	9.747	9.764	9.845	9.926	1.73%	no
16	0.7870	0.7921	0.7972	0.7900	0.7921	0.7941	0.00%	yes	18.185	18.208	18.231	18.110	18.208	18.306	0.00%	yes	9.470	9.538	9.606	9.623	9.704	9.785	1.74%	no
17	0.7766	0.7817	0.7868	0.7797	0.7817	0.7837	0.00%	yes	18.030	18.054	18.078	17.963	18.054	18.145	0.00%	yes	9.389	9.456	9.524	9.540	9.618	9.697	1.71%	no
18	0.7898	0.7949	0.8000	0.7929	0.7949	0.7970	0.00%	yes	18.091	18.110	18.130	18.014	18.110	18.206	0.00%	yes	9.613	9.682	9.750	9.768	9.850	9.933	1.74%	no
19	0.7858	0.7909	0.7960	0.7890	0.7909	0.7930	0.01%	yes	18.061	18.102	18.142	18.000	18.102	18.204	0.00%	yes	9.613	9.681	9.750	9.767	9.854	9.941	1.78%	no
20	0.8040	0.8092	0.8144	0.8072	0.8092	0.8112	0.00%	yes	18.170	18.187	18.205	18.092	18.187	18.283	0.00%	yes	9.503	9.571	9.639	9.655	9.733	9.812	1.70%	no
21	0.8074	0.8126	0.8178	0.8106	0.8126	0.8146	0.00%	yes	18.375	18.393	18.411	18.293	18.393	18.493	0.00%	yes	9.867	9.937	10.007	10.025	10.109	10.194	1.73%	no
22	0.7897	0.7948	0.7999	0.7927	0.7948	0.7968	-0.01%	yes	18.139	18.157	18.175	18.064	18.157	18.250	0.00%	yes	9.551	9.619	9.688	9.704	9.784	9.863	1.71%	no
23	0.8037	0.8089	0.8141	0.8069	0.8089	0.8110	0.00%	yes	18.210	18.228	18.246	18.128	18.228	18.329	0.00%	yes	9.561	9.629	9.698	9.716	9.798	9.880	1.75%	no
24	0.7915	0.7966	0.8017	0.7946	0.7966	0.7987	0.00%	yes	18.163	18.180	18.198	18.082	18.180	18.279	0.00%	yes	9.250	9.317	9.385	9.401	9.480	9.559	1.74%	no
25	0.8043	0.8095	0.8147	0.8074	0.8095	0.8115	-0.01%	yes	18.327	18.348	18.368	18.251	18.348	18.445	0.00%	yes	9.617	9.686	9.755	9.770	9.850	9.930	1.69%	no
26	0.7923	0.7974	0.8025	0.7954	0.7974	0.7994	0.00%	yes	18.208	18.241	18.274	18.143	18.241	18.339	0.00%	yes	9.788	9.857	9.926	9.943	10.029	10.115	1.75%	no
27	0.8154	0.8220	0.8286	0.8200	0.8220	0.8240	0.00%	yes	18.690	18.786	18.883	18.676	18.786	18.896	0.00%	yes	9.932	10.001	10.071	10.085	10.179	10.273	1.77%	no

Mono 4B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.9751	1.0834	1.1917	1.0805	1.0834	1.0862	0.00%	yes	40.112	40.140	40.168	39.816	40.140	40.464	0.00%	yes	31.832	32.018	32.205	31.574	31.941	32.308	-0.24%	yes
2	1.0056	1.1173	1.2290	1.1144	1.1173	1.1203	0.00%	yes	40.112	40.140	40.168	39.822	40.140	40.458	0.00%	yes	33.236	33.426	33.616	32.952	33.341	33.730	-0.26%	yes
3	1.0109	1.1232	1.2355	1.1203	1.1232	1.1262	0.00%	yes	40.188	40.216	40.244	39.897	40.216	40.536	0.00%	yes	33.672	33.864	34.056	33.389	33.783	34.177	-0.24%	yes
5	1.0135	1.1261	1.2387	1.1231	1.1261	1.1290	0.00%	yes	40.072	40.101	40.129	39.787	40.101	40.414	0.00%	yes	32.830	33.019	33.207	32.553	32.926	33.300	-0.28%	yes
6	1.0483	1.1648	1.2813	1.1618	1.1648	1.1679	0.00%	yes	40.020	40.048	40.076	39.743	40.048	40.353	0.00%	yes	34.204	34.397	34.589	33.907	34.293	34.680	-0.30%	yes
7	0.9671	1.0745	1.1820	1.0717	1.0745	1.0773	0.00%	yes	40.093	40.144	40.194	39.828	40.144	40.459	0.00%	yes	31.669	31.853	32.038	31.392	31.762	32.134	-0.29%	yes
8	1.0320	1.1467	1.2614	1.1437	1.1467	1.1498	0.00%	yes	40.132	40.175	40.219	39.864	40.175	40.487	0.00%	yes	34.243	34.436	34.630	33.949	34.343	34.738	-0.27%	yes
9	1.0293	1.1437	1.2581	1.1407	1.1437	1.1468	0.00%	yes	40.115	40.159	40.203	39.856	40.159	40.461	0.00%	yes	33.794	33.986	34.178	33.503	33.882	34.261	-0.31%	yes
10	1.0202	1.1335	1.2469	1.1305	1.1335	1.1365	0.00%	yes	40.135	40.179	40.224	39.878	40.179	40.480	0.00%	yes	33.202	33.392	33.583	32.929	33.289	33.651	-0.31%	yes
11	1.0543	1.1714	1.2885	1.1683	1.1714	1.1744	0.00%	yes	40.040	40.071	40.103	39.795	40.071	40.348	0.00%	yes	34.824	35.019	35.213	34.510	34.876	35.243	-0.41%	yes
13	0.6934	0.7704	0.8474	0.7691	0.7704	0.7717	0.00%	yes	40.004	40.057	40.110	39.772	40.057	40.342	0.00%	yes	22.877	23.039	23.201	22.728	22.950	23.173	-0.39%	yes
14	0.7413	0.8237	0.9061	0.8223	0.8237	0.8251	0.00%	yes	40.173	40.220	40.268	39.931	40.220	40.510	0.00%	yes	24.492	24.657	24.823	24.319	24.565	24.812	-0.37%	yes
15	0.7155	0.7950	0.8745	0.7937	0.7950	0.7963	0.00%	yes	39.941	39.993	40.045	39.701	39.993	40.285	0.00%	yes	23.148	23.311	23.474	23.001	23.227	23.452	-0.36%	yes
16	0.6798	0.7553	0.8308	0.7541	0.7553	0.7566	0.01%	yes	40.173	40.224	40.276	39.929	40.224	40.519	0.00%	yes	23.249	23.413	23.578	23.094	23.331	23.568	-0.35%	yes
17	0.7334	0.8149	0.8964	0.8135	0.8149	0.8163	0.00%	yes	40.049	40.097	40.144	39.808	40.097	40.385	0.00%	yes	24.011	24.174	24.337	23.844	24.084	24.325	-0.37%	yes
18	0.6784	0.7538	0.8292	0.7525	0.7538	0.7551	0.00%	yes	39.903	39.956	40.009	39.667	39.956	40.245	0.00%	yes	22.138	22.298	22.458	21.999	22.216	22.434	-0.37%	yes
19	0.7306	0.8118	0.8930	0.8105	0.8118	0.8131	0.00%	yes	39.965	40.011	40.057	39.718	40.011	40.303	0.00%	yes	23.383	23.545	23.707	23.227	23.458	23.688	-0.37%	yes
20	0.7320	0.8133	0.8946	0.8120	0.8133	0.8147	0.00%	yes	40.046	40.092	40.138	39.801	40.092	40.383	0.00%	yes	24.096	24.262	24.427	23.940	24.178	24.416	-0.35%	yes
21	0.7112	0.7902	0.8692	0.7889	0.7902	0.7916	0.00%	yes	40.018	40.063	40.107	39.773	40.063	40.353	0.00%	yes	23.731	23.896	24.061	23.575	23.810	24.044	-0.36%	yes

Mono 4B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.1459	2.3843	2.6227	2.3756	2.3834	2.3913	-0.04%	yes	39.557	39.596	39.634	38.822	39.328	39.832	-0.68%	yes	66.963	67.329	67.695	65.305	66.504	67.704	-1.23%	yes
2	2.1549	2.3943	2.6337	2.3869	2.3948	2.4028	0.02%	yes	39.468	39.507	39.546	38.818	39.313	39.808	-0.49%	yes	67.268	67.633	67.999	66.187	67.407	68.631	-0.33%	yes
3	2.1554	2.3949	2.6344	2.3861	2.3941	2.4021	-0.03%	yes	39.385	39.424	39.463	38.870	39.369	39.867	-0.14%	yes	67.912	68.280	68.648	66.740	67.974	69.212	-0.45%	yes
4	2.1873	2.4303	2.6733	2.4234	2.4312	2.4391	0.04%	yes	39.278	39.317	39.356	38.831	39.319	39.808	0.01%	yes	66.622	66.984	67.346	66.085	67.269	68.455	0.42%	yes
5	2.2054	2.4504	2.6954	2.4429	2.4508	2.4588	0.02%	yes	39.177	39.214	39.250	38.806	39.280	39.754	0.17%	yes	67.844	68.211	68.577	67.250	68.435	69.624	0.33%	yes
6	2.1254	2.3615	2.5977	2.3558	2.3636	2.3713	0.09%	yes	39.232	39.271	39.310	38.888	39.380	39.870	0.28%	yes	64.685	65.040	65.394	64.758	65.944	67.134	1.39%	yes
7	2.1801	2.4223	2.6645	2.4139	2.4220	2.4300	-0.01%	yes	39.184	39.221	39.258	38.885	39.370	39.855	0.38%	yes	68.049	68.417	68.784	67.447	68.665	69.888	0.36%	yes
8	2.1930	2.4367	2.6804	2.4293	2.4373	2.4454	0.03%	yes	39.184	39.222	39.261	38.970	39.440	39.909	0.55%	yes	67.390	67.755	68.119	67.258	68.435	69.617	1.01%	yes
9	2.1794	2.4215	2.6637	2.4121	2.4201	2.4281	-0.06%	yes	39.186	39.223	39.260	39.025	39.492	39.959	0.69%	yes	67.231	67.596	67.960	66.548	67.686	68.828	0.13%	yes
10	2.2157	2.4619	2.7081	2.4546	2.4627	2.4708	0.03%	yes	39.063	39.096	39.130	39.094	39.521	39.947	1.09%	yes	68.127	68.493	68.859	68.464	69.574	70.688	1.58%	yes

Mono 5B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.5575	1.5651	1.5727	1.5610	1.5654	1.5698	0.02%	yes	27.953	27.978	28.004	27.781	27.974	28.167	-0.01%	yes	30.017	30.169	30.322	29.744	30.052	30.361	-0.39%	yes
2	1.5163	1.5237	1.5311	1.5195	1.5238	1.5281	0.01%	yes	28.049	28.084	28.119	27.876	28.083	28.291	0.00%	yes	29.213	29.364	29.514	28.914	29.232	29.551	-0.45%	yes
3	1.5781	1.5858	1.5935	1.5816	1.5861	1.5905	0.02%	yes	27.888	27.920	27.951	27.705	27.914	28.124	-0.02%	yes	30.257	30.411	30.564	29.965	30.293	30.622	-0.39%	yes
4	1.4777	1.4850	1.4923	1.4808	1.4851	1.4893	0.00%	yes	27.915	27.951	27.987	27.741	27.950	28.160	0.00%	yes	27.597	27.741	27.885	27.327	27.627	27.929	-0.41%	yes
5	1.5609	1.5684	1.5759	1.5643	1.5686	1.5730	0.01%	yes	27.885	27.917	27.948	27.696	27.913	28.130	-0.01%	yes	29.899	30.051	30.204	29.597	29.931	30.267	-0.40%	yes
6	1.4990	1.5063	1.5136	1.5020	1.5062	1.5104	-0.01%	yes	27.644	27.678	27.712	27.469	27.679	27.889	0.00%	yes	27.811	27.956	28.100	27.504	27.813	28.124	-0.51%	yes
7	1.5485	1.5560	1.5635	1.5518	1.5562	1.5606	0.01%	yes	27.816	27.849	27.881	27.630	27.845	28.059	-0.01%	yes	29.592	29.743	29.894	29.314	29.647	29.981	-0.32%	yes
8	1.5095	1.5169	1.5243	1.5127	1.5169	1.5212	0.00%	yes	27.701	27.734	27.766	27.518	27.734	27.949	0.00%	yes	28.436	28.583	28.730	28.139	28.459	28.780	-0.43%	yes
9	1.5566	1.5641	1.5716	1.5600	1.5644	1.5688	0.02%	yes	27.634	27.667	27.700	27.451	27.661	27.872	-0.02%	yes	28.852	29.000	29.148	28.576	28.892	29.209	-0.37%	yes

Mono 5B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	4.2665	4.2857	4.3049	4.2747	4.2861	4.2974	0.01%	yes	28.424	28.456	28.488	28.377	28.544	28.710	0.31%	yes	82.930	83.314	83.698	82.817	83.572	84.331	0.31%	yes
2	4.2412	4.2602	4.2792	4.2502	4.2614	4.2727	0.03%	yes	28.564	28.593	28.622	28.422	28.602	28.782	0.03%	yes	81.768	82.147	82.527	81.545	82.340	83.138	0.24%	yes
3	4.2871	4.3063	4.3255	4.2932	4.3045	4.3158	-0.04%	yes	28.402	28.432	28.463	28.195	28.377	28.559	-0.19%	yes	83.087	83.471	83.855	82.155	82.958	83.764	-0.61%	yes
4	4.1282	4.1468	4.1654	4.1329	4.1440	4.1552	-0.07%	yes	28.685	28.712	28.740	28.297	28.479	28.661	-0.81%	no	80.710	81.086	81.462	78.974	79.748	80.524	-1.65%	no
5	4.2905	4.3097	4.3289	4.2994	4.3106	4.3220	0.02%	yes	28.334	28.363	28.391	28.160	28.349	28.539	-0.05%	yes	81.718	82.097	82.475	81.297	82.124	82.953	0.03%	yes
6	4.2373	4.2563	4.2753	4.2460	4.2572	4.2683	0.02%	yes	28.245	28.274	28.304	28.017	28.199	28.381	-0.27%	yes	79.795	80.166	80.537	79.331	80.117	80.905	-0.06%	yes
7	4.2421	4.2612	4.2803	4.2487	4.2600	4.2713	-0.03%	yes	28.315	28.344	28.373	28.103	28.290	28.477	-0.19%	yes	81.935	82.314	82.694	81.200	82.023	82.848	-0.35%	yes
8	4.2376	4.2566	4.2756	4.2455	4.2567	4.2679	0.00%	yes	28.238	28.268	28.297	28.026	28.213	28.401	-0.19%	yes	80.792	81.166	81.541	80.202	81.014	81.828	-0.19%	yes
9	4.2556	4.2747	4.2938	4.2653	4.2767	4.2880	0.05%	yes	28.100	28.135	28.170	27.946	28.130	28.313	-0.02%	yes	79.333	79.701	80.070	79.160	79.945	80.733	0.31%	yes

Mono 6B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.6035	1.6112	1.6189	1.6047	1.6111	1.6176	0.00%	yes	39.742	39.773	39.804	39.527	39.768	40.009	-0.01%	yes	46.696	46.929	47.162	46.351	46.789	47.228	-0.30%	yes
2	1.6000	1.6077	1.6154	1.6011	1.6077	1.6144	0.00%	yes	39.466	39.499	39.531	39.227	39.492	39.756	-0.02%	yes	46.216	46.447	46.678	45.882	46.350	46.821	-0.21%	yes
3	1.5917	1.5993	1.6069	1.5927	1.5994	1.6060	0.00%	yes	39.724	39.755	39.786	39.486	39.748	40.010	-0.02%	yes	46.249	46.480	46.711	45.919	46.384	46.851	-0.21%	yes
4	1.5803	1.5879	1.5955	1.5814	1.5879	1.5945	0.00%	yes	39.468	39.499	39.530	39.234	39.492	39.751	-0.02%	yes	45.439	45.667	45.895	45.097	45.550	46.004	-0.26%	yes
5	1.5983	1.6060	1.6137	1.5994	1.6060	1.6127	0.00%	yes	39.829	39.860	39.891	39.597	39.854	40.110	-0.02%	yes	46.761	46.994	47.227	46.433	46.895	47.359	-0.21%	yes
6	1.5765	1.5841	1.5917	1.5776	1.5841	1.5908	0.00%	yes	39.646	39.677	39.707	39.406	39.671	39.936	-0.01%	yes	45.991	46.222	46.452	45.671	46.141	46.612	-0.18%	yes
7	1.5963	1.6040	1.6117	1.5974	1.6040	1.6107	0.00%	yes	39.711	39.743	39.774	39.469	39.736	40.002	-0.02%	yes	46.418	46.650	46.882	46.071	46.543	47.016	-0.23%	yes
8	1.5866	1.5942	1.6018	1.5878	1.5943	1.6008	0.01%	yes	39.514	39.545	39.576	39.276	39.540	39.804	-0.01%	yes	45.850	46.079	46.308	45.512	45.977	46.443	-0.22%	yes
9	1.5745	1.5821	1.5897	1.5755	1.5821	1.5887	0.00%	yes	39.432	39.465	39.498	39.187	39.459	39.732	-0.01%	yes	45.923	46.153	46.382	45.585	46.067	46.551	-0.19%	yes
10	1.5244	1.5320	1.5396	1.5255	1.5320	1.5384	0.00%	yes	26.312	26.334	26.355	26.113	26.331	26.551	-0.01%	yes	29.395	29.544	29.693	29.035	29.401	29.769	-0.48%	yes
11	1.5178	1.5252	1.5326	1.5188	1.5252	1.5316	0.00%	yes	39.583	39.611	39.639	39.338	39.608	39.878	-0.01%	yes	44.600	44.826	45.052	44.257	44.717	45.180	-0.24%	yes
12	1.5026	1.5099	1.5172	1.5035	1.5098	1.5162	0.00%	yes	39.380	39.408	39.435	39.149	39.405	39.660	-0.01%	yes	43.417	43.639	43.861	43.083	43.508	43.936	-0.30%	yes
13	1.5076	1.5150	1.5224	1.5087	1.5150	1.5214	0.00%	yes	39.221	39.249	39.277	38.986	39.246	39.506	-0.01%	yes	43.466	43.688	43.909	43.124	43.555	43.987	-0.30%	yes
14	1.5044	1.5117	1.5190	1.5053	1.5117	1.5181	0.00%	yes	39.380	39.408	39.436	39.140	39.405	39.670	-0.01%	yes	43.824	44.046	44.269	43.496	43.944	44.394	-0.23%	yes
15	1.5103	1.5177	1.5251	1.5113	1.5177	1.5240	0.00%	yes	39.308	39.336	39.364	39.053	39.333	39.613	-0.01%	yes	43.617	43.839	44.060	43.284	43.751	44.219	-0.20%	yes
16	1.5092	1.5166	1.5240	1.5102	1.5166	1.5230	0.00%	yes	39.466	39.494	39.522	39.193	39.491	39.789	-0.01%	yes	44.088	44.312	44.536	43.734	44.226	44.720	-0.19%	yes
17	1.5226	1.5300	1.5374	1.5236	1.5300	1.5364	0.00%	yes	39.088	39.116	39.144	38.804	39.113	39.422	-0.01%	yes	43.548	43.769	43.990	43.196	43.698	44.202	-0.16%	yes
18	1.5192	1.5266	1.5340	1.5203	1.5267	1.5331	0.01%	yes	39.203	39.268	39.333	38.921	39.263	39.605	-0.01%	yes	43.345	43.565	43.785	42.974	43.518	44.064	-0.11%	yes

Mono 6B-- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.7743	3.0826	3.3909	3.0672	3.0794	3.0916	-0.10%	yes	40.217	40.246	40.275	39.887	40.119	40.351	-0.32%	yes	89.243	89.634	90.024	87.499	88.294	89.091	-1.50%	no
2	2.7542	3.0602	3.3662	3.0482	3.0607	3.0732	0.02%	yes	39.793	39.824	39.856	39.503	39.759	40.015	-0.16%	yes	87.150	87.532	87.914	86.654	87.522	88.392	-0.01%	yes
3	2.7465	3.0517	3.3569	3.0372	3.0497	3.0623	-0.07%	yes	40.060	40.090	40.120	39.781	40.035	40.288	-0.14%	yes	87.851	88.236	88.621	86.731	87.594	88.460	-0.73%	yes
4	2.7741	3.0823	3.3905	3.0716	3.0841	3.0967	0.06%	yes	39.856	39.886	39.916	39.564	39.814	40.064	-0.18%	yes	86.752	87.133	87.513	86.666	87.512	88.360	0.44%	yes
5	2.7680	3.0755	3.3831	3.0618	3.0743	3.0869	-0.04%	yes	40.216	40.246	40.276	39.917	40.165	40.413	-0.20%	yes	89.013	89.403	89.792	88.064	88.918	89.776	-0.54%	yes
6	2.7491	3.0546	3.3601	3.0425	3.0550	3.0677	0.01%	yes	39.999	40.030	40.060	39.706	39.962	40.218	-0.17%	yes	87.576	87.960	88.344	87.121	87.997	88.876	0.04%	yes
7	2.7495	3.0550	3.3605	3.0390	3.0515	3.0640	-0.12%	yes	40.067	40.098	40.129	39.737	39.995	40.254	-0.26%	yes	88.316	88.703	89.090	86.628	87.499	88.373	-1.36%	yes
8	2.8013	3.1125	3.4238	3.0977	3.1101	3.1227	-0.08%	yes	39.909	39.940	39.970	39.591	39.846	40.101	-0.23%	yes	88.937	89.326	89.715	87.623	88.492	89.364	-0.93%	yes
9	3.0354	3.0484	3.0614	3.0368	3.0494	3.0621	0.03%	yes	39.708	39.737	39.767	39.452	39.716	39.980	-0.05%	yes	86.884	87.265	87.646	86.629	87.529	88.433	0.30%	yes
10	3.0355	3.0486	3.0617	3.0351	3.0478	3.0605	-0.03%	yes	26.573	26.597	26.622	26.445	26.655	26.865	0.22%	yes	57.452	57.703	57.955	56.956	57.656	58.359	-0.08%	yes
11	3.0166	3.0296	3.0426	3.0182	3.0308	3.0435	0.04%	yes	40.002	40.031	40.059	39.673	39.934	40.196	-0.24%	yes	87.115	87.498	87.880	86.909	87.796	88.687	0.34%	yes
12	3.0299	3.0429	3.0559	3.0324	3.0450	3.0577	0.07%	yes	39.930	39.958	39.986	39.571	39.818	40.064	-0.35%	yes	86.100	86.478	86.857	86.043	86.875	87.710	0.46%	yes
13	3.0460	3.0591	3.0722	3.0468	3.0595	3.0723	0.01%	yes	39.814	39.842	39.870	39.402	39.653	39.904	-0.47%	yes	87.000	87.382	87.763	86.393	87.246	88.102	-0.16%	yes
14	3.0356	3.0486	3.0616	3.0365	3.0492	3.0620	0.02%	yes	39.878	39.907	39.935	39.524	39.780	40.036	-0.32%	yes	87.241	87.623	88.006	86.876	87.751	88.630	0.15%	yes
15	3.0260	3.0390	3.0520	3.0276	3.0402	3.0528	0.04%	yes	39.670	39.698	39.726	39.360	39.631	39.902	-0.17%	yes	85.833	86.210	86.586	85.697	86.601	87.508	0.45%	yes
16	2.9978	3.0107	3.0236	2.9972	3.0098	3.0224	-0.03%	yes	39.707	39.735	39.762	39.419	39.708	39.998	-0.07%	yes	86.260	86.638	87.017	85.560	86.512	87.468	-0.15%	yes
17	3.0534	3.0666	3.0798	3.0535	3.0661	3.0788	-0.02%	yes	39.248	39.276	39.303	38.998	39.299	39.599	0.06%	yes	85.781	86.157	86.533	85.312	86.293	87.277	0.16%	yes
18	2.9840	2.9969	3.0098	2.9847	2.9972	3.0097	0.01%	yes	39.012	39.040	39.067	38.936	39.270	39.604	0.59%	yes	81.917	82.277	82.638	82.056	83.085	84.116	0.98%	yes

Poly 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.0332	2.2591	2.4850	2.2542	2.2591	2.2639	0.00%	yes	28.996	29.046	29.096	28.788	29.046	29.304	0.00%	yes	45.115	45.322	45.530	44.498	45.066	45.637	-0.56%	yes
2	2.0376	2.2640	2.4904	2.2591	2.2640	2.2689	0.00%	yes	29.279	29.325	29.370	29.084	29.325	29.566	0.00%	yes	47.106	47.321	47.537	46.456	47.015	47.576	-0.65%	yes
3	1.9627	2.1808	2.3989	2.1760	2.1808	2.1856	0.00%	yes	28.987	29.036	29.084	28.780	29.036	29.291	0.00%	yes	45.890	46.101	46.312	45.244	45.826	46.411	-0.60%	yes
4	2.0066	2.2296	2.4526	2.2248	2.2296	2.2345	0.00%	yes	29.160	29.209	29.257	28.946	29.209	29.471	0.00%	yes	46.343	46.556	46.769	45.709	46.297	46.886	-0.56%	yes
5	1.9994	2.2215	2.4437	2.2167	2.2215	2.2264	0.00%	yes	28.946	29.003	29.059	28.739	29.003	29.267	0.00%	yes	44.421	44.627	44.833	43.842	44.391	44.941	-0.53%	yes
6	1.9565	2.1739	2.3913	2.1690	2.1739	2.1789	0.00%	yes	28.355	28.404	28.452	28.146	28.404	28.662	0.00%	yes	44.429	44.635	44.840	43.812	44.384	44.957	-0.56%	yes
7	2.0992	2.3324	2.5656	2.3274	2.3324	2.3375	0.00%	yes	28.751	28.789	28.828	28.533	28.789	29.046	0.00%	yes	43.660	43.862	44.065	43.130	43.645	44.161	-0.50%	yes
8	1.9895	2.2106	2.4317	2.2058	2.2106	2.2154	0.00%	yes	28.683	28.718	28.752	28.456	28.718	28.980	0.00%	yes	44.026	44.231	44.436	43.476	44.000	44.526	-0.52%	yes
9	1.8762	2.0847	2.2932	2.0799	2.0847	2.0895	0.00%	yes	28.111	28.147	28.183	27.887	28.147	28.407	0.00%	yes	43.113	43.314	43.514	42.491	43.062	43.635	-0.58%	yes
10	1.8656	2.0729	2.2802	2.0681	2.0729	2.0777	0.00%	yes	28.448	28.484	28.521	28.224	28.484	28.745	0.00%	yes	43.292	43.494	43.695	42.674	43.246	43.819	-0.57%	yes
11	1.7043	1.8937	2.0831	1.8875	1.8937	1.8999	0.00%	yes	29.155	29.216	29.277	28.909	29.216	29.524	0.00%	yes	39.076	39.263	39.450	38.424	39.018	39.615	-0.62%	yes
12	1.7715	1.9683	2.1651	1.9621	1.9683	1.9745	0.00%	yes	29.281	29.335	29.388	29.042	29.335	29.628	0.00%	yes	40.404	40.597	40.789	39.764	40.331	40.900	-0.66%	yes
13	1.7925	1.9917	2.1909	1.9854	1.9917	1.9980	0.00%	yes	29.187	29.243	29.299	28.935	29.243	29.551	0.00%	yes	39.223	39.411	39.598	38.623	39.176	39.732	-0.59%	yes
14	2.0250	2.2500	2.4750	2.2436	2.2500	2.2563	0.00%	yes	30.102	30.136	30.170	29.827	30.136	30.446	0.00%	yes	49.562	49.789	50.017	48.754	49.478	50.207	-0.62%	yes
15	1.7204	1.9116	2.1028	1.9055	1.9116	1.9177	0.00%	yes	29.157	29.216	29.275	28.900	29.216	29.533	0.00%	yes	40.047	40.237	40.428	39.365	39.991	40.620	-0.61%	yes
16	1.6694	1.8549	2.0404	1.8487	1.8549	1.8611	0.00%	yes	28.427	28.454	28.481	28.150	28.454	28.759	0.00%	yes	38.704	38.889	39.074	38.028	38.634	39.244	-0.65%	yes
17	1.6826	1.8696	2.0566	1.8634	1.8696	1.8758	0.00%	yes	28.699	28.729	28.758	28.419	28.729	29.039	0.00%	yes	39.366	39.554	39.742	38.706	39.309	39.916	-0.62%	yes
18	1.6830	1.8700	2.0570	1.8639	1.8700	1.8762	0.00%	yes	28.437	28.470	28.502	28.153	28.470	28.786	0.00%	yes	38.530	38.714	38.898	37.868	38.479	39.093	-0.61%	yes
19	1.7932	1.9924	2.1916	1.9861	1.9924	1.9987	0.00%	yes	28.769	28.801	28.834	28.495	28.801	29.109	0.00%	yes	39.278	39.465	39.652	38.648	39.220	39.794	-0.62%	yes
20	1.7650	1.9611	2.1572	1.9551	1.9611	1.9671	0.00%	yes	28.982	29.015	29.047	28.698	29.015	29.333	0.00%	yes	41.067	41.261	41.455	40.345	40.991	41.642	-0.65%	yes
21	1.9935	2.2150	2.4365	2.2085	2.2150	2.2216	0.00%	yes	27.624	27.646	27.668	27.347	27.646	27.945	0.00%	yes	42.722	42.920	43.118	42.044	42.694	43.346	-0.53%	yes
22	2.0264	2.2516	2.4768	2.2452	2.2516	2.2581	0.00%	yes	27.420	27.442	27.465	27.156	27.442	27.730	0.00%	yes	36.713	36.887	37.061	36.215	36.722	37.229	-0.45%	yes
23	1.8826	2.0918	2.3010	2.0855	2.0918	2.0980	0.00%	yes	27.224	27.246	27.267	26.955	27.246	27.537	0.00%	yes	39.830	40.015	40.201	39.128	39.772	40.420	-0.61%	yes
24	1.9516	2.1684	2.3852	2.1621	2.1684	2.1748	0.00%	yes	28.047	28.069	28.092	27.816	28.069	28.323	0.00%	yes	41.963	42.158	42.352	41.281	41.862	42.447	-0.70%	yes
25	1.9017	2.1130	2.3243	2.1067	2.1130	2.1193	0.00%	yes	27.268	27.289	27.311	27.004	27.289	27.576	0.00%	yes	40.422	40.610	40.798	39.732	40.362	40.996	-0.61%	yes
26	1.8884	2.0982	2.3080	2.0919	2.0982	2.1046	0.00%	yes	27.021	27.043	27.065	26.758	27.043	27.329	0.00%	yes	39.775	39.961	40.146	39.096	39.720	40.347	-0.60%	yes
27	1.8385	2.0428	2.2471	2.0365	2.0428	2.0491	0.00%	yes	26.702	26.732	26.761	26.444	26.732	27.020	0.00%	yes	38.828	39.009	39.191	38.153	38.780	39.410	-0.59%	yes
28	2.0052	2.2280	2.4508	2.2218	2.2280	2.2342	0.00%	yes	27.136	27.166	27.196	26.887	27.166	27.446	0.00%	yes	40.704	40.894	41.083	40.057	40.645	41.236	-0.61%	yes
29	2.0245	2.2494	2.4743	2.2430	2.2494	2.2558	0.00%	yes	27.193	27.222	27.251	26.945	27.222	27.499	0.00%	yes	41.421	41.612	41.803	40.725	41.344	41.966	-0.64%	yes
30	2.1825	2.4250	2.6675	2.4185	2.4250	2.4315	0.00%	yes	28.399	28.430	28.460	28.151	28.430	28.708	0.00%	yes	43.990	44.192	44.393	43.286	43.911	44.538	-0.63%	yes

Poly 1A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
11	3.1707	3.5230	3.8753	3.5152	3.5196	3.5240	-0.10%	yes	28.470	28.514	28.557	28.396	28.398	28.400	-0.41%	no	69.298	69.631	69.965	68.451	68.537	68.623	-1.57%	no
12	3.3012	3.6680	4.0348	3.6644	3.6688	3.6732	0.02%	yes	28.604	28.650	28.695	28.622	28.624	28.626	-0.09%	yes	71.347	71.689	72.031	71.462	71.549	71.637	-0.19%	yes
13	3.2706	3.6340	3.9974	3.6295	3.6338	3.6381	-0.01%	yes	28.438	28.485	28.532	28.397	28.399	28.401	-0.30%	no	67.967	68.296	68.625	67.624	67.706	67.787	-0.86%	no
14	3.7800	4.2000	4.6200	4.2036	4.2080	4.2126	0.19%	yes	29.312	29.347	29.382	29.309	29.311	29.312	-0.12%	yes	84.538	84.931	85.324	86.420	86.512	86.605	1.86%	no
15	3.2193	3.5770	3.9347	3.5722	3.5765	3.5809	-0.01%	yes	28.367	28.414	28.461	28.340	28.342	28.344	-0.26%	no	69.980	70.316	70.652	69.895	69.980	70.065	-0.48%	yes
16	3.1258	3.4731	3.8204	3.4691	3.4735	3.4779	0.01%	yes	27.674	27.703	27.732	27.648	27.650	27.652	-0.19%	no	67.473	67.798	68.123	67.684	67.770	67.857	-0.04%	yes
17	3.1353	3.4837	3.8321	3.4774	3.4818	3.4862	-0.05%	yes	27.917	27.944	27.971	27.896	27.898	27.900	-0.16%	no	68.622	68.952	69.283	68.177	68.263	68.350	-1.00%	no
18	3.1323	3.4803	3.8283	3.4745	3.4788	3.4832	-0.04%	yes	27.609	27.636	27.662	27.577	27.579	27.581	-0.21%	no	66.561	66.882	67.204	66.275	66.358	66.441	-0.78%	no
19	3.3170	3.6855	4.0541	3.6849	3.6893	3.6937	0.10%	yes	28.000	28.027	28.053	27.972	27.974	27.976	-0.19%	no	67.702	68.028	68.355	68.246	68.327	68.408	0.44%	yes
20	3.2364	3.5960	3.9556	3.5915	3.5957	3.5999	-0.01%	yes	28.101	28.128	28.155	28.088	28.089	28.091	-0.14%	no	69.317	69.650	69.982	69.079	69.157	69.236	-0.71%	no
21	3.5722	3.9691	4.3660	3.9606	3.9655	3.9705	-0.09%	yes	27.414	27.441	27.468	27.333	27.335	27.337	-0.39%	no	73.259	73.603	73.948	72.391	72.481	72.571	-1.53%	no
22	3.6266	4.0296	4.4326	4.0096	4.0145	4.0194	-0.38%	yes	27.381	27.408	27.435	27.257	27.260	27.262	-0.54%	no	69.934	70.265	70.596	67.235	67.326	67.417	-4.18%	no
23	3.4382	3.8202	4.2022	3.8132	3.8180	3.8229	-0.06%	yes	27.014	27.048	27.081	26.984	26.987	26.989	-0.23%	no	67.590	67.910	68.229	68.804	68.890	68.977	1.44%	no
24	3.5377	3.9308	4.3239	3.9303	3.9352	3.9401	0.11%	yes	27.949	27.978	28.007	27.979	27.981	27.983	0.01%	yes	72.266	72.607	72.948	73.210	73.300	73.389	0.95%	no
25	3.4782	3.8647	4.2512	3.8578	3.8627	3.8675	-0.05%	yes	27.095	27.124	27.153	27.056	27.058	27.060	-0.24%	no	70.098	70.428	70.759	70.039	70.126	70.213	-0.43%	yes
26	3.4414	3.8238	4.2062	3.8174	3.8223	3.8273	-0.04%	yes	26.816	26.843	26.870	26.804	26.806	26.808	-0.14%	no	69.692	70.021	70.351	69.491	69.581	69.671	-0.63%	no
27	3.3767	3.7519	4.1271	3.7461	3.7511	3.7560	-0.02%	yes	26.514	26.540	26.566	26.497	26.499	26.501	-0.16%	no	68.323	68.646	68.970	68.336	68.428	68.519	-0.32%	yes
28	3.6529	4.0588	4.4647	4.0540	4.0588	4.0636	0.00%	yes	26.971	26.997	27.024	26.966	26.968	26.970	-0.11%	no	71.117	71.451	71.786	71.118	71.202	71.286	-0.35%	yes
29	3.6525	4.0583	4.4641	4.0604	4.0653	4.0702	0.17%	yes	26.963	26.989	27.015	27.005	27.007	27.009	0.07%	yes	69.502	69.829	70.156	70.701	70.784	70.866	1.37%	no
30	3.8700	4.3000	4.7300	4.3177	4.3226	4.3275	0.53%	yes	28.152	28.196	28.241	28.194	28.196	28.198	0.00%	yes	71.641	71.977	72.313	74.225	74.304	74.384	3.23%	no

Poly 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.3700	1.5222	1.6744	1.5090	1.5222	1.5356	0.00%	yes	17.546	18.200	18.854	18.082	18.199	18.316	-0.01%	yes	19.287	19.386	19.486	19.149	19.370	19.592	-0.09%	yes
2	1.3099	1.4554	1.6009	1.4424	1.4552	1.4682	-0.01%	yes	18.212	18.253	18.293	18.113	18.255	18.396	0.01%	yes	17.773	17.867	17.961	17.668	17.900	18.134	0.19%	yes
3	1.3566	1.5073	1.6580	1.4941	1.5073	1.5207	0.00%	yes	18.307	18.386	18.464	18.247	18.385	18.522	-0.01%	yes	19.382	19.482	19.583	19.247	19.490	19.736	0.04%	yes
4	1.3730	1.5256	1.6782	1.5120	1.5257	1.5396	0.01%	yes	18.240	18.263	18.285	18.120	18.259	18.399	-0.02%	yes	19.391	19.491	19.591	19.242	19.494	19.748	0.02%	yes
5	1.2637	1.4041	1.5445	1.3915	1.4040	1.4167	0.00%	yes	18.221	18.240	18.259	18.103	18.243	18.383	0.02%	yes	17.998	18.093	18.189	17.894	18.131	18.371	0.21%	yes
6	1.3682	1.5202	1.6722	1.5073	1.5201	1.5331	-0.01%	yes	18.388	18.442	18.497	18.303	18.444	18.585	0.01%	yes	19.151	19.250	19.349	19.032	19.278	19.525	0.14%	yes
7	1.3638	1.5153	1.6668	1.5021	1.5155	1.5290	0.01%	yes	18.249	18.338	18.426	18.192	18.336	18.479	-0.01%	yes	18.924	19.023	19.121	18.795	19.045	19.296	0.12%	yes
8	1.2767	1.4185	1.5604	1.4054	1.4181	1.4310	-0.03%	yes	18.035	18.153	18.272	18.008	18.156	18.305	0.02%	yes	16.882	16.973	17.063	16.787	17.016	17.246	0.25%	yes
9	1.3533	1.5037	1.6541	1.4906	1.5037	1.5169	0.00%	yes	18.290	18.392	18.493	18.252	18.392	18.531	0.00%	yes	18.988	19.086	19.184	18.859	19.106	19.356	0.11%	yes
10	1.4349	1.5943	1.7537	1.5809	1.5945	1.6083	0.02%	yes	18.447	18.548	18.649	18.422	18.543	18.665	-0.02%	yes	19.953	20.055	20.156	19.803	20.033	20.264	-0.11%	yes
11	1.3088	1.4542	1.5996	1.4416	1.4541	1.4668	0.00%	yes	18.557	18.576	18.594	18.439	18.578	18.717	0.01%	yes	19.592	19.693	19.794	19.450	19.707	19.966	0.07%	yes
12	1.3316	1.4795	1.6275	1.4665	1.4795	1.4927	0.00%	yes	18.197	18.215	18.232	18.076	18.215	18.354	0.00%	yes	18.449	18.546	18.642	18.330	18.568	18.809	0.12%	yes
13	1.4233	1.5814	1.7395	1.5683	1.5815	1.5948	0.01%	yes	18.490	18.508	18.526	18.377	18.507	18.637	-0.01%	yes	19.769	19.870	19.971	19.635	19.871	20.109	0.01%	yes
14	1.4132	1.4202	1.4272	1.4075	1.4202	1.4330	0.00%	yes	18.236	18.254	18.272	18.107	18.256	18.405	0.01%	yes	18.296	18.392	18.489	18.194	18.443	18.694	0.27%	yes
15	1.4459	1.4530	1.4601	1.4401	1.4530	1.4660	0.00%	yes	18.348	18.366	18.384	18.223	18.367	18.511	0.01%	yes	18.730	18.827	18.925	18.607	18.858	19.110	0.16%	yes

Poly 2A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	3.6077	4.0085	4.4094	3.9723	4.0068	4.0418	-0.04%	yes	18.259	18.316	18.373	18.257	18.371	18.485	0.30%	yes	49.588	49.821	50.054	49.250	49.805	50.364	-0.03%	yes
2	3.5239	3.9154	4.3069	3.8768	3.9108	3.9453	-0.12%	yes	18.338	18.361	18.383	18.159	18.299	18.439	-0.33%	yes	48.696	48.926	49.155	47.610	48.238	48.870	-1.41%	yes
3	3.5779	3.9754	4.3729	3.9396	3.9742	4.0093	-0.03%	yes	18.454	18.477	18.499	18.290	18.425	18.561	-0.28%	yes	50.704	50.942	51.181	49.952	50.585	51.223	-0.70%	yes
4	3.5681	3.9645	4.3610	3.9276	3.9629	3.9987	-0.04%	yes	18.275	18.297	18.319	18.139	18.277	18.415	-0.11%	yes	50.210	50.446	50.682	49.538	50.194	50.854	-0.50%	yes
5	3.4602	3.8447	4.2292	3.8138	3.8479	3.8824	0.08%	yes	18.316	18.338	18.360	18.154	18.292	18.430	-0.25%	yes	48.303	48.532	48.762	48.202	48.829	49.460	0.61%	yes
6	3.6664	4.0738	4.4812	4.0366	4.0708	4.1053	-0.07%	yes	18.489	18.551	18.614	18.338	18.477	18.617	-0.40%	yes	51.226	51.465	51.704	50.385	51.034	51.687	-0.84%	yes
7	3.5798	3.9776	4.3754	3.9422	3.9770	4.0123	-0.01%	yes	18.338	18.417	18.497	18.194	18.336	18.478	-0.44%	yes	50.073	50.309	50.544	49.366	50.019	50.676	-0.58%	yes
8	3.4664	3.8515	4.2367	3.8160	3.8501	3.8846	-0.04%	yes	18.170	18.273	18.375	18.018	18.166	18.313	-0.58%	yes	47.686	47.913	48.139	46.735	47.375	48.019	-1.12%	yes
9	3.5960	3.9956	4.3952	3.9600	3.9944	4.0293	-0.03%	yes	18.369	18.458	18.547	18.287	18.426	18.564	-0.17%	yes	50.455	50.692	50.928	49.934	50.583	51.236	-0.21%	yes
10	3.7147	4.1274	4.5401	4.0950	4.1300	4.1654	0.06%	yes	18.559	18.645	18.732	18.568	18.686	18.805	0.22%	yes	51.489	51.730	51.971	51.502	52.084	52.671	0.68%	yes
11	3.5702	3.9669	4.3636	3.9336	3.9677	4.0022	0.02%	yes	18.716	18.742	18.768	18.492	18.629	18.766	-0.60%	yes	52.097	52.341	52.585	51.557	52.224	52.896	-0.22%	yes
12	3.5543	3.9492	4.3441	3.9136	3.9481	3.9829	-0.03%	yes	18.335	18.358	18.381	18.119	18.256	18.393	-0.56%	yes	49.379	49.612	49.845	48.538	49.164	49.795	-0.90%	yes
13	3.7557	4.1730	4.5903	4.1393	4.1738	4.2087	0.02%	yes	18.658	18.681	18.705	18.474	18.602	18.730	-0.43%	yes	52.216	52.460	52.704	51.621	52.229	52.841	-0.44%	yes
14	3.8262	3.8437	3.8612	3.8130	3.8470	3.8815	0.09%	yes	18.246	18.269	18.291	18.085	18.233	18.381	-0.20%	yes	48.159	48.387	48.615	48.122	48.783	49.447	0.82%	yes
15	3.9048	3.9226	3.9404	3.8869	3.9215	3.9565	-0.03%	yes	18.359	18.381	18.404	18.238	18.381	18.524	0.00%	yes	49.940	50.175	50.410	49.441	50.106	50.775	-0.14%	yes

Poly 3A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.1380	2.1476	2.1572	2.1353	2.1476	2.1601	0.00%	yes	36.278	36.480	36.682	36.226	36.479	36.732	0.00%	yes	60.214	60.492	60.771	59.761	60.457	61.156	-0.06%	yes
2	2.0614	2.0707	2.0800	2.0583	2.0706	2.0831	0.00%	yes	36.353	36.400	36.447	36.135	36.400	36.664	0.00%	yes	57.893	58.163	58.433	57.457	58.143	58.833	-0.03%	yes
3	2.1358	2.1454	2.1550	2.1329	2.1455	2.1581	0.00%	yes	36.450	36.480	36.509	36.239	36.479	36.719	0.00%	yes	59.318	59.593	59.868	58.894	59.556	60.222	-0.06%	yes
4	2.5239	2.5350	2.5461	2.5171	2.5350	2.5532	0.00%	yes	36.431	36.458	36.484	36.141	36.458	36.774	0.00%	yes	71.827	72.149	72.471	71.079	72.116	73.161	-0.05%	yes
5	2.5768	2.5882	2.5996	2.5700	2.5883	2.6067	0.00%	yes	36.460	36.486	36.513	36.168	36.486	36.803	0.00%	yes	73.064	73.390	73.717	72.303	73.371	74.446	-0.03%	yes
6	2.5157	2.5268	2.5379	2.5093	2.5268	2.5446	0.00%	yes	25.037	25.058	25.079	24.880	25.059	25.238	0.00%	yes	47.888	48.103	48.318	47.265	47.892	48.526	-0.44%	yes
7	2.6511	2.6629	2.6747	2.6445	2.6634	2.6825	0.02%	yes	36.370	36.396	36.422	36.079	36.399	36.717	0.01%	yes	72.875	73.200	73.526	72.318	73.394	74.479	0.26%	yes
8	2.6697	2.6813	2.6929	2.6647	2.6813	2.6980	0.00%	yes	36.336	36.362	36.388	36.079	36.361	36.642	0.00%	yes	75.732	76.069	76.405	75.042	76.008	76.981	-0.08%	yes
9	2.6832	2.6949	2.7066	2.6781	2.6949	2.7118	0.00%	yes	36.393	36.420	36.446	36.132	36.419	36.706	0.00%	yes	75.168	75.503	75.837	74.495	75.451	76.414	-0.07%	yes
10	2.7331	2.7452	2.7573	2.7284	2.7456	2.7629	0.01%	yes	36.498	36.524	36.550	36.240	36.526	36.810	0.00%	yes	76.501	76.841	77.180	75.983	76.977	77.978	0.18%	yes
11	2.6934	2.7051	2.7168	2.6880	2.7052	2.7225	0.00%	yes	36.137	36.163	36.189	35.879	36.166	36.453	0.01%	yes	73.834	74.164	74.494	73.308	74.261	75.221	0.13%	yes

Poly 3A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	4.3223	4.3419	4.3615	4.3131	4.3408	4.3687	-0.03%	yes	35.134	35.177	35.221	34.786	35.096	35.407	-0.23%	yes	116.522	117.055	117.589	114.611	116.254	117.906	-0.68%	yes
2	4.2026	4.2215	4.2404	4.1936	4.2214	4.2495	0.00%	yes	34.930	34.961	34.992	34.609	34.935	35.260	-0.07%	yes	112.759	113.278	113.796	111.572	113.240	114.918	-0.03%	yes
3	4.2807	4.2999	4.3191	4.2706	4.2984	4.3264	-0.03%	yes	35.315	35.346	35.376	34.948	35.241	35.533	-0.30%	yes	115.918	116.449	116.981	113.820	115.387	116.964	-0.91%	yes

Poly 1B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.2044	1.3382	1.4720	1.3359	1.3382	1.3404	0.00%	yes	19.081	19.101	19.122	18.981	19.101	19.222	0.00%	yes	17.788	17.883	17.978	17.644	17.807	17.970	-0.43%	yes
2	1.3187	1.4652	1.6117	1.4627	1.4652	1.4677	0.00%	yes	19.176	19.199	19.221	19.075	19.199	19.322	0.00%	yes	17.474	17.568	17.663	17.375	17.515	17.654	-0.30%	yes
3	1.2268	1.3631	1.4994	1.3608	1.3631	1.3654	0.00%	yes	19.081	19.103	19.126	18.979	19.103	19.228	0.00%	yes	17.018	17.110	17.203	16.904	17.051	17.197	-0.35%	yes
4	1.2242	1.3602	1.4962	1.3579	1.3602	1.3624	0.00%	yes	19.215	19.236	19.256	19.110	19.236	19.362	0.00%	yes	17.652	17.747	17.843	17.524	17.679	17.835	-0.38%	yes
5	1.2182	1.3536	1.4890	1.3513	1.3536	1.3559	0.00%	yes	19.099	19.120	19.140	18.995	19.120	19.244	0.00%	yes	17.297	17.391	17.485	17.175	17.327	17.479	-0.37%	yes
6	1.1979	1.3310	1.4641	1.3288	1.3310	1.3332	0.00%	yes	19.196	19.217	19.238	19.093	19.217	19.340	0.00%	yes	16.957	17.049	17.141	16.824	16.978	17.131	-0.42%	yes
7	1.2199	1.3554	1.4909	1.3531	1.3554	1.3577	0.00%	yes	19.189	19.208	19.228	19.085	19.208	19.332	0.00%	yes	18.075	18.172	18.269	17.945	18.104	18.263	-0.38%	yes
8	1.2340	1.3711	1.5082	1.3688	1.3711	1.3734	0.00%	yes	19.393	19.411	19.429	19.285	19.411	19.537	0.00%	yes	18.815	18.914	19.014	18.672	18.843	19.014	-0.38%	yes
9	1.2393	1.3770	1.5147	1.3748	1.3770	1.3793	0.00%	yes	19.182	19.200	19.218	19.076	19.200	19.324	0.00%	yes	17.474	17.569	17.663	17.356	17.504	17.651	-0.37%	yes
10	1.2389	1.3765	1.5142	1.3742	1.3765	1.3787	0.00%	yes	19.001	19.019	19.037	18.902	19.019	19.137	0.00%	yes	17.310	17.403	17.496	17.178	17.328	17.478	-0.43%	yes
11	1.1634	1.2927	1.4220	1.2904	1.2927	1.2950	0.00%	yes	19.182	19.200	19.217	19.076	19.200	19.323	0.00%	yes	17.817	17.913	18.009	17.674	17.840	18.007	-0.41%	yes
12	1.2156	1.3507	1.4858	1.3484	1.3507	1.3530	0.00%	yes	19.164	19.182	19.200	19.058	19.182	19.306	0.00%	yes	17.819	17.915	18.010	17.685	17.846	18.007	-0.38%	yes
13	1.2376	1.3751	1.5126	1.3728	1.3751	1.3775	0.00%	yes	19.049	19.067	19.085	18.945	19.067	19.188	0.00%	yes	17.266	17.359	17.451	17.134	17.290	17.447	-0.39%	yes
14	1.2617	1.4019	1.5421	1.3995	1.4019	1.4042	0.00%	yes	9.146	9.164	9.181	9.082	9.164	9.246	0.00%	yes	7.434	7.475	7.516	7.325	7.410	7.494	-0.87%	yes
15	1.2095	1.3439	1.4783	1.3417	1.3439	1.3461	0.00%	yes	19.319	19.342	19.364	19.215	19.342	19.468	0.00%	yes	15.846	15.934	16.022	15.736	15.875	16.014	-0.37%	yes
16	1.1688	1.2987	1.4286	1.2965	1.2987	1.3009	0.00%	yes	19.188	19.209	19.229	19.085	19.209	19.332	0.00%	yes	17.470	17.565	17.659	17.332	17.492	17.653	-0.41%	yes
17	1.2184	1.3538	1.4892	1.3515	1.3538	1.3560	0.00%	yes	18.914	18.936	18.957	18.822	18.936	19.050	0.00%	yes	17.198	17.290	17.382	17.055	17.206	17.358	-0.48%	yes
18	1.1742	1.3047	1.4352	1.3024	1.3047	1.3069	0.00%	yes	19.028	19.048	19.067	18.923	19.048	19.172	0.00%	yes	17.725	17.820	17.915	17.583	17.750	17.918	-0.39%	yes
19	1.2241	1.3601	1.4961	1.3578	1.3601	1.3624	0.00%	yes	19.017	19.038	19.058	18.923	19.038	19.152	0.00%	yes	17.773	17.868	17.963	17.634	17.788	17.942	-0.45%	yes
20	1.2222	1.3580	1.4938	1.3557	1.3580	1.3603	0.00%	yes	19.167	19.186	19.204	19.071	19.186	19.301	0.00%	yes	18.196	18.293	18.390	18.056	18.211	18.366	-0.45%	yes
21	1.2338	1.3709	1.5080	1.3687	1.3709	1.3732	0.00%	yes	19.098	19.122	19.145	19.010	19.122	19.234	0.00%	yes	18.710	18.808	18.907	18.553	18.713	18.874	-0.51%	yes

Poly 1B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.1457	2.3841	2.6225	2.3814	2.3854	2.3895	0.06%	yes	18.851	18.873	18.895	18.667	18.788	18.908	-0.45%	yes	30.320	30.486	30.652	30.311	30.598	30.885	0.37%	yes
2	2.2526	2.5029	2.7532	2.4957	2.4999	2.5041	-0.12%	yes	18.956	18.979	19.001	18.751	18.875	18.998	-0.55%	yes	30.556	30.725	30.893	29.866	30.129	30.392	-1.94%	no
3	2.1800	2.4222	2.6644	2.4145	2.4186	2.4227	-0.15%	yes	18.866	18.888	18.911	18.658	18.782	18.907	-0.56%	yes	29.968	30.134	30.299	29.266	29.536	29.806	-1.98%	no
4	2.2093	2.4548	2.7003	2.4563	2.4604	2.4645	0.23%	yes	18.948	18.971	18.993	18.779	18.905	19.030	-0.35%	yes	29.999	30.165	30.331	30.260	30.540	30.821	1.24%	yes
5	2.1595	2.3994	2.6393	2.3929	2.3970	2.4011	-0.10%	yes	18.846	18.868	18.890	18.658	18.782	18.907	-0.45%	yes	29.788	29.952	30.117	29.293	29.565	29.838	-1.29%	yes
6	2.1318	2.3687	2.6056	2.3597	2.3636	2.3676	-0.21%	yes	18.940	18.962	18.985	18.759	18.882	19.006	-0.42%	yes	28.598	28.757	28.916	27.966	28.234	28.503	-1.82%	no
7	2.1678	2.4087	2.6496	2.4037	2.4078	2.4119	-0.04%	yes	18.948	18.970	18.993	18.762	18.886	19.009	-0.44%	yes	31.007	31.177	31.347	30.641	30.927	31.213	-0.80%	yes
8	2.2060	2.4511	2.6962	2.4475	2.4516	2.4557	0.02%	yes	19.187	19.210	19.233	18.940	19.066	19.192	-0.75%	yes	32.412	32.588	32.764	32.072	32.375	32.679	-0.65%	yes
9	2.2199	2.4665	2.7132	2.4600	2.4640	2.4680	-0.10%	yes	19.124	19.147	19.169	18.759	18.883	19.007	-1.38%	no	31.136	31.307	31.479	30.196	30.466	30.736	-2.69%	no
10	2.1935	2.4372	2.6809	2.4320	2.4361	2.4402	-0.04%	yes	18.957	18.981	19.004	18.614	18.731	18.848	-1.31%	no	30.198	30.364	30.530	29.549	29.814	30.079	-1.81%	no
11	2.0819	2.3132	2.5445	2.3084	2.3125	2.3166	-0.03%	yes	18.928	18.951	18.973	18.747	18.870	18.993	-0.42%	yes	30.494	30.662	30.830	30.224	30.516	30.810	-0.47%	yes
12	2.1595	2.3994	2.6393	2.3946	2.3987	2.4028	-0.03%	yes	18.926	18.949	18.972	18.721	18.845	18.969	-0.55%	yes	30.686	30.855	31.023	30.329	30.615	30.902	-0.78%	yes
13	2.1884	2.4315	2.6747	2.4269	2.4310	2.4351	-0.02%	yes	18.822	18.859	18.895	18.627	18.748	18.869	-0.58%	yes	29.960	30.126	30.291	29.471	29.747	30.025	-1.26%	yes
14	2.2176	2.4640	2.7104	2.4521	2.4563	2.4605	-0.31%	yes	9.033	9.054	9.074	8.983	9.062	9.142	0.09%	yes	13.268	13.342	13.417	12.797	12.959	13.122	-2.87%	no
15	2.1506	2.3896	2.6286	2.3758	2.3797	2.3835	-0.42%	yes	19.097	19.120	19.142	18.869	18.996	19.122	-0.65%	yes	27.459	27.614	27.768	26.571	26.822	27.072	-2.87%	no
16	2.1054	2.3393	2.5732	2.3356	2.3396	2.3437	0.01%	yes	18.954	18.977	18.999	18.766	18.889	19.012	-0.46%	yes	29.973	30.139	30.304	29.739	30.023	30.308	-0.38%	yes
17	2.1665	2.4072	2.6479	2.4076	2.4116	2.4157	0.18%	yes	18.767	18.789	18.812	18.559	18.672	18.785	-0.63%	yes	28.615	28.773	28.930	29.015	29.278	29.542	1.76%	no
18	2.0951	2.3279	2.5607	2.3221	2.3262	2.3304	-0.07%	yes	18.830	18.852	18.875	18.583	18.707	18.832	-0.77%	yes	30.803	30.972	31.141	30.272	30.568	30.865	-1.31%	yes
19	2.1630	2.4033	2.6436	2.3983	2.4024	2.4065	-0.04%	yes	18.901	18.923	18.945	18.657	18.770	18.884	-0.81%	no	30.730	30.898	31.066	30.295	30.566	30.837	-1.07%	yes
20	2.1629	2.4032	2.6435	2.3982	2.4023	2.4064	-0.04%	yes	19.043	19.066	19.088	18.800	18.915	19.029	-0.79%	no	31.226	31.396	31.567	30.746	31.019	31.291	-1.20%	yes
21	2.1623	2.4025	2.6428	2.3958	2.3997	2.4037	-0.12%	yes	19.025	19.054	19.083	18.748	18.858	18.969	-1.03%	no	32.012	32.186	32.359	31.173	31.447	31.721	-2.30%	no

Poly 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0266	1.1407	1.2548	1.1361	1.1407	1.1452	0.00%	yes	19.319	19.337	19.355	19.207	19.337	19.467	0.00%	yes	16.803	16.897	16.992	16.653	16.833	17.014	-0.38%	yes
2	1.0226	1.1362	1.2498	1.1316	1.1362	1.1407	0.00%	yes	19.242	19.260	19.278	19.130	19.261	19.391	0.00%	yes	16.395	16.487	16.580	16.251	16.427	16.604	-0.36%	yes
3	1.0229	1.1365	1.2502	1.1319	1.1365	1.1411	0.00%	yes	19.307	19.325	19.343	19.194	19.325	19.457	0.00%	yes	16.496	16.589	16.682	16.354	16.533	16.713	-0.34%	yes
4	1.0765	1.1961	1.3157	1.1916	1.1961	1.2006	0.00%	yes	19.573	19.591	19.609	19.457	19.592	19.727	0.00%	yes	17.513	17.610	17.706	17.359	17.547	17.736	-0.35%	yes
5	1.0132	1.1258	1.2384	1.1213	1.1258	1.1304	0.00%	yes	19.266	19.284	19.302	19.154	19.284	19.415	0.00%	yes	16.534	16.627	16.720	16.385	16.563	16.743	-0.38%	yes
6	1.0187	1.1319	1.2451	1.1273	1.1319	1.1365	0.00%	yes	19.183	19.201	19.219	19.068	19.201	19.334	0.00%	yes	16.290	16.383	16.475	16.151	16.329	16.508	-0.33%	yes
7	1.0166	1.1295	1.2425	1.1249	1.1295	1.1341	0.00%	yes	19.286	19.304	19.322	19.173	19.304	19.435	0.00%	yes	16.510	16.603	16.696	16.371	16.549	16.727	-0.33%	yes
8	1.0068	1.1187	1.2306	1.1142	1.1187	1.1233	0.00%	yes	19.321	19.339	19.357	19.208	19.340	19.472	0.00%	yes	16.550	16.643	16.736	16.399	16.579	16.760	-0.38%	yes
9	1.0148	1.1276	1.2404	1.1230	1.1276	1.1321	0.00%	yes	19.353	19.371	19.389	19.243	19.371	19.500	0.00%	yes	16.603	16.696	16.790	16.450	16.627	16.806	-0.41%	yes
10	1.0128	1.1253	1.2378	1.1207	1.1253	1.1298	0.00%	yes	19.302	19.320	19.337	19.196	19.320	19.444	0.00%	yes	16.388	16.481	16.573	16.237	16.407	16.579	-0.45%	yes
11	1.0147	1.1274	1.2401	1.1229	1.1274	1.1320	0.00%	yes	19.294	19.312	19.330	19.192	19.312	19.432	0.00%	yes	16.450	16.543	16.636	16.306	16.473	16.640	-0.43%	yes
12	1.0225	1.1361	1.2497	1.1316	1.1361	1.1407	0.00%	yes	19.307	19.325	19.343	19.197	19.325	19.453	0.00%	yes	16.585	16.678	16.771	16.432	16.609	16.787	-0.41%	yes
13	1.0229	1.1366	1.2503	1.1320	1.1365	1.1411	0.00%	yes	19.348	19.366	19.384	19.236	19.367	19.497	0.00%	yes	16.657	16.751	16.844	16.498	16.676	16.856	-0.44%	yes
14	1.0157	1.1285	1.2414	1.1240	1.1285	1.1331	0.00%	yes	19.356	19.374	19.392	19.245	19.374	19.504	0.00%	yes	16.602	16.695	16.789	16.455	16.632	16.810	-0.38%	yes
15	1.0745	1.1939	1.3133	1.1893	1.1939	1.1985	0.00%	yes	19.580	19.608	19.636	19.475	19.608	19.741	0.00%	yes	17.397	17.493	17.589	17.253	17.439	17.625	-0.31%	yes
16	1.1196	1.1257	1.1318	1.1211	1.1257	1.1303	0.00%	yes	19.386	19.412	19.438	19.281	19.412	19.544	0.00%	yes	16.694	16.788	16.882	16.549	16.728	16.909	-0.36%	yes
17	1.1685	1.1747	1.1809	1.1701	1.1747	1.1793	0.00%	yes	19.595	19.622	19.648	19.488	19.622	19.755	0.00%	yes	17.347	17.443	17.540	17.199	17.386	17.572	-0.33%	yes
18	1.1240	1.1301	1.1362	1.1255	1.1301	1.1347	0.00%	yes	19.327	19.353	19.378	19.225	19.353	19.480	0.00%	yes	16.481	16.574	16.667	16.331	16.507	16.683	-0.40%	yes
19	1.1372	1.1433	1.1494	1.1387	1.1433	1.1478	0.00%	yes	19.370	19.400	19.429	19.271	19.400	19.529	0.00%	yes	16.565	16.658	16.751	16.417	16.593	16.769	-0.39%	yes
20	1.1127	1.1188	1.1249	1.1143	1.1188	1.1233	0.00%	yes	19.345	19.373	19.400	19.243	19.373	19.502	0.00%	yes	16.721	16.815	16.909	16.567	16.746	16.925	-0.41%	yes
21	1.1266	1.1327	1.1388	1.1281	1.1327	1.1372	0.00%	yes	19.221	19.287	19.352	19.166	19.287	19.408	0.00%	yes	16.567	16.660	16.754	16.428	16.594	16.760	-0.40%	yes

Poly 3B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0945	1.2161	1.3377	1.2108	1.2161	1.2214	0.00%	yes	38.385	38.502	38.619	38.238	38.502	38.766	0.00%	yes	33.580	33.765	33.950	33.253	33.637	34.022	-0.38%	yes
2	1.0813	1.2014	1.3215	1.1961	1.2014	1.2067	0.00%	yes	38.377	38.495	38.614	38.207	38.495	38.784	0.00%	yes	33.616	33.804	33.992	33.322	33.710	34.100	-0.28%	yes
3	1.0637	1.1819	1.3001	1.1766	1.1819	1.1872	0.00%	yes	38.486	38.607	38.728	38.335	38.607	38.880	0.00%	yes	33.580	33.767	33.953	33.254	33.647	34.041	-0.36%	yes
4	1.0386	1.1540	1.2694	1.1487	1.1540	1.1593	0.00%	yes	38.569	38.690	38.810	38.409	38.690	38.970	0.00%	yes	32.747	32.933	33.118	32.456	32.837	33.219	-0.29%	yes
5	1.0355	1.1505	1.2656	1.1453	1.1505	1.1558	0.00%	yes	38.282	38.404	38.525	38.128	38.404	38.679	0.00%	yes	33.057	33.243	33.428	32.748	33.134	33.523	-0.33%	yes
6	1.0707	1.1897	1.3087	1.1845	1.1897	1.1949	0.00%	yes	38.290	38.435	38.580	38.176	38.435	38.694	0.00%	yes	32.445	32.625	32.805	32.116	32.488	32.863	-0.42%	yes
7	1.0587	1.1763	1.2939	1.1714	1.1763	1.1813	0.00%	yes	38.150	38.310	38.469	38.077	38.310	38.543	0.00%	yes	29.844	30.013	30.182	29.512	29.837	30.164	-0.59%	yes
8	1.0853	1.2059	1.3265	1.2006	1.2059	1.2111	0.00%	yes	38.538	38.672	38.807	38.432	38.672	38.913	0.00%	yes	31.707	31.884	32.061	31.378	31.725	32.074	-0.50%	yes
9	1.0736	1.1929	1.3122	1.1878	1.1929	1.1981	0.00%	yes	38.544	38.667	38.790	38.445	38.667	38.890	0.00%	yes	32.344	32.524	32.705	32.005	32.333	32.664	-0.59%	yes
10	1.0751	1.1945	1.3140	1.1892	1.1945	1.1998	0.00%	yes	38.291	38.325	38.359	38.056	38.325	38.593	0.00%	yes	33.433	33.618	33.803	33.104	33.496	33.889	-0.36%	yes
11	1.0666	1.1851	1.3036	1.1798	1.1851	1.1905	0.00%	yes	38.763	38.794	38.826	38.507	38.794	39.081	0.00%	yes	34.409	34.600	34.791	34.094	34.502	34.912	-0.28%	yes
12	1.0499	1.1666	1.2833	1.1614	1.1666	1.1719	0.00%	yes	38.756	38.789	38.822	38.510	38.789	39.067	0.00%	yes	33.773	33.961	34.149	33.458	33.854	34.253	-0.31%	yes
13	1.0703	1.1892	1.3081	1.1838	1.1892	1.1946	0.00%	yes	38.602	38.635	38.667	38.354	38.635	38.915	0.00%	yes	34.161	34.350	34.540	33.845	34.247	34.652	-0.30%	yes
14	1.0616	1.1795	1.2975	1.1742	1.1795	1.1848	0.00%	yes	38.664	38.699	38.734	38.428	38.699	38.969	0.00%	yes	32.448	32.629	32.810	32.134	32.515	32.898	-0.35%	yes
15	1.0888	1.2098	1.3308	1.2044	1.2098	1.2152	0.00%	yes	38.741	38.774	38.807	38.507	38.774	39.042	0.00%	yes	34.739	34.930	35.121	34.410	34.806	35.204	-0.36%	yes
16	1.1841	1.1904	1.1967	1.1851	1.1904	1.1957	0.00%	yes	38.868	38.901	38.934	38.643	38.901	39.159	0.00%	yes	33.950	34.138	34.326	33.633	34.011	34.392	-0.37%	yes
17	1.1981	1.2044	1.2107	1.1991	1.2044	1.2097	0.00%	yes	38.779	38.809	38.838	38.547	38.809	39.071	0.00%	yes	35.955	36.151	36.348	35.616	36.016	36.419	-0.37%	yes
18	1.1807	1.1870	1.1933	1.1817	1.1870	1.1924	0.00%	yes	38.807	38.840	38.873	38.577	38.840	39.103	0.00%	yes	34.284	34.473	34.663	33.965	34.352	34.740	-0.35%	yes

Poly 3B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	3.1653	3.1809	3.1965	3.1671	3.1841	3.2011	0.10%	yes	38.392	38.586	38.779	38.368	38.731	39.094	0.38%	yes	78.183	78.570	78.958	80.146	81.381	82.624	3.58%	no
2	3.2071	3.2223	3.2375	3.2072	3.2245	3.2419	0.07%	yes	38.346	38.504	38.662	38.234	38.634	39.034	0.34%	yes	85.880	86.305	86.729	85.923	87.284	88.652	1.13%	yes
3	3.1374	3.1524	3.1674	3.1407	3.1578	3.1750	0.17%	yes	38.473	38.636	38.798	38.447	38.822	39.198	0.48%	yes	81.580	81.984	82.388	83.342	84.652	85.968	3.25%	no
4	3.1000	3.1148	3.1296	3.0973	3.1146	3.1320	-0.01%	yes	38.615	38.767	38.920	38.530	38.918	39.306	0.39%	yes	86.442	86.870	87.298	86.030	87.388	88.754	0.60%	yes
5	3.0890	3.1038	3.1186	3.0866	3.1037	3.1210	0.00%	yes	38.303	38.461	38.618	38.243	38.623	39.003	0.42%	yes	85.181	85.603	86.025	84.995	86.323	87.658	0.84%	yes
6	3.1531	3.1681	3.1831	3.1842	3.2011	3.2180	1.04%	no	38.300	38.523	38.745	38.401	38.755	39.110	0.60%	yes	73.737	74.106	74.476	79.100	80.320	81.547	8.38%	no
7	3.1115	3.1264	3.1413	3.2475	3.2638	3.2802	4.39%	no	38.189	38.447	38.706	38.548	38.862	39.177	1.08%	yes	63.467	63.799	64.131	77.324	78.374	79.430	22.85%	no
8	3.1476	3.1626	3.1776	3.2070	3.2239	3.2409	1.94%	no	38.506	38.695	38.884	38.765	39.092	39.420	1.03%	yes	71.216	71.578	71.941	80.360	81.457	82.559	13.80%	no
9	3.1386	3.1536	3.1686	3.1629	3.1793	3.1959	0.82%	yes	38.496	38.669	38.842	38.923	39.222	39.521	1.43%	no	75.562	75.941	76.321	81.208	82.242	83.282	8.30%	no
10	3.1689	3.1840	3.1991	3.1731	3.1903	3.2076	0.20%	yes	38.358	38.391	38.424	38.191	38.560	38.930	0.44%	yes	82.262	82.669	83.075	83.986	85.293	86.608	3.17%	no
11	3.1263	3.1412	3.1561	3.1220	3.1393	3.1567	-0.06%	yes	38.750	38.784	38.818	38.518	38.916	39.314	0.34%	yes	88.209	88.644	89.078	87.122	88.528	89.943	-0.13%	yes
12	3.1202	3.1351	3.1500	3.1170	3.1342	3.1516	-0.03%	yes	38.835	38.868	38.900	38.605	38.990	39.375	0.31%	yes	86.244	86.670	87.095	85.776	87.137	88.506	0.54%	yes
13	3.1205	3.1354	3.1503	3.1170	3.1344	3.1519	-0.03%	yes	38.658	38.692	38.725	38.404	38.793	39.182	0.26%	yes	86.329	86.755	87.180	85.505	86.884	88.272	0.15%	yes
14	3.1201	3.1350	3.1499	3.1225	3.1396	3.1567	0.15%	yes	38.721	38.755	38.789	38.553	38.925	39.298	0.44%	yes	78.369	78.758	79.148	80.030	81.290	82.557	3.21%	no
15	3.1783	3.1934	3.2085	3.1859	3.2033	3.2209	0.31%	yes	38.778	38.812	38.847	38.638	39.007	39.376	0.50%	yes	84.476	84.895	85.313	86.412	87.726	89.047	3.34%	no
16	3.1494	3.1644	3.1794	3.1523	3.1696	3.1870	0.16%	yes	39.012	39.047	39.082	38.871	39.224	39.578	0.45%	yes	83.265	83.677	84.088	85.204	86.465	87.735	3.33%	no
17	3.1748	3.1901	3.2054	3.1728	3.1900	3.2073	0.00%	yes	38.856	38.889	38.922	38.724	39.084	39.445	0.50%	yes	90.251	90.693	91.135	90.173	91.519	92.873	0.91%	yes
18	3.1439	3.1589	3.1739	3.1415	3.1588	3.1763	0.00%	yes	38.833	38.869	38.905	38.764	39.126	39.488	0.66%	yes	87.158	87.588	88.017	87.157	88.462	89.774	1.00%	yes

Poly 4B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.0868	1.0928	1.0988	1.0902	1.0928	1.0955	0.00%	yes	35.930	35.968	36.005	35.690	35.965	36.241	-0.01%	yes	27.715	27.877	28.039	27.439	27.758	28.078	-0.43%	yes
2	1.1046	1.1106	1.1166	1.1080	1.1106	1.1133	0.00%	yes	36.164	36.202	36.240	35.909	36.199	36.490	-0.01%	yes	27.918	28.082	28.246	27.618	27.934	28.251	-0.53%	yes
3	1.1322	1.1384	1.1446	1.1359	1.1385	1.1411	0.01%	yes	36.071	36.108	36.144	35.829	36.104	36.379	-0.01%	yes	28.652	28.817	28.982	28.368	28.692	29.017	-0.44%	yes
4	1.0854	1.0914	1.0974	1.0889	1.0915	1.0941	0.01%	yes	35.936	35.975	36.013	35.697	35.973	36.249	-0.01%	yes	27.363	27.523	27.684	27.092	27.406	27.720	-0.43%	yes
5	1.1110	1.1171	1.1232	1.1145	1.1171	1.1197	0.00%	yes	36.052	36.086	36.119	35.823	36.083	36.343	-0.01%	yes	28.302	28.465	28.629	28.031	28.343	28.657	-0.43%	yes
6	1.0848	1.0908	1.0968	1.0883	1.0909	1.0935	0.01%	yes	36.013	36.051	36.088	35.789	36.049	36.309	-0.01%	yes	27.353	27.514	27.674	27.089	27.389	27.691	-0.45%	yes
7	1.1236	1.1297	1.1358	1.1273	1.1300	1.1327	0.02%	yes	35.979	36.012	36.045	35.742	36.009	36.276	-0.01%	yes	27.881	28.044	28.206	27.663	27.971	28.280	-0.26%	yes
8	1.0894	1.0954	1.1014	1.0928	1.0954	1.0980	0.00%	yes	35.969	36.002	36.036	35.729	36.001	36.274	0.00%	yes	27.803	27.965	28.128	27.530	27.846	28.163	-0.43%	yes
9	1.1005	1.1065	1.1125	1.1040	1.1066	1.1092	0.01%	yes	35.938	35.982	36.025	35.728	35.979	36.231	-0.01%	yes	27.776	27.937	28.099	27.508	27.806	28.106	-0.47%	yes

Poly 4B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	2.9168	2.9310	2.9452	2.9231	2.9315	2.9399	0.02%	yes	36.502	36.533	36.564	36.018	36.391	36.764	-0.39%	yes	73.701	74.075	74.448	72.712	73.860	75.014	-0.29%	yes
2	2.9629	2.9773	2.9917	2.9687	2.9771	2.9855	-0.01%	yes	36.662	36.694	36.725	36.182	36.577	36.972	-0.32%	yes	74.607	74.984	75.362	73.438	74.625	75.819	-0.48%	yes
3	3.0165	3.0318	3.0471	3.0228	3.0311	3.0395	-0.02%	yes	36.663	36.694	36.726	36.145	36.517	36.889	-0.48%	yes	76.095	76.477	76.859	74.809	75.966	77.130	-0.67%	yes
4	2.9270	2.9412	2.9554	2.9335	2.9419	2.9503	0.02%	yes	36.544	36.576	36.607	36.053	36.426	36.799	-0.41%	yes	73.651	74.024	74.396	72.785	73.932	75.086	-0.12%	yes
5	2.9694	2.9838	2.9982	2.9753	2.9837	2.9921	0.00%	yes	36.703	36.735	36.766	36.244	36.593	36.944	-0.38%	yes	74.819	75.195	75.572	73.921	75.023	76.132	-0.23%	yes
6	2.9092	2.9234	2.9376	2.9144	2.9228	2.9311	-0.02%	yes	36.776	36.808	36.840	36.235	36.584	36.934	-0.61%	yes	73.565	73.938	74.311	72.392	73.468	74.550	-0.64%	yes
7	2.9459	2.9602	2.9745	2.9512	2.9596	2.9680	-0.02%	yes	36.674	36.705	36.736	36.132	36.493	36.854	-0.58%	yes	74.394	74.769	75.145	73.138	74.260	75.388	-0.68%	yes
8	2.9223	2.9365	2.9507	2.9285	2.9369	2.9453	0.01%	yes	36.658	36.690	36.721	36.103	36.470	36.838	-0.60%	yes	74.747	75.125	75.502	73.602	74.753	75.911	-0.49%	yes
9	2.9384	2.9527	2.9670	2.9433	2.9516	2.9600	-0.04%	yes	36.748	36.779	36.811	36.202	36.538	36.875	-0.66%	yes	74.438	74.815	75.191	72.977	74.022	75.073	-1.06%	yes

Poly 5B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.5989	1.6066	1.6143	1.5918	1.6066	1.6216	0.00%	yes	55.330	55.388	55.446	54.948	55.400	55.851	0.02%	yes	62.943	63.260	63.578	62.309	63.270	64.241	0.01%	yes
2	1.6187	1.6265	1.6343	1.6115	1.6264	1.6416	-0.01%	yes	55.421	55.474	55.526	55.035	55.482	55.930	0.02%	yes	64.177	64.499	64.821	63.481	64.458	65.447	-0.06%	yes
3	1.5856	1.5932	1.6008	1.5786	1.5932	1.6081	0.00%	yes	54.998	55.060	55.123	54.618	55.078	55.537	0.03%	yes	60.649	60.958	61.268	60.229	61.145	62.071	0.31%	yes
4	1.5982	1.6059	1.6136	1.5913	1.6062	1.6213	0.02%	yes	53.949	54.000	54.050	53.555	54.015	54.476	0.03%	yes	58.183	58.482	58.782	57.882	58.741	59.609	0.44%	yes
5	1.6509	1.6588	1.6667	1.6436	1.6588	1.6742	0.00%	yes	54.953	55.007	55.062	54.562	55.014	55.466	0.01%	yes	64.367	64.688	65.010	63.667	64.650	65.645	-0.06%	yes
6	1.5990	1.6067	1.6144	1.5918	1.6067	1.6217	0.00%	yes	54.326	54.387	54.448	53.944	54.404	54.865	0.03%	yes	60.276	60.583	60.890	59.803	60.723	61.652	0.23%	yes
7	1.6198	1.6276	1.6354	1.6126	1.6276	1.6429	0.00%	yes	55.087	55.162	55.236	54.714	55.169	55.624	0.01%	yes	63.418	63.736	64.055	62.756	63.728	64.712	-0.01%	yes
8	1.5927	1.6004	1.6081	1.5861	1.6007	1.6157	0.02%	yes	55.056	55.172	55.288	54.729	55.193	55.656	0.04%	yes	59.227	59.532	59.838	59.042	59.903	60.773	0.62%	yes
9	0.9824	0.9881	0.9938	0.9799	0.9876	0.9953	-0.05%	yes	57.306	57.378	57.449	56.976	57.403	57.830	0.04%	yes	39.085	39.333	39.581	38.877	39.392	39.912	0.15%	yes
10	0.9633	0.9689	0.9745	0.9611	0.9686	0.9762	-0.03%	yes	57.006	57.087	57.169	56.711	57.139	57.566	0.09%	yes	35.834	36.075	36.315	36.137	36.578	37.023	1.40%	yes
11	0.9951	1.0008	1.0065	0.9931	1.0009	1.0087	0.01%	yes	57.048	57.122	57.197	56.731	57.160	57.589	0.07%	yes	37.325	37.571	37.816	37.583	38.034	38.488	1.23%	yes
12	0.9843	0.9900	0.9957	0.9822	0.9899	0.9977	-0.01%	yes	56.973	57.041	57.109	56.657	57.083	57.509	0.07%	yes	36.332	36.574	36.815	36.619	37.056	37.497	1.32%	yes
13	0.9974	1.0031	1.0088	0.9949	1.0027	1.0106	-0.04%	yes	56.953	57.026	57.099	56.654	57.062	57.471	0.06%	yes	36.558	36.799	37.040	36.675	37.111	37.550	0.85%	yes
14	0.9863	0.9920	0.9977	0.9840	0.9917	0.9995	-0.03%	yes	57.856	57.929	58.002	57.540	57.957	58.375	0.05%	yes	38.815	39.065	39.315	38.790	39.275	39.764	0.54%	yes
15	0.9986	1.0043	1.0100	0.9961	1.0039	1.0119	-0.04%	yes	56.880	56.954	57.029	56.568	56.987	57.406	0.06%	yes	36.603	36.844	37.085	36.694	37.138	37.585	0.80%	yes
16	0.9902	0.9959	1.0016	0.9876	0.9954	1.0032	-0.05%	yes	57.010	57.075	57.139	56.685	57.098	57.511	0.04%	yes	39.065	39.312	39.558	38.791	39.303	39.819	-0.02%	yes
17	1.4978	1.5051	1.5124	1.4937	1.5049	1.5163	-0.01%	yes	29.993	30.016	30.039	29.693	30.017	30.342	0.01%	yes	32.597	32.763	32.930	31.819	32.402	32.991	-1.10%	yes
18	1.5374	1.5449	1.5524	1.5334	1.5448	1.5563	-0.01%	yes	57.965	58.003	58.041	57.585	58.023	58.460	0.03%	yes	63.293	63.618	63.943	62.939	63.743	64.554	0.20%	yes
19	1.5734	1.5810	1.5886	1.5703	1.5819	1.5937	0.06%	yes	57.361	57.398	57.436	56.976	57.427	57.878	0.05%	yes	57.478	57.785	58.091	57.762	58.414	59.070	1.09%	yes
20	1.5557	1.5632	1.5707	1.5523	1.5638	1.5755	0.04%	yes	57.206	57.244	57.282	56.824	57.274	57.723	0.05%	yes	58.101	58.409	58.716	58.305	58.991	59.680	1.00%	yes
21	1.4467	1.4538	1.4609	1.4435	1.4533	1.4632	-0.03%	yes	57.292	57.343	57.394	56.924	57.364	57.804	0.04%	yes	57.699	58.003	58.308	57.335	58.034	58.737	0.05%	yes
22	1.4646	1.4718	1.4790	1.4616	1.4714	1.4813	-0.03%	yes	57.990	58.054	58.117	57.639	58.076	58.513	0.04%	yes	58.639	58.948	59.257	58.378	59.066	59.757	0.20%	yes
23	1.4577	1.4649	1.4721	1.4552	1.4649	1.4747	0.00%	yes	58.077	58.136	58.196	57.728	58.169	58.610	0.06%	yes	57.855	58.162	58.469	57.877	58.542	59.209	0.65%	yes
24	1.4556	1.4628	1.4700	1.4527	1.4625	1.4723	-0.02%	yes	57.989	58.040	58.092	57.623	58.063	58.502	0.04%	yes	59.453	59.764	60.075	59.013	59.735	60.462	-0.05%	yes
25	1.5478	1.5553	1.5628	1.5452	1.5551	1.5652	-0.01%	yes	58.252	58.313	58.374	57.949	58.343	58.737	0.05%	yes	62.610	62.934	63.257	62.554	63.229	63.907	0.47%	yes
26	1.5309	1.5383	1.5457	1.5278	1.5378	1.5479	-0.03%	yes	57.517	57.588	57.659	57.216	57.616	58.017	0.05%	yes	59.895	60.206	60.518	59.706	60.371	61.040	0.27%	yes
27	1.5086	1.5160	1.5234	1.5055	1.5155	1.5255	-0.04%	yes	57.433	57.504	57.574	57.128	57.533	57.937	0.05%	yes	58.586	58.893	59.200	58.444	59.097	59.753	0.35%	yes
28	1.4826	1.4899	1.4972	1.4810	1.4908	1.5006	0.06%	yes	57.223	57.307	57.392	56.944	57.345	57.746	0.07%	yes	56.232	56.533	56.834	56.672	57.260	57.852	1.29%	yes
29	1.4967	1.5040	1.5113	1.4936	1.5035	1.5135	-0.03%	yes	57.390	57.428	57.467	57.062	57.454	57.846	0.04%	yes	58.970	59.279	59.587	58.716	59.370	60.028	0.15%	yes
30	1.4956	1.5029	1.5102	1.4932	1.5029	1.5128	0.00%	yes	57.548	57.585	57.623	57.223	57.621	58.019	0.06%	yes	59.266	59.577	59.888	59.389	60.035	60.684	0.77%	yes
31	1.4512	1.4584	1.4656	1.4488	1.4585	1.4683	0.01%	yes	57.257	57.296	57.335	56.920	57.327	57.734	0.05%	yes	57.919	58.225	58.531	57.938	58.592	59.251	0.63%	yes
32	1.4706	1.4778	1.4850	1.4676	1.4773	1.4871	-0.03%	yes	57.167	57.204	57.241	56.840	57.244	57.649	0.07%	yes	56.706	57.007	57.308	56.754	57.385	58.021	0.66%	yes

Hybrid 1A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4039	0.4488	0.4937	0.4480	0.4488	0.4496	-0.01%	yes	44.112	44.165	44.217	43.881	44.164	44.447	0.00%	yes	15.341	15.501	15.661	15.284	15.423	15.562	-0.50%	yes
2	0.4007	0.4452	0.4897	0.4444	0.4452	0.4460	0.01%	yes	59.981	60.027	60.073	59.716	60.026	60.337	0.00%	yes	21.061	21.280	21.498	21.050	21.209	21.369	-0.33%	yes
3	0.4019	0.4466	0.4913	0.4458	0.4466	0.4474	-0.01%	yes	59.521	59.566	59.611	59.261	59.565	59.870	0.00%	yes	20.973	21.190	21.406	20.957	21.115	21.273	-0.35%	yes
4	0.4034	0.4482	0.4930	0.4475	0.4482	0.4490	0.01%	yes	59.619	59.664	59.709	59.352	59.663	59.974	0.00%	yes	21.108	21.326	21.545	21.092	21.252	21.412	-0.35%	yes
5	0.4027	0.4474	0.4921	0.4466	0.4474	0.4482	-0.01%	yes	59.699	59.743	59.788	59.439	59.742	60.046	0.00%	yes	20.973	21.191	21.409	20.956	21.111	21.267	-0.38%	yes
6	0.3980	0.4422	0.4864	0.4414	0.4422	0.4430	-0.01%	yes	59.470	59.514	59.558	59.213	59.513	59.814	0.00%	yes	20.903	21.120	21.337	20.881	21.037	21.193	-0.39%	yes
7	0.4042	0.4491	0.4940	0.4483	0.4491	0.4498	-0.01%	yes	59.751	59.799	59.848	59.478	59.799	60.119	0.00%	yes	21.404	21.623	21.843	21.377	21.542	21.708	-0.37%	yes
8	0.3977	0.4419	0.4861	0.4411	0.4419	0.4427	0.01%	yes	60.952	61.011	61.069	60.693	61.010	61.327	0.00%	yes	21.207	21.428	21.649	21.195	21.357	21.520	-0.33%	yes
9	0.4036	0.4484	0.4932	0.4476	0.4484	0.4492	0.00%	yes	59.742	59.795	59.847	59.479	59.794	60.110	0.00%	yes	21.378	21.597	21.816	21.356	21.521	21.687	-0.35%	yes
10	0.4095	0.4550	0.5005	0.4542	0.4550	0.4558	0.00%	yes	60.495	60.550	60.604	60.248	60.548	60.849	0.00%	yes	20.990	21.206	21.423	20.987	21.142	21.296	-0.31%	yes
11	0.4143	0.4603	0.5063	0.4595	0.4603	0.4611	0.00%	yes	60.784	60.839	60.893	60.530	60.837	61.144	0.00%	yes	21.567	21.787	22.007	21.563	21.722	21.882	-0.30%	yes
12	0.4135	0.4594	0.5053	0.4586	0.4594	0.4602	0.01%	yes	60.449	60.509	60.570	60.205	60.509	60.812	0.00%	yes	22.163	22.385	22.607	22.158	22.324	22.490	-0.27%	yes

Hybrid 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.6056	0.6103	0.6150	0.6074	0.6099	0.6124	-0.07%	yes	63.496	63.587	63.678	63.269	63.603	63.938	0.03%	yes	28.324	28.565	28.807	28.134	28.383	28.634	-0.64%	yes
2	0.6032	0.6079	0.6126	0.6050	0.6075	0.6100	-0.07%	yes	63.084	63.176	63.268	62.859	63.195	63.531	0.03%	yes	27.920	28.159	28.398	27.730	27.978	28.227	-0.64%	yes
3	0.6107	0.6154	0.6201	0.6125	0.6151	0.6177	-0.05%	yes	63.513	63.605	63.697	63.281	63.620	63.958	0.02%	yes	28.693	28.936	29.179	28.558	28.811	29.065	-0.43%	yes
4	0.5964	0.6010	0.6056	0.5981	0.6006	0.6031	-0.07%	yes	63.407	63.496	63.584	63.174	63.516	63.859	0.03%	yes	28.112	28.353	28.595	27.931	28.184	28.438	-0.60%	yes
5	0.6068	0.6115	0.6162	0.6085	0.6110	0.6136	-0.08%	yes	62.581	62.668	62.755	62.349	62.686	63.023	0.03%	yes	27.793	28.031	28.268	27.636	27.883	28.131	-0.53%	yes
6	0.5964	0.6010	0.6056	0.5981	0.6006	0.6031	-0.06%	yes	64.216	64.332	64.449	63.988	64.352	64.715	0.03%	yes	28.480	28.724	28.968	28.299	28.563	28.828	-0.56%	yes
7	0.5943	0.5989	0.6035	0.5961	0.5986	0.6010	-0.06%	yes	63.957	64.078	64.200	63.746	64.100	64.454	0.03%	yes	28.366	28.609	28.852	28.160	28.421	28.683	-0.66%	yes
8	0.6051	0.6098	0.6145	0.6069	0.6093	0.6118	-0.08%	yes	63.186	63.302	63.418	62.987	63.331	63.674	0.05%	yes	28.119	28.359	28.599	27.963	28.215	28.469	-0.51%	yes
9	0.6095	0.6142	0.6189	0.6112	0.6137	0.6163	-0.08%	yes	64.482	64.599	64.715	64.285	64.618	64.950	0.03%	yes	28.709	28.953	29.198	28.518	28.767	29.017	-0.64%	yes
10	0.6043	0.6090	0.6137	0.6062	0.6087	0.6112	-0.05%	yes	63.629	63.743	63.857	63.422	63.764	64.106	0.03%	yes	28.785	29.028	29.270	28.597	28.857	29.117	-0.59%	yes
11	0.6161	0.6208	0.6255	0.6179	0.6205	0.6230	-0.06%	yes	62.855	62.909	62.963	62.594	62.926	63.257	0.03%	yes	28.279	28.519	28.760	28.198	28.441	28.685	-0.27%	yes
12	0.6132	0.6179	0.6226	0.6152	0.6177	0.6202	-0.04%	yes	63.300	63.342	63.384	63.023	63.358	63.694	0.03%	yes	28.950	29.194	29.438	28.860	29.113	29.366	-0.28%	yes
13	0.6077	0.6124	0.6171	0.6095	0.6120	0.6145	-0.07%	yes	62.597	62.638	62.678	62.341	62.656	62.971	0.03%	yes	27.660	27.897	28.135	27.523	27.757	27.993	-0.50%	yes
14	0.6081	0.6128	0.6175	0.6099	0.6124	0.6150	-0.06%	yes	62.559	62.600	62.641	62.296	62.616	62.936	0.03%	yes	27.889	28.127	28.366	27.735	27.974	28.215	-0.55%	yes
15	0.6413	0.6464	0.6515	0.6433	0.6460	0.6487	-0.06%	yes	62.950	62.992	63.033	62.698	62.996	63.294	0.01%	yes	28.306	28.546	28.786	28.142	28.368	28.595	-0.62%	yes

Hybrid 1B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	1.1363	1.1426	1.1489	1.1405	1.1425	1.1446	0.00%	yes	56.728	56.787	56.846	56.404	56.787	57.170	0.00%	yes	48.138	48.411	48.683	47.869	48.320	48.771	-0.19%	yes
2	1.1114	1.1176	1.1238	1.1156	1.1176	1.1196	0.00%	yes	56.299	56.360	56.421	55.985	56.360	56.735	0.00%	yes	47.990	48.262	48.534	47.706	48.158	48.611	-0.22%	yes
3	1.1257	1.1318	1.1379	1.1298	1.1319	1.1339	0.01%	yes	55.505	55.565	55.626	55.193	55.565	55.938	0.00%	yes	47.136	47.402	47.669	46.857	47.306	47.757	-0.20%	yes
4	1.1364	1.1425	1.1486	1.1405	1.1426	1.1446	0.01%	yes	56.605	56.669	56.734	56.268	56.669	57.070	0.00%	yes	46.873	47.141	47.408	46.616	47.068	47.520	-0.16%	yes
5	1.0586	1.0645	1.0704	1.0625	1.0645	1.0664	0.00%	yes	58.580	58.634	58.688	58.315	58.634	58.953	0.00%	yes	45.799	46.067	46.336	45.580	45.945	46.309	-0.27%	yes
6	1.0862	1.0922	1.0982	1.0902	1.0922	1.0942	0.00%	yes	57.812	57.860	57.909	57.556	57.860	58.164	0.00%	yes	45.525	45.790	46.055	45.310	45.661	46.012	-0.28%	yes
7	1.1034	1.1102	1.1170	1.1082	1.1102	1.1122	0.00%	yes	58.217	58.255	58.293	57.943	58.255	58.567	0.00%	yes	47.384	47.658	47.932	47.171	47.532	47.894	-0.26%	yes
8	1.1006	1.1066	1.1126	1.1046	1.1066	1.1085	0.00%	yes	58.991	59.033	59.074	58.739	59.033	59.327	0.00%	yes	47.521	47.796	48.072	47.309	47.650	47.992	-0.31%	yes

Hybrid 1B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
5	1.8498	1.8605	1.8712	1.8600	1.8612	1.8624	0.04%	yes	58.076	58.129	58.181	58.083	58.085	58.087	-0.08%	yes	78.468	78.945	79.421	79.509	79.562	79.616	0.78%	no
6	1.8748	1.8855	1.8962	1.8852	1.8864	1.8876	0.05%	yes	57.449	57.501	57.552	57.384	57.386	57.388	-0.20%	no	77.431	77.900	78.368	78.472	78.525	78.578	0.80%	no
7	1.9000	1.9108	1.9216	1.9101	1.9114	1.9126	0.03%	yes	57.683	57.733	57.783	57.725	57.726	57.728	-0.01%	yes	80.116	80.598	81.079	80.942	80.996	81.050	0.49%	yes
8	1.8982	1.9090	1.9198	1.9079	1.9091	1.9103	0.01%	yes	58.525	58.580	58.634	58.637	58.639	58.640	0.10%	no	81.094	81.582	82.070	81.720	81.774	81.828	0.23%	yes

Hybrid 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.7052	0.7101	0.7150	0.7084	0.7101	0.7118	0.00%	yes	13.771	14.000	14.229	13.853	14.000	14.148	0.00%	yes	7.261	7.314	7.367	7.016	7.128	7.241	-2.54%	no
2	0.7080	0.7129	0.7178	0.7111	0.7129	0.7146	0.00%	yes	63.620	63.661	63.702	63.341	63.661	63.982	0.00%	yes	33.832	34.086	34.339	33.722	33.977	34.232	-0.32%	yes
3	0.7286	0.7336	0.7386	0.7318	0.7336	0.7353	0.00%	yes	46.291	46.325	46.358	46.053	46.325	46.596	0.00%	yes	24.481	24.664	24.847	24.322	24.528	24.735	-0.55%	yes
4	0.7201	0.7250	0.7299	0.7232	0.7250	0.7267	0.00%	yes	46.675	46.707	46.739	46.434	46.707	46.981	0.00%	yes	24.741	24.927	25.113	24.585	24.793	25.000	-0.54%	yes
5	0.7447	0.7498	0.7549	0.7481	0.7499	0.7517	0.01%	yes	45.565	45.603	45.641	45.347	45.603	45.859	0.00%	yes	24.296	24.475	24.654	24.127	24.328	24.530	-0.60%	yes
6	0.7167	0.7216	0.7265	0.7198	0.7216	0.7233	0.00%	yes	45.850	45.885	45.919	45.627	45.885	46.143	0.00%	yes	23.810	23.989	24.169	23.646	23.843	24.041	-0.61%	yes
7	0.7421	0.7471	0.7521	0.7453	0.7471	0.7489	0.00%	yes	61.247	61.338	61.428	61.021	61.338	61.654	0.00%	yes	33.795	34.040	34.285	33.658	33.922	34.186	-0.35%	yes
8	0.7278	0.7328	0.7378	0.7310	0.7328	0.7346	0.00%	yes	45.858	45.912	45.965	45.638	45.912	46.185	0.00%	yes	24.748	24.931	25.113	24.579	24.795	25.013	-0.54%	yes

Thin 1A -- low irradiance

Module	Measured Isc (A) Low Bound	Measured Isc (A) Value	Measured Isc (A) High Bound	Modeled Isc (A) Low Bound	Modeled Isc (A) Value	Modeled Isc (A) High Bound	% Diff (Mod vs. Meas)	Isc in Agreement?	Measured Voc (V) Low Bound	Measured Voc (V) Value	Measured Voc (V) High Bound	Modeled Voc (V) Low Bound	Modeled Voc (V) Value	Modeled Voc (V) High Bound	% Diff (Mod vs. Meas)	Voc in Agreement?	Measured Pmax (W) Low Bound	Measured Pmax (W) Value	Measured Pmax (W) High Bound	Modeled Pmax (W) Low Bound	Modeled Pmax (W) Value	Modeled Pmax (W) High Bound	% Diff (Mod vs. Meas)	Pmax in Agreement?
1	0.6128	0.6176	0.6224	0.6145	0.6175	0.6205	-0.01%	yes	44.242	44.444	44.646	44.153	44.448	44.742	0.01%	yes	18.316	18.476	18.636	18.236	18.437	18.639	-0.21%	yes
2	0.6092	0.6139	0.6186	0.6108	0.6138	0.6168	-0.02%	yes	44.238	44.272	44.305	43.992	44.275	44.559	0.01%	yes	17.954	18.112	18.271	17.879	18.071	18.264	-0.23%	yes
3	0.6023	0.6070	0.6117	0.6038	0.6068	0.6098	-0.03%	yes	44.187	44.337	44.487	44.058	44.343	44.629	0.01%	yes	17.775	17.933	18.092	17.695	17.886	18.079	-0.26%	yes
4	0.5936	0.5982	0.6028	0.5948	0.5977	0.6007	-0.08%	yes	44.072	44.132	44.192	43.873	44.141	44.409	0.02%	yes	16.839	16.994	17.149	16.758	16.932	17.107	-0.37%	yes
5	0.5938	0.5984	0.6030	0.5947	0.5977	0.6007	-0.12%	yes	43.854	43.887	43.920	43.645	43.896	44.147	0.02%	yes	15.408	15.557	15.707	15.356	15.505	15.655	-0.33%	yes
6	0.6099	0.6146	0.6193	0.6115	0.6145	0.6175	-0.02%	yes	44.178	44.310	44.442	44.038	44.313	44.589	0.01%	yes	17.557	17.714	17.872	17.491	17.674	17.858	-0.23%	yes
7	0.6102	0.6149	0.6196	0.6117	0.6148	0.6178	-0.02%	yes	44.206	44.355	44.504	44.080	44.358	44.636	0.01%	yes	17.779	17.937	18.095	17.708	17.895	18.083	-0.23%	yes
8	0.6032	0.6079	0.6126	0.6048	0.6077	0.6108	-0.03%	yes	44.247	44.278	44.310	44.013	44.283	44.553	0.01%	yes	17.544	17.702	17.859	17.474	17.656	17.838	-0.26%	yes
9	0.5966	0.6012	0.6058	0.5979	0.6009	0.6039	-0.05%	yes	43.993	44.054	44.116	43.806	44.060	44.314	0.01%	yes	16.583	16.736	16.889	16.503	16.672	16.841	-0.39%	yes
10	0.5869	0.5915	0.5961	0.5882	0.5911	0.5941	-0.06%	yes	44.101	44.253	44.405	44.006	44.262	44.518	0.02%	yes	17.507	17.664	17.821	17.379	17.560	17.742	-0.59%	yes
11	0.6559	0.6607	0.6655	0.6580	0.6604	0.6628	-0.04%	yes	43.933	43.969	44.004	43.676	43.976	44.275	0.02%	yes	18.959	19.118	19.277	18.878	19.064	19.252	-0.28%	yes
12	0.6648	0.6697	0.6746	0.6671	0.6694	0.6718	-0.04%	yes	44.068	44.111	44.154	43.834	44.117	44.400	0.01%	yes	19.170	19.330	19.489	19.100	19.281	19.461	-0.25%	yes
13	0.6535	0.6583	0.6631	0.6555	0.6579	0.6603	-0.06%	yes	44.003	44.037	44.071	43.765	44.045	44.326	0.02%	yes	18.766	18.924	19.083	18.683	18.860	19.037	-0.34%	yes
14	0.6530	0.6578	0.6626	0.6548	0.6571	0.6595	-0.10%	yes	43.782	43.818	43.854	43.563	43.828	44.093	0.02%	yes	17.675	17.829	17.983	17.603	17.760	17.918	-0.38%	yes
15	0.6552	0.6600	0.6648	0.6569	0.6593	0.6617	-0.11%	yes	43.560	43.596	43.631	43.350	43.606	43.862	0.02%	yes	16.885	17.037	17.188	16.850	16.991	17.132	-0.27%	yes
16	0.6517	0.6565	0.6613	0.6537	0.6560	0.6584	-0.07%	yes	43.951	43.985	44.019	43.719	43.995	44.272	0.02%	yes	18.845	19.004	19.162	18.742	18.919	19.097	-0.44%	yes
17	0.6476	0.6524	0.6572	0.6495	0.6518	0.6541	-0.09%	yes	44.005	44.039	44.073	43.770	44.051	44.333	0.03%	yes	19.008	19.167	19.325	18.853	19.038	19.223	-0.67%	yes
18	0.6490	0.6538	0.6586	0.6508	0.6531	0.6554	-0.11%	yes	43.901	43.938	43.974	43.671	43.950	44.230	0.03%	yes	18.358	18.514	18.671	18.242	18.416	18.590	-0.53%	yes
19	0.6521	0.6569	0.6617	0.6539	0.6562	0.6586	-0.10%	yes	43.748	43.784	43.820	43.525	43.796	44.068	0.03%	yes	18.593	18.749	18.905	18.452	18.627	18.803	-0.65%	yes
20	0.6553	0.6601	0.6649	0.6574	0.6597	0.6621	-0.06%	yes	44.087	44.120	44.153	43.857	44.130	44.403	0.02%	yes	19.490	19.651	19.811	19.369	19.552	19.736	-0.50%	yes

Thin 1A -- med irradiance

Module	Measured Isc (A) Low Bound	Measured Isc (A) Value	Measured Isc (A) High Bound	Modeled Isc (A) Low Bound	Modeled Isc (A) Value	Modeled Isc (A) High Bound	% Diff (Mod vs. Meas)	Isc in Agreement?	Measured Voc (V) Low Bound	Measured Voc (V) Value	Measured Voc (V) High Bound	Modeled Voc (V) Low Bound	Modeled Voc (V) Value	Modeled Voc (V) High Bound	% Diff (Mod vs. Meas)	Voc in Agreement?	Measured Pmax (W) Low Bound	Measured Pmax (W) Value	Measured Pmax (W) High Bound	Modeled Pmax (W) Low Bound	Modeled Pmax (W) Value	Modeled Pmax (W) High Bound	% Diff (Mod vs. Meas)	Pmax in Agreement?
1	1.4424	1.4519	1.4614	1.4351	1.4477	1.4604	-0.29%	yes	41.783	41.822	41.860	40.075	40.928	41.780	-2.14%	no	39.923	40.210	40.497	37.621	38.765	39.912	-3.59%	no
2	1.4421	1.4516	1.4611	1.4355	1.4481	1.4609	-0.24%	yes	41.681	41.723	41.765	40.142	40.958	41.775	-1.83%	yes	39.509	39.795	40.080	37.460	38.553	39.649	-3.12%	yes
3	1.4456	1.4551	1.4646	1.4398	1.4525	1.4653	-0.18%	yes	41.651	41.693	41.734	40.201	41.021	41.842	-1.61%	yes	39.407	39.692	39.977	37.606	38.707	39.811	-2.48%	yes
4	1.4462	1.4557	1.4652	1.4404	1.4531	1.4659	-0.18%	yes	41.700	41.743	41.785	40.399	41.160	41.923	-1.40%	yes	38.858	39.141	39.425	37.202	38.208	39.217	-2.38%	yes
5	1.4500	1.4595	1.4690	1.4425	1.4552	1.4680	-0.29%	yes	41.742	41.785	41.828	40.559	41.262	41.967	-1.25%	yes	37.759	38.040	38.321	36.046	36.929	37.814	-2.92%	yes
6	1.4360	1.4455	1.4550	1.4292	1.4418	1.4545	-0.26%	yes	42.099	42.181	42.263	40.367	41.154	41.943	-2.43%	no	39.375	39.661	39.946	37.276	38.319	39.366	-3.38%	no
7	1.4369	1.4464	1.4559	1.4300	1.4427	1.4554	-0.26%	yes	41.807	41.850	41.894	40.350	41.147	41.945	-1.68%	yes	39.440	39.726	40.013	37.426	38.490	39.557	-3.11%	yes
8	1.4379	1.4474	1.4569	1.4301	1.4428	1.4556	-0.32%	yes	41.858	41.898	41.938	40.464	41.233	42.005	-1.59%	yes	39.620	39.906	40.193	37.564	38.601	39.643	-3.27%	yes
9	1.4366	1.4461	1.4556	1.4301	1.4428	1.4557	-0.23%	yes	41.810	41.852	41.894	40.609	41.324	42.041	-1.26%	yes	38.784	39.068	39.352	37.127	38.085	39.048	-2.52%	yes
10	1.4376	1.4471	1.4566	1.4336	1.4463	1.4592	-0.06%	yes	42.013	42.055	42.097	40.772	41.491	42.213	-1.34%	yes	39.749	40.037	40.325	38.390	39.398	40.414	-1.59%	yes

Thin 2A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.2817	0.3130	0.3443	0.3113	0.3131	0.3149	0.03%	yes	86.011	86.089	86.166	85.624	86.083	86.541	-0.01%	yes	18.899	19.179	19.459	19.026	19.231	19.436	0.27%	yes
2	0.2817	0.3130	0.3443	0.3113	0.3131	0.3149	0.03%	yes	86.383	86.458	86.533	85.986	86.451	86.915	-0.01%	yes	18.946	19.228	19.509	19.081	19.287	19.493	0.31%	yes
3	0.2817	0.3130	0.3443	0.3113	0.3131	0.3149	0.02%	yes	85.099	85.172	85.245	84.729	85.168	85.607	-0.01%	yes	18.467	18.741	19.016	18.580	18.778	18.977	0.19%	yes
4	0.2818	0.3131	0.3444	0.3114	0.3132	0.3151	0.04%	yes	86.299	86.373	86.448	85.912	86.366	86.821	-0.01%	yes	18.948	19.229	19.511	19.086	19.289	19.494	0.31%	yes
5	0.2835	0.3150	0.3465	0.3133	0.3151	0.3169	0.03%	yes	84.624	84.969	85.313	84.492	84.960	85.429	-0.01%	yes	18.585	18.859	19.133	18.746	18.953	19.162	0.50%	yes
6	0.2844	0.3160	0.3476	0.3143	0.3162	0.3180	0.05%	yes	86.324	86.649	86.974	86.132	86.641	87.149	-0.01%	yes	19.005	19.286	19.566	19.168	19.387	19.607	0.53%	yes
7	0.2843	0.3159	0.3475	0.3142	0.3160	0.3178	0.03%	yes	85.595	85.925	86.255	85.389	85.916	86.442	-0.01%	yes	18.961	19.240	19.518	19.128	19.353	19.579	0.59%	yes
8	0.2847	0.3163	0.3479	0.3146	0.3164	0.3181	0.02%	yes	86.122	86.461	86.799	85.948	86.457	86.966	0.00%	yes	18.769	19.048	19.327	18.858	19.073	19.289	0.13%	yes
9	0.2180	0.2422	0.2664	0.2408	0.2422	0.2436	0.00%	yes	86.033	86.088	86.143	85.643	86.085	86.527	0.00%	yes	14.546	14.821	15.096	14.669	14.825	14.983	0.03%	yes
10	0.2169	0.2410	0.2651	0.2397	0.2411	0.2425	0.02%	yes	85.107	85.163	85.218	84.701	85.158	85.615	-0.01%	yes	14.319	14.593	14.868	14.462	14.618	14.775	0.17%	yes
11	0.2178	0.2420	0.2662	0.2407	0.2421	0.2435	0.04%	yes	85.319	85.375	85.430	84.902	85.370	85.839	0.00%	yes	14.804	15.080	15.356	14.953	15.118	15.284	0.25%	yes
12	0.2169	0.2410	0.2651	0.2397	0.2411	0.2425	0.02%	yes	82.994	83.048	83.102	82.581	83.042	83.502	-0.01%	yes	13.797	14.063	14.330	13.939	14.092	14.245	0.20%	yes
13	0.2214	0.2460	0.2706	0.2451	0.2460	0.2470	0.01%	yes	84.866	84.920	84.974	84.607	84.915	85.223	-0.01%	yes	14.614	14.887	15.159	14.804	14.913	15.022	0.18%	yes
14	0.2194	0.2438	0.2682	0.2430	0.2439	0.2449	0.05%	yes	83.902	83.965	84.028	83.653	83.959	84.264	-0.01%	yes	14.194	14.462	14.730	14.399	14.506	14.613	0.30%	yes
15	0.2189	0.2432	0.2675	0.2424	0.2433	0.2443	0.06%	yes	83.163	83.236	83.309	82.936	83.229	83.522	-0.01%	yes	14.019	14.286	14.553	14.224	14.327	14.430	0.29%	yes
16	0.2225	0.2472	0.2719	0.2463	0.2472	0.2482	0.01%	yes	85.845	85.913	85.981	85.574	85.908	86.242	-0.01%	yes	14.909	15.187	15.465	15.095	15.208	15.322	0.14%	yes
17	0.3340	0.3381	0.3422	0.3368	0.3381	0.3395	0.01%	yes	84.933	84.989	85.045	84.612	84.983	85.354	-0.01%	yes	19.706	19.984	20.263	19.851	20.010	20.170	0.13%	yes
18	0.3339	0.3380	0.3421	0.3368	0.3381	0.3395	0.04%	yes	84.266	84.322	84.379	83.945	84.315	84.684	-0.01%	yes	19.080	19.353	19.627	19.239	19.394	19.549	0.21%	yes
19	0.3352	0.3393	0.3434	0.3381	0.3394	0.3408	0.04%	yes	85.272	85.327	85.382	84.963	85.320	85.678	-0.01%	yes	19.850	20.130	20.409	20.006	20.162	20.319	0.16%	yes
20	0.3366	0.3408	0.3450	0.3398	0.3412	0.3425	0.11%	yes	83.005	83.061	83.116	82.703	83.046	83.390	-0.02%	yes	17.642	17.908	18.174	17.815	17.947	18.079	0.21%	yes
21	0.3329	0.3370	0.3411	0.3357	0.3371	0.3384	0.03%	yes	84.481	84.535	84.588	84.120	84.527	84.934	-0.01%	yes	19.124	19.400	19.675	19.273	19.436	19.599	0.19%	yes
22	0.3353	0.3395	0.3437	0.3383	0.3396	0.3410	0.04%	yes	84.956	85.009	85.062	84.619	85.004	85.388	-0.01%	yes	19.327	19.604	19.881	19.468	19.626	19.783	0.11%	yes
23	0.3346	0.3387	0.3428	0.3376	0.3389	0.3403	0.06%	yes	83.289	83.341	83.393	82.968	83.328	83.688	-0.02%	yes	17.516	17.787	18.057	17.649	17.778	17.906	-0.05%	yes
24	0.3322	0.3363	0.3404	0.3352	0.3365	0.3379	0.07%	yes	84.610	84.663	84.716	84.276	84.650	85.024	-0.01%	yes	18.330	18.606	18.881	18.489	18.632	18.775	0.14%	yes

Thin 2A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.5676	0.6307	0.6938	0.6288	0.6335	0.6382	0.44%	yes	84.044	84.718	85.391	83.324	84.083	84.841	-0.75%	yes	36.073	36.572	37.071	37.124	37.693	38.266	3.07%	no
2	0.6197	0.6274	0.6351	0.6250	0.6296	0.6343	0.36%	yes	84.601	84.955	85.309	83.626	84.396	85.165	-0.66%	yes	36.127	36.629	37.131	36.974	37.545	38.120	2.50%	yes
3	0.6192	0.6269	0.6346	0.6262	0.6308	0.6355	0.63%	yes	83.508	83.884	84.261	82.585	83.306	84.028	-0.69%	yes	34.828	35.317	35.807	36.194	36.735	37.280	4.01%	no
4	0.6177	0.6254	0.6331	0.6240	0.6287	0.6334	0.52%	yes	84.892	85.228	85.563	83.634	84.385	85.135	-0.99%	yes	35.804	36.307	36.809	36.892	37.452	38.014	3.15%	no
5	0.6175	0.6252	0.6329	0.6235	0.6282	0.6329	0.48%	yes	82.896	82.956	83.016	82.053	82.830	83.607	-0.15%	yes	34.820	35.308	35.796	35.983	36.555	37.131	3.53%	no
6	0.6198	0.6275	0.6352	0.6254	0.6300	0.6347	0.40%	yes	84.273	84.334	84.395	83.349	84.201	85.051	-0.16%	yes	35.670	36.168	36.665	36.648	37.260	37.876	3.02%	yes
7	0.6153	0.6230	0.6307	0.6211	0.6257	0.6304	0.44%	yes	83.345	83.403	83.461	82.414	83.300	84.185	-0.12%	yes	35.084	35.576	36.068	36.181	36.811	37.444	3.47%	no
8	0.6195	0.6272	0.6349	0.6251	0.6296	0.6342	0.38%	yes	84.687	84.753	84.818	83.140	83.994	84.845	-0.90%	yes	35.501	36.000	36.499	36.163	36.760	37.358	2.11%	yes
9	0.6221	0.6298	0.6375	0.6302	0.6348	0.6395	0.79%	yes	84.892	84.980	85.068	84.094	84.812	85.530	-0.20%	yes	35.568	36.068	36.569	37.608	38.152	38.699	5.78%	no
10	0.6165	0.6242	0.6319	0.6225	0.6271	0.6318	0.47%	yes	84.125	84.183	84.242	83.003	83.749	84.495	-0.52%	yes	35.566	36.065	36.564	36.793	37.344	37.899	3.55%	no
11	0.6150	0.6227	0.6304	0.6216	0.6263	0.6310	0.58%	yes	84.252	84.310	84.369	83.073	83.840	84.607	-0.56%	yes	35.823	36.323	36.823	37.349	37.927	38.509	4.42%	no
12	0.6128	0.6205	0.6282	0.6191	0.6237	0.6284	0.52%	yes	82.482	82.539	82.596	80.806	81.560	82.314	-1.19%	no	34.288	34.775	35.262	35.264	35.806	36.350	2.96%	no

Thin 3A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.5155	0.5200	0.5245	0.5199	0.5203	0.5206	0.05%	yes	106.226	106.309	106.392	105.897	106.295	106.694	-0.01%	yes	38.019	38.391	38.763	38.082	38.287	38.493	-0.27%	yes
2	0.4982	0.5026	0.5070	0.5023	0.5027	0.5031	0.02%	yes	104.936	105.016	105.095	104.617	105.006	105.396	-0.01%	yes	34.730	35.094	35.459	34.758	34.933	35.108	-0.46%	yes
3	0.5021	0.5065	0.5109	0.5062	0.5065	0.5069	0.01%	yes	103.930	104.003	104.076	103.583	103.997	104.412	-0.01%	yes	35.822	36.186	36.549	35.824	36.022	36.220	-0.45%	yes
4	0.5087	0.5132	0.5177	0.5130	0.5134	0.5137	0.03%	yes	104.345	104.418	104.491	104.007	104.409	104.812	-0.01%	yes	36.404	36.770	37.136	36.424	36.619	36.815	-0.41%	yes
5	0.6108	0.6155	0.6202	0.6155	0.6160	0.6166	0.08%	yes	106.986	107.080	107.173	106.684	107.056	107.428	-0.02%	yes	43.246	43.632	44.018	43.271	43.486	43.701	-0.33%	yes
6	0.6081	0.6128	0.6175	0.6126	0.6131	0.6136	0.05%	yes	106.851	106.937	107.023	106.502	106.917	107.333	-0.02%	yes	44.762	45.151	45.539	44.768	45.021	45.275	-0.29%	yes
7	0.6043	0.6090	0.6137	0.6088	0.6094	0.6099	0.06%	yes	106.691	106.780	106.869	106.333	106.757	107.181	-0.02%	yes	43.279	43.662	44.046	43.294	43.538	43.783	-0.28%	yes
8	0.6046	0.6093	0.6140	0.6090	0.6095	0.6100	0.03%	yes	107.367	107.453	107.539	106.994	107.434	107.875	-0.02%	yes	44.701	45.091	45.481	44.702	44.965	45.229	-0.28%	yes
9	0.5073	0.5118	0.5163	0.5116	0.5120	0.5123	0.03%	yes	105.564	105.640	105.716	105.191	105.625	106.059	-0.01%	yes	36.369	36.738	37.106	36.405	36.609	36.814	-0.35%	yes
10	0.5035	0.5079	0.5123	0.5076	0.5080	0.5084	0.02%	yes	105.287	105.363	105.439	104.921	105.351	105.783	-0.01%	yes	36.204	36.572	36.941	36.236	36.439	36.643	-0.36%	yes
11	0.4960	0.5004	0.5048	0.5001	0.5004	0.5008	0.01%	yes	104.950	105.025	105.101	104.568	105.020	105.472	0.00%	yes	37.200	37.570	37.939	37.205	37.433	37.662	-0.36%	yes
12	0.5146	0.5191	0.5236	0.5190	0.5194	0.5198	0.06%	yes	104.554	104.629	104.705	104.169	104.613	105.057	-0.02%	yes	36.478	36.845	37.212	36.534	36.741	36.949	-0.28%	yes
13	0.5982	0.6028	0.6074	0.6027	0.6032	0.6037	0.07%	yes	107.406	107.486	107.566	107.074	107.464	107.856	-0.02%	yes	42.617	43.000	43.383	42.658	42.883	43.109	-0.27%	yes
14	0.6003	0.6050	0.6097	0.6047	0.6052	0.6058	0.04%	yes	106.529	106.604	106.679	106.134	106.587	107.041	-0.02%	yes	44.102	44.488	44.874	44.087	44.354	44.622	-0.30%	yes
15	0.5880	0.5926	0.5972	0.5924	0.5930	0.5935	0.06%	yes	105.699	105.778	105.857	105.293	105.762	106.232	-0.02%	yes	42.030	42.408	42.785	42.047	42.309	42.572	-0.23%	yes
16	0.5915	0.5961	0.6007	0.5958	0.5963	0.5969	0.04%	yes	106.435	106.511	106.587	106.005	106.497	106.990	-0.01%	yes	43.536	43.921	44.306	43.511	43.793	44.077	-0.29%	yes
17	0.4972	0.5016	0.5060	0.5014	0.5018	0.5021	0.03%	yes	106.143	106.277	106.412	105.808	106.265	106.723	-0.01%	yes	35.572	35.942	36.312	35.608	35.812	36.015	-0.36%	yes
18	0.5023	0.5067	0.5111	0.5064	0.5068	0.5072	0.02%	yes	105.172	105.299	105.426	104.839	105.285	105.731	-0.01%	yes	36.478	36.847	37.215	36.523	36.736	36.948	-0.30%	yes
19	0.5099	0.5144	0.5189	0.5143	0.5146	0.5150	0.04%	yes	105.440	105.562	105.684	105.088	105.545	106.003	-0.02%	yes	36.958	37.326	37.694	37.029	37.250	37.472	-0.20%	yes
20	0.5153	0.5198	0.5243	0.5196	0.5200	0.5204	0.03%	yes	104.258	104.377	104.495	103.901	104.360	104.819	-0.02%	yes	36.501	36.866	37.232	36.543	36.758	36.974	-0.29%	yes
21	0.5928	0.5977	0.6026	0.5975	0.5981	0.5986	0.06%	yes	105.085	105.185	105.284	104.749	105.163	105.579	-0.02%	yes	40.800	41.171	41.541	40.819	41.048	41.278	-0.30%	yes
22	0.5837	0.5883	0.5929	0.5879	0.5884	0.5890	0.02%	yes	105.500	105.592	105.683	105.107	105.579	106.051	-0.01%	yes	42.089	42.469	42.848	42.064	42.327	42.591	-0.33%	yes
23	0.5812	0.5858	0.5904	0.5855	0.5860	0.5865	0.04%	yes	106.425	106.516	106.607	106.003	106.503	107.005	-0.01%	yes	41.684	42.065	42.446	41.675	41.942	42.209	-0.29%	yes
24	0.5763	0.5809	0.5855	0.5806	0.5811	0.5816	0.03%	yes	105.608	105.697	105.785	105.168	105.685	106.202	-0.01%	yes	41.019	41.396	41.773	40.998	41.270	41.542	-0.30%	yes

Thin 3A -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
5	1.0600	1.0685	1.0770	1.0691	1.0695	1.0700	0.10%	yes	108.535	108.620	108.705	108.307	108.309	108.311	-0.29%	no	78.969	79.686	80.404	79.616	79.654	79.692	-0.04%	yes
6	1.0615	1.0701	1.0787	1.0706	1.0711	1.0715	0.09%	yes	108.233	108.312	108.392	107.886	107.889	107.891	-0.39%	no	80.279	80.997	81.714	81.088	81.125	81.163	0.16%	yes
7	1.0565	1.0650	1.0735	1.0656	1.0661	1.0666	0.10%	yes	108.158	108.242	108.326	107.720	107.722	107.724	-0.48%	no	78.494	79.207	79.919	79.144	79.181	79.218	-0.03%	yes
8	1.0575	1.0660	1.0745	1.0665	1.0669	1.0674	0.09%	yes	108.706	108.792	108.879	108.307	108.309	108.311	-0.44%	no	80.285	81.005	81.725	81.090	81.127	81.165	0.15%	yes
13	1.0472	1.0557	1.0642	1.0564	1.0569	1.0573	0.11%	yes	108.933	109.011	109.090	108.606	108.608	108.610	-0.37%	no	77.983	78.698	79.413	78.735	78.773	78.810	0.09%	yes
14	1.0542	1.0627	1.0712	1.0633	1.0638	1.0642	0.10%	yes	107.707	107.784	107.861	107.405	107.407	107.409	-0.35%	no	79.191	79.903	80.615	80.134	80.171	80.208	0.33%	yes
15	1.0341	1.0426	1.0511	1.0431	1.0436	1.0441	0.10%	yes	106.927	107.002	107.077	106.529	106.531	106.533	-0.44%	no	76.484	77.187	77.890	77.232	77.269	77.305	0.11%	yes
16	1.0414	1.0499	1.0584	1.0503	1.0507	1.0512	0.08%	yes	107.534	107.611	107.688	107.143	107.145	107.147	-0.43%	no	78.325	79.035	79.745	79.077	79.114	79.150	0.10%	yes
21	1.0389	1.0474	1.0559	1.0479	1.0484	1.0489	0.10%	yes	106.450	106.535	106.620	106.141	106.143	106.145	-0.37%	no	74.774	75.467	76.160	75.260	75.296	75.332	-0.23%	yes
22	1.0275	1.0360	1.0445	1.0363	1.0368	1.0372	0.07%	yes	106.579	106.661	106.743	106.335	106.337	106.339	-0.30%	no	76.372	77.074	77.775	77.061	77.098	77.134	0.03%	yes
23	1.0247	1.0332	1.0417	1.0335	1.0340	1.0344	0.08%	yes	107.489	107.573	107.657	107.190	107.192	107.194	-0.35%	no	76.362	77.069	77.776	76.942	76.979	77.016	-0.12%	yes
24	1.0204	1.0289	1.0374	1.0295	1.0300	1.0304	0.10%	yes	106.579	106.661	106.743	106.287	106.289	106.291	-0.35%	no	74.959	75.658	76.356	75.720	75.756	75.792	0.13%	yes

Thin 4A -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4789	0.4833	0.4877	0.4829	0.4836	0.4843	0.06%	yes	97.313	97.384	97.455	97.140	97.360	97.590	-0.02%	yes	31.127	31.458	31.789	31.211	31.355	31.504	-0.33%	yes
2	0.4781	0.4825	0.4869	0.4820	0.4827	0.4833	0.03%	yes	97.378	97.449	97.519	97.216	97.428	97.651	-0.02%	yes	31.267	31.598	31.929	31.347	31.491	31.639	-0.34%	yes
3	0.4846	0.4890	0.4934	0.4886	0.4892	0.4899	0.05%	yes	96.562	96.632	96.703	96.379	96.612	96.855	-0.02%	yes	31.398	31.728	32.057	31.461	31.612	31.767	-0.37%	yes
4	0.4955	0.4999	0.5043	0.4995	0.5002	0.5008	0.05%	yes	99.054	99.124	99.193	98.814	99.096	99.388	-0.03%	yes	33.092	33.435	33.777	33.107	33.278	33.453	-0.47%	yes
5	0.4681	0.4725	0.4769	0.4720	0.4726	0.4733	0.03%	yes	98.212	98.735	99.258	98.163	98.721	99.285	-0.01%	yes	31.172	31.507	31.842	31.140	31.404	31.670	-0.33%	yes
6	0.4775	0.4819	0.4863	0.4815	0.4821	0.4828	0.04%	yes	98.485	99.034	99.583	98.490	99.017	99.550	-0.02%	yes	31.319	31.656	31.992	31.299	31.547	31.797	-0.34%	yes
7	0.4741	0.4785	0.4829	0.4779	0.4786	0.4792	0.02%	yes	98.852	99.439	100.026	98.916	99.423	99.937	-0.02%	yes	31.340	31.679	32.018	31.311	31.550	31.791	-0.41%	yes
8	0.4856	0.4900	0.4944	0.4895	0.4902	0.4908	0.04%	yes	99.499	99.999	100.499	99.419	99.974	100.534	-0.03%	yes	32.553	32.897	33.241	32.510	32.773	33.038	-0.38%	yes
9	0.4962	0.5006	0.5050	0.5002	0.5008	0.5015	0.04%	yes	97.229	97.298	97.367	96.902	97.270	97.646	-0.03%	yes	32.771	33.107	33.442	32.774	32.981	33.191	-0.38%	yes
10	0.5134	0.5179	0.5224	0.5179	0.5186	0.5193	0.13%	yes	96.547	96.614	96.681	96.287	96.567	96.857	-0.05%	yes	31.909	32.239	32.569	31.972	32.134	32.300	-0.32%	yes
11	0.4966	0.5010	0.5054	0.5006	0.5013	0.5019	0.05%	yes	98.494	98.564	98.633	98.241	98.531	98.831	-0.03%	yes	33.143	33.484	33.824	33.168	33.345	33.526	-0.41%	yes
12	0.4863	0.4907	0.4951	0.4903	0.4910	0.4917	0.06%	yes	98.092	98.160	98.229	97.930	98.134	98.348	-0.03%	yes	32.127	32.463	32.800	32.203	32.345	32.491	-0.36%	yes
13	0.3082	0.3123	0.3164	0.3126	0.3129	0.3132	0.19%	yes	95.657	96.119	96.582	95.700	96.038	96.381	-0.08%	yes	19.958	20.270	20.581	20.178	20.288	20.399	0.09%	yes
14	0.3118	0.3159	0.3200	0.3160	0.3164	0.3167	0.14%	yes	96.851	97.296	97.742	96.906	97.220	97.539	-0.08%	yes	20.899	21.218	21.537	21.095	21.205	21.316	-0.06%	yes
15	0.3018	0.3059	0.3100	0.3061	0.3064	0.3067	0.16%	yes	97.020	97.476	97.933	97.030	97.407	97.789	-0.07%	yes	20.325	20.645	20.964	20.499	20.620	20.742	-0.12%	yes
16	0.3062	0.3103	0.3144	0.3106	0.3109	0.3113	0.21%	yes	96.787	97.254	97.722	96.828	97.163	97.504	-0.09%	yes	19.869	20.185	20.501	20.059	20.165	20.273	-0.10%	yes
17	0.3121	0.3162	0.3203	0.3163	0.3166	0.3170	0.14%	yes	96.971	97.043	97.115	96.686	96.954	97.228	-0.09%	yes	20.751	21.070	21.389	20.889	20.986	21.084	-0.40%	yes
18	0.3129	0.3170	0.3211	0.3173	0.3176	0.3179	0.19%	yes	97.085	97.159	97.233	96.783	97.066	97.355	-0.10%	yes	20.744	21.064	21.384	20.845	20.944	21.044	-0.57%	yes
19	0.3142	0.3183	0.3224	0.3186	0.3189	0.3193	0.20%	yes	96.729	96.804	96.879	96.500	96.714	96.933	-0.09%	yes	20.807	21.125	21.442	20.989	21.074	21.161	-0.24%	yes
20	0.3154	0.3195	0.3236	0.3196	0.3199	0.3203	0.13%	yes	97.059	97.136	97.212	96.833	97.058	97.289	-0.08%	yes	21.386	21.707	22.029	21.543	21.634	21.726	-0.34%	yes
21	0.3051	0.3092	0.3133	0.3093	0.3097	0.3100	0.15%	yes	97.590	97.666	97.742	97.292	97.589	97.890	-0.08%	yes	20.469	20.790	21.111	20.607	20.708	20.811	-0.39%	yes
22	0.3092	0.3133	0.3174	0.3135	0.3138	0.3141	0.16%	yes	97.317	97.384	97.451	97.098	97.313	97.535	-0.07%	yes	20.803	21.117	21.431	21.194	21.284	21.376	0.79%	yes
23	0.3051	0.3092	0.3133	0.3094	0.3097	0.3101	0.17%	yes	98.255	98.324	98.393	97.914	98.239	98.569	-0.09%	yes	20.461	20.783	21.106	20.609	20.716	20.824	-0.33%	yes
24	0.3114	0.3155	0.3196	0.3157	0.3161	0.3164	0.17%	yes	97.792	97.864	97.936	97.513	97.781	98.054	-0.08%	yes	20.800	21.123	21.445	20.933	21.028	21.125	-0.45%	yes

Thin 2B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.4785	0.4829	0.4873	0.4821	0.4829	0.4837	0.00%	yes	35.654	35.692	35.729	35.599	35.692	35.785	0.00%	yes	6.472	6.563	6.653	6.481	6.508	6.535	-0.84%	yes
2	0.4608	0.4652	0.4696	0.4645	0.4652	0.4660	0.01%	yes	36.218	36.244	36.271	36.171	36.244	36.319	0.00%	yes	6.404	6.496	6.589	6.423	6.444	6.466	-0.80%	yes
3	0.3896	0.3938	0.3980	0.3933	0.3938	0.3943	0.00%	yes	30.194	30.221	30.248	29.994	30.221	30.450	0.00%	yes	4.401	4.474	4.547	4.358	4.399	4.441	-1.68%	yes
4	0.3980	0.4022	0.4064	0.4016	0.4022	0.4028	-0.01%	yes	34.356	34.381	34.407	34.217	34.381	34.547	0.00%	yes	5.084	5.169	5.255	5.080	5.110	5.140	-1.16%	yes
5	0.3618	0.3660	0.3702	0.3653	0.3659	0.3666	-0.02%	yes	27.807	27.844	27.882	27.629	27.844	28.061	0.00%	yes	3.616	3.682	3.748	3.581	3.619	3.657	-1.71%	yes
6	0.3568	0.3610	0.3652	0.3604	0.3610	0.3617	0.00%	yes	31.443	31.494	31.545	31.438	31.494	31.552	0.00%	yes	4.091	4.165	4.240	4.112	4.127	4.143	-0.91%	yes
7	0.3616	0.3658	0.3700	0.3651	0.3658	0.3665	-0.01%	yes	32.411	32.676	32.942	32.544	32.676	32.810	0.00%	yes	4.150	4.227	4.304	4.155	4.180	4.205	-1.12%	yes
8	0.3905	0.3947	0.3989	0.3939	0.3947	0.3955	0.00%	yes	35.563	35.837	36.111	35.744	35.837	35.932	0.00%	yes	5.093	5.181	5.269	5.113	5.137	5.160	-0.86%	yes
9	0.4102	0.4145	0.4188	0.4139	0.4145	0.4150	-0.01%	yes	36.085	36.111	36.138	35.974	36.111	36.251	0.00%	yes	5.695	5.785	5.875	5.690	5.720	5.749	-1.13%	yes
10	0.3525	0.3567	0.3609	0.3561	0.3566	0.3572	-0.02%	yes	30.303	30.333	30.363	30.100	30.333	30.568	0.00%	yes	3.392	3.460	3.528	3.381	3.412	3.444	-1.38%	yes
11	0.4493	0.4536	0.4579	0.4529	0.4536	0.4544	0.00%	yes	29.475	29.498	29.521	29.287	29.498	29.712	0.00%	yes	4.590	4.661	4.732	4.557	4.598	4.638	-1.36%	yes
12	0.4785	0.4830	0.4875	0.4822	0.4830	0.4837	-0.01%	yes	36.089	36.115	36.141	36.046	36.115	36.185	0.00%	yes	6.899	6.992	7.084	6.908	6.932	6.956	-0.86%	yes
13	0.3797	0.3839	0.3881	0.3834	0.3840	0.3845	0.01%	yes	27.788	27.811	27.833	27.545	27.811	28.079	0.00%	yes	3.516	3.580	3.644	3.479	3.519	3.559	-1.69%	yes
14	0.4020	0.4063	0.4106	0.4057	0.4063	0.4068	0.00%	yes	34.757	34.782	34.808	34.666	34.782	34.900	0.00%	yes	5.387	5.473	5.560	5.390	5.415	5.441	-1.07%	yes
15	0.3701	0.3743	0.3785	0.3736	0.3743	0.3750	0.00%	yes	32.231	32.312	32.394	32.175	32.312	32.452	0.00%	yes	4.459	4.536	4.613	4.448	4.478	4.508	-1.27%	yes
16	0.3583	0.3625	0.3667	0.3619	0.3625	0.3631	0.00%	yes	33.458	33.530	33.601	33.447	33.530	33.613	0.00%	yes	4.396	4.476	4.557	4.414	4.433	4.452	-0.97%	yes
17	0.5716	0.5762	0.5808	0.5754	0.5762	0.5771	0.01%	yes	35.179	35.206	35.232	35.095	35.206	35.318	0.00%	yes	7.855	7.946	8.037	7.839	7.875	7.912	-0.89%	yes
18	0.5503	0.5548	0.5593	0.5540	0.5548	0.5556	0.00%	yes	34.157	34.185	34.212	34.153	34.185	34.217	0.00%	yes	7.505	7.594	7.683	7.526	7.542	7.558	-0.69%	yes
19	0.5457	0.5502	0.5547	0.5491	0.5502	0.5514	0.00%	yes	37.190	37.320	37.451	37.315	37.320	37.327	0.00%	yes	7.278	7.368	7.458	7.314	7.333	7.352	-0.48%	yes
20	0.5551	0.5597	0.5643	0.5587	0.5597	0.5607	0.00%	yes	42.024	42.140	42.256	42.068	42.140	42.211	0.00%	yes	9.792	9.905	10.018	9.840	9.877	9.915	-0.28%	yes
21	0.4961	0.5005	0.5049	0.4996	0.5005	0.5014	0.00%	yes	34.335	34.538	34.741	34.505	34.538	34.572	0.00%	yes	6.091	6.174	6.256	6.117	6.133	6.150	-0.66%	yes
22	0.4960	0.5004	0.5048	0.4996	0.5004	0.5012	-0.01%	yes	38.386	38.421	38.456	38.267	38.421	38.577	0.00%	yes	7.082	7.178	7.273	7.062	7.103	7.143	-1.04%	yes
23	0.5226	0.5271	0.5316	0.5263	0.5271	0.5279	0.00%	yes	36.232	36.384	36.535	36.334	36.384	36.434	0.00%	yes	8.084	8.183	8.283	8.100	8.122	8.144	-0.75%	yes
24	0.5313	0.5358	0.5403	0.5350	0.5358	0.5366	0.00%	yes	30.305	30.457	30.608	30.186	30.457	30.729	0.00%	yes	6.618	6.703	6.787	6.540	6.597	6.654	-1.58%	yes
25	0.5442	0.5487	0.5532	0.5478	0.5487	0.5497	0.01%	yes	37.103	37.132	37.160	37.078	37.132	37.187	0.00%	yes	7.866	7.959	8.052	7.872	7.898	7.925	-0.76%	yes
26	0.5405	0.5450	0.5495	0.5441	0.5450	0.5460	0.01%	yes	37.890	37.919	37.949	37.912	37.919	37.928	0.00%	yes	7.969	8.066	8.163	8.006	8.020	8.035	-0.57%	yes
27	0.5509	0.5554	0.5599	0.5547	0.5555	0.5563	0.01%	yes	32.174	32.220	32.267	32.003	32.220	32.440	0.00%	yes	6.108	6.186	6.265	6.063	6.114	6.163	-1.18%	yes
28	0.5962	0.6008	0.6054	0.5999	0.6008	0.6018	0.00%	yes	40.198	40.262	40.326	40.127	40.262	40.396	0.00%	yes	9.751	9.860	9.968	9.804	9.853	9.901	-0.07%	yes
29	0.5306	0.5351	0.5396	0.5342	0.5351	0.5361	0.00%	yes	31.973	31.998	32.022	31.786	31.998	32.211	0.00%	yes	5.847	5.925	6.002	5.802	5.851	5.900	-1.24%	yes
30	0.5764	0.5810	0.5856	0.5800	0.5810	0.5820	-0.01%	yes	40.220	40.248	40.277	40.247	40.248	40.251	0.00%	yes	9.376	9.484	9.592	9.419	9.437	9.455	-0.50%	yes
31	0.5041	0.5086	0.5131	0.5078	0.5086	0.5093	0.00%	yes	29.016	29.039	29.062	28.818	29.039	29.262	0.00%	yes	5.028	5.096	5.165	4.968	5.019	5.069	-1.52%	yes
32	0.4937	0.4981	0.5025	0.4973	0.4981	0.4990	0.01%	yes	34.702	34.728	34.753	34.580	34.728	34.878	0.00%	yes	6.148	6.234	6.319	6.135	6.171	6.207	-1.00%	yes

Thin 2B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
17	0.9854	0.9938	1.0022	1.0133	1.0140	1.0147	2.03%	no	38.472	38.588	38.704	36.643	36.644	36.645	-5.04%	no	15.990	16.178	16.366	15.908	15.921	15.933	-1.59%	no
18	0.9623	0.9706	0.9789	0.9915	0.9921	0.9927	2.22%	no	36.556	36.587	36.618	35.079	35.080	35.081	-4.12%	no	14.767	14.942	15.117	15.000	15.010	15.020	0.46%	yes
25	0.9448	0.9531	0.9614	1.0047	1.0057	1.0066	5.52%	no	39.096	39.129	39.162	38.262	38.263	38.265	-2.21%	no	14.858	15.042	15.226	16.368	16.385	16.402	8.93%	no
26	0.9352	0.9435	0.9518	1.0405	1.0414	1.0424	10.38%	no	33.139	33.170	33.200	38.764	38.765	38.766	16.87%	no	11.882	12.033	12.183	17.278	17.295	17.313	43.74%	no
27	0.9477	0.9560	0.9643	0.9351	0.9357	0.9363	-2.13%	no	36.144	36.185	36.227	34.348	34.349	34.350	-5.07%	no	13.016	13.183	13.350	11.887	11.896	11.905	-9.77%	no
28	1.0192	1.0277	1.0362	1.0522	1.0529	1.0536	2.45%	no	42.504	42.540	42.577	40.118	40.119	40.119	-5.69%	no	19.210	19.425	19.640	19.258	19.274	19.290	-0.78%	yes

Thin 3B -- low irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
1	0.1438	0.1598	0.1758	0.1588	0.1598	0.1608	-0.01%	yes	85.205	85.267	85.328	84.567	85.267	85.967	0.00%	yes	7.402	7.656	7.910	7.538	7.634	7.729	-0.30%	yes
2	0.1422	0.1580	0.1738	0.1570	0.1580	0.1590	0.01%	yes	84.355	84.416	84.476	83.733	84.416	85.099	0.00%	yes	7.006	7.254	7.501	7.145	7.236	7.327	-0.24%	yes
3	0.1436	0.1596	0.1756	0.1587	0.1597	0.1606	0.04%	yes	83.980	84.043	84.105	83.364	84.043	84.723	0.00%	yes	6.859	7.102	7.345	6.996	7.084	7.173	-0.24%	yes
4	0.1373	0.1526	0.1679	0.1516	0.1526	0.1536	0.01%	yes	85.557	85.611	85.666	84.913	85.611	86.310	0.00%	yes	7.618	7.876	8.135	7.751	7.855	7.961	-0.27%	yes
5	0.1372	0.1524	0.1676	0.1515	0.1524	0.1534	0.02%	yes	84.551	84.605	84.660	83.931	84.605	85.280	0.00%	yes	7.236	7.488	7.740	7.366	7.463	7.561	-0.33%	yes
6	0.1400	0.1555	0.1711	0.1545	0.1555	0.1565	-0.01%	yes	83.210	83.271	83.332	82.575	83.271	83.968	0.00%	yes	7.274	7.523	7.773	7.402	7.500	7.599	-0.31%	yes
7	0.1398	0.1553	0.1708	0.1544	0.1553	0.1563	0.03%	yes	83.501	83.601	83.701	82.890	83.601	84.313	0.00%	yes	7.334	7.583	7.832	7.461	7.564	7.667	-0.26%	yes
8	0.1393	0.1548	0.1703	0.1538	0.1548	0.1557	-0.03%	yes	84.223	84.333	84.443	83.645	84.333	85.022	0.00%	yes	7.125	7.374	7.623	7.260	7.356	7.452	-0.25%	yes
9	0.1394	0.1549	0.1704	0.1540	0.1550	0.1559	0.05%	yes	83.364	83.479	83.595	82.838	83.479	84.121	0.00%	yes	6.927	7.170	7.413	7.056	7.148	7.240	-0.31%	yes
10	0.1661	0.1846	0.2031	0.1836	0.1847	0.1857	0.03%	yes	85.849	85.964	86.079	85.293	85.964	86.636	0.00%	yes	8.611	8.863	9.116	8.729	8.834	8.939	-0.33%	yes
11	0.1666	0.1851	0.2036	0.1841	0.1852	0.1862	0.04%	yes	85.353	85.450	85.546	84.776	85.450	86.123	0.00%	yes	9.095	9.350	9.605	9.205	9.321	9.437	-0.32%	yes
12	0.1643	0.1826	0.2009	0.1816	0.1826	0.1837	0.03%	yes	86.132	86.237	86.342	85.570	86.237	86.905	0.00%	yes	8.792	9.050	9.308	8.920	9.026	9.132	-0.27%	yes
13	0.1722	0.1913	0.2104	0.1902	0.1912	0.1923	-0.04%	yes	86.028	86.088	86.147	85.435	86.088	86.741	0.00%	yes	9.274	9.532	9.789	9.385	9.496	9.607	-0.38%	yes
14	0.1733	0.1925	0.2118	0.1915	0.1925	0.1936	0.02%	yes	85.319	85.379	85.439	84.751	85.379	86.008	0.00%	yes	8.780	9.029	9.278	8.891	8.995	9.100	-0.37%	yes
15	0.1685	0.1872	0.2059	0.1861	0.1871	0.1882	-0.05%	yes	85.393	85.452	85.512	84.813	85.452	86.093	0.00%	yes	8.757	9.010	9.262	8.874	8.979	9.084	-0.34%	yes
16	0.1645	0.1828	0.2011	0.1818	0.1828	0.1838	0.01%	yes	85.224	85.320	85.417	84.648	85.320	85.993	0.00%	yes	8.708	8.962	9.217	8.832	8.939	9.047	-0.26%	yes
17	0.1728	0.1920	0.2112	0.1910	0.1920	0.1931	0.02%	yes	84.715	84.809	84.903	84.147	84.809	85.472	0.00%	yes	8.749	8.998	9.247	8.869	8.974	9.079	-0.27%	yes
18	0.1716	0.1907	0.2098	0.1896	0.1907	0.1917	-0.01%	yes	85.787	85.885	85.983	85.246	85.885	86.525	0.00%	yes	8.987	9.241	9.495	9.103	9.208	9.314	-0.36%	yes
19	0.1762	0.1958	0.2154	0.1943	0.1958	0.1974	0.00%	yes	80.357	80.407	80.458	79.432	80.407	81.383	0.00%	yes	8.516	8.749	8.982	8.557	8.724	8.892	-0.28%	yes
20	0.1708	0.1898	0.2088	0.1883	0.1898	0.1914	0.01%	yes	77.857	77.919	77.982	77.029	77.919	78.812	0.00%	yes	7.572	7.793	8.015	7.627	7.769	7.911	-0.32%	yes
21	0.1783	0.1981	0.2179	0.1965	0.1981	0.1997	-0.01%	yes	81.508	81.568	81.628	80.623	81.568	82.515	0.00%	yes	9.083	9.324	9.565	9.126	9.298	9.472	-0.27%	yes
22	0.1759	0.1954	0.2149	0.1939	0.1955	0.1971	0.05%	yes	79.224	79.343	79.462	78.467	79.343	80.222	0.00%	yes	8.741	8.978	9.215	8.791	8.949	9.107	-0.33%	yes
23	0.1750	0.1944	0.2138	0.1928	0.1944	0.1961	0.01%	yes	77.423	77.517	77.610	76.632	77.517	78.403	0.00%	yes	8.555	8.784	9.014	8.585	8.747	8.911	-0.42%	yes
24	0.1766	0.1962	0.2158	0.1946	0.1962	0.1979	0.03%	yes	79.575	79.650	79.724	78.798	79.650	80.504	0.00%	yes	8.982	9.220	9.458	9.019	9.183	9.348	-0.41%	yes
25	0.1627	0.1808	0.1989	0.1794	0.1809	0.1823	0.04%	yes	80.478	80.544	80.609	79.621	80.544	81.468	0.00%	yes	7.539	7.770	8.002	7.605	7.743	7.881	-0.35%	yes
26	0.1584	0.1760	0.1936	0.1745	0.1760	0.1775	0.00%	yes	78.325	78.396	78.467	77.535	78.396	79.259	0.00%	yes	7.009	7.233	7.457	7.083	7.208	7.333	-0.35%	yes
27	0.1760	0.1955	0.2151	0.1939	0.1955	0.1972	0.02%	yes	78.638	78.696	78.753	77.789	78.696	79.604	0.00%	yes	8.745	8.980	9.216	8.787	8.953	9.119	-0.31%	yes

Thin 3B -- med irradiance

Module	Measured Isc (A)			Modeled Isc (A)			% Diff	Isc in	Measured Voc (V)			Modeled Voc (V)			% Diff	Voc in	Measured Pmax (W)			Modeled Pmax (W)			% Diff	Pmax in
	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?	Low Bound	Value	High Bound	Low Bound	Value	High Bound	(Mod vs. Meas)	Agreement?
10	0.3713	0.3795	0.3877	0.3823	0.3832	0.3841	0.97%	yes	85.677	85.791	85.906	85.454	85.466	85.478	-0.38%	no	18.255	18.790	19.325	19.596	19.648	19.699	4.56%	no
11	0.3658	0.3738	0.3818	0.3751	0.3760	0.3769	0.58%	yes	85.374	85.470	85.567	84.790	84.803	84.815	-0.78%	no	19.017	19.550	20.083	20.025	20.079	20.133	2.70%	yes
12	0.3612	0.3692	0.3772	0.3700	0.3709	0.3718	0.45%	yes	86.521	86.626	86.731	85.707	85.720	85.733	-1.05%	no	18.970	19.528	20.085	19.644	19.699	19.753	0.88%	yes
13	0.3762	0.3842	0.3922	0.3859	0.3868	0.3877	0.68%	yes	86.083	86.143	86.202	85.608	85.620	85.632	-0.61%	no	19.379	19.917	20.455	20.424	20.478	20.533	2.82%	yes
14	0.3774	0.3854	0.3934	0.3861	0.3870	0.3879	0.41%	yes	85.596	85.656	85.716	85.101	85.114	85.127	-0.63%	no	19.167	19.711	20.256	19.865	19.920	19.976	1.06%	yes
15	0.3680	0.3760	0.3840	0.3765	0.3774	0.3783	0.36%	yes	85.425	85.484	85.544	85.085	85.098	85.111	-0.45%	no	18.920	19.465	20.010	19.653	19.708	19.763	1.25%	yes
16	0.3640	0.3721	0.3802	0.3734	0.3743	0.3752	0.60%	yes	85.432	85.528	85.625	84.750	84.763	84.775	-0.90%	no	18.679	19.224	19.770	19.536	19.589	19.643	1.90%	yes
17	0.3802	0.3883	0.3964	0.3901	0.3910	0.3919	0.70%	yes	84.841	84.936	85.030	84.276	84.288	84.300	-0.76%	no	18.699	19.231	19.764	19.624	19.675	19.727	2.31%	yes
18	0.3759	0.3839	0.3919	0.3857	0.3866	0.3875	0.69%	yes	85.913	86.011	86.109	85.532	85.545	85.557	-0.54%	no	19.044	19.583	20.122	20.055	20.109	20.163	2.69%	yes

APPENDIX F

PV MODULE PERFORMANCE VARIATION AND LOSSES

F.1. Statistical Distributions

The following tables include information about the module-level statistical distributions of key I-V curve points short circuit current (I_{sc}), maximum power points current (I_{mp}), open circuit voltage (V_{oc}), maximum power point voltage (V_{mp}), and maximum power point (P_{mp}) for the 27 arrays with collected data. Each parameter of each array has its distribution checked for normality using a Lilliefors test. As many of the parameter distributions do not follow a normal Gaussian, the parameter variations are described using the average absolute deviation (AAD) and maximum absolute deviation (MAD) of the modules from their respective array level mean. Tables are divided into groupings of crystalline silicon and thin film arrays, and high and low light data. The number of runs required to collect the high and low light data is also noted, as arrays with a dataset collected under multiple runs will have more uncertainty in the parameter variation calculations.

Module Performance Mismatch -- Crystalline Silicon -- High Irradiance

Array	Runs	Isc			Imp			Voc			Vmp			Pmp		
		Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)
Mono 1A	1	no	1.1%	8.7%	no	1.2%	10.4%	yes	0.7%	2.3%	yes	1.0%	2.9%	no	2.0%	11.4%
Mono 2A	1	yes	0.6%	2.0%	yes	0.7%	2.6%	yes	0.6%	1.5%	yes	0.8%	1.7%	yes	1.4%	3.2%
Mono 1B	1	yes	0.2%	0.8%	yes	1.4%	3.0%	no	0.6%	2.0%	yes	1.6%	4.4%	yes	2.9%	7.2%
Mono 2B	2	yes	0.9%	2.0%	yes	3.9%	14.9%	no	30.9%	37.1%	no	32.7%	62.0%	no	32.7%	60.4%
Mono 3B	1	yes	0.9%	3.5%	yes	0.6%	2.1%	yes	0.5%	2.1%	yes	1.0%	2.5%	yes	1.2%	3.2%
Mono 4B	2	no	0.8%	3.3%	yes	0.5%	2.0%	yes	0.4%	1.4%	yes	0.7%	1.9%	yes	1.1%	3.7%
Mono 5B	1	yes	0.6%	1.8%	no	0.6%	1.5%	yes	0.6%	1.0%	yes	1.0%	2.1%	yes	1.3%	3.0%
Mono 6B	1	yes	1.1%	3.5%	yes	1.0%	3.4%	no	3.6%	31.8%	no	3.9%	32.5%	no	4.3%	33.1%
Poly 1A	3	no	2.4%	13.4%	no	1.6%	14.6%	yes	1.4%	3.8%	yes	1.6%	6.0%	no	2.8%	21.5%
Poly 2A	1	yes	1.5%	4.3%	yes	1.3%	2.9%	yes	0.9%	2.3%	yes	1.0%	2.7%	yes	2.0%	3.6%
Poly 3A	3	no	0.9%	2.7%	yes	0.9%	2.6%	no	4.9%	26.9%	no	5.4%	29.9%	no	5.5%	30.1%
Poly 1B	1	no	1.1%	3.8%	yes	2.4%	7.3%	no	4.8%	50.6%	no	6.2%	53.5%	no	7.9%	55.6%
Poly 2B	1	no	1.2%	5.4%	no	1.0%	3.9%	yes	0.4%	1.3%	yes	0.5%	1.7%	yes	1.1%	3.6%
Poly 3B	1	no	0.6%	2.0%	no	5.6%	16.5%	yes	0.5%	1.2%	yes	3.5%	7.8%	yes	8.8%	22.7%
Poly 4B	1	yes	0.8%	2.3%	yes	0.6%	1.6%	yes	0.2%	0.4%	yes	0.3%	0.6%	yes	0.7%	1.9%
Poly 5B	5	yes	0.7%	2.0%	yes	1.2%	2.6%	no	3.0%	47.9%	no	2.9%	46.1%	no	3.2%	44.9%
Hybrid 1A	1	yes	0.8%	1.8%	yes	0.9%	2.0%	no	4.2%	25.0%	no	4.3%	25.7%	no	4.4%	25.7%
Hybrid 2A	1	no	0.4%	1.8%	no	0.6%	1.8%	yes	0.6%	2.1%	yes	0.8%	1.9%	yes	1.1%	2.4%
Hybrid 1B	1	yes	0.6%	1.6%	yes	0.8%	1.4%	yes	0.7%	2.0%	yes	0.8%	2.0%	yes	1.4%	3.5%
Hybrid 2B	1	yes	0.6%	1.9%	no	1.4%	4.9%	no	18.0%	70.2%	no	18.5%	69.8%	no	18.6%	71.5%

Module Performance Mismatch -- Thin Film -- High Irradiance

Array	Runs	Isc			Imp			Voc			Vmp			Pmp		
		Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)
Thin 1A	2	no	1.4%	2.1%	yes	1.5%	4.4%	yes	0.7%	1.7%	yes	1.2%	3.0%	no	1.1%	2.9%
Thin 2A	2	yes	0.6%	2.2%	no	0.9%	7.5%	yes	0.8%	2.3%	yes	0.9%	2.8%	yes	1.6%	6.7%
Thin 3A	2	yes	0.7%	1.7%	yes	1.1%	2.5%	yes	0.9%	2.2%	yes	0.9%	2.5%	yes	1.3%	3.7%
Thin 4A	2	yes	0.8%	1.9%	yes	1.6%	3.2%	yes	0.8%	1.9%	yes	1.2%	2.7%	yes	1.0%	2.5%
Thin 1B	1	yes	1.3%	3.0%	yes	0.8%	3.3%	yes	1.0%	2.1%	yes	1.1%	2.2%	yes	1.1%	4.1%
Thin 2B	6	yes	2.2%	9.8%	yes	4.9%	20.4%	yes	3.7%	13.3%	yes	6.3%	14.7%	yes	10.8%	21.5%
Thin 3B	3	yes	1.7%	3.9%	no	2.1%	11.8%	yes	1.2%	3.2%	yes	1.8%	4.0%	yes	3.4%	15.0%

Module Performance Mismatch -- Crystalline Silicon -- Low Irradiance

Array	Runs	Isc			Imp			Voc			Vmp			Pmp		
		Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)
Mono 1A	1	yes	2.4%	8.6%	yes	2.9%	9.4%	yes	0.4%	1.8%	yes	0.7%	2.7%	yes	2.7%	10.3%
Mono 2A	1	no	1.0%	3.4%	no	0.8%	3.4%	yes	0.2%	0.5%	yes	0.3%	0.7%	no	0.9%	3.7%
Mono 1B	1	yes	0.5%	1.5%	yes	0.6%	1.0%	yes	0.3%	0.7%	yes	0.5%	2.3%	yes	1.0%	2.4%
Mono 2B	2	yes	0.8%	3.3%	no	3.5%	12.7%	no	38.2%	61.8%	no	38.5%	68.3%	no	40.0%	72.6%
Mono 3B	1	no	0.9%	3.3%	yes	1.1%	3.3%	no	0.5%	3.2%	yes	0.7%	1.8%	yes	1.6%	4.2%
Mono 4B	2	yes	3.5%	8.1%	yes	3.8%	8.9%	yes	0.2%	0.4%	yes	0.6%	1.5%	yes	3.9%	9.3%
Mono 5B	1	yes	1.9%	3.7%	yes	2.2%	5.0%	yes	0.4%	0.8%	yes	0.7%	1.5%	yes	2.8%	5.1%
Mono 6B	1	no	2.5%	3.3%	no	2.5%	3.8%	no	3.6%	32.1%	no	3.6%	32.5%	no	4.6%	33.3%
Poly 1A	3	no	7.0%	21.5%	no	6.5%	16.2%	yes	1.6%	5.3%	yes	1.4%	4.1%	no	7.4%	17.9%
Poly 2A	1	yes	3.1%	7.0%	yes	3.0%	8.4%	yes	0.6%	1.3%	yes	0.8%	2.1%	yes	3.5%	10.4%
Poly 3A	3	yes	1.5%	3.5%	yes	1.5%	4.1%	no	5.3%	29.0%	no	5.5%	30.5%	no	5.9%	31.4%
Poly 1B	1	no	1.8%	8.0%	yes	2.3%	7.3%	no	4.9%	51.1%	no	5.1%	53.2%	no	6.2%	56.7%
Poly 2B	1	no	1.3%	5.0%	no	1.1%	4.1%	no	0.4%	1.3%	yes	0.5%	1.1%	no	1.4%	5.0%
Poly 3B	1	yes	1.1%	3.1%	yes	1.5%	4.1%	yes	0.4%	0.8%	no	2.0%	6.1%	yes	2.7%	9.4%
Poly 4B	1	yes	1.3%	2.7%	yes	1.3%	2.6%	yes	0.2%	0.4%	yes	0.6%	2.2%	yes	1.0%	2.8%
Poly 5B	5	yes	2.5%	6.9%	yes	3.5%	8.6%	no	3.0%	48.1%	no	3.4%	49.4%	no	5.2%	47.0%
Hybrid 1A	1	no	1.0%	2.4%	yes	1.0%	3.6%	no	4.1%	24.8%	no	4.2%	25.1%	no	4.3%	26.1%
Hybrid 2A	1	yes	1.1%	5.5%	yes	0.6%	1.5%	yes	0.8%	1.9%	yes	0.8%	1.6%	yes	1.1%	2.2%
Hybrid 1B	2	yes	1.3%	3.7%	yes	2.0%	3.5%	yes	0.9%	1.6%	yes	1.5%	3.4%	yes	3.5%	5.6%
Hybrid 2B	1	yes	1.6%	2.9%	yes	1.6%	3.9%	no	18.1%	69.8%	no	18.6%	70.5%	no	19.0%	70.9%

Module Performance Mismatch -- Thin Film -- Low Irradiance

Array	Runs	Isc			Imp			Voc			Vmp			Pmp		
		Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)	Normal?	AAD (%)	MAD(%)
Thin 1A	2	yes	1.0%	3.0%	no	2.5%	9.0%	yes	0.4%	1.1%	no	0.9%	2.5%	no	3.3%	11.3%
Thin 2A	3	yes	0.9%	1.7%	no	3.4%	10.9%	yes	0.9%	2.5%	yes	2.1%	4.8%	yes	3.3%	9.7%
Thin 3A	2	yes	1.4%	3.1%	yes	1.8%	4.5%	yes	0.7%	1.5%	yes	0.9%	2.0%	yes	2.2%	5.3%
Thin 4A	2	no	8.5%	11.9%	no	9.2%	12.7%	yes	0.8%	2.2%	yes	2.5%	5.3%	no	6.7%	11.3%
Thin 1B	1	yes	0.7%	1.1%	yes	1.4%	3.7%	yes	1.3%	2.8%	yes	1.9%	3.7%	yes	2.9%	7.3%
Thin 2B	6	yes	5.2%	17.3%	yes	6.7%	24.0%	yes	8.4%	22.8%	yes	12.8%	34.7%	yes	19.1%	49.3%
Thin 3B	3	yes	3.0%	6.9%	yes	3.3%	11.5%	yes	1.1%	3.9%	yes	2.3%	5.7%	no	5.0%	13.9%

F.2 Hypothesis Testing -- Equivalence of Multiple Run Operating Conditions

In arrays that require multiple high and/or low light level runs to gather a full set of module-level performance data, each module's measured I-V curve is first fitted to a five parameter single diode model. The module models are then used to translate each module's performance from its measured irradiance and temperature (which vary between runs) to a common irradiance and temperature (averaged over the array). Any inaccuracy in the runs' original temperature and irradiance values may lead to modules in different runs being translated to slightly different operating conditions, relative to one another. This may mask or introduce mismatch to the array in question.

Once the modules' performance curves are translated to a common set of operating conditions, one can compare the runs' sets of module-level key I-V curve points (I_{sc}, V_{oc}, P_{mp}) to one another, and use statistical testing (two-sample Kolmogorov-Smirnov hypothesis test) to determine whether or not the translated module data from different runs are likely to have come from the same underlying distribution. The Kolmogorov-Smirnov test determines whether data from two different runs are likely to have come from different distributions (alternate hypothesis), or from the same distribution (null hypothesis). Observed parameter variation in single-run arrays indicates that modules with data taken simultaneously may still show significant performance differences relative to one another, so it is reasonable to assume that this will be the case in arrays with data taken in multiple runs as well. Thus the p-value for accepting the alternate hypothesis, that the two runs' data come from different distributions, is set to 1%.

The following table shows all of the arrays with data taken in multiple runs, and the results of the hypothesis testing for the I_{sc} and P_{mp} key curve points. Most of the arrays indicate failure to reject the null hypothesis; i.e. there is not strong enough evidence to say that different runs' translated data come from different operating conditions. Notable exceptions include Thin 1A and Poly 5B, both of which have statistically significant run-to-run variations in translated I_{sc} but not P_{mp}, and Thin 2A and Thin 2B, both of which have statistically significant run-to-run variations in translated I_{sc} and P_{mp} under low light conditions.

Array	High Irradiance Non-Equivalent Runs		Low Irradiance Non-Equivalent Runs	
	Isc	Pmp	Isc	Pmp
Mono 4B	No	No	No	No
Poly 1A	No	No	No	No
Poly 3A	No	No	No	No
Poly 5B	Yes	No	Yes	No
Hybrid 1B	---	---	No	No
Thin 1A	Yes	No	Yes	No
Thin 2A	No	No	Yes	Yes
Thin 3A	No	No	No	No
Thin 4A	No	No	No	No
Thin 2B	No	No	Yes	Yes
Thin 3B	No	No	No	No

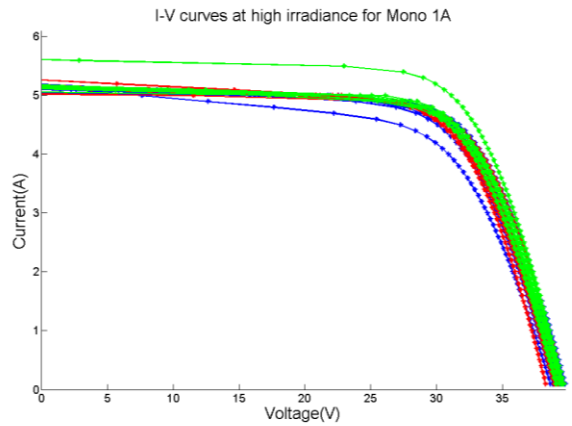
F.3. Array Loss Details

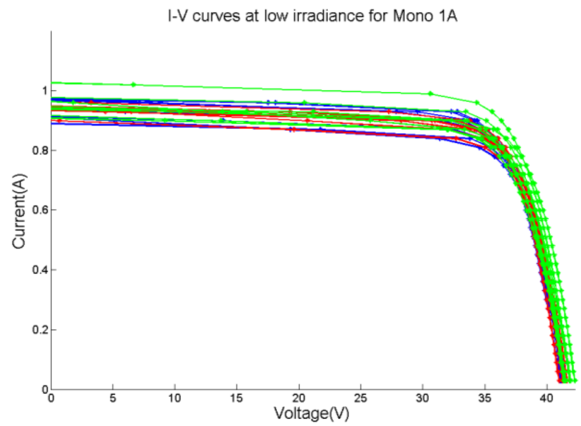
In Chapter 6, five arrays, Mono 1A, Mono 3B, Poly 3B, Hybrid 2B, and Thin 2B, are chosen for further analysis of mismatch losses. Their module level current vs. voltage (I-V) and power vs. current (P-I) curves are shown in this appendix, as are each array's string level power vs. voltage (P-V) curves, operating under both high and low light conditions. These curves may be used to better visualize and understand mismatch losses and loss mechanisms.

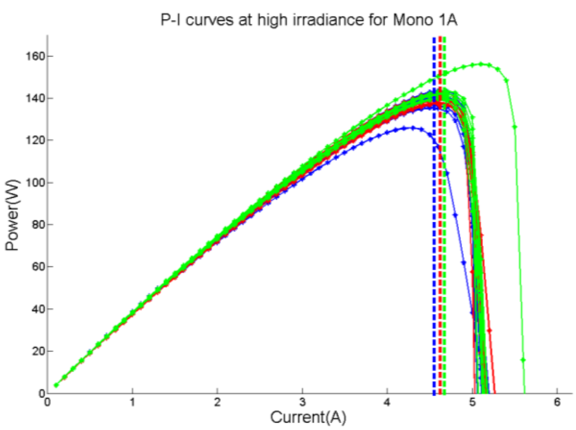
Each array's module level I-V and P-I curves are color coded by string, to illustrate modules which must conduct the same current. The P-I curve figures have vertical dashed lines showing the operating current for each string when the array as a whole operates at its centrally-determined maximum power point. Figures of the string level P-V curves each have a single dashed line, showing the array's centrally-determined maximum power point string voltage.

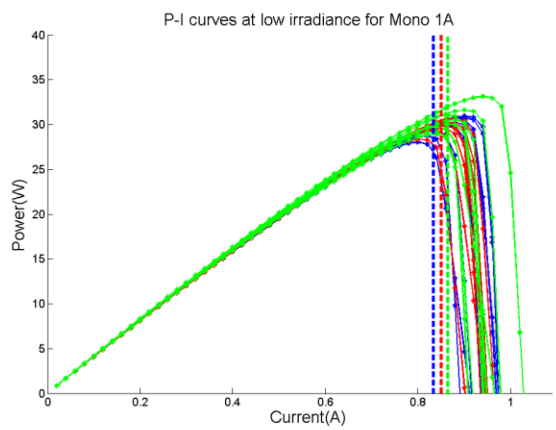
Mono 1A

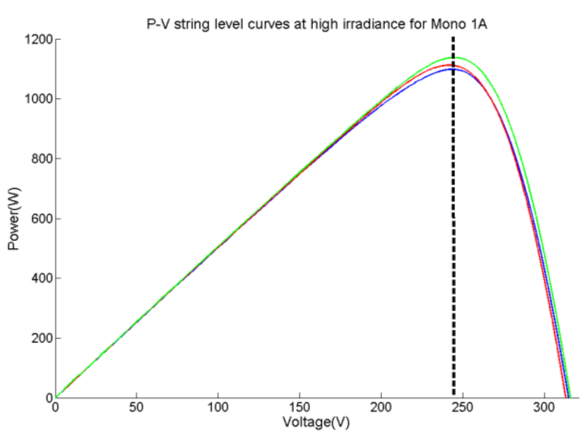
Mismatch losses come mostly from module-to-module performance variation within series strings, and are more significant under low light operating conditions.

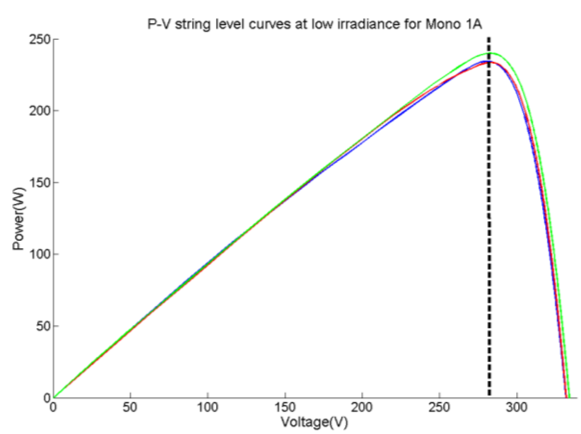






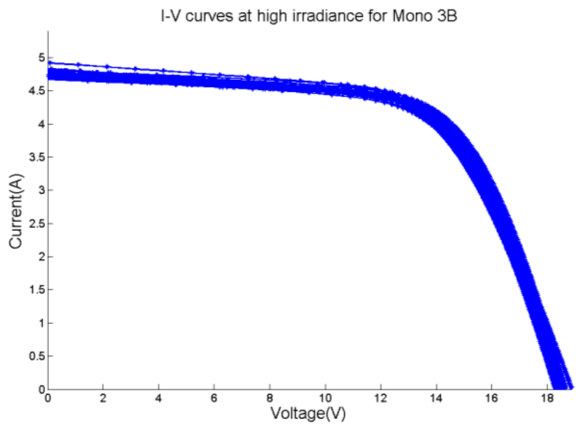


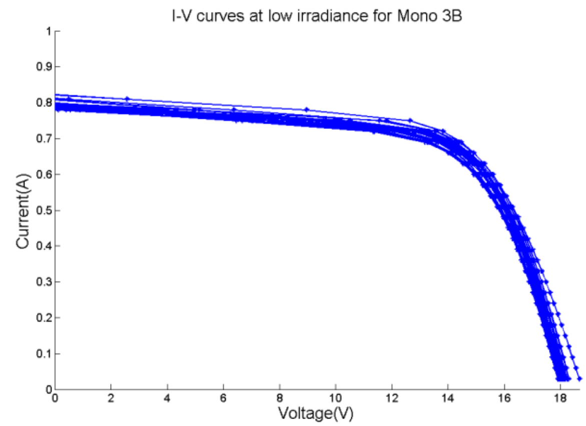


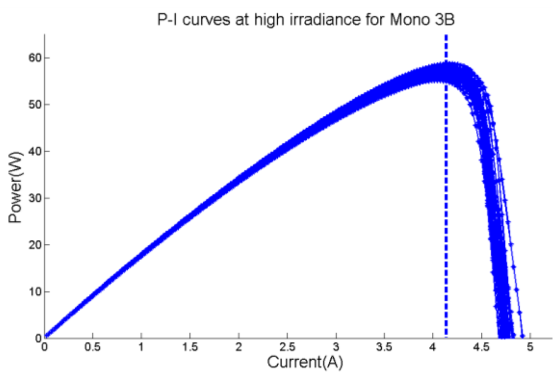


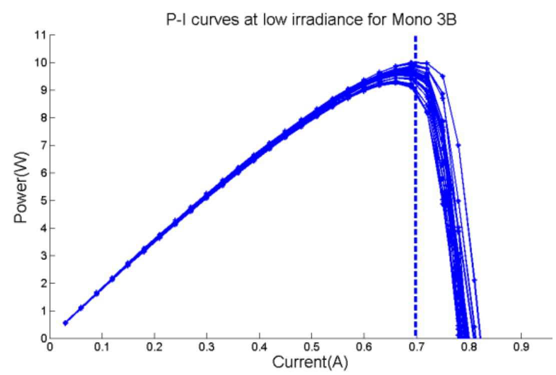
Mono 3B

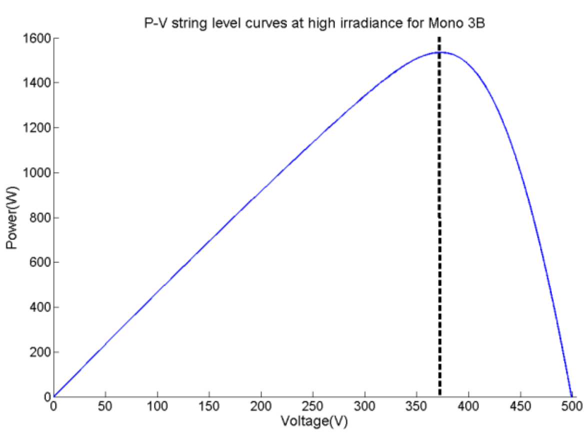
Mono 3B exhibits very little mismatch loss

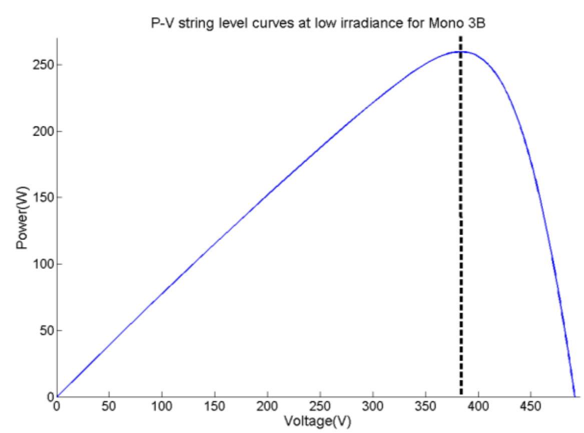






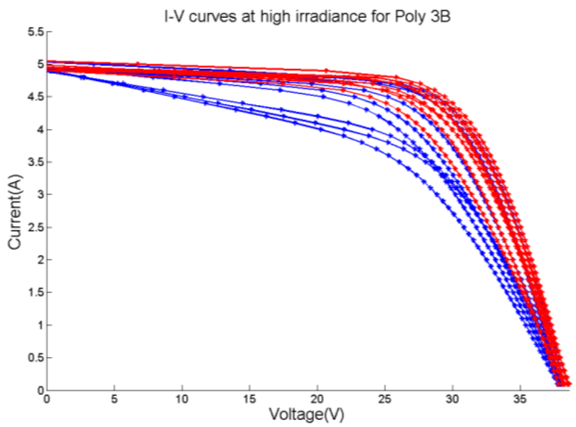


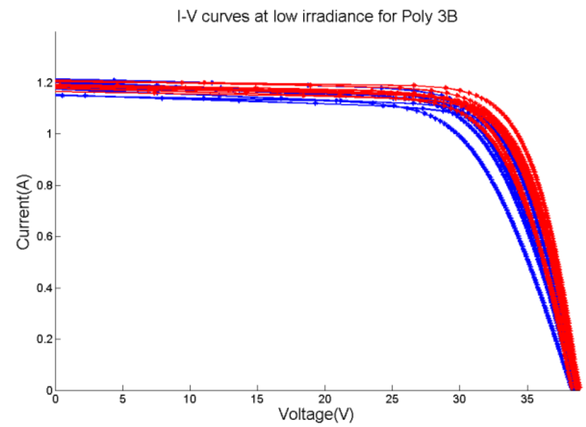


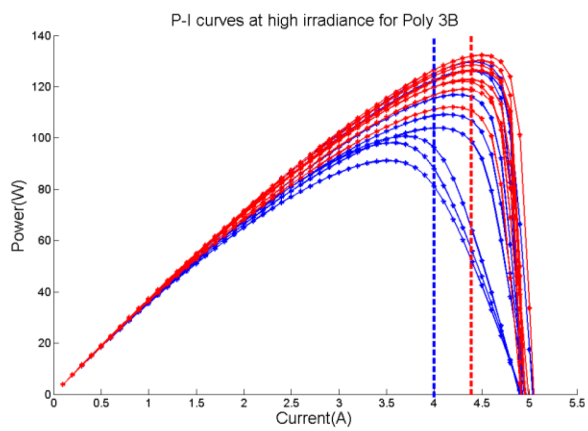


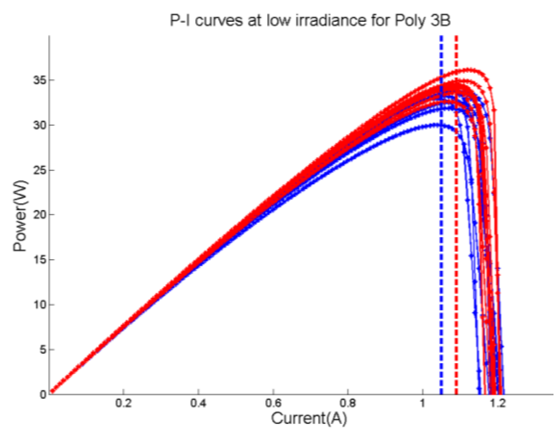
Poly 3B

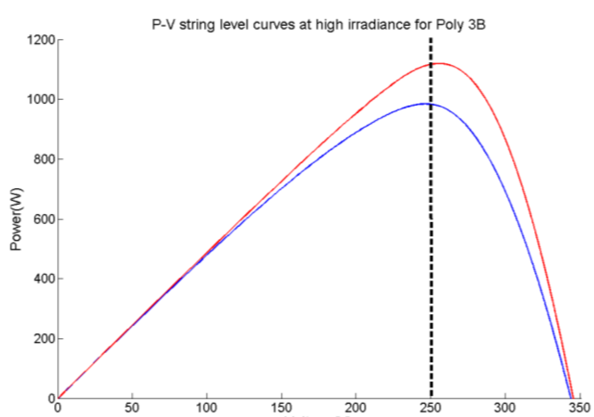
Mismatch loss in this array is again confined mostly to within the series strings (as opposed to between the parallel strings). There is more mismatch loss at high irradiance, where several modules experience shunted behavior and have much lower maximum power point current than the rest.

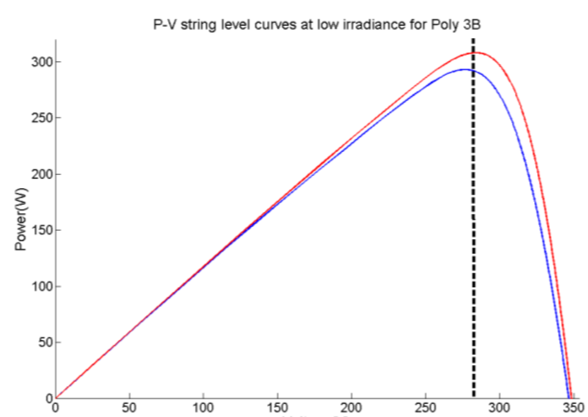






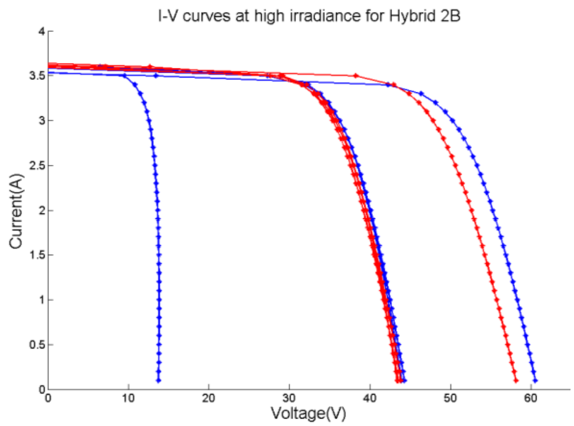


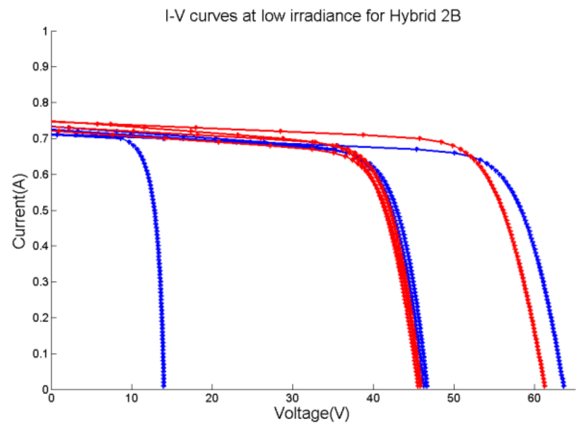


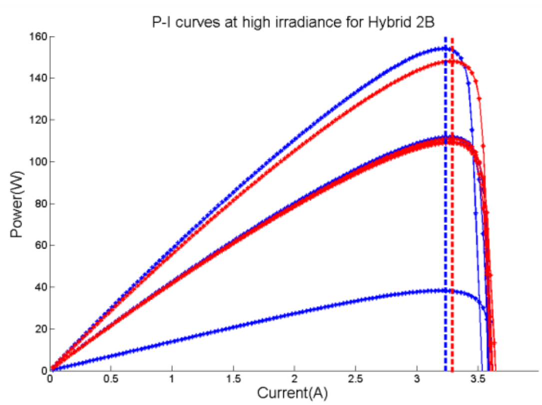


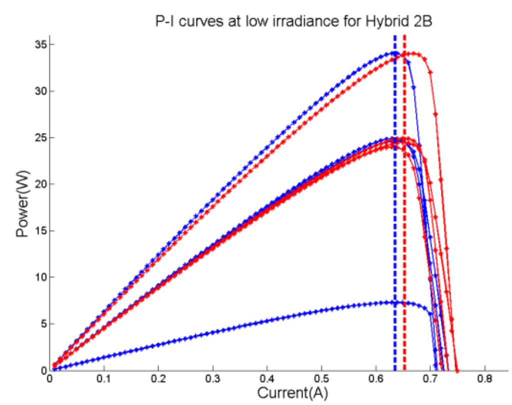
Hybrid 2B

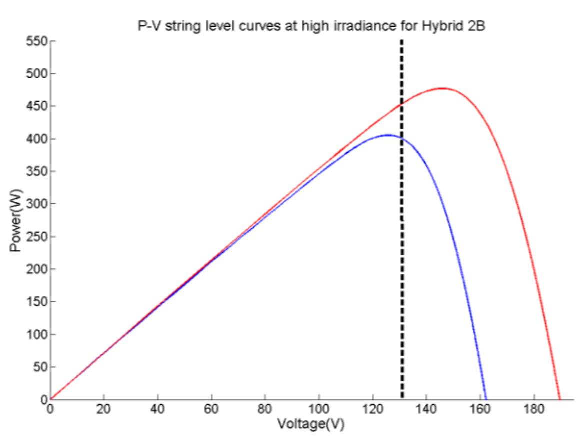
In this array most of the modules' maximum power point currents are well matched, so there is little mismatch loss within series strings. Instead, mismatch losses come from the difference in maximum power voltage between the two strings, which is caused by defective bypass diode substrings in the majority of the array's modules.

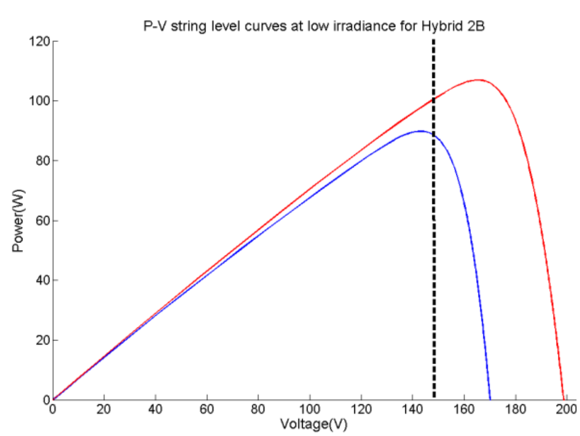






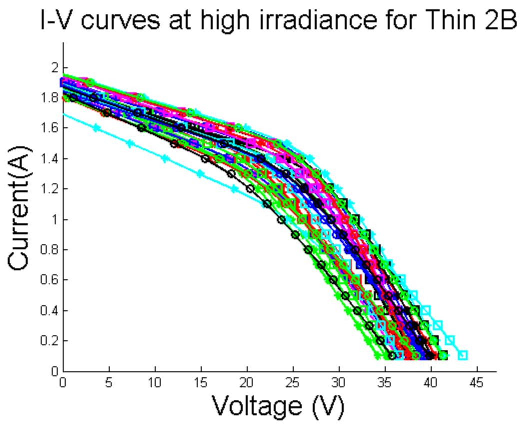


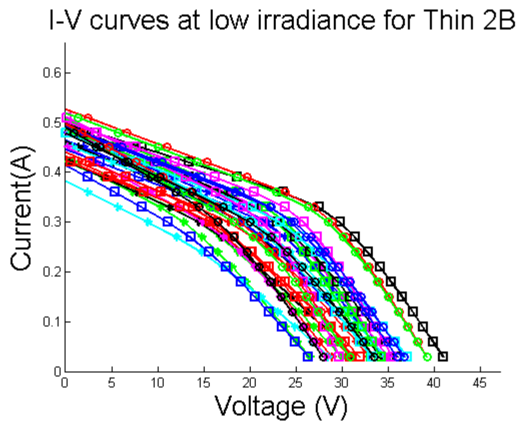


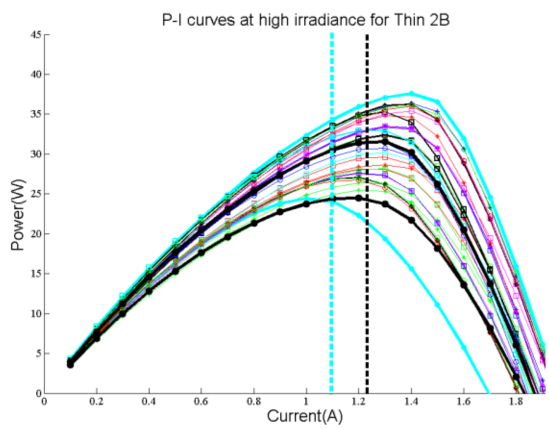


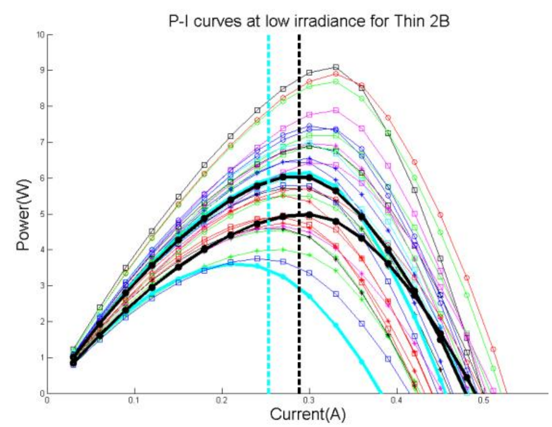
Thin 2B

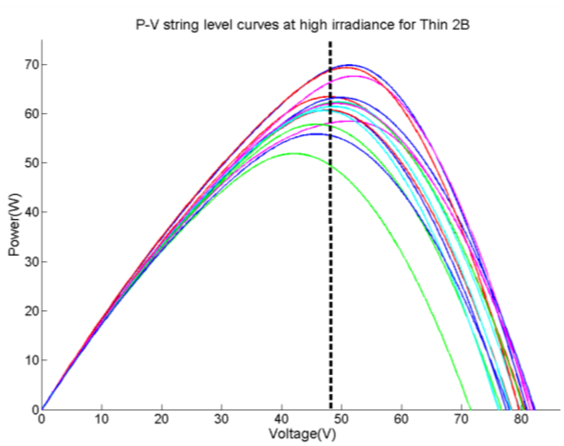
Significant mismatch losses in this array occur because of both current mismatch within series strings and voltage mismatch between parallel strings. Because this array has many (16) parallel strings, the P-I curves focus on the operating currents of just two of the strings.

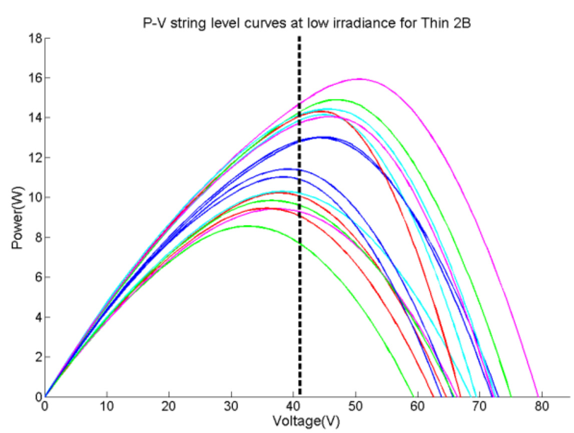












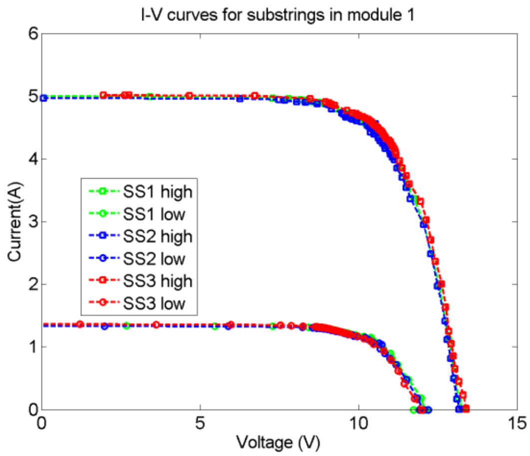
APPENDIX G

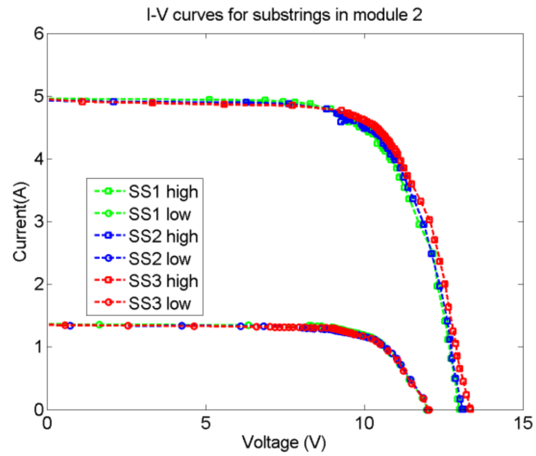
SUBMODULE DATA

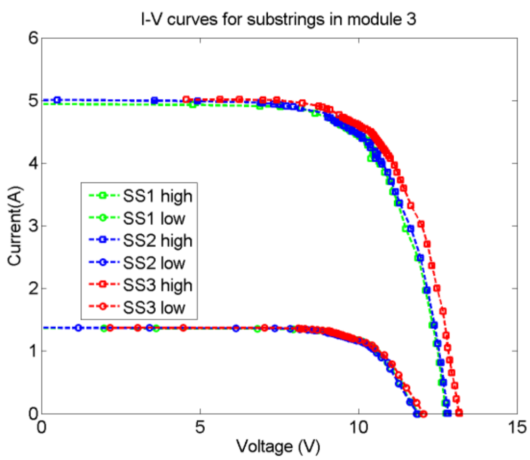
G.1. Measured I-V Curves

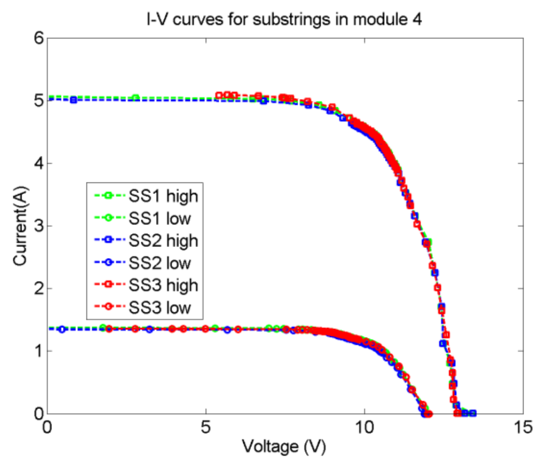
I-V curve data are collected for an array of 24, 180W monocrystalline silicon PV modules, located on top of the University of Colorado's engineering center, under both high light (990-1050 W/m^2) and low light (230-290W/m^2) operating conditions. The rooftop module monitoring system allows measurement of the voltage and current of each module substring, using custom printed circuit boards in each module's junction box and can handle up to three modules at a time. However, because of ongoing problems with several of the monitoring boards, data could only be collected for 21 of the 24 array modules. The other three are each modeled as a module with existing data and behavior best matching their own, as measured at the module level. Module 24 is modeled as module 6; module 19 as module 5, and module 18 as module 14.

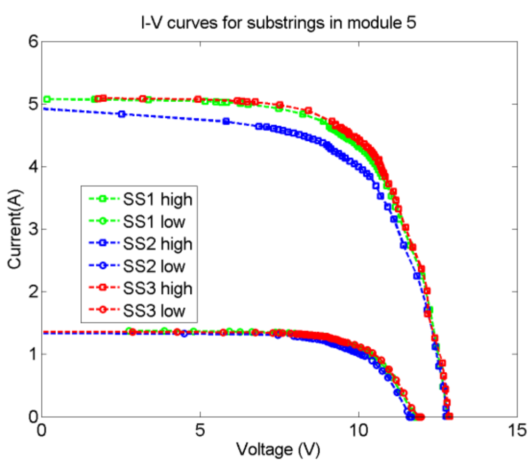
While the substrings generally exhibited uniform I-V curves across each module, there are some notable variations. Substring 2 of module 5 exhibits considerable degradation of shunt resistance. Variations in substring short circuit currents are observed in modules 1, 2, 6, 11, 14, and 21. Modules 8 and 15 exhibit larger variations that may indicate defective cells or bonds. Variations in substring open-circuit voltages are observed in panels 2, 3, 7, 9, 10, 11, 15, 16, and 17.

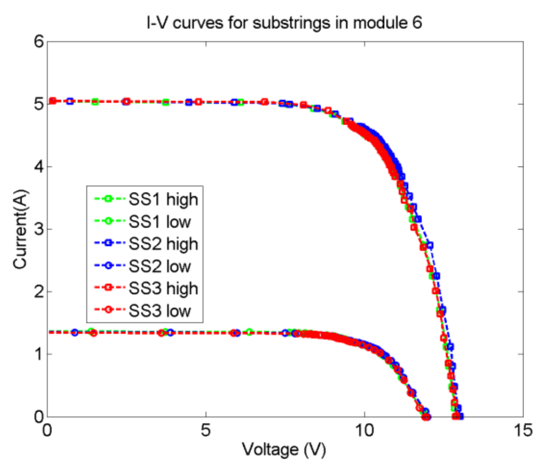

I-V curves for substrings in module 1
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

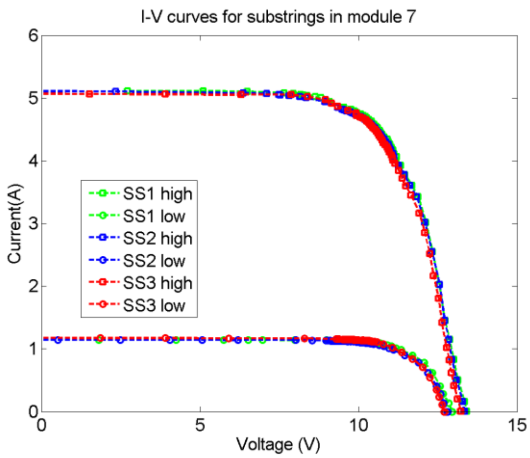

I-V curves for substrings in module 2
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

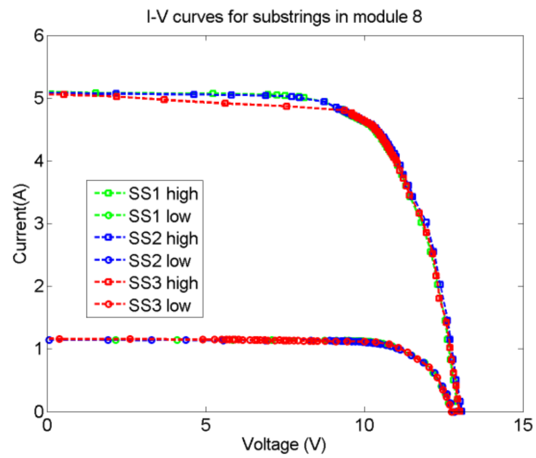

I-V curves for substrings in module 3
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

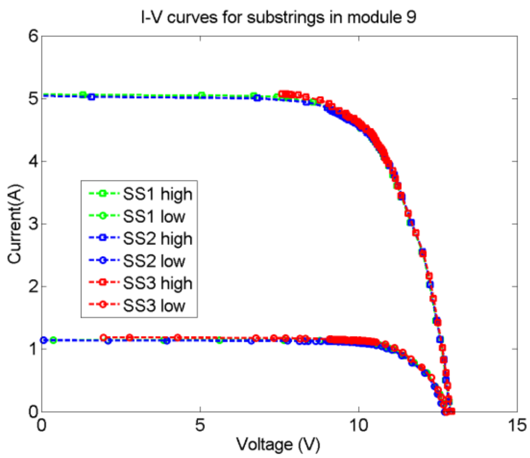

I-V curves for substrings in module 4
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

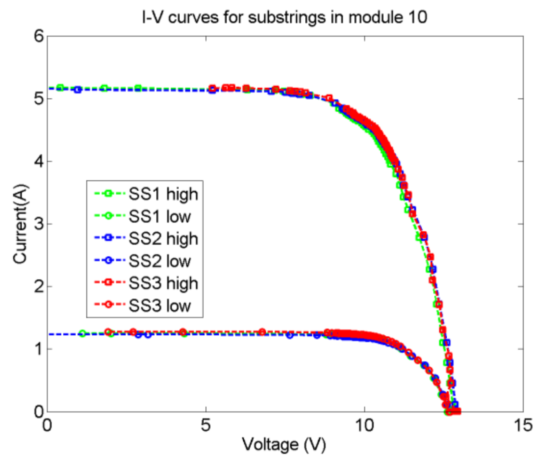

I-V curves for substrings in module 5
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

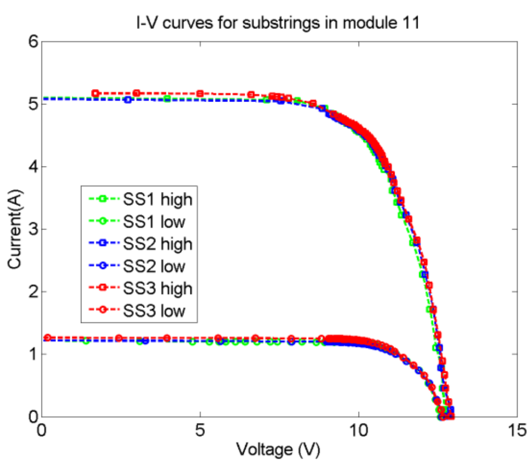

I-V curves for substrings in module 6
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

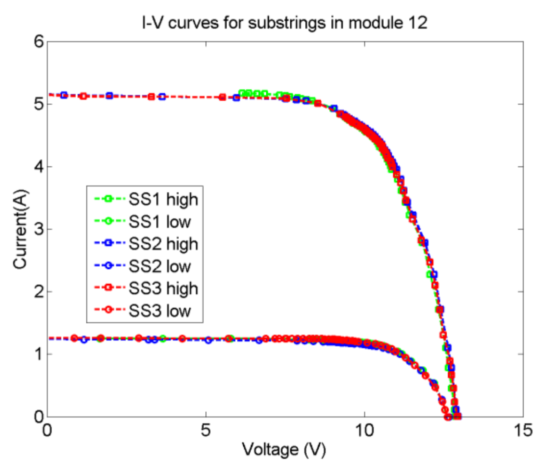

I-V curves for substrings in module 7
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

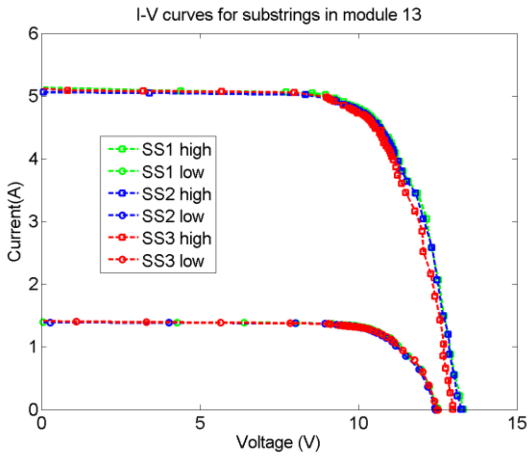

I-V curves for substrings in module 8
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

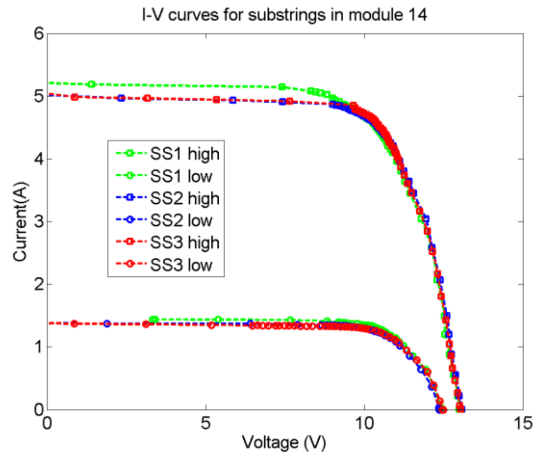

I-V curves for substrings in module 9
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

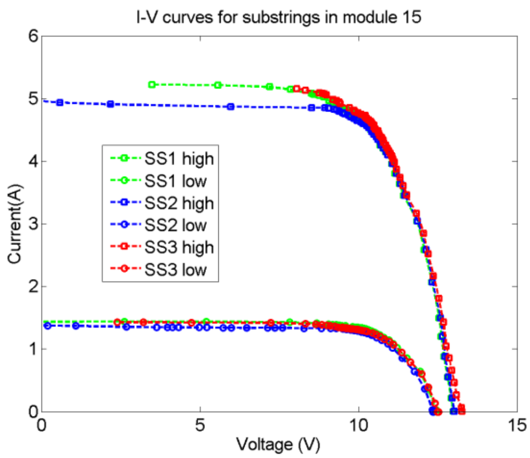

I-V curves for substrings in module 10
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

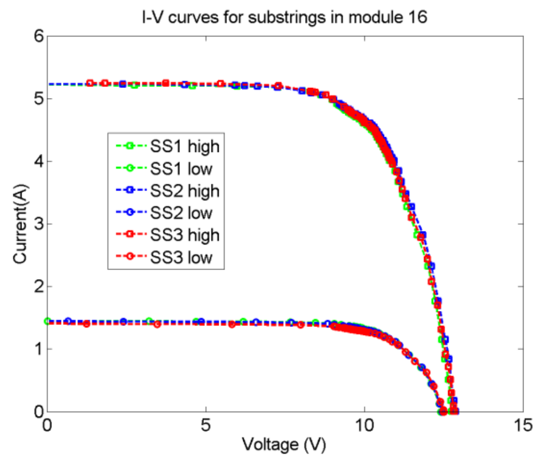

I-V curves for substrings in module 11
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low

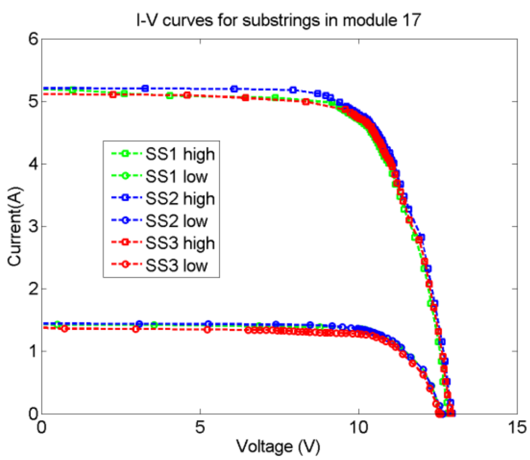

I-V curves for substrings in module 12
Current(A)
Voltage (V)
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low


I-V curves for substrings in module 13
Current(A)
Voltage (V)
0
1
2
3
4
5
6
0
5
10
15
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low


I-V curves for substrings in module 14
Current(A)
Voltage (V)
0
1
2
3
4
5
6
0
5
10
15
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low


I-V curves for substrings in module 15
Current(A)
Voltage (V)
0
1
2
3
4
5
6
0
5
10
15
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low


I-V curves for substrings in module 16
Current(A)
Voltage (V)
0
1
2
3
4
5
6
0
5
10
15
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low


I-V curves for substrings in module 17
Current(A)
Voltage (V)
0
1
2
3
4
5
6
0
5
10
15
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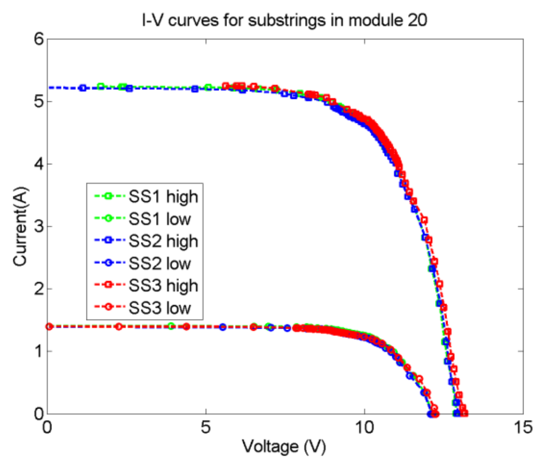
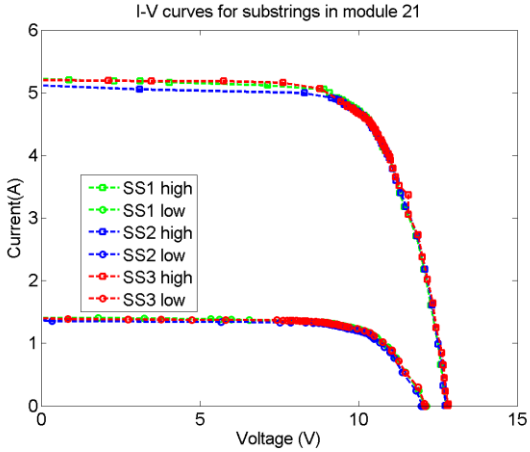
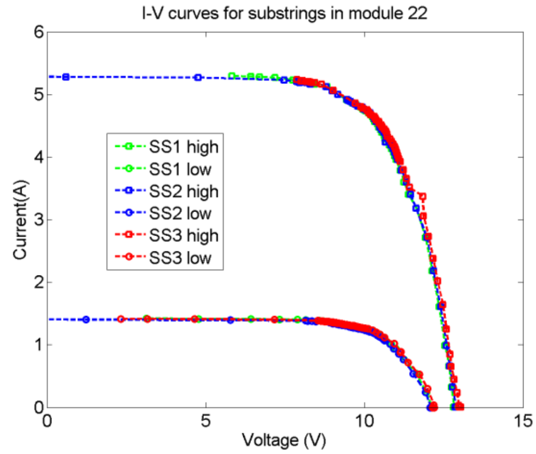
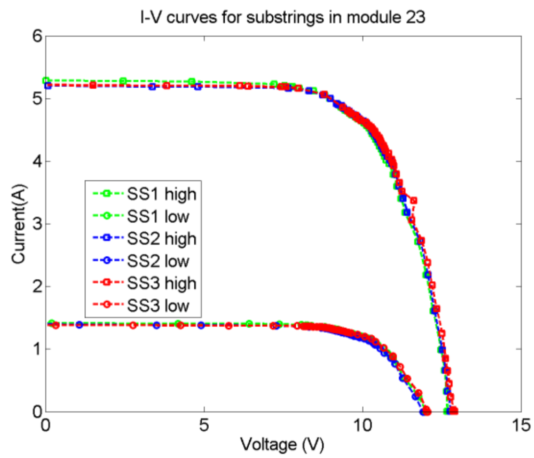
SS2 high
SS2 low
SS3 high
SS3 low


I-V curves for substrings in module 20
Current(A)
Voltage (V)
0
1
2
3
4
5
6
0
5
10
15
SS1 high
SS1 low
SS2 high
SS2 low
SS3 high
SS3 low







G.2. Single Diode Model Parameters

Each set of the measured submodules' I-V curves in the array in Appendix G.1. is fitted to a 7 parameter single diode model, as described in Chapter 4.1. Details of the data collection conditions, as well as parameters for each submodule's 7 parameter fitted model, are found in the following table.

		Weather Conditions				Seven Parameters							Notes
Module	Substring	Radhi (W/m^2)	Temphi (c)	Radlo(W/m^2)	Templo (c)	Rs	Rsh	Io	I L	a	m	delta	
Panel 1	1	989.5	57	265.2	56.4	0.6823	192	4.20E-08	5.016	2.149	0.1394	-0.00236	
	2	989.5	57	265.6	56.4	0.577	168.7	4.56E-08	4.995	2.143	0.3664	-0.00204	
	3	994.8	55.3	271.6	57.6	0.6287	203.6	3.36E-08	5.029	2.14	0.8291	-0.00162	
Panel 2	1	989.5	57	271.2	56.4	0.6204	123.9	4.94E-08	4.983	2.138	0.2597	-0.00193	
	2	989.5	57	270.2	56.4	0.5829	155.7	4.75E-08	4.944	2.139	0.1877	-0.00211	
	3	994.8	55.3	272.3	57.6	0.6891	230.1	3.48E-08	4.96	2.136	0.793	-0.00234	
Panel 3	1	989.5	57	274.1	56.4	0.6169	160	6.21E-08	4.962	2.119	0.4253	-0.00426	
	2	989.5	57	271.2	56.4	0.6204	126.6	6.20E-08	5.03	2.12	0.6211	-0.00362	
	3	994.8	55.3	272.3	57.6	0.5849	136	4.02E-08	5.04	2.127	0.8799	-0.00155	
Panel 4	1	1000	55.9	270.9	58.2	0.8423	126.1	3.54E-08	5.093	2.148	0.8334	-0.00179	
	2	1000	55.9	269.7	58.2	0.8697	121.7	3.45E-08	5.05	2.149	1.101	-0.00166	
	3	1003	57.1	268.7	58.4	0.554	113.2	5.52E-08	5.096	2.132	0.6471	-0.00205	
Panel 5	1	1000	55.9	271.6	58.2	0.5679	61.75	5.74E-08	5.12	2.115	0.7729	0.000356	shunting
	2	1000	55.9	272.2	58.2	0.599	43.47	5.67E-08	4.991	2.119	0.8307	0.004187	poor low rad model
	3	1003	57.1	267.1	58.4	0.5427	70.19	5.84E-08	5.126	2.131	0.6403	0.000223	
Panel 6	1	1000	55.9	270.8	58.2	0.5536	115.1	5.20E-08	5.064	2.118	0.559	-0.00233	
	2	1000	55.9	267.6	58.2	0.5286	124.8	4.86E-08	5.077	2.122	0.5114	-0.00197	
	3	1003	57.1	266.2	58.4	0.5459	99.71	5.81E-08	5.099	2.129	0.5857	-0.00182	
Panel 7	1	1010	55.9	236.5	35.2	0.7089	188.2	3.52E-08	5.142	2.147	0.873	-0.00201	
	2	1010	55.9	236.4	35.2	0.7114	169.2	3.66E-08	5.133	2.144	0.9561	-0.00203	
	3	1015	56.5	243.6	35.2	0.6883	300.9	4.30E-08	5.081	2.139	0.8692	-0.00346	
Panel 8	1	1010	55.9	236.7	35.2	0.5666	123.4	4.90E-08	5.125	2.118	0.6476	-0.00246	
	2	1010	55.9	237.7	35.2	0.5515	129.7	4.60E-08	5.099	2.127	0.701	-0.00187	
	3	1015	56.5	243.8	35.2	0.5857	191.7	5.16E-08	5.068	2.126	0.5848	-0.00362	
Panel 9	1	1010	55.9	238.5	35.2	0.5454	121.3	5.23E-08	5.087	2.117	0.601	-0.00256	
	2	1010	55.9	238.6	35.2	0.5372	136.9	5.34E-08	5.057	2.115	0.5845	-0.00309	
	3	1015	56.5	243.2	35.2	0.5707	133.6	5.49E-08	5.122	2.123	0.5435	-0.00307	
Panel 10	1	1021	55.6	247.3	36.5	0.5458	91.76	5.56E-08	5.201	2.11	0.5614	-0.00211	
	2	1021	55.6	244.9	36.5	0.5497	110.1	5.25E-08	5.177	2.114	0.5809	-0.0025	
	3	1025	55.1	255.5	37.4	0.5559	112.3	4.73E-08	5.174	2.114	0.6683	-0.00211	
Panel 11	1	1021	55.6	244	36.5	0.6318	145.8	5.43E-08	5.118	2.109	0.504	-0.00395	
	2	1021	55.6	244.9	36.5	0.6297	143.8	5.01E-08	5.101	2.115	0.6343	-0.00336	
	3	1025	55.1	253.7	37.4	0.5593	97.33	4.92E-08	5.198	2.111	0.613	-0.00185	
Panel 12	1	1021	55.6	243.6	36.5	0.5639	73.55	5.30E-08	5.29	2.116	0.6082	-0.00078	
	2	1021	55.6	247	36.5	0.5668	103.8	5.04E-08	5.18	2.117	0.606	-0.00205	
	3	1025	55.1	253.2	37.4	0.5675	99.59	4.88E-08	5.168	2.112	0.6239	-0.0019	
Panel 13	1	1029	53.5	281.8	52.7	0.6786	245.7	3.08E-08	5.148	2.119	0.03613	-0.00262	
	2	1029	53.5	282.9	52.7	0.6681	350.9	3.16E-08	5.077	2.115	0.07421	-0.00313	
	3	1033	53.2	284.4	51.9	0.5002	172.6	4.08E-08	5.145	2.093	-0.296	-0.00322	
Panel 14	1	1029	53.5	284.2	52.7	0.6473	113.9	3.96E-08	5.233	2.103	-0.2557	-0.00239	
	2	1029	53.5	283	52.7	0.57	256.2	3.73E-08	5.018	2.102	-0.08341	-0.00344	
	3	1033	53.2	282.3	51.9	0.5801	491.9	3.80E-08	5.037	2.096	-0.2181	-0.00454	
Panel 15	1	1029	53.5	280.8	52.7	0.6389	96.83	3.97E-08	5.294	2.104	-0.2069	-0.00184	
	2	1029	53.5	285.9	52.7	0.5952	408.1	3.83E-08	4.961	2.099	-0.06511	-0.00428	
	3	1033	53.2	279.7	51.9	0.7118	112.7	3.27E-08	5.313	2.114	-0.05459	-0.00177	
Panel 16	1	1038	55.5	283.7	51	0.5536	94.78	5.73E-08	5.249	2.107	0.0517	-0.00266	
	2	1038	55.5	280.9	51	0.5401	99.03	5.39E-08	5.259	2.111	-0.04136	-0.00231	
	3	1041	56.4	276.7	50.1	0.5595	95.13	6.03E-08	5.275	2.117	-0.08608	-0.00259	
Panel 17	1	1038	55.5	280	51	0.5519	153.7	5.47E-08	5.217	2.108	-0.09959	-0.00401	
	2	1038	55.5	281.2	51	0.5282	188.2	5.09E-08	5.225	2.113	-0.05065	-0.00391	
	3	1041	56.4	277	50.1	0.5554	431.3	5.55E-08	5.119	2.118	-0.1801	-0.00532	
Panel 18	1	1029	53.5	284.2	52.7	0.6473	113.9	3.96E-08	5.233	2.103	-0.2557	-0.00239	This is panel 14
	2	1029	53.5	283	52.7	0.57	256.2	3.73E-08	5.018	2.102	-0.08341	-0.00344	
	3	1033	53.2	282.3	51.9	0.5801	491.9	3.80E-08	5.037	2.096	-0.2181	-0.00454	
Panel 19	1	1000	55.9	271.6	58.2	0.5679	61.75	5.74E-08	5.12	2.115	0.7729	0.000356	This is panel 5
	2	1000	55.9	272.2	58.2	0.599	43.47	5.67E-08	4.991	2.119	0.8307	0.004187	
	3	1003	57.1	267.1	58.4	0.5427	70.19	5.84E-08	5.126	2.131	0.6403	0.000223	
Panel 20	1	1038	55.5	278	53.7	0.6158	105.4	4.99E-08	5.271	2.117	0.04438	-0.00249	
	2	1038	55.5	276.5	53.7	0.5871	92.93	4.92E-08	5.251	2.119	0.114	-0.00167	
	3	1041	56.4	276.1	53.8	0.6745	100	4.59E-08	5.306	2.139	0.1572	-0.00169	
Panel 21	1	1044	56.5	281	55.8	0.5225	151	6.50E-08	5.239	2.111	-0.1846	-0.00462	
	2	1044	56.5	278.6	55.8	0.5235	232.4	6.18E-08	5.118	2.112	-0.07418	-0.00522	
	3	1045	56.2	282.1	53.3	0.4844	114.1	5.99E-08	5.222	2.113	0.01687	-0.00299	
Panel 22	1	1044	56.5	275.5	55.8	0.5688	86.17	6.08E-08	5.433	2.121	-0.1225	-0.00238	
	2	1044	56.5	277.4	55.8	0.5702	130.1	5.84E-08	5.305	2.12	-0.1042	-0.00356	
	3	1045	56.2	274.3	53.3	0.568	75.3	5.12E-08	5.441	2.13	0.1578	-0.00062	
Panel 23	1	1044	56.5	279.1	55.8	0.5724	86.39	6.43E-08	5.323	2.115	0.2744	-0.00269	
	2	1044	56.5	278.5	55.8	0.5538	112.2	6.29E-08	5.24	2.114	0.6697	-0.00348	
	3	1045	56.2	273.2	53.3	0.5822	82.03	5.50E-08	5.317	2.123	0.2935	-0.00152	
Panel 24	1	1000	55.9	270.8	58.2	0.5536	115.1	5.20E-08	5.064	2.118	0.559	-0.00233	This is panel 6
	2	1000	55.9	267.6	58.2	0.5286	124.8	4.86E-08	5.077	2.122	0.5114	-0.00197	
	3	1003	57.1	266.2	58.4	0.5459	99.71	5.81E-08	5.099	2.129	0.5857	-0.00182	

APPENDIX H

ANNUAL SHADE SCENARIOS AND MAPPING

H.1 Shading Scenario Details

In Chapter 7, light, medium, and heavy shading scenarios are described for a PV array. Annual energy simulation of this array include the effects of partial shading, with shade mapped onto the array as part of the simulation environment described in Chapter 5. The array is simulated in both Boulder, CO (sunny climate) and Orlando, FL (cloudy climate).

Site 1: Unshaded

An unshaded case is simulated to investigate the potential for increased energy capture in arrays with no appreciable shading, in both sunny and cloudy climates.

Site 2: Light Shading

Example: 1310 Oakhurst Ave Los Altos, CA

Light shading depicted in SketchUp

Shading Obstacles and annual losses:

all dimensions in inches

Obstacle	Xpos	Ypos	Zpos	Diameter	Height
Pine	-300	60	0	120	300
Pine	-300	-60	0	120	300
Pine	-300	-180	0	120	300
Chimney	393.6	-48	0	24	78
			Denver	**Orlando**	
SHADE LOSS - SOLMETRIC			5.75%	5.5%	
SHADE LOSS - OTHER			3.3%	2.6%	

Site 3: Moderate Shading

Example: 2390 Dartmouth Ave Boulder, CO

Moderate shading depicted in SketchUp

Shading Obstacles and annual losses:

all dimensions in inches

Obstacle	Xpos	Ypos	Zpos	Diameter	Height
Branch	-24	300	0	12	360
Branch	-60	300	0	12	360
Branch	-96	300	0	12	360
Branch	24	300	0	12	360
Branch	60	300	0	12	360
Branch	96	300	0	12	360
Pine	-72	-240	0	120	300
Pine	681.6	-72	0	120	300
Leaves	0	300	0	240	420
			Denver	**Orlando**	
SHADE LOSS - SOLMETRIC			13.9%	10.8%	
SHADE LOSS - OTHER			6.6%	4.2%	

Site 4: Heavy Shading

Example: 8940 W. 4th Ave Lakewood, CO

Heavy shading depicted in SketchUp

Shading Obstacles and annual losses:

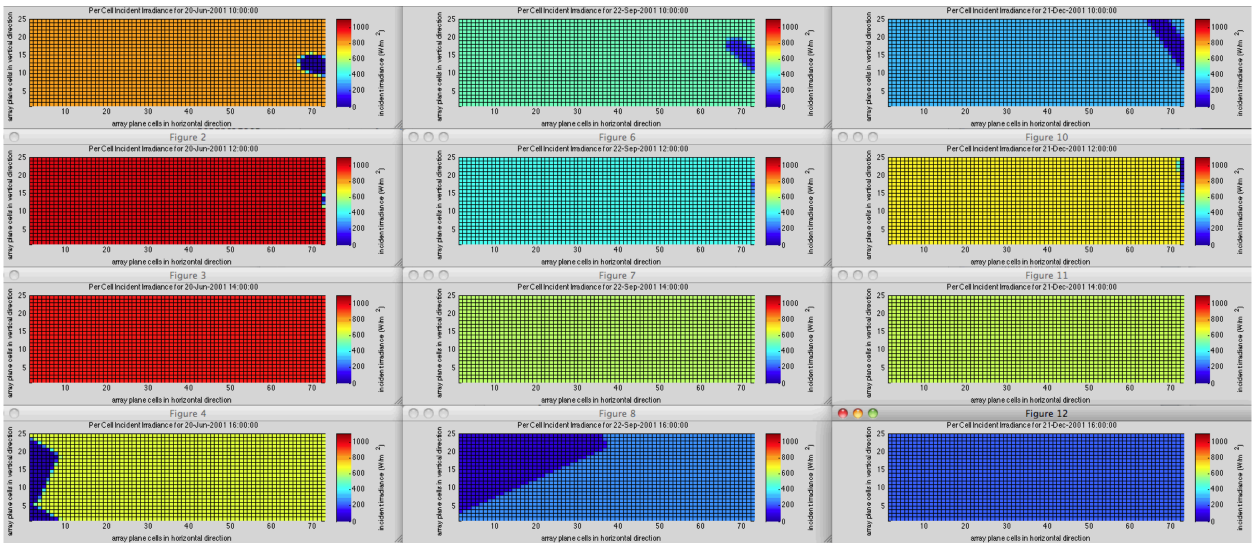
all dimensions in inches

Obstacle	Xpos	Ypos	Zpos	Diameter	Height
Branch	166.8	300	0	12	360
Branch	130.8	300	0	12	360
Branch	94.8	300	0	12	360
Branch	214.8	300	0	12	360
Branch	250.8	300	0	12	360
Branch	286.8	300	0	12	360
Pine	513.6	0	0	120	300
Pine	513.6	-144	0	120	300
Pine	-300	-120	0	120	300
Leaves	190.8	300	0	240	420
			Denver	**Orlando**	
SHADE LOSS - SOLMETRIC			24.3%	20.2%	
SHADE LOSS - OTHER			13.7%	9.5%	

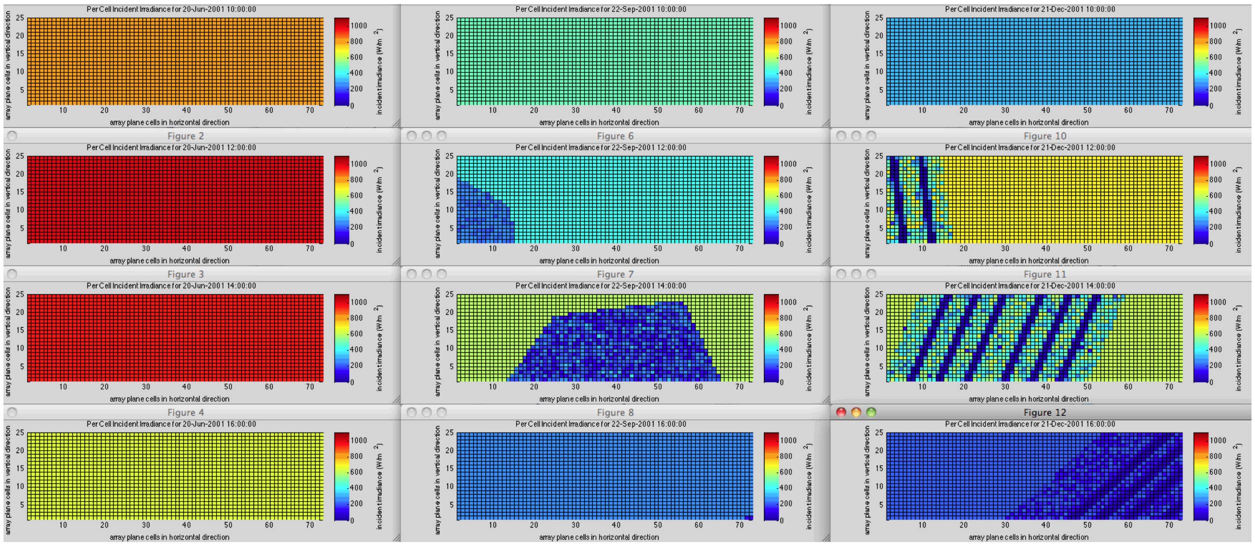
H.2. Shade Mapping

Samples of the shade mapping onto the array for each shading scenario (Appendix H.1), in each climate, are shown in this appendix section. Each figure shows the shading during the summer, fall (which also represents spring), and winter seasons, at 2-hour intervals from 10AM to 4PM (prime solar energy harvesting hours).

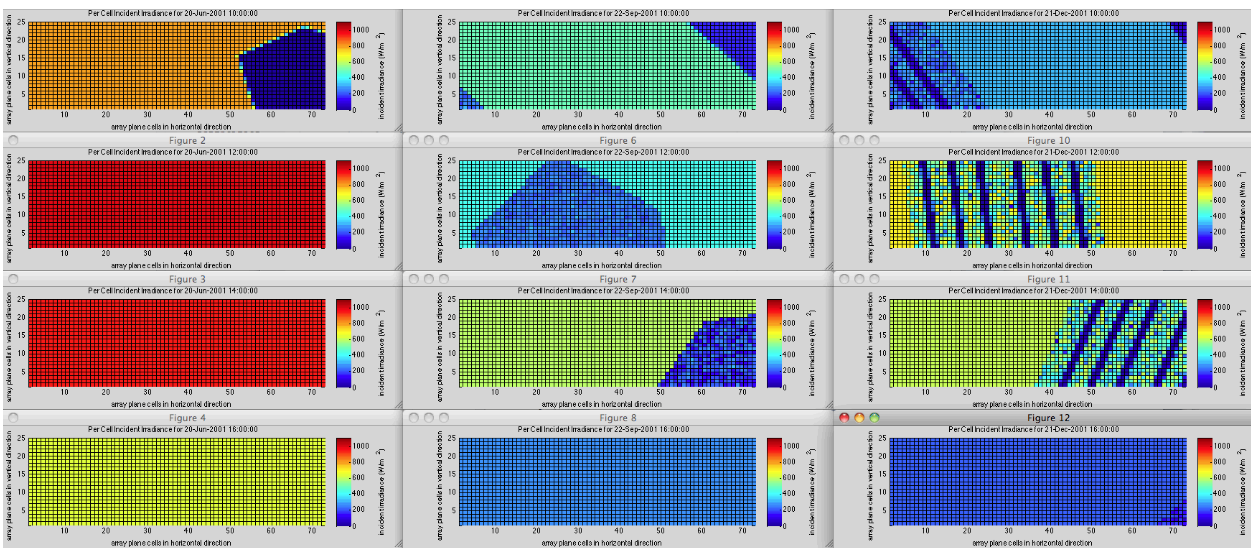
Denver Light Shading



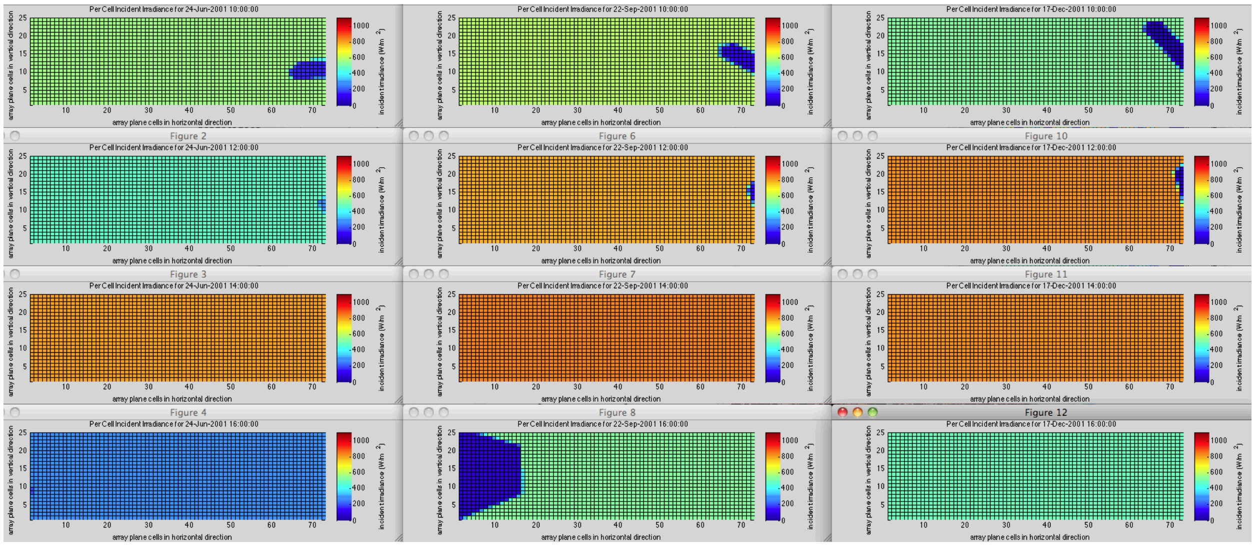
Denver Medium Shading



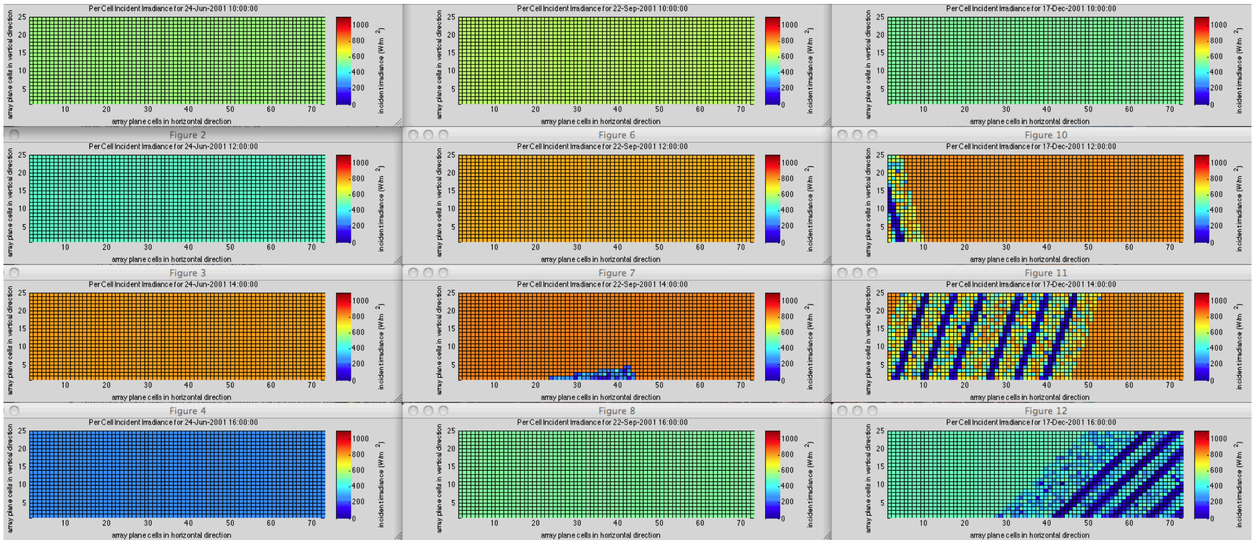
Denver Heavy Shading



Orlando Light Shading



Orlando Medium Shading



Orlando Heavy Shading