Power Rating of Photovoltaic Modules:

Repeatability of Measurements and Validation of Translation Procedures

by

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ABSTRACT

Power rating photovoltaic modules at six irradiance and four temperature matrix levels of IEC 61853-1 draft standard is one of the most important requirements to accurately predict energy production of photovoltaic modules at different climatic conditions. Two studies were carried out in this investigation: a measurement repeatability study and a translation procedure validation study. The repeatability study was carried out to define a testing methodology that allows generating repeatable power rating results under outdoor conditions. The validation study was carried out to validate the accuracy of the four translation procedures: the first three procedures are from the IEC 60891 standard and the fourth procedure is reported by NREL. These translation procedures are needed to translate the measured data from the actual test conditions to the reporting rating conditions required by the IEC 61853-1 draft standard.

All the measurements were carried out outdoors on clear days using a manual, 2-axis tracker, located in Mesa/Tempe, Arizona. Four module technologies were investigated: crystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide. The modules were cooled and then allowed to naturally warm up to obtain current-voltage data at different temperatures. Several black mesh

screens with a wide range of transmittance were used for varying irradiance levels.

From the measurements repeatability study, it was determined that: (i) a certain minimum distance (2 inches) should be maintained between module surface and the screen surface; (ii) the reference cell should be kept outside the screen (calibrated screen) as opposed to inside the screen (uncalibrated screen); and (iii) the air mass should not exceed 2.5. From the translation procedure validation study, it was determined that the accuracy of the translation procedure depends on the irradiance and temperature range of translation. The difference between measured and translatet power at maximum power point (P_{max}) is determined to be less than 3% for all the technologies, all the irradiance/ temperature ranges investigated and all the procedures except Procedure 2 of IEC 60891 standard. For the Procedure 2, the difference was found to fall between 3% and 17% depending on the irradiance range used for the translation. The difference of 17% is very large and unacceptable. This work recommends reinvestigating the cause for this large difference for Procedure 2.

Finally, a complete power rating matrix for each of the four module technologies has been successfully generated as per IEC 61853-1 draft standard.

DEDICATION

I would like to dedicate this work to my husband, Paul, who has been such a blessing with his patience and support all throughout my time in graduate school.

ACKNOWLEDGMENTS

I would like to express my utmost gratitude to Dr. Govindasamy Tamizhmani for his patience and guidance throughout this work. He has given me a great opportunity to work under his supervision thus learning so much about the PV industry and solar PV testing in general.

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Finally, words alone cannot express the thanks I owe to my family for raising me as a responsible and conscientious individual. Without them and the blessing from the one above, it would never have been possible.

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Chapter 1

INTRODUCTION

1.1 Overview

The current practice of the PV industry is to rate at standard test conditions of 1000 W/m^2, 25°C and air mass 1.5. PV modules in the field experience a wide range of conditions that greatly influence the performance and ultimately power output. These critical factors influencing the power output of the PV module are irradiance and temperature over a linear region. There is a direct relationship of irradiance to short circuit current and logarithmic relationship to open circuit voltage. On the other hand, temperature variations greatly influence open circuit voltage. These two important factors can greatly impact the maximum power output and these relationships are true for most crystalline silicon materials but are not yet determined for thin films. The move to rate the power as influenced over a range of irradiances and module temperatures is an important effort to be able to come close to actual performance conditions.

The International Electrotechnical Commission (IEC) is currently working on a different type of classification methodology in terms of performance testing and power rating as described by the draft standard IEC61853 particularly Part 1: Irradiance and Temperature Performance

Measurements and Power Rating. The irradiance-temperature matrix outlined in Table 1 [1] is the main objective and instead of using extensive modeling, actual measurements at a defined irradiance and temperature conditions are measured. Since the conditions outlined by the performance matrix cannot be exactly taken, translation methods can be used as outlined by IEC 60891 [2].

Table 1: Temperature and irradiance matrix as per IEC 61853-draft standard [1]

Irradiance (W/m^2)	Module Temperature (°C)			
	15	25	50	75
1100	NA			
1000				
800				
600				
400				NA
200				NA
100			NA	NA

1.2 Objective

There are three objectives of the research as outlined below:

1) To validate the repeatability of photovoltaic power rating measurements at different temperature and irradiance levels using outdoor natural sunlight as per IEC 61853 standard (draft) [1].

2) To validate translation methods namely: (i) Procedure 1 - IEC 60891 Method [2], (ii) Procedure 2 - IEC 60891 Method [2], (iii)

Procedure 3 - IEC 60891 Method [2], (iv) Procedure 4 - NREL Bilinear interpolation method [3]

3) To generate the irradiance-temperature (power) matrix for maximum power output (P_{max}) and other performance parameters for some translation procedures.

Chapter 2

LITERATURE REVIEW

2.1 I-V Curve Translation Procedures

As mentioned in the objective section four (4) different translation procedures will be validated. Three of these are from IEC60891 [2] standard namely Procedure 1, Procedure 2, and Procedure 3. The fourth translation, developed by Marion, et al [3] of NREL, using bilinear interpolation using 4 reference curves will also be validated. These translation procedures are then used to derive any test conditions. This chapter will explain the equations and methods for obtaining the performance characteristics at test conditions.

2.1.1 Procedure 1 - IEC 60891 Method

IEC 60891 Procedure 1 [2] can be used to translate a single measured I-V characteristic to selected temperature and irradiance or test conditions by using equations (1) and (2).

$$I_2 = I_1 + I_{sc}\,[(G_2/G_1) - 1] + \alpha\,(T_2 - T_1) \qquad (1)$$

$$V_2 = V_1 - R_s\,(I_2 - I_1) - \kappa\, I_2\,(T_2 - T_1) + \beta\,(T_2 - T_1) \qquad (2)$$

where:

I_1 and V_1 are coordinates of the measured I-V curve

I_2 and V_2 are the coordinates of the translated I-V curve

G_1 is the irradiance measured with the primary reference cell

G_2 is the irradiance at desired conditions in the matrix

T_1 is the module temperature

T_2 is the desired temperature in the matrix

I_{sc} is the measured short circuit current of the test specimen at measured I-V curve.

R_s is the internal resistance of the test module

κ is the curve correction factor derived from measured conditions

Two constants α and β need to be obtained before any translation is done. These are temperature coefficients at the target irradiances. (i) α is the temperature coefficient at short circuit current; (ii) β is the temperature coefficient at open circuit voltage.

IEC 60891 standard also describes the procedures in obtaining R_s and κ values and will be shown in the methodology section. This method will be described in the methodology section

This procedure is limited to a less than 20% irradiance correction.

2.1.2 Procedure 2 - IEC 60891 Method

IEC 60891 Procedure 2 [2] is similar to Procedure 1 with additional correction parameters required. The following equations below are used to be able to achieve the current and voltage coordinates of the translated curve.

$$I_2 = I_1 * (1 + \alpha_{rel} * (T_2 - T_1)) * G_2/G_1 \quad (3)$$

$V_2 = V_1 + V_{oc1} * (\beta_{rel} * (T_2 – T_1) + \alpha * \ln (G_2/G_1)) – R'_s * (I_2 – I_1) – \kappa' * I_2 * (T_2 – T_1)$ (4)

α_{rel} and β_{rel} are the current and voltage temperature coefficients at standard test conditions, 1000 W/m^2 related to the short circuit current and open circuit voltage at STC (standard test conditions)

R'_s is the internal resistance of the test specimen

κ' is the temperature coefficient of the series resistance R'_s.

These two parameters are derived and the procedure outlined by IEC60891 will again be discussed in the methodology section.

2.1.3 Procedure 3 - IEC 60891 Method

IEC 60891 Procedure 3 [2] has three (3) parts as described in the same standard but in this particular paper only two (2) will be explored. The general equations are stated below and the sections to be explored will be utilizing two (2) and three (3) curves as reference curves for subsequent translations to test conditions.

$V_3 = V_1 + \alpha * (V_2 – V_1)$ (5)

$I_3 = I_1 + \alpha * (I_1 – I_1)$ (6)

Where:

I_3 and V_3 are coordinates of the translated curve at G_3 and T_3

I_1 , V_1 , I_2 , V_2 are the coordinates of the two (2) measured reference IV curves at conditions G_1, T_1 and G_2 , T_2 consecutively.

These two measured reference IV curves with coordinates (I_1 , V_1) and (I_2 , V_2) should satisfy the condition:

$I_2 - I_1 = I_{sc2} - I_{sc1}$ where I_{sc1} and I_{sc2} [2] are the measured short circuit current.

The constant α in this procedure is the constant for interpolation which can be obtained by using the equations below.

$$G_3 = G_1 + \alpha * (G_2 - G_1) \quad (7)$$

$$T_3 = T_1 + \alpha * (T_2 - T_1) \quad (8)$$

With these equations, it should be noted that G_3 and T_3 cannot be obtained independently when G_1, T_1 and G_2, T_2 are fixed. In this case, using only two reference measured I-V curves do not always yield to the desired matrix conditions for a given set of reference curves.

Extending it to three measured reference I-V curves instead of two using the general procedures described can extend IEC 60891 Procedure 3 to obtain an actual matrix condition. The figure below illustrates how a desired matrix condition G_n, T_n can be obtained.

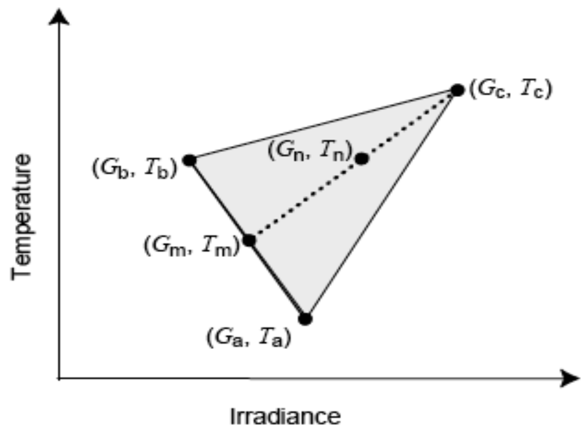


Figure 1. Procedure 3: Area enclosing interpolation range [2]

In this method, it starts with three measured reference I-V curves with coordinates (G_a, T_a), (G_b, T_b) and (G_c , T_c) [2] as shown in Figure 1. To obtain (G_m , T_m) it is calculated from (G_a, T_a), (G_b, T_b) from which (G_n , T_n) coordinate is subsequently calculated from (G_c , T_c) and (G_m , T_m). The step-by-step procedure will be described in the methodology section.

2.1.4 Procedure 4 - NREL Method

The NREL method named here as Procedure 4 developed by Marion, et al [3] makes use of four (4) measured reference I-V curves and using a process called bilinear interpolation. The following steps below are used to describe the procedure. Four (4) measured reference IV curves at conditions (T_x) and irradiance (E_x) settings such that $G_1=G_2=G_H$, $G_3=G_4=G_L$, $T_1=T_3=T_L$, and $T_2=T_4=T_H$ [3] are satisfied with G_H as higher irradiances and G_L as low irradiances with corresponding T_H as high temperatures and T_L as low temperatures. An illustration of the starting measured reference curves as well as the bilinear interpolation is shown in Figure 2.

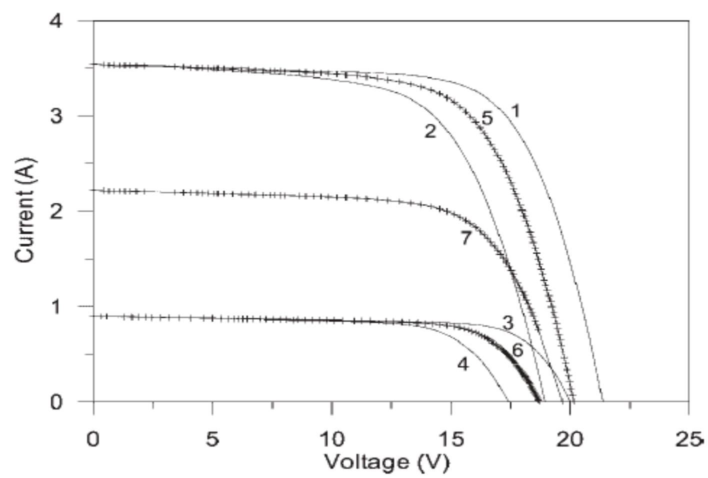


Figure 2: NREL Bilinear Interpolation Method illustration [3]

Step 1: Calculating correction factors α, β, m, and b

The first step as described in the process flow is to obtain the temperature and irradiance correction factors. The equations for I_{sc} and V_{oc} used are:

$$I_{sc} = (G/G_1) * I_{sc(1)} * [1 + \alpha (T-T_1) \quad (9)$$

$$V_{oc} = V_{oc(1)} * [1 + \beta (T-T_1)]*[1 + (mT + b) * \ln (G/G_1)] \quad (10)$$

To be able to determine the correction factor α the equation below is used.

$$\alpha = [(I_{sc(2)}\, G_1/I_{sc(1)}\, G_2) - 1]/(T_2 - T_1) \qquad (11)$$

Correction factors β, m, and b are determined by solving for three nonlinear equations wherein G, T, and V_{oc} values of reference IV curves 2, 3, and 4 are used. The system of nonlinear equations is derived from equation (12).

$$F(\beta, m, b) = [1 + \beta (T - T_1)][1 + (mT + b) \ln (G/G_1)] - V_{oc}/V_{oc\,(1)} = 0 \qquad (12)$$

The G values for reference curves 3 and 4 will be derived using equation (13) below

$$G = I_{sc}\, G_1/I_{sc(1)}\, [1 + \alpha (T - T_1)] \qquad (13)$$

Step 2: Adjusting Measured Reference curves 2 and 4

Measured reference curves 2 and 4 are adjusted to accommodate for variations in irradiance settings where $G_1 \neq G_2$ or $G_3 \neq G_4$ [3]. The equations below are used for adjustments and will be termed as their primes (‘).

Coordinates for I'_2 and V'_2 :

$$I'_2 = I_2 * (I_{sc(1)}/I_{sc(2)}) \qquad (14)$$

$$V'_2 = V_2 * (V_{oc(2)'}/V_{oc(2)}) \qquad (15)$$

To be able to determine $V_{oc(2)'}$ equation (10) is used with E'_2 obtained from equation (13).

Coordinates for I'_4 and V'_4

$I'_4 = I_4 * (I_{sc(3)}/I_{sc(4)})$ (16)

$V'_4 = V_4 * (V_{oc(4)'}/V_{oc(4)})$ (17)

To be able to determine $V_{oc(4)'}$ equation (10) is used with E'_4 obtained from equation (13).

Step 3: I-V curve interpolation

It is called bilinear interpolation because the procedure allows two interpolation regions with I-V curves 5 interpolated from measured reference curves 1 and 2 while I-V curve 6 interpolated from measured reference curves 3 and 6. This is illustrated in Figure 2. Curve 7 is then translated from interpolated curves 5 and 6.

As illustrated in Figure 2, to obtain IV curve 5, IV curve 1 is translated while keeping the current constant. To be able to do this, the equations below are needed.

$I_5 = I_1 = I'_2$ (18)

$V_5 = V_1 + (V'_2 – V_1)*(V_{oc(5)} - V_{oc(1)}) ÷ (V_{oc(2)'} – V_{oc(1)})$ (19)

Note: To obtain $V_{oc(5)}$ use equation (10) with E_5 obtained from equation (13) and T is the desired temperature.

It is the case wherein the I-V curves of 1 and 2' are not the same, values of V'_2 pair I'_2, is interpolated from adjacent point or using curve-fitting adjacent points. This is illustrated in the figure below.

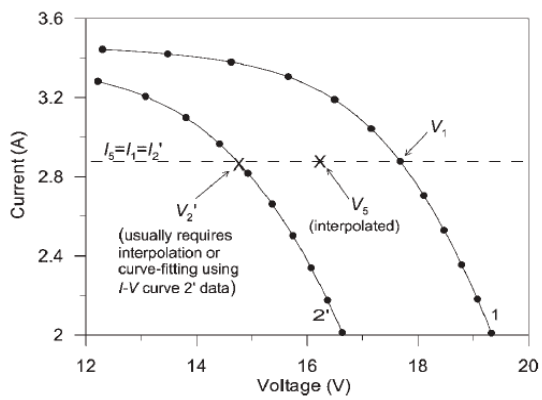


Figure 3. Translating I-V curve 1 to 5 [3]

Similarly, I-V curve 6 is translated from I-V curve 3 while keeping the current constant. V'_4 values of I-V curve pair V'_4 and I'_4 is interpolated from adjacent points to correspond to I-V curve 3. Similar equations to equations (18) and (19) is used with corresponding subscripts. To obtain $V_{oc(6)}$, equation (10) is again used and to obtain E_6 for $V_{oc(6)}$ use equation (13) where T is the desired temperature.

Finally I-V curve 7 (desired temperature and irradiance conditions) is interpolated with respect to I_{sc} as shown in Figure 4 from I-V curve 5 and 6. This time, values of I_6 corresponding to V_6 are interpolated from adjacent points.

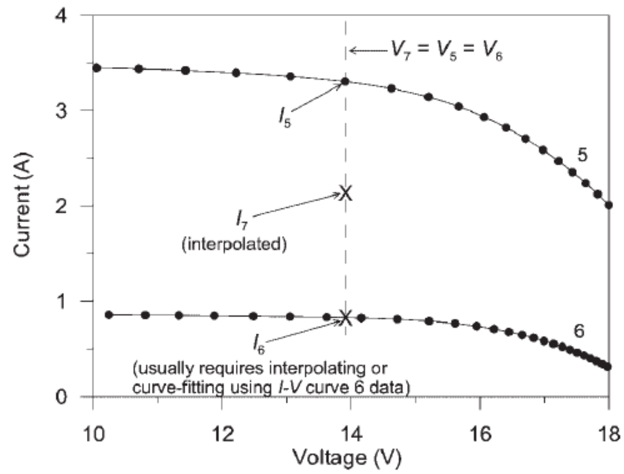


Figure 4. Translating I-V curve 6 to 7 [3]

To obtain the values of I-V curve 7 the equations below are used.

$$V_7 = V_5 = V_6 \tag{20}$$

$$I_7 = I_6 + (I_5 - I_6) * (I_{sc(7)} - I_{sc(6)}) \div (I_{sc(5)} - I_{sc(6)}) \tag{21}$$

Note: To obtain $I_{sc(7)}$ equation (9) with E and T the desired irradiance and temperature conditions.

Chapter 3

METHODOLOGY

3.1 Overall data collection

The data collection for both repeatability and translation procedure validation studies are shown in figure 5 below. There are three major parts of the whole research. The purpose of this study is to establish a streamlined testing procedure that would be repeatable over long periods of time. Several experimental runs were performed in year 2009 on a clear sunny day with five (5) irradiance screens and five (5) and matching reference cells. Three independent sets of outdoor measurements were obtained and compared in terms of percent deviation from each measurement. The acceptable limit is 1%. The results are discussed in Chapter 4.

The second goal was to validate the different translation procedures as outlined by IEC 60891 and NREL. The purpose of this study is to determine the accuracy of each of the four (4) translation procedures. The experimental run was done middle of year 2010 with only one independent data collected. There were some modifications implemented in the 2010 data collection and these were: (i) a certain minimum distance (2 inches) shall be maintained between module surface and the screen surface; (ii) the reference cell shall be kept outside the screen (calibrated screen) as opposed to inside the screen (uncalibrated screen); and (iii) the air mass shall not exceed 2.5. Four (4) translation procedures were used, three (3) of which are from IEC 60891 standard and one (1) developed by NREL. The procedure for translation for each method is outlined in the succeeding sections of the methodology section.

Finally, a temperature-irradiance matrix for P_{max} and other performance parameters were obtained using the four (4) translation procedures.

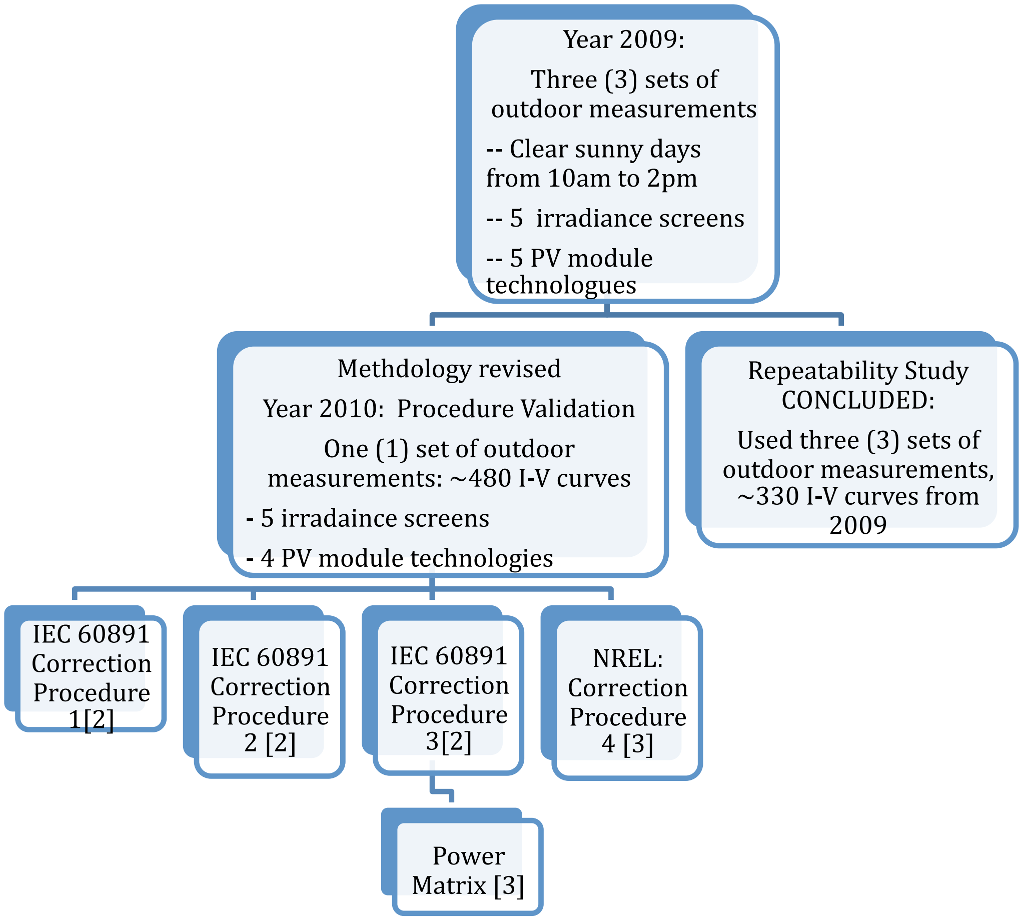


Figure 5. Overview of data collection and processing

3.2 Test set-up and equipment

- Outdoor measurement condition
    - Sunny days: clear sunny days (> 90% direct normal irradiance) at lower air mass values (< 2.5) shall be used.

- Test equipment
  - Two-axis tracker: a manual or an automatic 2-axis tracker shall be used for mounting the test module.
  - Curve tracer: a fast (< 1 second) current-voltage curve tracer to minimize issues related to changing irradiance, spectrum and module temperature.
  - Reference cell: a matched technology (or spectral response) reference cell to practically eliminate spectral mismatch error (for c-Si and CIGS modules, use c-Si reference cell; for CdTe modules use either CdTe or GaAs reference cell; for a-Si modules use filtered c-Si reference cell).
  - Mesh screen: a transmittance calibrated neutral-density mesh screen with good spatial uniformity to change the irradiance level (to improve the light uniformity on the module, a 1.5 inch minimum distance shall be maintained between test module surface and mesh screen; to accurately measure the irradiance without screen thread shadowing, the small area reference cell which is used in the test set up shall be kept outside the screen).
  - Pre-cooled module: a pre-cooled test module to naturally change the module temperature while exposed to sunlight

(to obtain data at the temperature of 75^{o}C, a thermal insulating foam on the backside of test module can be inserted.

3.2.1 Set-up for Year 2009 data collection

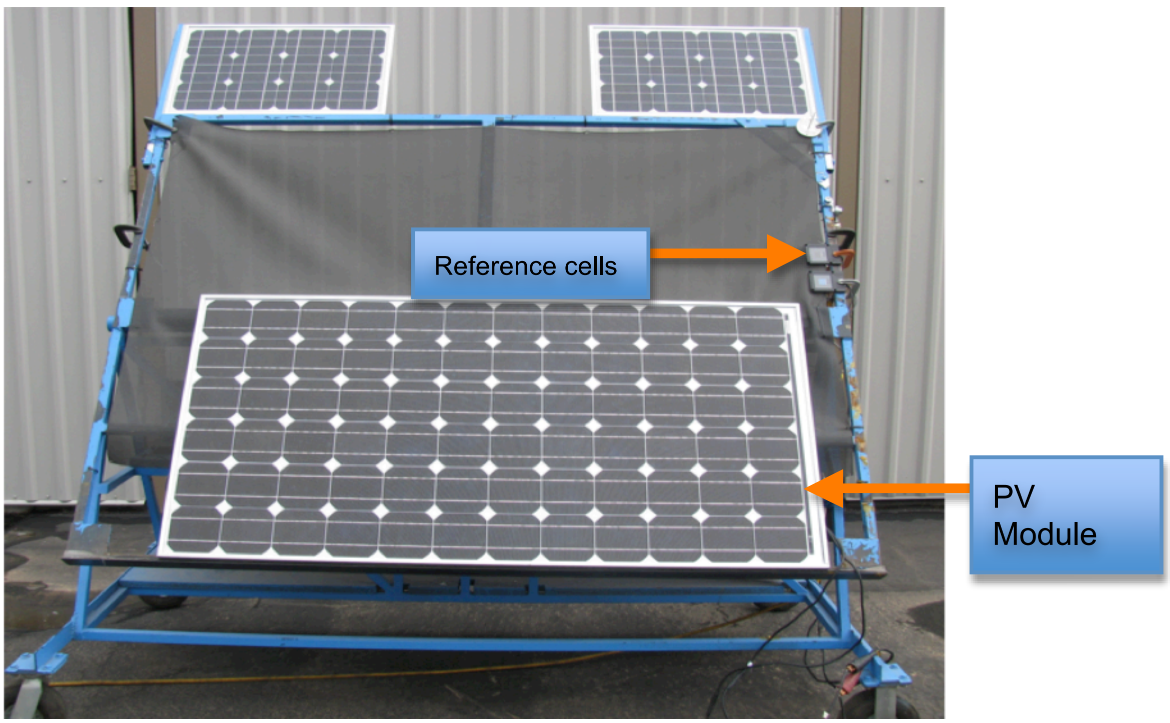


Figure 6: Test set-up for Repeatability Study1. Without irradiance screen

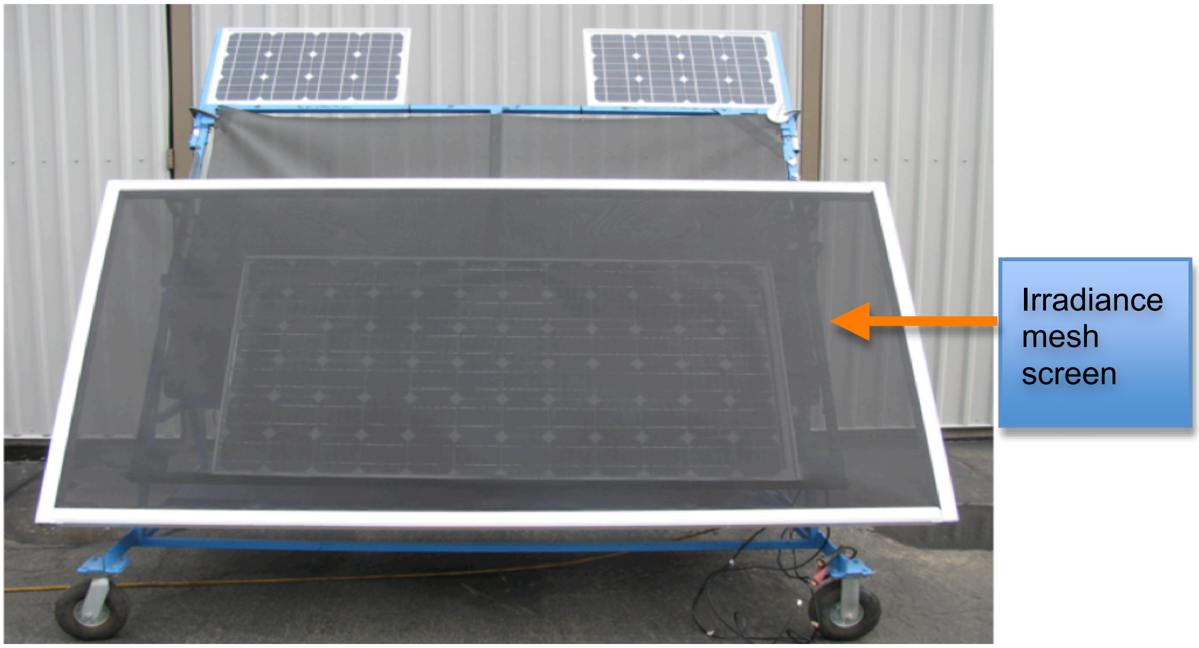


Figure 7: Test set-up for Repeatability Study 2. WITH irradiance screen

Referring to Figure 7, five mesh screens were used to vary the irradiance level on the test modules. The module and the screen were mounted on a manual 2-axis tracker.

These screens are designated as S-100 (smallest opening screen providing approximately 10% transmittance), S-200, S-400, S-600 and S-800 (largest opening screen providing approximately 80% transmittance). The dimension of each mesh screen used was 100”x50”. The mesh screens are made of vinyl coated fiberglass typical to a sun-screen and framed in aluminum bars for stability. These screens were purchased from Phifer Incorporated, Tuscaloosa, Alabama.

3.1.2 Set-up for Year 2010 data collection

The set-up for the translation procedure validation had some minor changes to be able to address the non-uniformity of the screen when the distance from the module surface is zero (0) inches. With this data collection, a distance was set ~2inches from the surface of the PV module. Also, the set up shows that the reference cells are outside of the screen. These were the two major changes from year 2009 data collection. The PV module and screen were mounted on an automated 2-axis tracker for more accurate tracking.

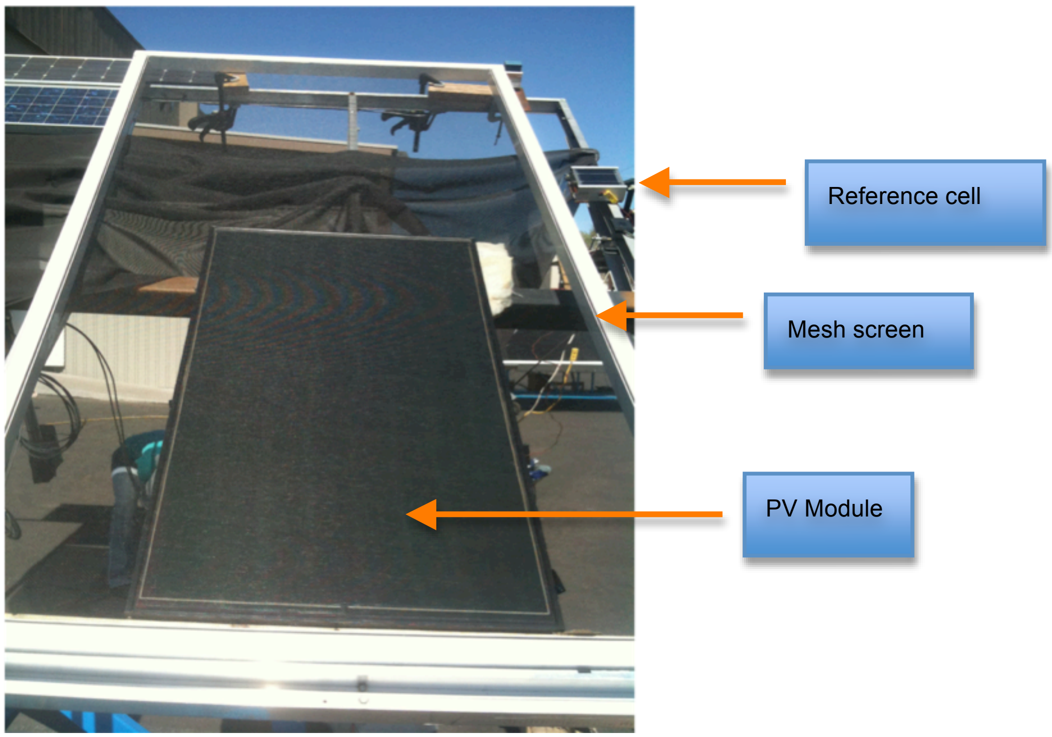


Figure 8. PV Module and mesh screen set-up for 2010 data

In addition, an insulating material was attached to the back surface of the module such that the module heats up to more than 75°C as what is required by the performance matrix.

3.1.3 I-Curve Tracer set-up

To measure the I-V curve of the module an equipment called I-V Curve Tracer is used, in this particular case, Daystar DS-100C. A schematic of the I-V curve tracer connecting to the PV module is shown in Figure 9.

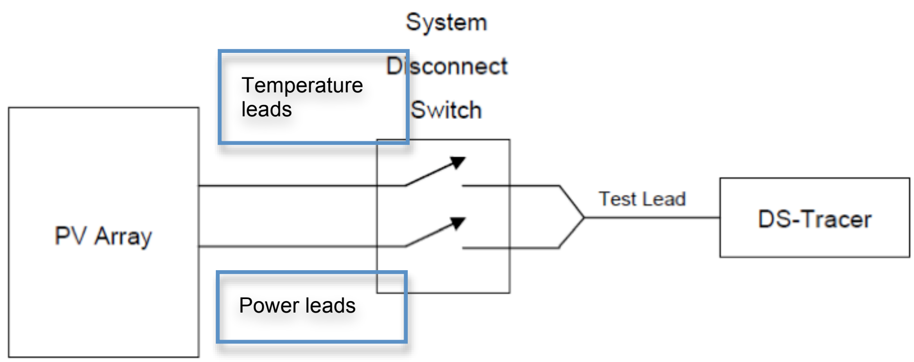


Figure 9. Schematic of PV module to the I-V curve tracer

The I-V curve output is fed into a laptop with the I-V PC software which came along with the Daystar DS-100C curve tracer. The actual set-up is shown in Figure 10 with the laptop connected to the I-V curve tracer equipment.

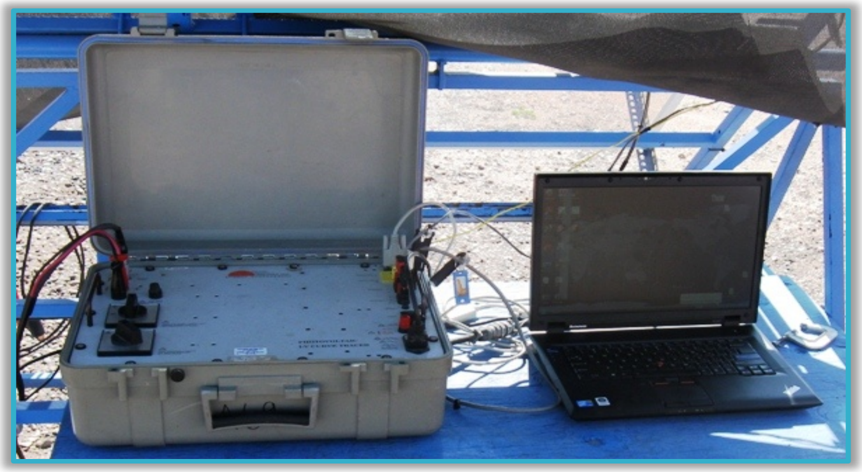


Figure 10. I-V Curve tracer Daystar DS-100C connected to laptop.

3.3 Data collection for the repeatability study and translation validation

The repeatability study was done in 2009 with three independent experimental runs spread throughout a few months to capture day-to-day and month-to-month variability. These measurements were carried out on clear sunny days with modules placed on a 2-axis tracker when the air mass was less than 2.5. Table 2 summarizes the experimental strategy and these measurements were carried out for four commercial flat plate module technologies of c-Si, a-Si, CdTe and CIGS. Reference cells with matching or close to matching the PV module technology were used to measure the irradiance levels. To vary irradiance levels, different mesh screens with varying light transmittance were used. To obtain data at various temperatures, the test module was pre-cooled in an air conditioned wooden cabin or a cooling reliability chamber. On thermocouple attached to the backside of the PV module was used and measurements were taken as the PV module naturally warms up.

Table 2. Test module technology and matching reference cells

Test Module Technology	Reference cell Technology	
	Primary Reference Cell	**Secondary Reference Cell**
Monocrystalline Silicon (mono-Si)	Mono-Si	Mono-Si
Amorphous Silicon (a-Si)	Mono-Si (filtered)	Mono-Si
Cadmium Telluride (CdTe)	GaAs	Mono-Si
Cadmium Indium Gallium diSelenide (CIGS)	Mono-Si	Mono-Si

A block diagram of the data collections done in Year 2009 Year and 2010 are shown in Figures 10 and 11 to illustrate how the processes were carried on. Figure 10 is the old methodology with reference cells under the mesh screen with zero (0) clearance from the surface of the PV module.

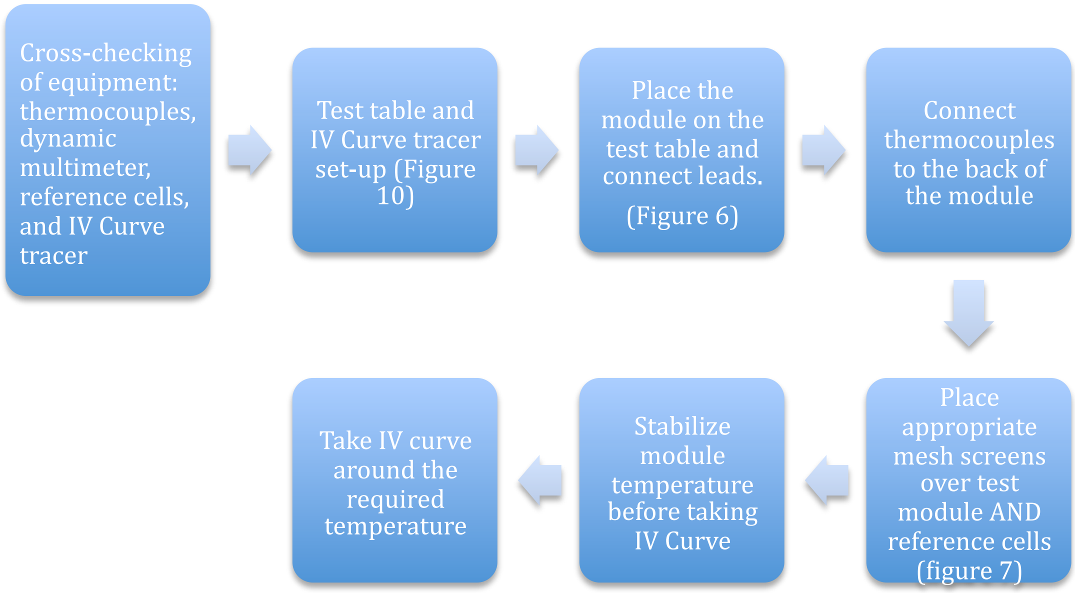


Figure 11. Year 2009 Data collection.

Note: Old methodology with reference cells under mesh screen and zero (0) distance.

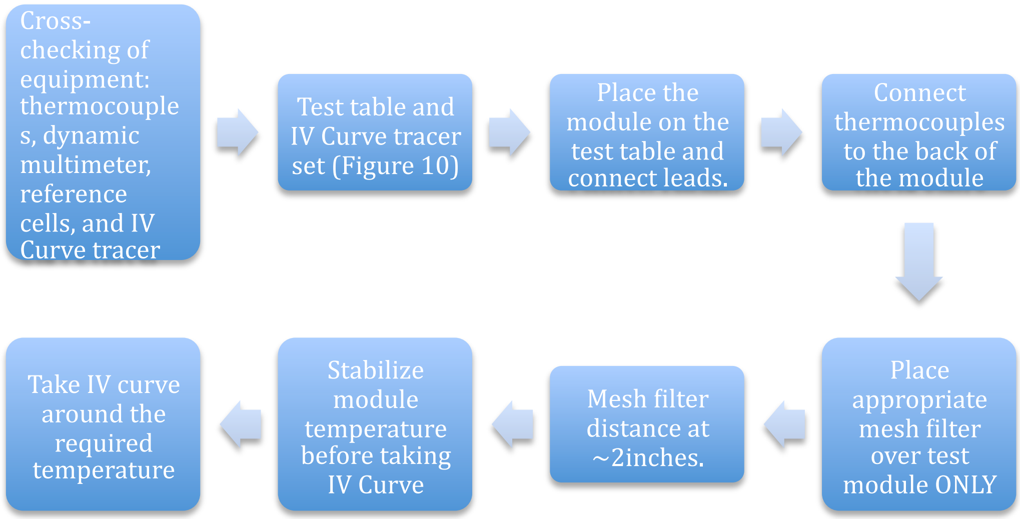


Figure 12. Year 2010 data collection.

Note: New methodology with reference cells outside mesh screen and ~2 inch distance.

Figure 12 above outlines the process flow for the new methodology.

3.3.1 Calibration of the mesh screens

Calibrating the mesh screens serves two purposes. The first one is to explore the variation in irradiance levels because of the non-uniform grids which would translate to non-uniformity of irradiance levels absorbed by the PV module and reference cells. The second purpose is to define the % transmittance per mesh screen such that the screen will no longer cover reference cells during measurements.

The screens were divided into different quadrants. Each quadrant represents the location of the reference cell when irradiance levels were obtained. To gather voltage values, a datalogger is used called Campbell Scientific CR1000 with leads connected to the reference cell. The diagram below explains the locations where data was collected. The actual set-up is also shown in Figure 13.

Figure 13. Reference cell location along the screen area

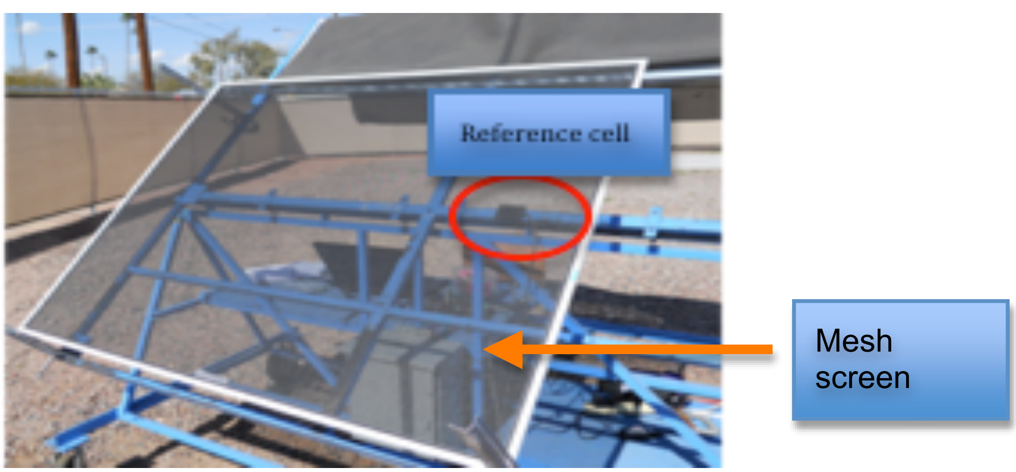


Figure 14. Screen calibration set-up with reference cell and screen

3.4 Data processing for translation procedures validation

This section applies to a step-by-step description of each of the translation procedures in terms of processes followed during calculations. Also, these procedures are a reflection of what were discussed in the literature review section for each of the translation procedures. It should be noted that a program called JMP by SAS is used for most of the complex interpolations and graphical representations.

3.4.1 IEC60891 Procedure 1 and 2

The block diagram below in Figure 15 describes overall calculation procedure for Procedure 1 in the IEC60891 standard. Similar process is employed on Procedure 2 except for an additional constant, a.

Figure 16 describes the calculation of the parametric constant R_s, series resistance. The value of κ or curve correction factor for Procedure 1 is obtained by following the steps in Figure 17. Procedure 2, on the other hand, has three parametric constants R'_s, κ', and **a** (irradiance correction factor for $V_{oc)}$ described in the procedure. R'_s and κ' can be obtained by following the process flows described in Figures 17 and 18. The additional constant **a** is simultaneously obtained with R'_s using the process flow described in Figure 18.

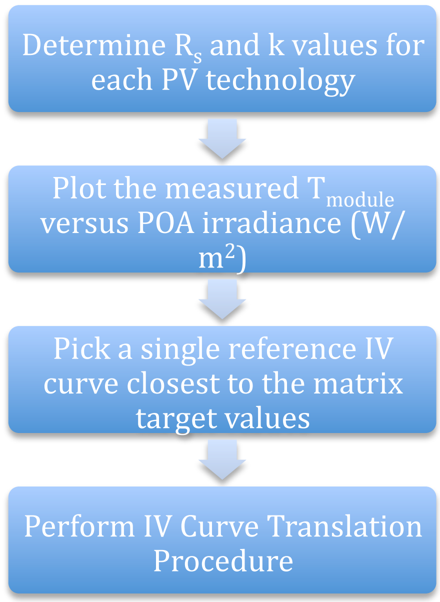


Figure 15. IEC 60891 Procedure 1 block diagram

Determination of R_s value for IEC 60891 Procedure 1

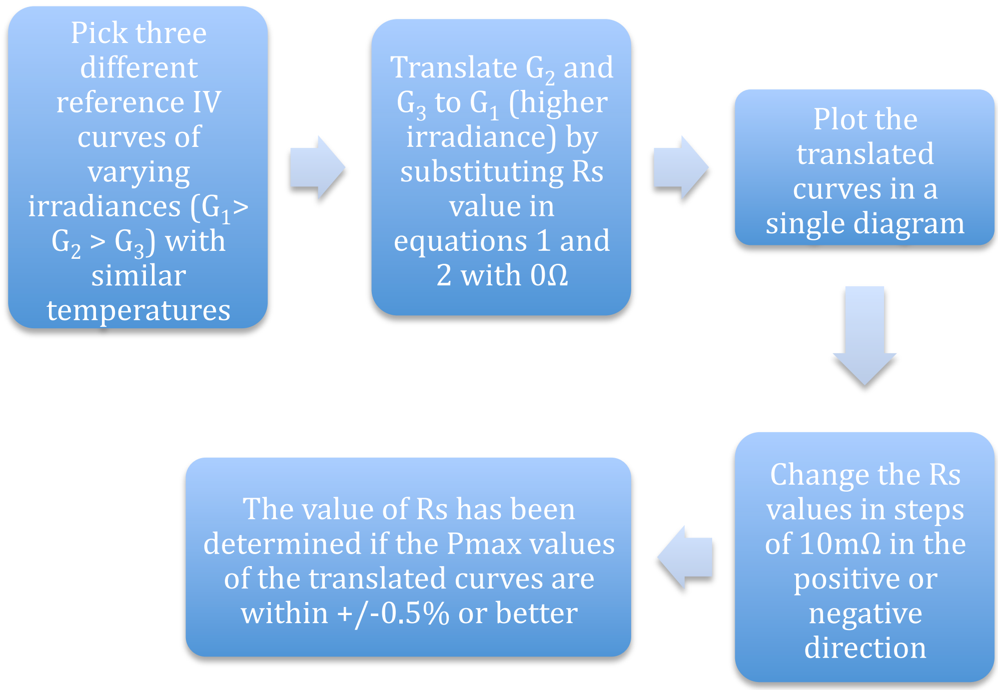


Figure 16. R_s value calculation for Procedure 1

Determination of κ and κ’ value for IEC 60891 Procedures 1 and 2

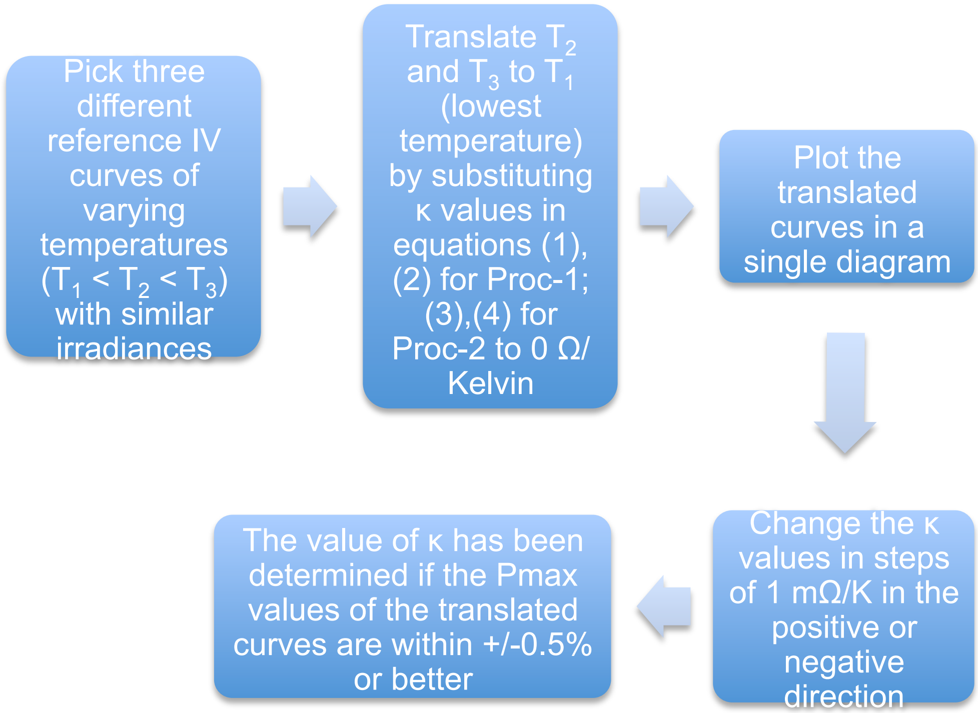


Figure 17. *κ and κ’ value* calculation for Procedures 1 and 2

Determination of R'_s and a value for IEC 60891 Procedure 2

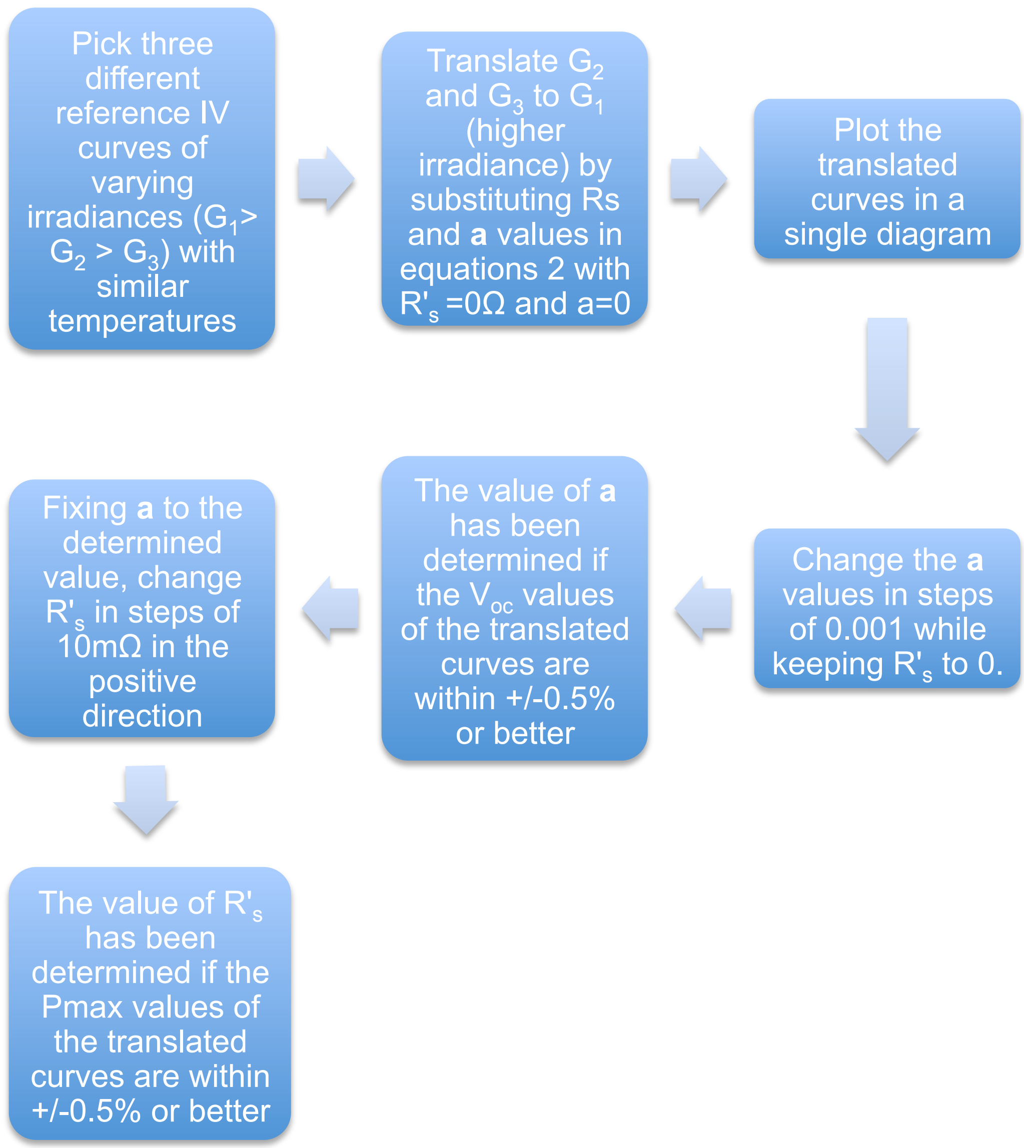


Figure 18. R'_s and a values for Procedure 2

3.4.2 IEC 60891 Procedure 3

IEC 60891 Procedure 3 is mainly based on linear interpolation/extrapolation of two or more measured reference IV curves. This method does not require any correction factors or curve fitting parameters as it only utilizes measured reference IV curves to desired temperature and irradiance values through translations.

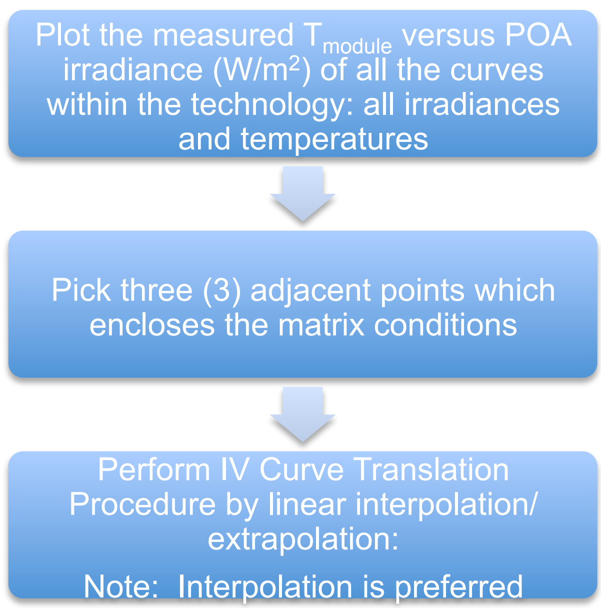


Figure 19. IEC 60891 Procedure 3 process flow

Figure 19 described the process flow for performance the translation procedure starting with three (3) reference measured curves with the point enclosed within these three I-V curves to describing a linear interpolation. It is noted that extrapolation beyond the three (3) reference measured curves may induce greater errors. The equations for this procedure can be found in Chapter 2, literature review for Procedure 3.

3.4.2 Procedure 4 – NREL Method

NREL Method developed by Marion,et al [3] makes use of four (4) reference curves at two irradiance levels and temperature levels with the translated method enclosed within those four (4) curves. The block diagram below outlines the step-by-step process of the procedure. Figure 20 below summarizes the whole translation procedure as what was detailed out in Chapter 2 Literature Review.

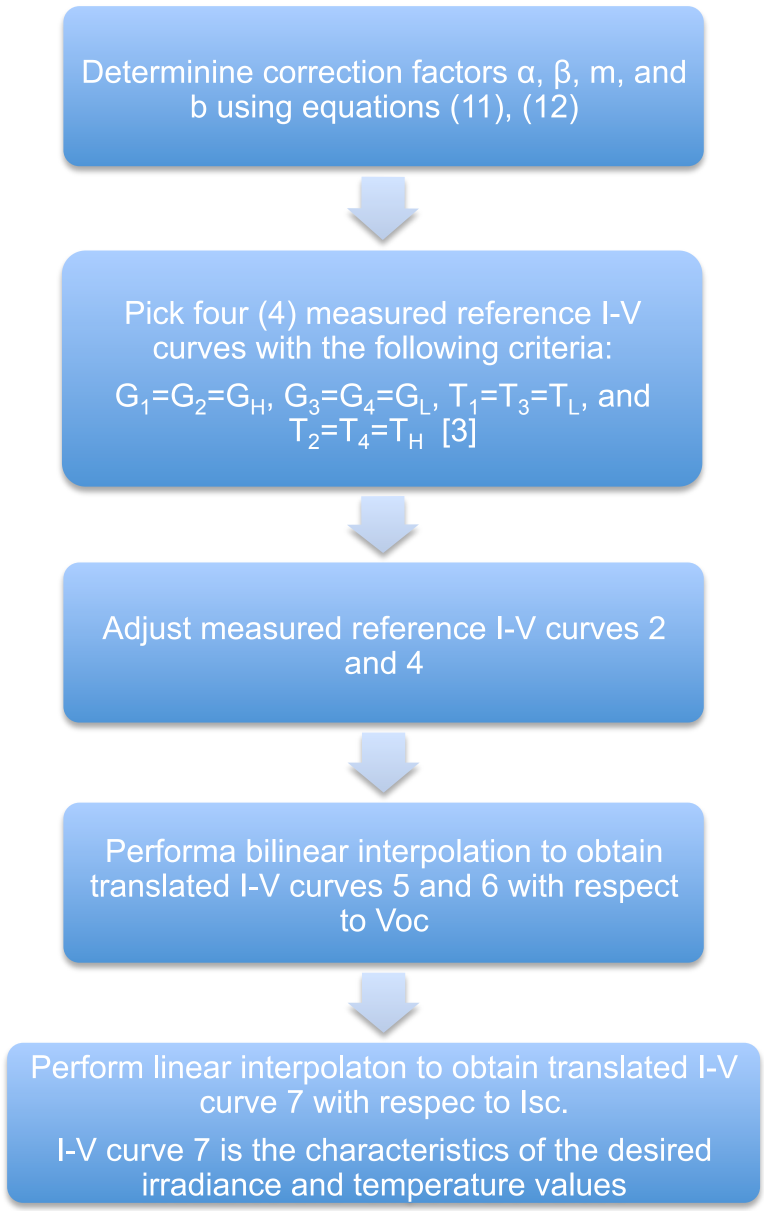


Figure 20. Procedure 4- NREL Methods process flow

Chapter 4

RESULTS AND DISCUSSION

The measurements were carried out on clear sunny days with modules placed on a 2-axis tracker when the air mass was less than 2.5G. To measure incident irradiance on the test modules with minimized spectral mismatch errors, appropriate reference cells were used as shown in Table 2. There are three major objectives to this research as outlined in Chapter 1. The first objective, repeatability of measurements, is to establish a streamlined testing procedure which would be a repeatable over a long period of time. The second main objective, validation of translation procedure accuracy, is to determine the accuracy of each of the four (4) translation procedures as an individual measured data point is translated and then measured output characteristics are then compared in terms of average % error and RMSE as indicators. The final output of the research is to generate the temperature-irradiance matrix specifically P_{max}, and other performance parameters for some translation procedures.

4.1 Repeatability of outdoor performance measurements

4.1.1 Transmittance of Un-calibrated mesh screens

The un-calibrated mesh screens can be used to reduce irradiance levels on the test module; however, this method requires the calibrated reference cells be placed under the screens. Since the area of a typical reference cell is very small (less than 1” x 1”), the reference cell output is very sensitive to the spatial uniformity of the mesh screen.

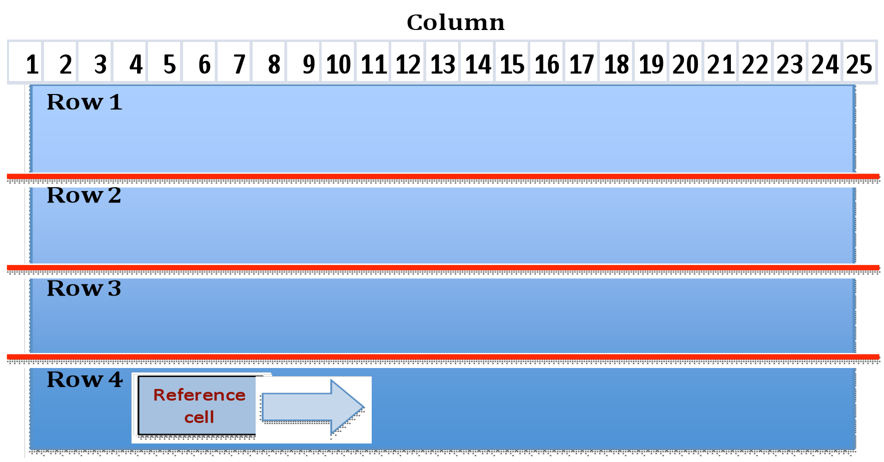
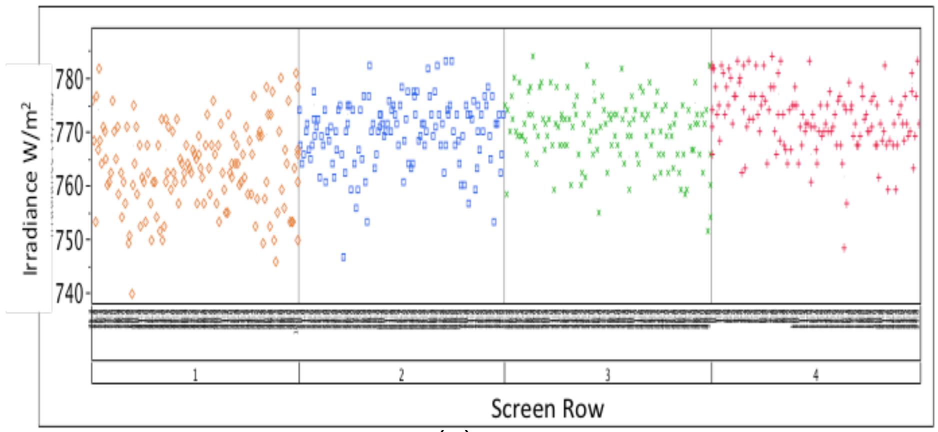
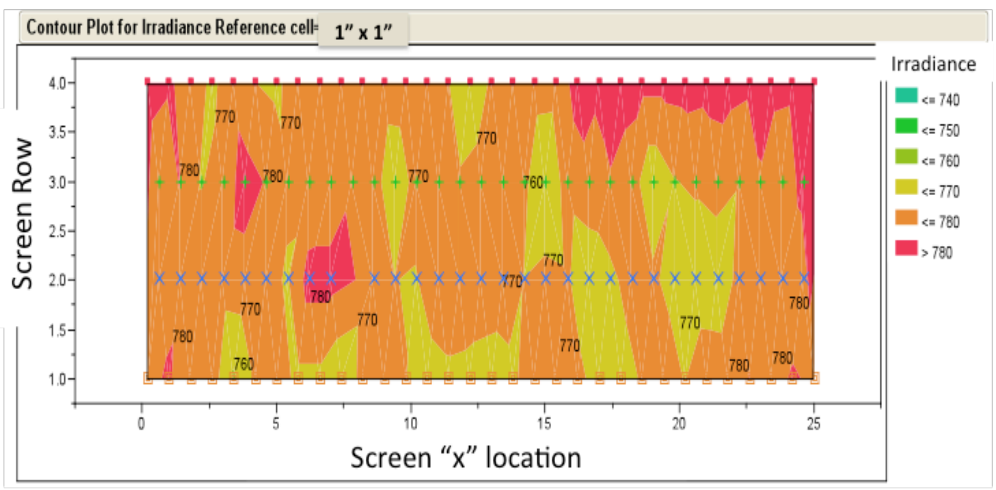


Figure 21: Division of a mesh screen for spatial uniformity determination



(a)

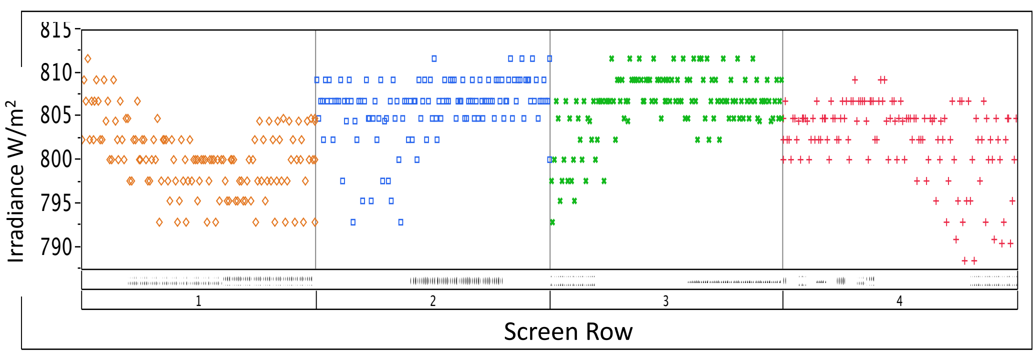


(b)

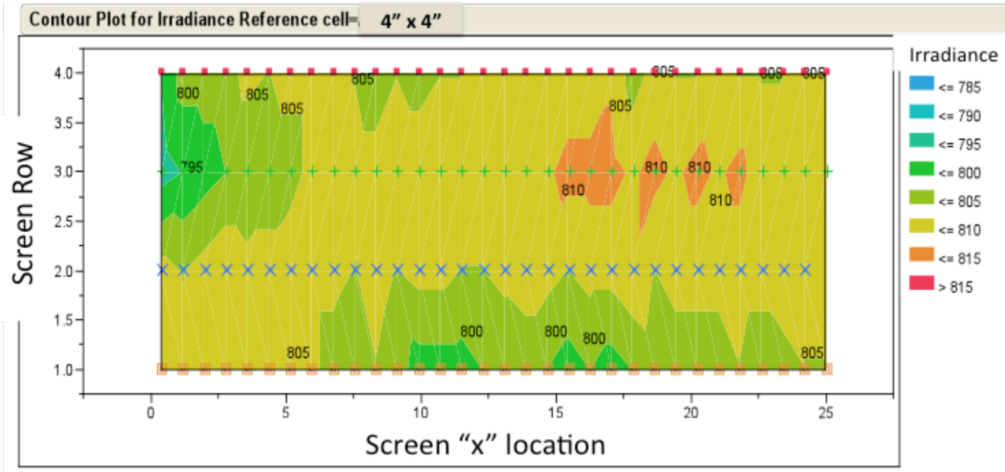
Figure 22: a) Control Chart b) Contour map showing uniformity mapping of S-800 screen using 1"x1" polycrystalline reference cell

(Zero inch distance between the cell and screen)

The spatial non-uniformity influence on the irradiance measurement can be reduced if the 1”x1” reference cell is replaced with a 4”x4” reference cell. The results obtained with the 4”x4” cell are shown in Figure 23. The lower standard deviation with 4”x4” reference cell (7.5 W/m^2) as compared to 1”x1” reference cell (4.7 W/m^2) further indicates an improvement in measurement accuracy with 4”x4” reference cell. The 4% difference in irradiance between Figures 22 and 23 is attributed to the difference in incident irradiance at the time of testing. The irradiance measurement error due to spatial non-uniformity can be further reduced by increasing the distance between the screen and test/reference device, and it is shown below.



(a)



(b)

Figure 23: a) Variability chart b) Contour map of S-800 screen for 4"x4" reference cell

Note: (Zero inch distance between the cell and screen)

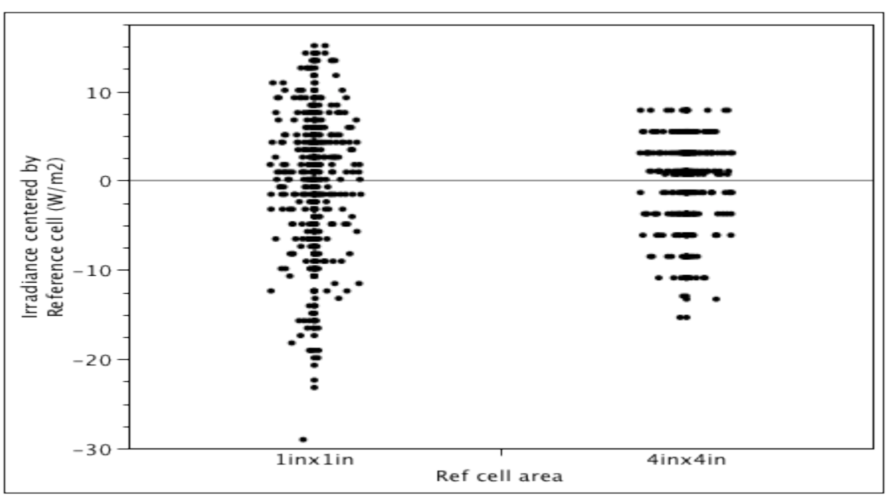


Figure 24: Deviation of data points from the average for small (1"x1") and large (4"x4") area irradiance sensors

Note: (S-800 screen. 0” screen gap from irradiance sensor)

As shown above, the spatial uniformity of the screens has an influence on the irradiance measurements (and hence module performance measurements). One way to reduce this spatial non-uniformity issue to a negligible level is to increase the distance/gap between the module/cell surface and screen. To determine the optimum gap distance between the test device (in this case a 1”x1” reference cell) and screen, the S-800 screen was used. The distances of 1.5, 3, and 6.5 inches were arbitrarily chosen and the collected irradiance data were compared with the zero inch irradiance data. The data was collected at six different locations under each of the screen. About 40 data points were collected at each location leading to a total of about 240 data points for the six locations. The average and standard deviation for these six locations at each of four distances are provided in Table 3. The zero-inch data showed a standard deviation of 12.7 W/m^2 whereas the 1.5-6.5 inch data shows a standard deviation of 4.5-5.7 W/m^2 only, which is less than half of the zero-inch distance condition. A visual representation of the distribution of these 240 data points for each of the distances is shown in Figure 25 (the average is shown by a green line across the data points). Therefore, this study recommends maintaining a minimum distance of 1.5” between the module and screen. The transmittance data obtained on all the screens with a distance of 6.5” is presented in Table 3. The higher standard deviation of the transmittance data with S-100 screen shown in Table 3 could be attributed to a higher spatial non-uniformity of this particular screen.

Table 3: Influence of gap between the screen and irradiance sensor

Disctance (inch)	Number of data points	Mean (W/m^2)	Std Deviation (W/m^2)
0	240	845.599	7.07
1.5	240	841.640	5.72
3	240	838.692	5.51
6.5	240	844.640	4.57

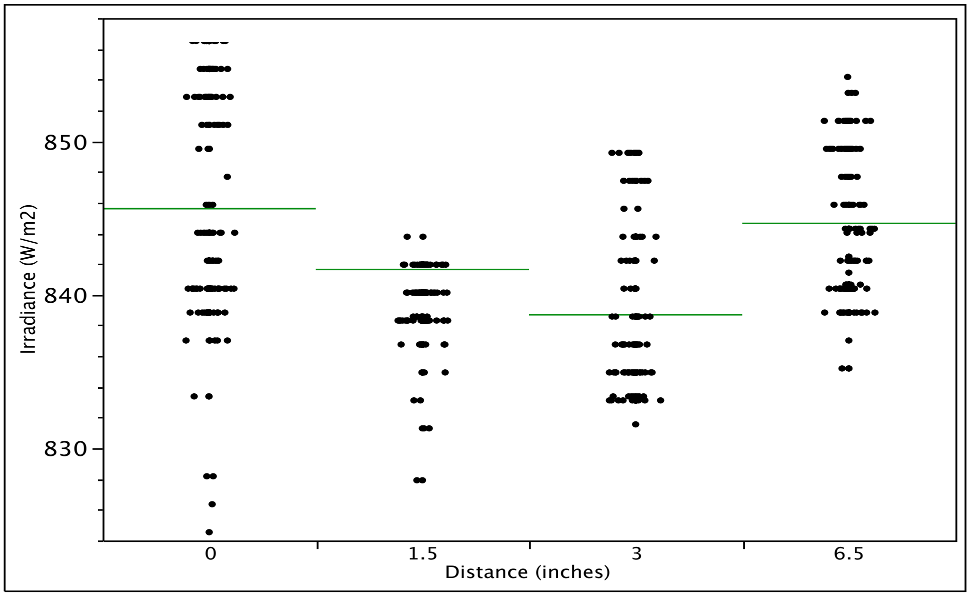


Figure 25: Influence of distance between screen (S-800) and irradiance sensor

Note: (1”x1” reference cell; due to higher sensitivity of small area cell to screen spatial uniformity, the 1”x1” cells was chosen for this experiment)

Table 4: Percent Transmittance Calibration of Mesh Screens

Screen Code	Average Irradiance under the screen (W/m^2)	Average Irradiance outside the screen (W/m^2)	% Transmission	Standard Deviation
S-100	156.16	1074.25	14.54	2.25
S-200	178.27	1063.55	16.76	4.72
S-400	468.15	1067.46	43.86	3.73
S-600	618.01	1075.50	57.46	3.11
S-800	871.58	1086.10	80.25	4.90

Note: Using 1”x1” Reference cell (Screen distance from reference cell = 6.5 inches)

4.1.2 Power rating measurements (zero inch distance)

Based on the results presented above, the worst case repeatability issue is expected to occur when the screen is placed directly on the test module surface (zero inch air gap) and on the 1”x1” reference cell surface (zero inch air gap). The three runs spanned over 75 days between May 16, 2009 and July 30, 2009.

The processing of the output characteristics used a different translation method, which is a modified version of ASTM1036 [5]. The process flow of the translations is outlined in Figure 26. At the time of the repeatability study, translation procedures that were indicated here were not yet explored so this modified method was used. The goal was just to determine if the methodology itself is repeatable and not the translation procedures.

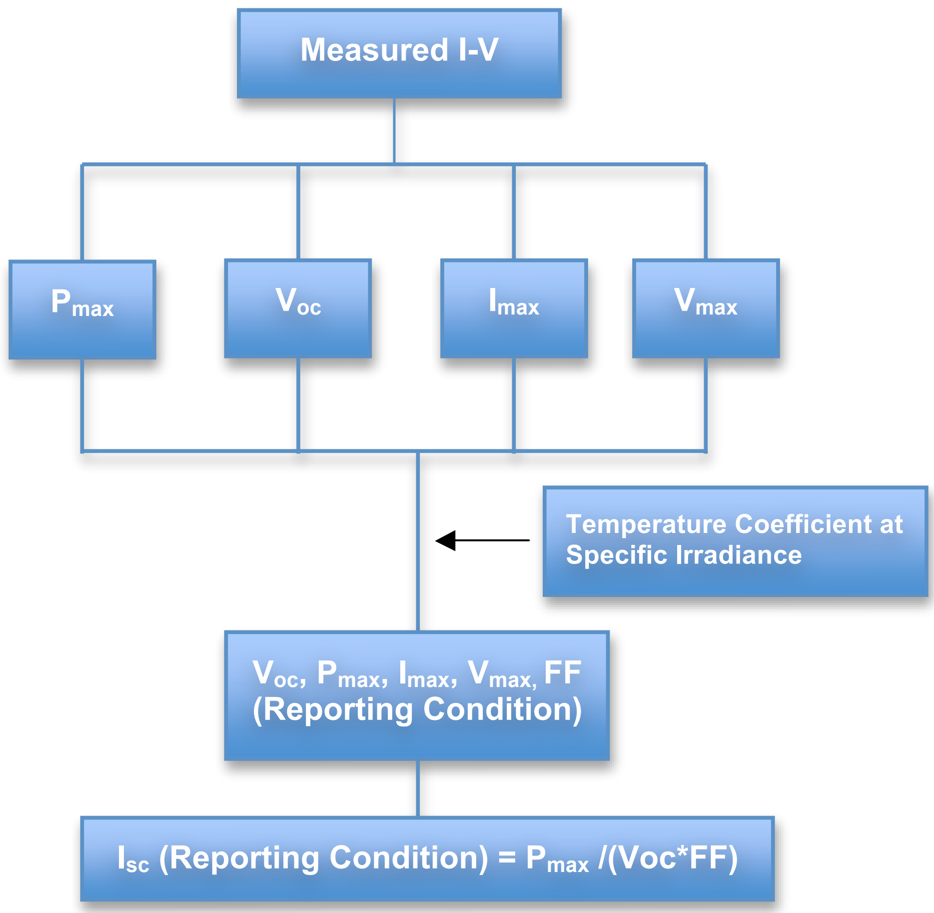


Figure 26. Modified ASTM 1036 [5] process flow

The reporting conditions as indicated in Figure 26 are derived by using temperature coefficients and using the formula below.

$$Voc = V_{oc\text{-}measured} + [TC_{(voc)} * (T - Tm - 2.5)] \quad (22)$$

$$Vmax = V_{max\text{-}measured} + [TC_{(vmax)} * (T - Tm - 2.5)] \quad (23)$$

$$FF = FF_{measured} + [TC_{(FF)} * (T - Tm - 2.5)] \quad (24)$$

$$Pmax = [P_{max\text{-}measured}/G_{measured}]*G_{rc} + [TC_{(Pmax)}*(T - Tm - 2.5)] \quad (25)$$

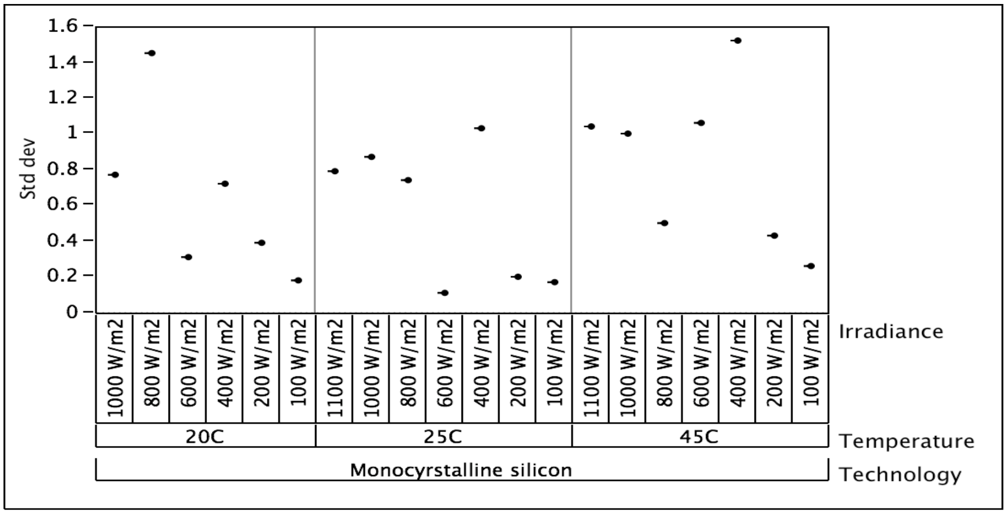
The equations for calculating the individual I-V coordinates are indicated in equations (26) and (27) below for reference. The repeatability results only showed the output measurement characteristics but not the reporting conditions (RC) I-V curve.

$$V = [V_{meas} / V_{oc\ meas.}] * V_{oc\ (rc)} \quad (26)$$

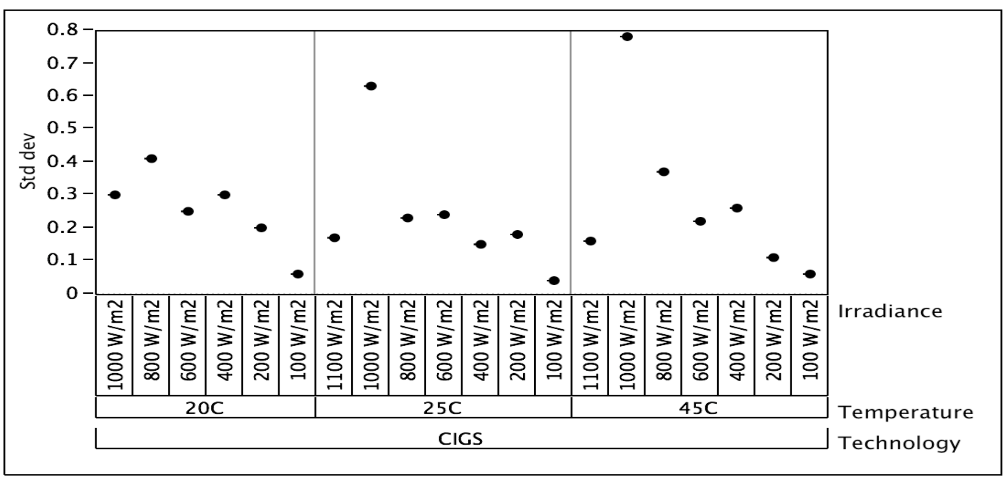
$$I = [I_{meas.} / I_{sc\ meas.}] * I_{sc\ (rc)} \quad (27)$$

For all the four technologies tested, the standard deviation was found to be less than one watt for all but two data points (70 out of 72 data points). Unfortunately, only three runs were available for this standard deviation calculation. The measurement repeatability of the three runs was also determined from maximum Pmax deviation over the average – i.e.,[(Highest Pmax-Lowest Pmax) / Average Pmax] and the repeatability data

(% Pmax deviation from Average) is presented in Figures 27, 28, and 29 all figures. The %Pmax deviation obtained in this measurement repeatability study is higher (as high as 6%) than the acceptable limit of 1-2% and is presented in Figures 28 and 29.



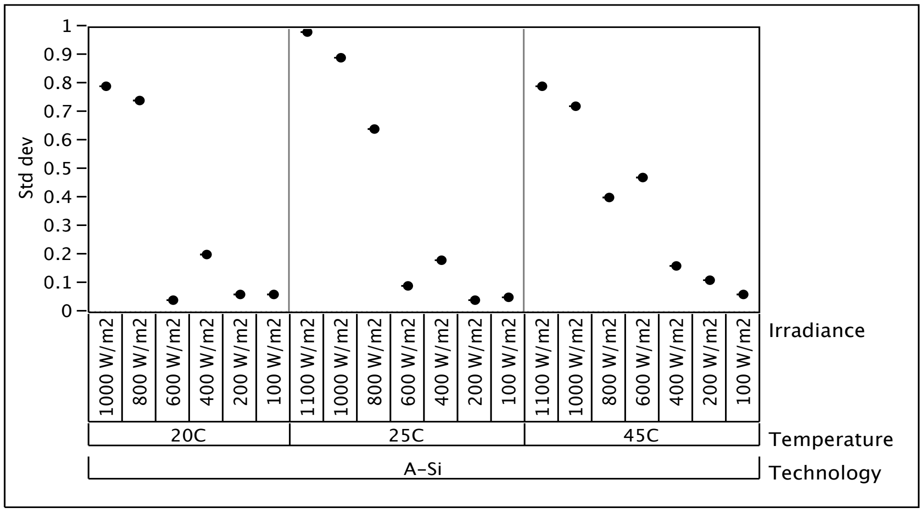
(a)



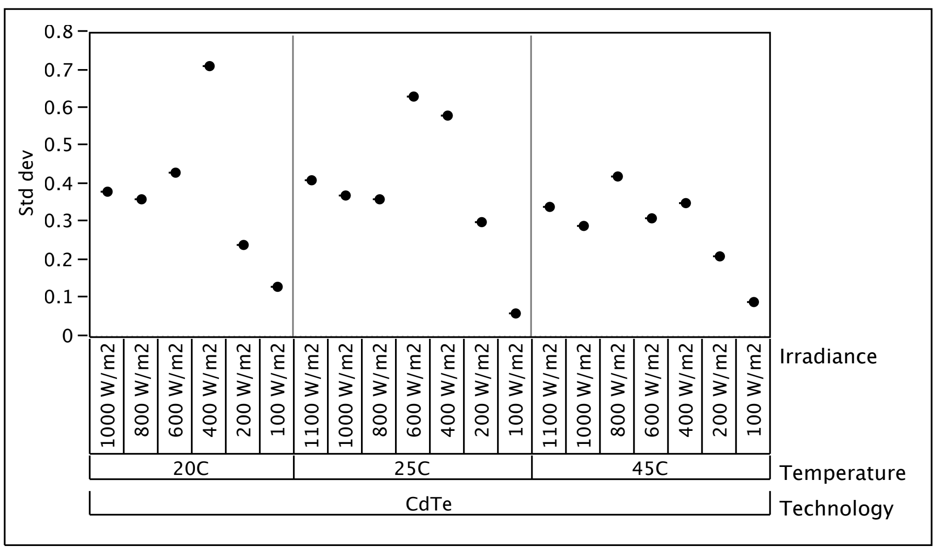
(b)

Figures 27a & 27b: Mono-Si and CIGS Measurement repeatability of Pmax over three runs

(Standard Deviation)

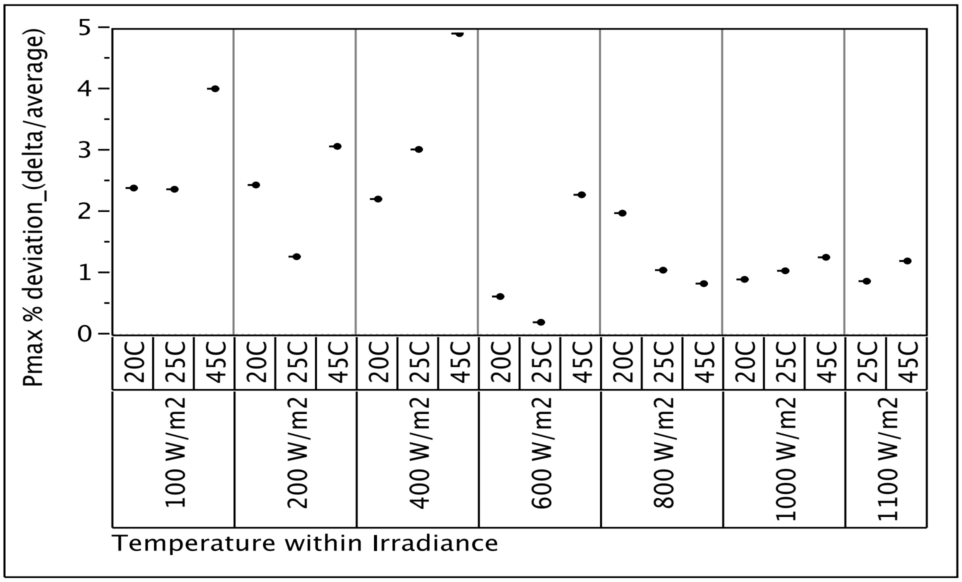


(c)

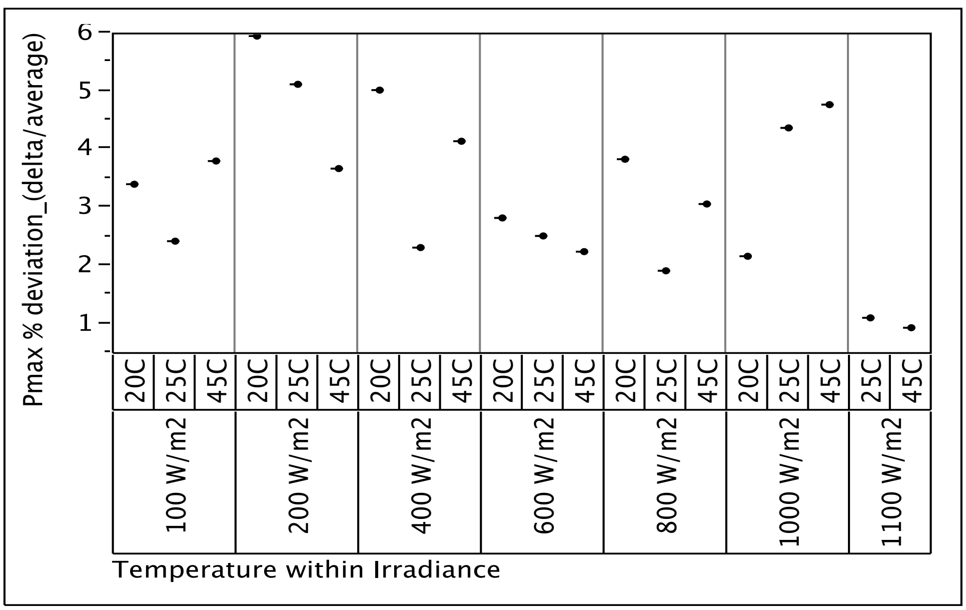


(d)

Figures 27c & 27d: a-Si and CdTe measurement repeatability of Pmax over three runs



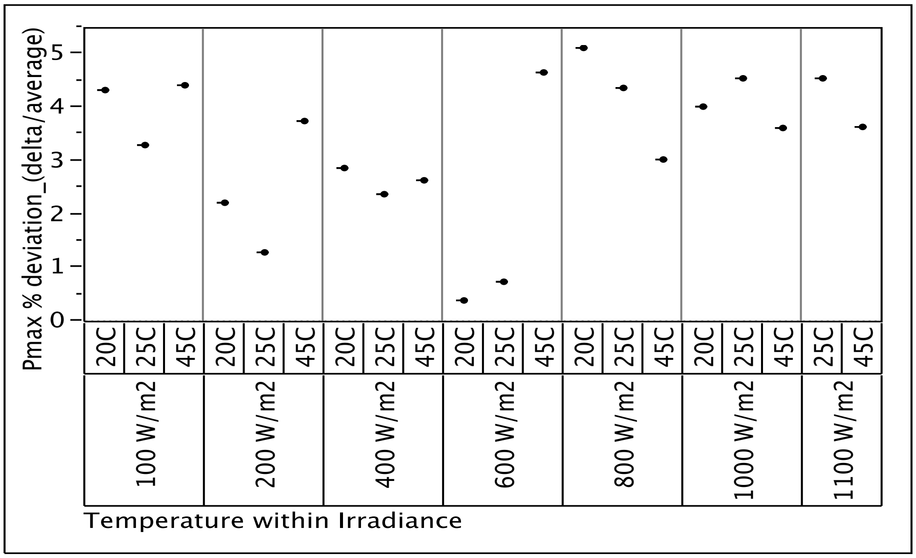
(a)



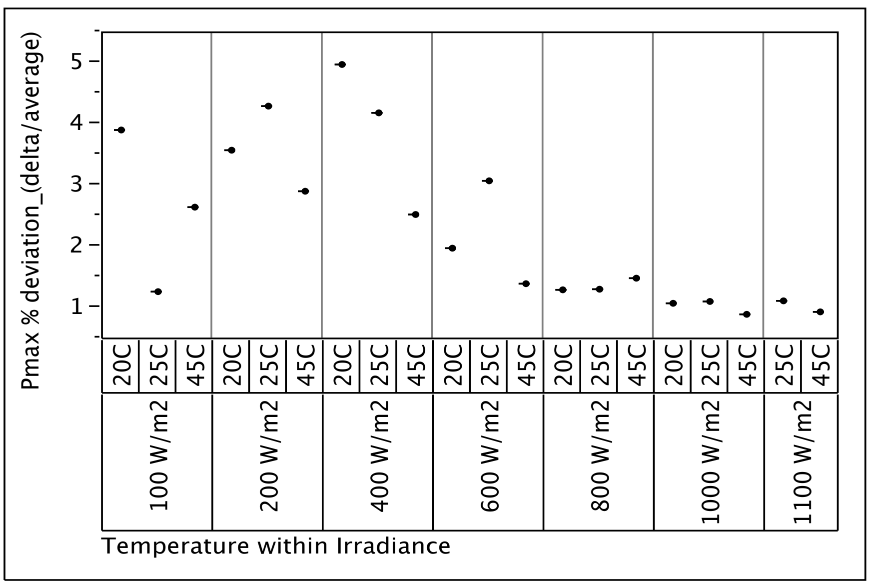
(b)

Figures 28a & 28b: Mono-Si and CIGS Measurement repeatability of Pmax over three runs

Note: (maximum Pmax deviation from average)



(a)



(b)

Figures 29a & 29b: a-Si and CdTe measurement repeatability of Pmax over three runs

Note: (maximum Pmax deviation from average)

4.2 Validation of Translation Procedures

4.2.1 IEC 60891 Procedure 1

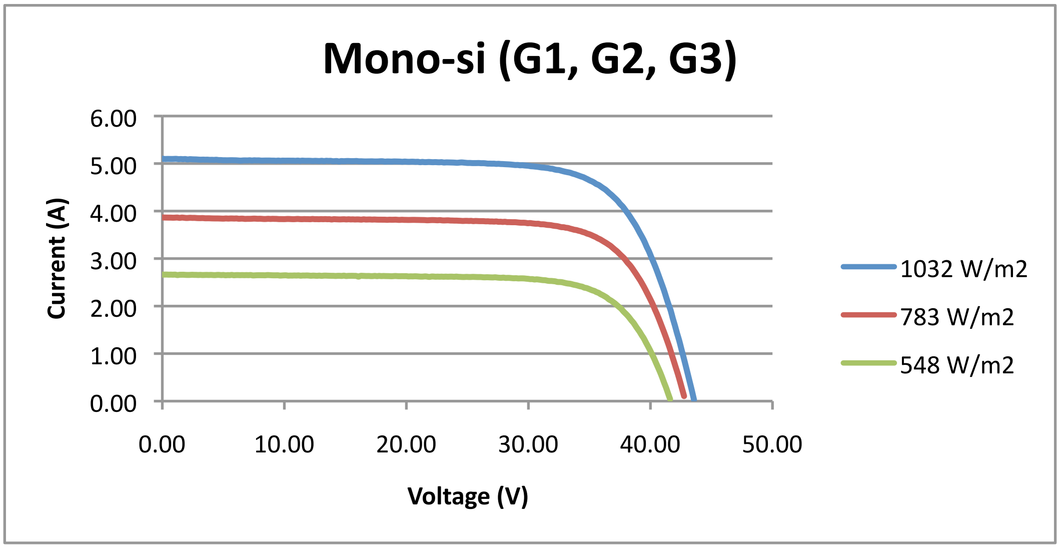
4.2.1.1 Determination of R_s and κ values

Procedure 1 as outlined in the methodology section required the calculation of two constants for each technology. These two constants specifically are: (a) R_s , the internal resistance of the module (b) κ, the curve correction factors.

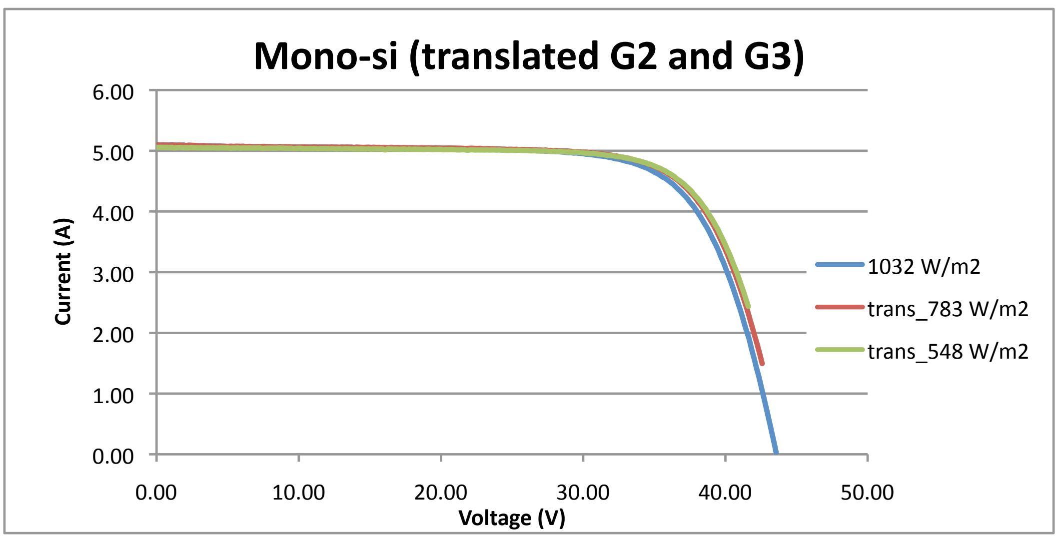
Determination of R_s values

The internal resistance (R_s) is obtained by a trial and error process wherein three different irradiance curves at a similar temperature is translated to the highest irradiance and then back calculated by changing the R_s values in steps of 10mΩ in the positive and negative direction until P_{max} are within +/-0.5% or better.

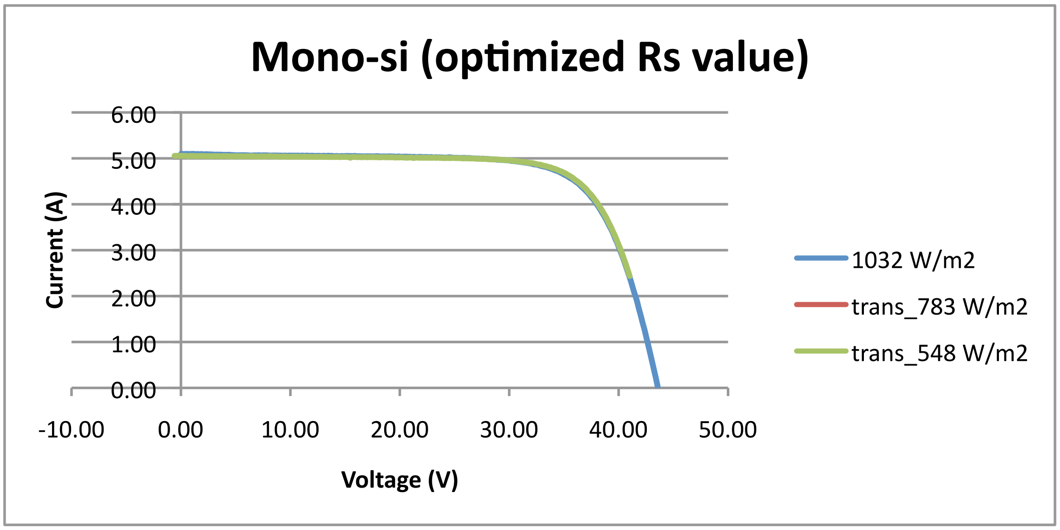
The IV curves are plotted below in Figure 28. For illustration purposes the mono-crystalline module is used as an example.



a) Three (3) different irradiance levels at similar temperatures G1, G2, G3



b) 800 W/m^2 and 600 W/m^2 translated to 1000 W/m^2 with $R_s = 0$



c) All curves are translated at R_s = optimal

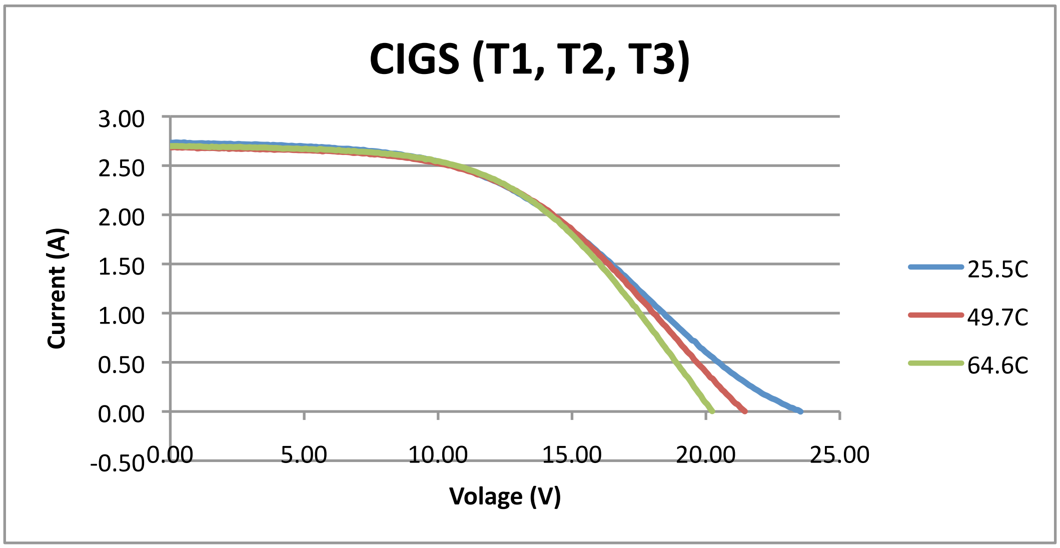
Figure 30 (a), (b), (c). Calculation of R_s values.

Figure 30 (a), (b), (c) are the corresponding I-V curves when translated to different conditions to be able to obtain the value of R_s. Figure 30 (a) shows the measured I-V curves of three different irradiance levels as described in the grahs. Figure 30 (b) are the translated curves with respect to the highest irradiance measured I-V curve when R_s value is set to zero (0) from equations (1) and (2). Figure 30 (c) for all the three curves at the optimal value of series resistance.

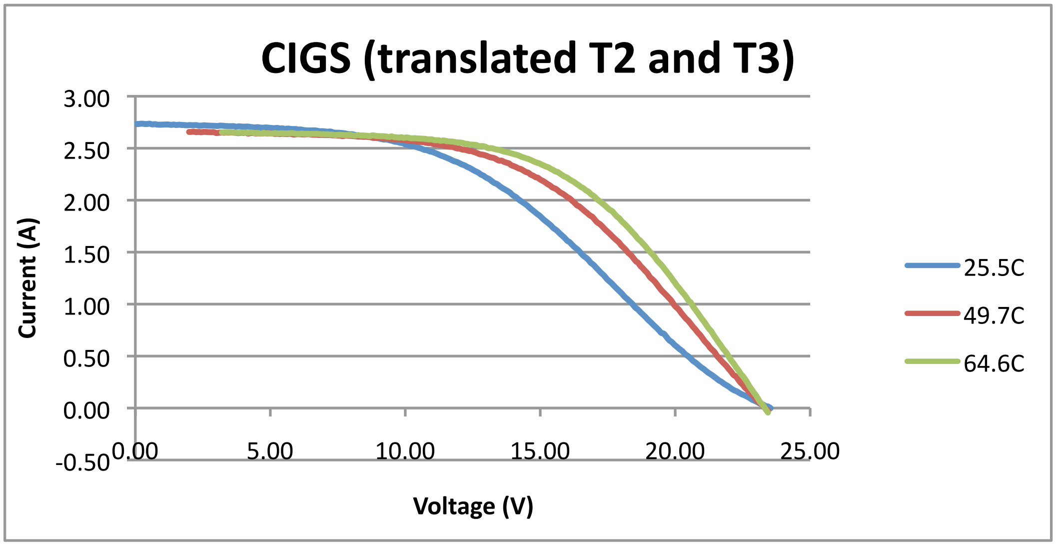
Calculation of κ values

The curve correction factor κ, is obtained by first identifying three different curves with similar irradiance levels at different temperatures. The same procedure is used as determining the R_s value by using trial and error to get to the same output power as translated. Three curves at three different temperatures say T_1 to T_3 with irradiance values not more than 1%. The appropriate κ value is reached once the output maximum power of T_2 and T_3 are within +/- 0.5% or better.

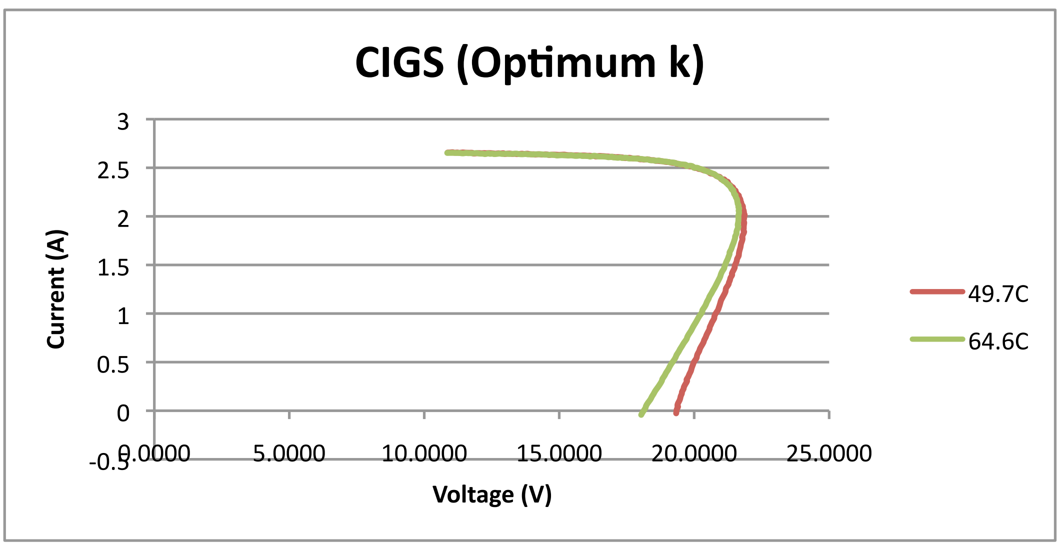
The IV curves are plotted below in figure 29. For illustration purposes the CIGS module is used as an example.



a) Three IV curves with similar irradiance values at different temperatures



b) T2 and T3 are translated to T1 at κ = 0



c) Corrected characteristics with κ = optimal

Figure 31 (a), (b), (c). Calculation of κ values

Figure 31 (a) shows the three measured I-V reference curves at different temperatures but similar irradiances. Irradiance values differ by 1% only. Figure 31 (b) shows the translated T2 and T3 to T1 by substituting into equations (1) and (2) with $\kappa = 0$. The third plot in figure 31 (c) shows translated I-V curves of T2 and T3 when κ is optimal.

The results of the different translations for all the PV technologies are shown below in Table 5 below.

Table 5. R_s and κ values for all PV technologies

Technology	**R_s (Ω)**	**κ (Ω/°C)**
Monocrystalline Silicon	0.25	-0.085
CIGS	3.7	-0.2
a-si	49	-1.6
CdTe	7.5	-1.3

Other methods of calculating R_s

There are three (3) options to calculating Rs values. Two methods are introduced in the following sections for calculating Rs values.

The first method is using three different irradiances G1, G2, and G3 values and solving for the inverse of the slope of the three points chosen from each reference I-V curves. G1 is with the highest value at 1000 W/m^2 , G2 at 800 W/m^2, and G3 at 600 W/m^2. An actual chart is shown below to illustrate this method.

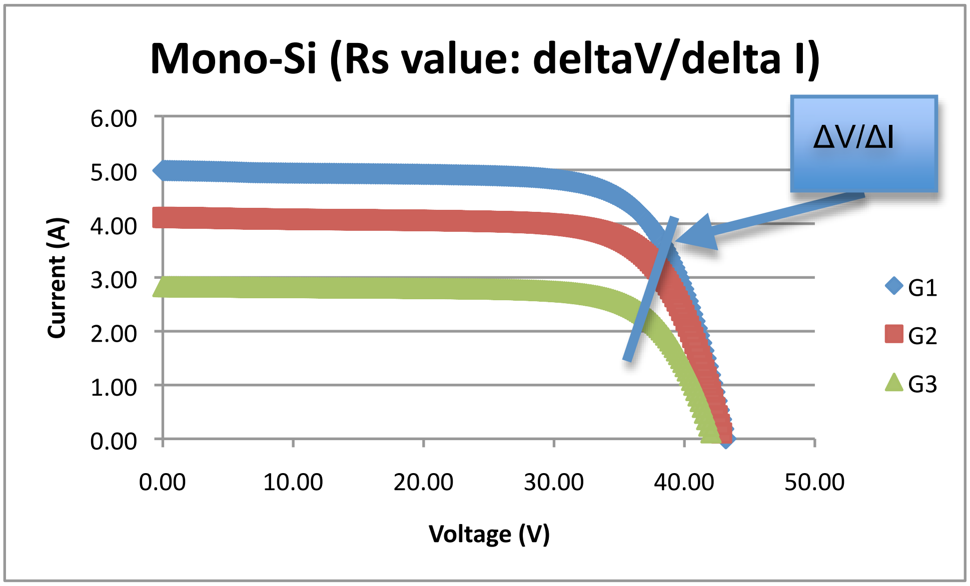


Figure 32. $R_s = \Delta V/\Delta I$ calculation method

In this method as described in Figure 32, a point is chosen below the P_{max} coordinate from the highest to the lowest irradiance. The difference between the voltages and irradiances is the R_s value, which is basically the inverse of the slope from for the three points chosen. The module chosen as an example is the monocrystalline silicon module.

The second method of determining R_s is using one irradiance value and choosing points after the P_{max} close to the V_{oc}. By drawing a line through these points a slope is obtained and the inverse of the slope is considered the R_s value. Taking the negative value of the slope in this case.

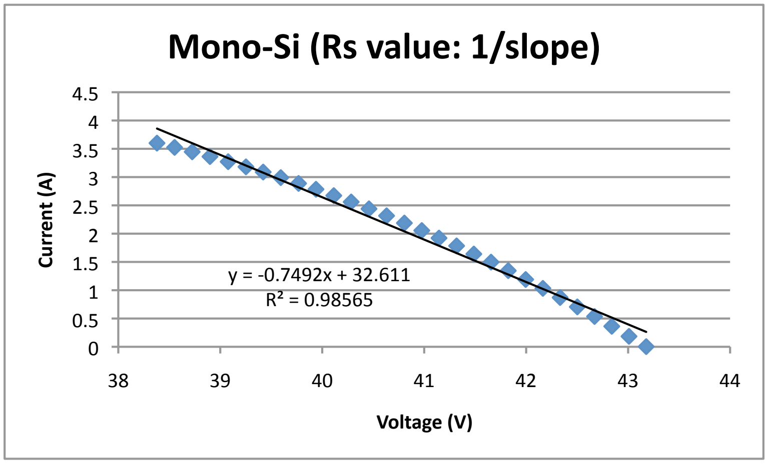


Figure 33. Slope method for R_s calcualtion

The table below summarizes the Rs values of the three different methods explored in obtaining the series resistance per technology.

Table 6. Different methods for calculation R_s values

Technology	Rs Ω (ΔV/ΔI)	Rs Ω (single slope)	Rs Ω(IEC60891)
Monocrystalline Silicon	0.147	1.33	0.25
CIGS	2.08	4.37	3.7
CdTe	5.13	7.87	7.5
a-Si	7.99	34.97	49

4.2.1.2 Validation of Model to Measured values for Procedure 1

The translation procedure is done two times to verify the sensitivity of the models in predicting actual measured values. The first one is to translate from 100 W/m^2 to 400 W/m^2 screen levels and the second one is from 400 W/m^2 to 1000 W/m^2 screen values. The methodology of obtaining irradiance values are dictated by the screen transmittance levels so there are no irradiance values other than the transmittance per screen. Thus, the irradiance levels from one screen to another are more than 20% between two measured values. This makes most of the translation levels more than what is appropriate to each method. With this in mind, the final RMSE values to be used for the final matrix should be the values less than 20% which is a translation within a screen irradiance level. The results per technology is shown in the graph below with the % parameter error (deviation) and the RMSE values shown

Mono-si

The nature of the methodology of using screens only allows a higher percent irradiance deviation so it is limited to translation to the nearest screen value. For the mono-crystalline silicon module used the highest irradiance delta of translation is not more than 37%. The RMSE and average % error is shown in the graph below.

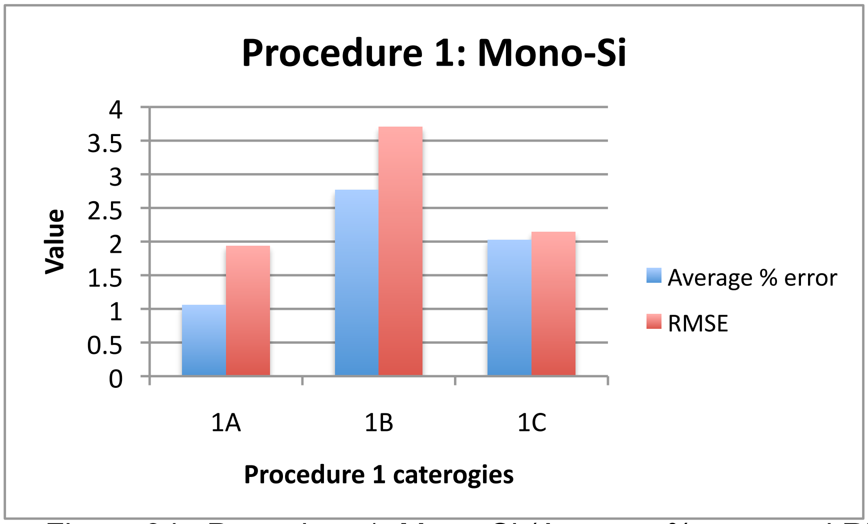


Figure 34. Procedure 1: Mono-Si (Average % error and RMSE)

Legend

1A translation limit: 0.1%, 4°C (data points: 26)

1B translation limit <25%, 6°C (data points: 6, irradiance range of 426 W/m^2 to 1053.5 W/m^2)

1C translation limit <37%, 6°C (data points: 10; irradiance range of 96.82 W/m^2 to 428.19 W/m^2)

For all irradiance levels and temperature levels the highest average % error was less than 3%. The highest RMSE value was 3.6% of translation limit less than 25% of irradiance level difference.

CIGS

For the CIGS module the %irradiance difference to the translated value is kept to 39% which was the limitation of the methodology.

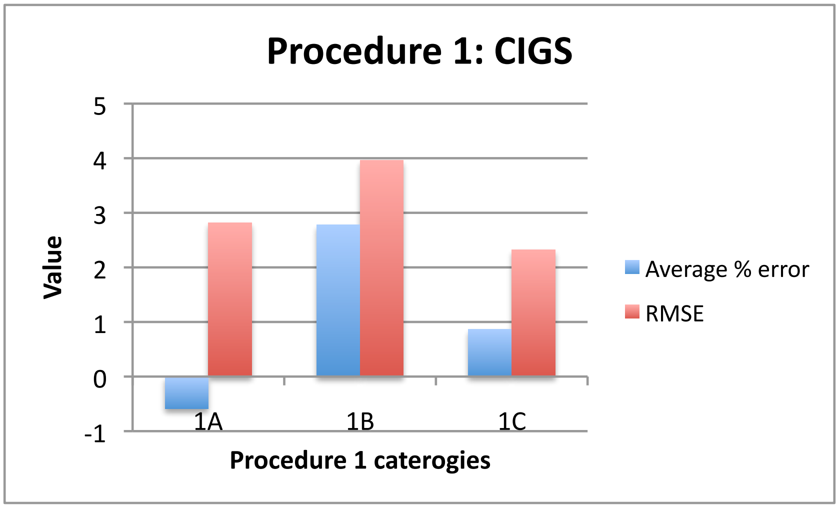


Figure 35. Procedure 1: CIGS (Average % error and RMSE)

Legend

1A translation limit 0.35%, 2.6°C (data points: 12)

1B translation limit < 28%, 4.3°C (data points: 10; irradiance range of 429.2 W/m^2 to 792.999 W/m^2)

1C translation limit < 39%, 3°C(data points: 9; irradiance range of 261.9 W/m^2 to 432.5 W/m^2)

For all irradiance levels and temperature levels the highest average % error was less than 3%. The highest RMSE value was 4.0% of translations limit less than 28% of irradiance level difference.

a-Si

Figure 36 below shows the average % error and RMSE for both the translation limit of less than 1% with less than 0.5% as average % error and 2.1% of RMSE. The translation limit of less than 38% yielded an average error of less than 2%. Other levels were not obtained due to lack of data points for that particular technology.

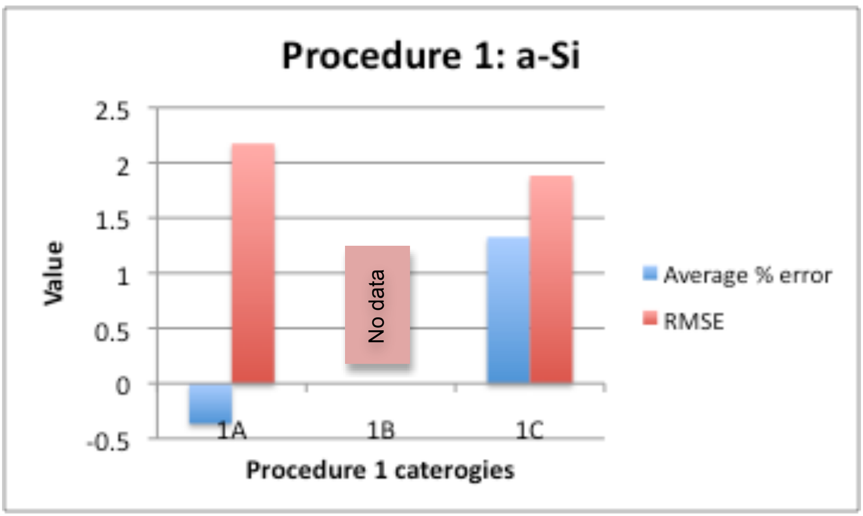


Figure 36. Procedure 1: a-Si (Average % error and RMSE)

Legend:

1A translation limit < 1%, 4°C (data points: 19)

1C translation limit < 38% , 3°C (data points: 8; irradiance range of 263.72 W/m^2 to 430.08 W/m^2)

CdTe

The original module was broken when the experiment was continued in 2010 so a new CdTe module is used with a limited data obtained. The data below only shows the cluster data obtained within a particular mesh screen. Figure 37 shows an average % error of less than 1% with RMSE of less than 2%.

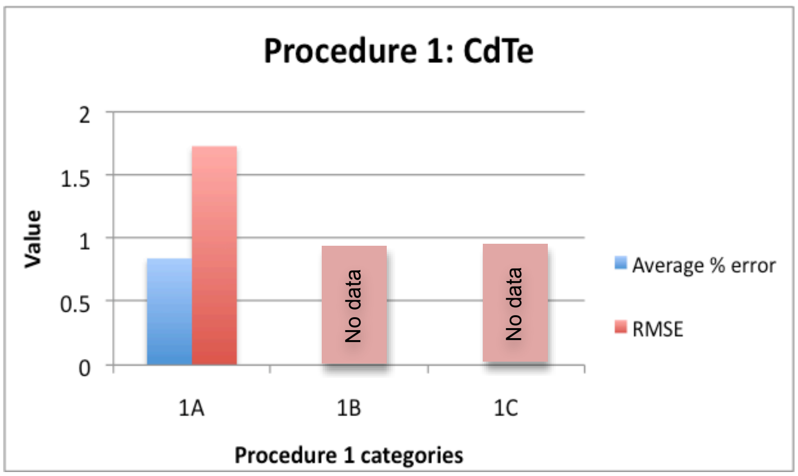


Figure 37. Procedure 1: CdTe (Average % error and RMSE)

Legend:

1A translation limit 0.3%, < 2.2°C (data points: 6)

4.2.2 IEC 60891 Procedure 2

4.2.2.1 Determination of R_s', κ', and a values

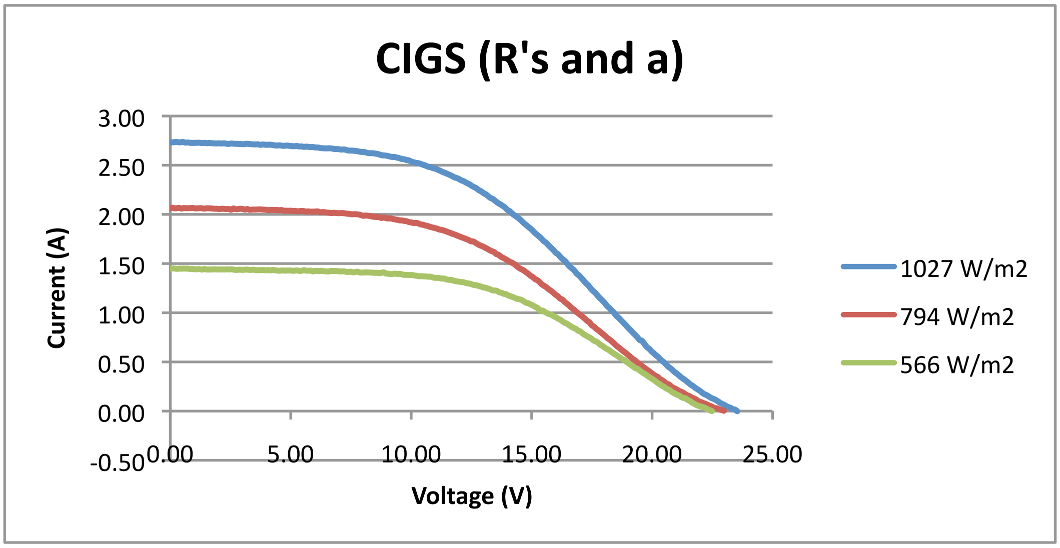
Procedure 2 as outlined in the methodology section required the calculation of three constants for each technology. These three constants are: (a) R_s' which is the internal resistance of the module (b) κ', which is the curve correction factor and (c) a, irradiance correction factor for Voc.

The values for R_s' and **a** values are determined simultaneously using three different irradiance values at similar temperatures. In this case, ~26°C was chosen at different irradiance levels. Similar to procedure 1 R_s' and **a** values are obtained by translating lower irradiance levels to the highest irradiance level which is in this case 1032.1 W/m^2. The different steps are illustrated in the succeeding sections.

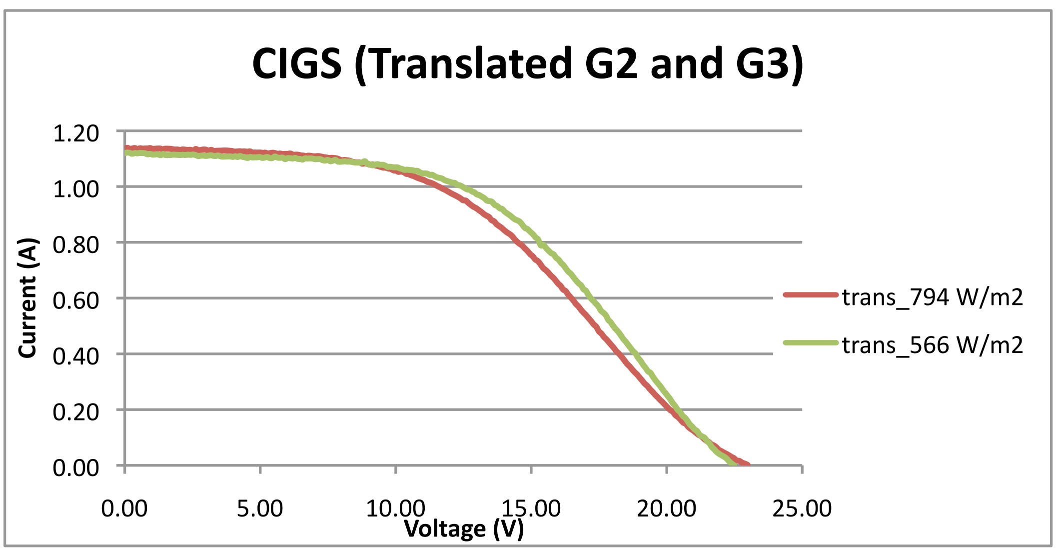
Determination of Rs' and a values

For illustration purposes a CIGS module is used to show the different steps in obtaining $R_{s'}$ and **a** values.

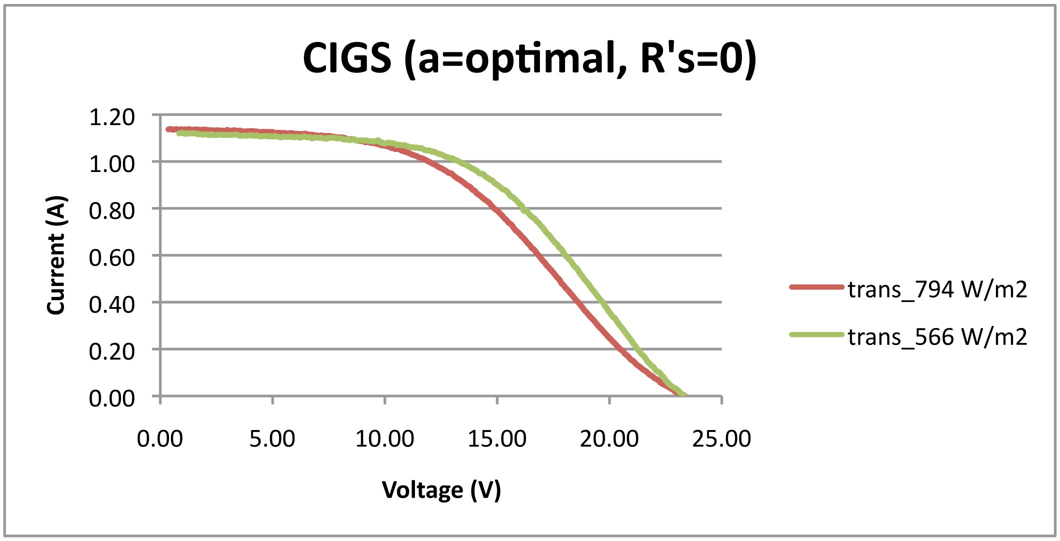
The internal resistance (R_s) is obtained by a trial and error process wherein three different irradiance curves at a similar temperature and translated to the highest irradiance and then back calculated by changing the R_s values in steps of 10mΩ in the positive and negative direction until P_{max} are within +/-0.5% or better. Equations (3) and (4) are used for the translations.



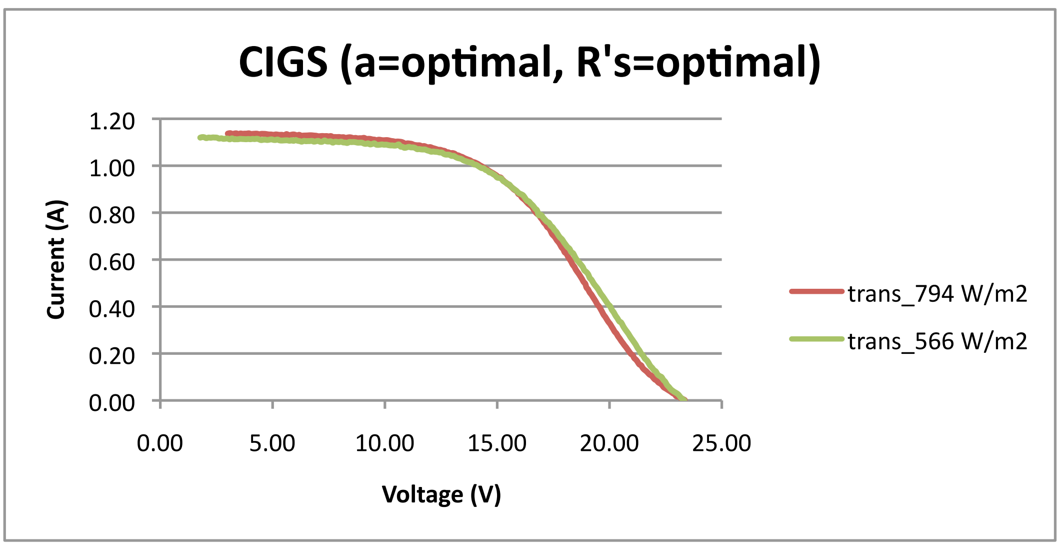
a) Measured IV characteristics at different irradiances and constant temperature



b) Corrected IV characteristics at a=0 and Rs’=0



c) Corrected IV characteristics at a=optimal and Rs'=0Ω



d) Corrected IV characteristics at a=optimal and Rs'=optimal

Figure 38 (a), (b), (c), (d). Calculation of a, R'_s

k' values are obtained with the same as Procedure 1 except for different translation equations used. For Procedure 2, equations (3) and (4) are used instead of equations (1) and (2).

The results of the different translations are shown below in Table 7 below.

Table 7. R_s', a, κ' values for all PV technologies

Technology	R_s' (Ω)	a	κ' (Ω/K)
Monocrystalline Silicon	0.5	-0.075	-0.045
CIGS	2.85	-0.06	-0.005
CdTe	1.5	-0.1	-0.7
a-Si	-17	-0.0095	-0.09

4.2.2.2 Validation of Model to Measured values for Procedure 2

Mono-si

Figure 39 shows the average % error and RMSE values on Procedure 2. For this procedure the highest average % error is 8% and with RMSE value of 7%. The values were relatively high except for the data with the tight translation limit, 2A. This would eventually be used for the power rating translation.

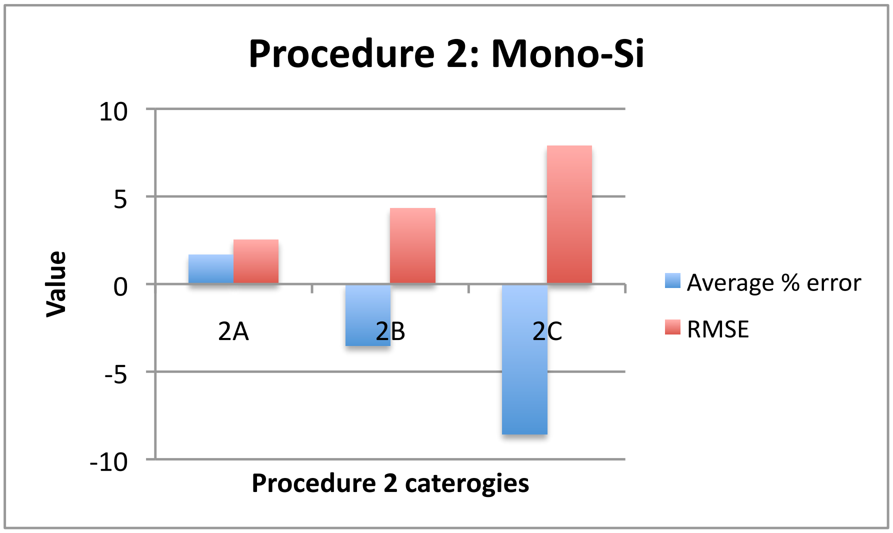


Figure 39. Procedure 2: Mono-Si (Average % error and RMSE)

Legend

2A translation limit < 1.07%, <4.3°C (data points: 26)

2B translation limit < 31% (data points: 13; irradiance range of 427.64 W/m^2 to 1053.5 W/m^2)

2C translation limit < 37% (data points: 7; irradiance range of 265.64 W/m^2 to 428.82 W/m^2)

CIGS

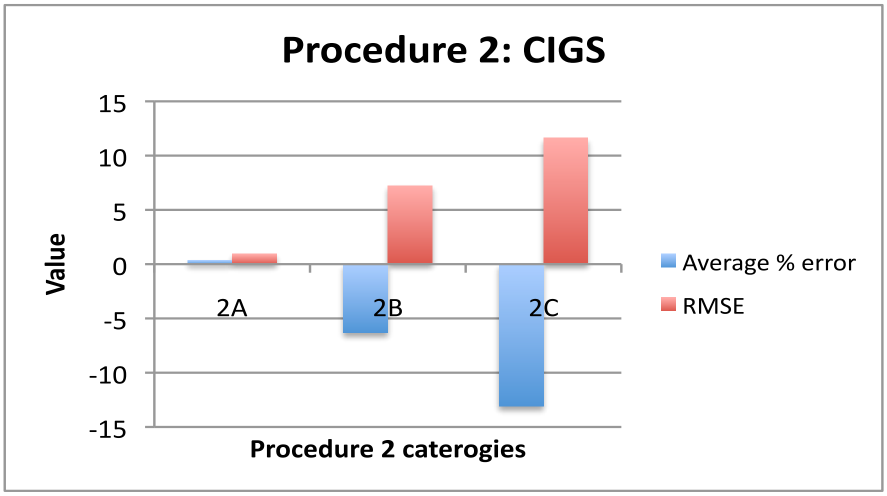


Figure 40. Procedure 2: CIGS (Average % error and RMSE)

Legend

2A translation limit < 3.7% , < 3.7°C (data points: 33)

2B translation limit < 28%, < 4°C (data points: 13 ; irradiance range of 429.28 W/m^2 to 797.74 W/m^2)

2C translation limit < 39% irradiance translation with irradiance range of 262.31 W/m^2 to 431.80 W/m^2 (data points: 7)

Figure 40 shows data for the CIGS module. Average % error of 13% with RMSE value of 11% as the highest among Procedure 2 categories. Again, the lowest average % error and RMSE came from the tight translation limit of less than 3.7%.

a-Si

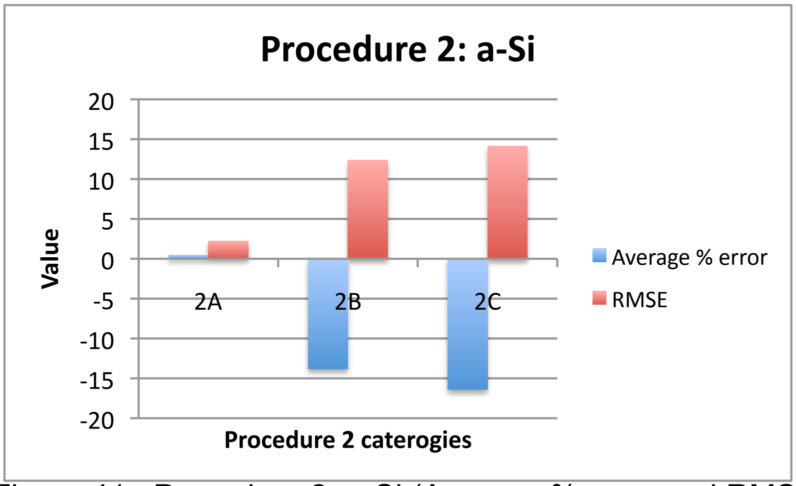


Figure 41. Procedure 2: a-Si (Average % error and RMSE)

Legend:

2A translation limit < 0.4% , <4.6°C (data points: 28)

2B translation limit < 25% , < 4°C (data points: 4; % irradiance range of 774.79 W/m^2 to 1031 W/m^2)

2D translation limit < 39% , 3.5°C (data points: 7; irradiance range of 263.72 W/m^2 to 430.08 W/m^2)

Figure 41 shows data for a-Si module. Average % error of 16% with RMSE value of 14% as the highest among the procedure categories. The lowest was below 3% for both average % error and RMSE for the tight translation limit of less than 0.4%.

CdTe

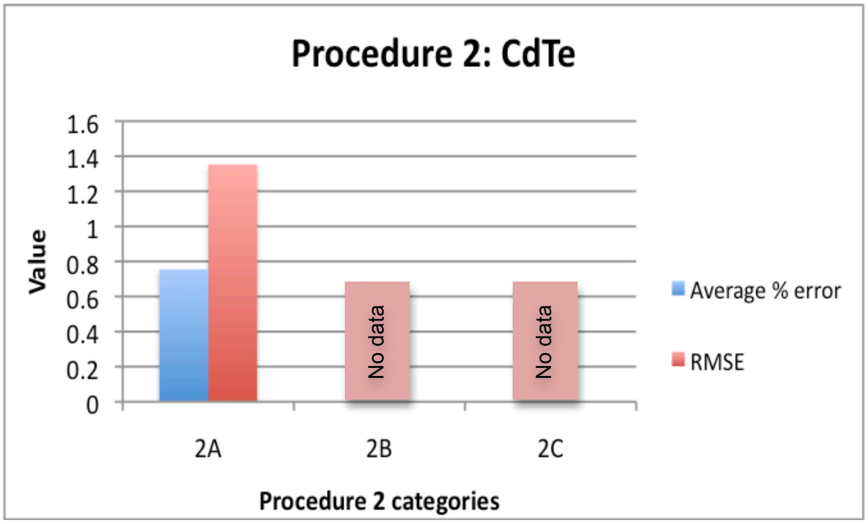


Figure 42. Procedure 2: CdTe (Average % error and RMSE)

Legend:

2A translation limit < 0.4% , 3.9°C (data points: 16)

For the CdTe module, the data shown is for the tightest translation limit of less than 0.4%. The average % error and RMSE are at less than 1.5% for both values. Again, this was so because of the limited data obtained with this particular module.

4.2.3 IEC 60891 Procedure 3

Procedure 3 has two parts but uses the same concept of translation. This procedure utilizes linear interpolation with using either two (2) or three (3) measured IV characteristics at different irradiances and temperatures. Similar to Procedures 1 and 2, several ranges of irradiance values were defined to compare these different procedures.

4.2.3.1 IEC 60891 Procedure 3 with two (2) curves

This procedure only used two curves to interpolate a given irradiance and temperature values. It cannot however interpolate to the exact temperature-irradiance combination in the matrix. The formula given does not allow for obtaining temperature independently. The results are given in the succeeding tables below but it does not translate to the actual measured values so the model is not tested for all PV module technologies but the monocrystalline silicon.

Table 8. P_{max} values of Mon-Si using Procedure 3 (2 curves)

	Temperature (°C)			
Irradiance (W/m^2)	15	25	50	75
1100	NA	**175**	**151**	**135**
		1053/26	679/51	1123/75
1000	**168**	**158**	**136**	**121**
	980/14	982/26	679/51	913/75
800	**127**	**120**	**107**	**93**
	791/16	773/26	826/47	786/75
600	**96**	**91**	**80**	**69**
	571/16	547/25	625/50	624/75
400	**65**	**63**	**53**	NA
	410/14	364/26	311/51	
200	**45**	**55**	**36**	NA
	216/15	224/24	171/50	
100	**35**	**14**	NA	NA
	93/16	117/24		

Sample IV curves are shown below. The IV curves are with the adjusted, interpolated and translated values.

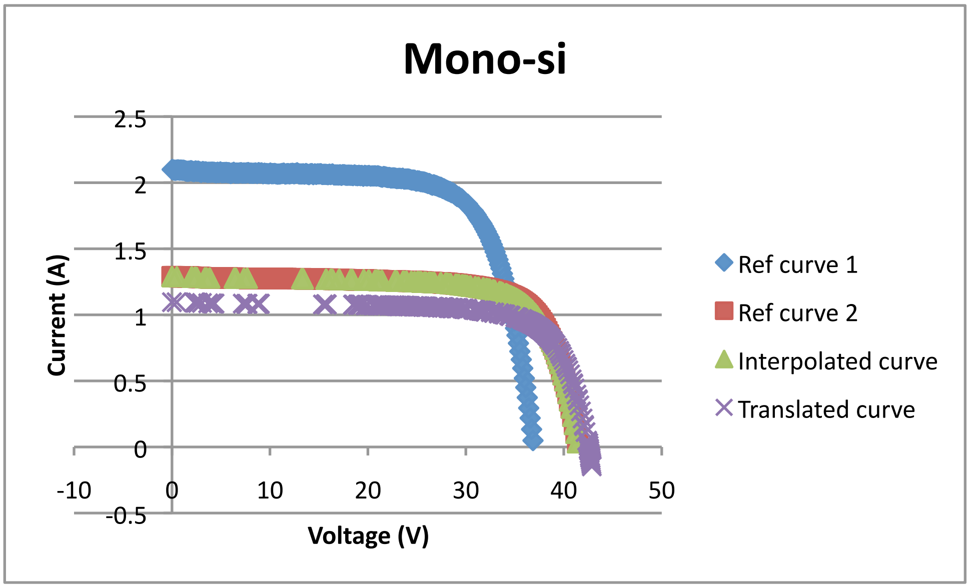


Figure 43. Sample curve for Procedure 3 translation (2 curves)

Figure 43 above shows the interpolation/extrapolation of one set of data. It starts with two measured reference I-V curves and then picking a measured value, those two curves were then used to translate to that particular point. The interpolated curve is an interpolation of reference curve 2 wherein the points satisfy the condition specified in that procedure: $I_2 - I_1 = I_{sc2} - I_{sc1}$ [2].

4.2.3.2 IEC 60891 Procedure 3 with three (3) curves

Procedure 3 as described above is just extended to three curves but still using the same interpolation procedures. Irradiance and temperature ranges are chosen to see if translating at wider range would affect the results between the modeled value and the actual measured value. These translation limits are then specified under the legend.

Mono-Si

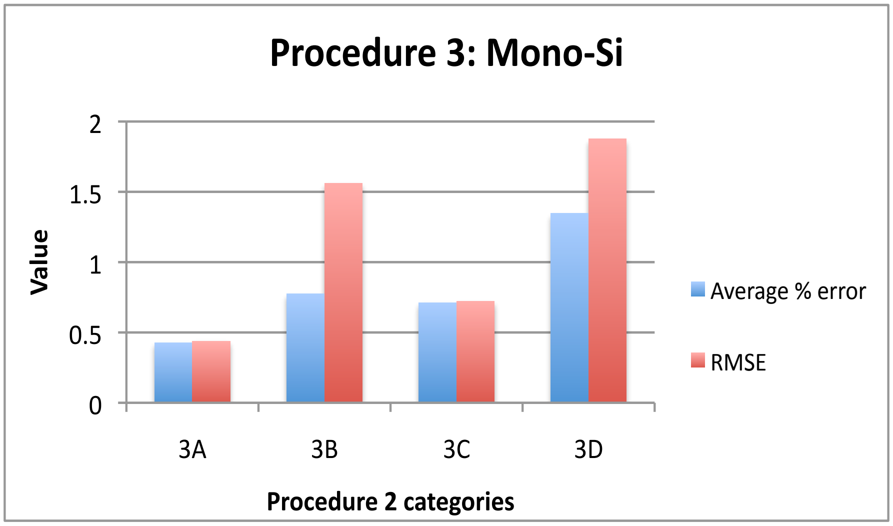


Figure 44. Procedure 3: Mono-Si (Average % error and RMSE)

Legend:

3A translation limit < 200 W/m^2 <10°C (data points: 17)

3B translation limit 428.48-1029.40W/m^2, 8.5°C-73.5°C (data points: 14)

3C translation limit 97.14-528.01 W/m^2, 8.5°C-51.2°C (data points: 6)

3D translation limit 525.94-1050.50 W/m^2, 13.5°C-74.7°C (data points: 6)

Figure 44 shows the average % error and RMSE values for monocrystalline silicon module using Procedure 3 (3 curves). The highest average % error was less than 1.5% with an RMSE of less than 2%. Overall for all Procedure 3 categories, the highest average % error was less than 1.5 %. Even with the widest irradiance range of 428.5 W/m^2 to 1029.4 W/m^2.

Sample IV curves with reference curves and translated curves of a monocrystalline silicon module used are shown below.

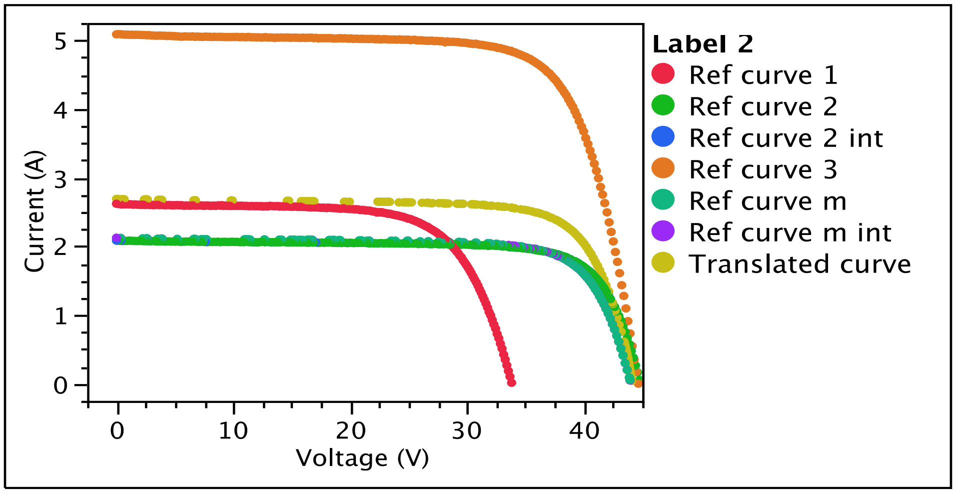


Figure 45. I-V curve translation for 549.39 W/m^2 and 14.6°C

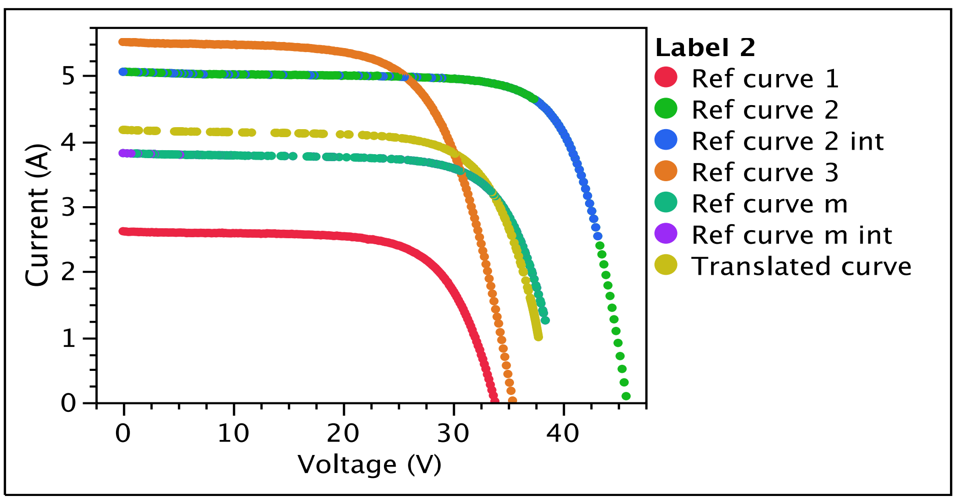


Figure 46. I-V curve translation for 830.35 W/m^2 and 50.5°C

CIGS

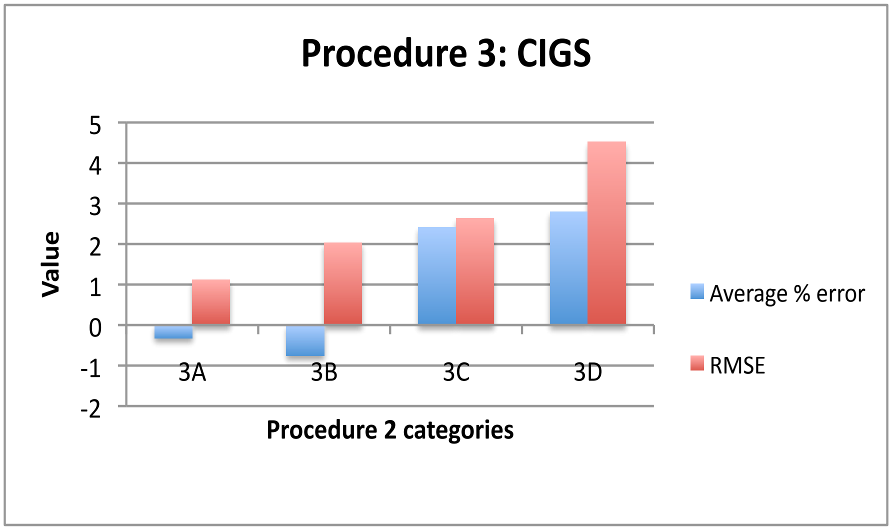


Figure 47. Procedure 3: CIGS (Average % error and RMSE)

Legend:

3A translation limit < 200 W/m^2, <10°C (data points: 17)

3B translation limit 432.10-1034.1W/m^2, 11.2°C-74.8°C (data points: 15)

3C translation limit 104.43-563.97 W/m^2, 8.5°C-51.2°C (data points: 6)

3D translation limit 565.99-1030 W/m^2, 8.8°C-44.6°C (data points: 6)

Sample IV curves with reference curves and translated curves of a CIGS module used are shown below. The curves were translated to actual measured values in which the modeled values are then compared to actual measured values.

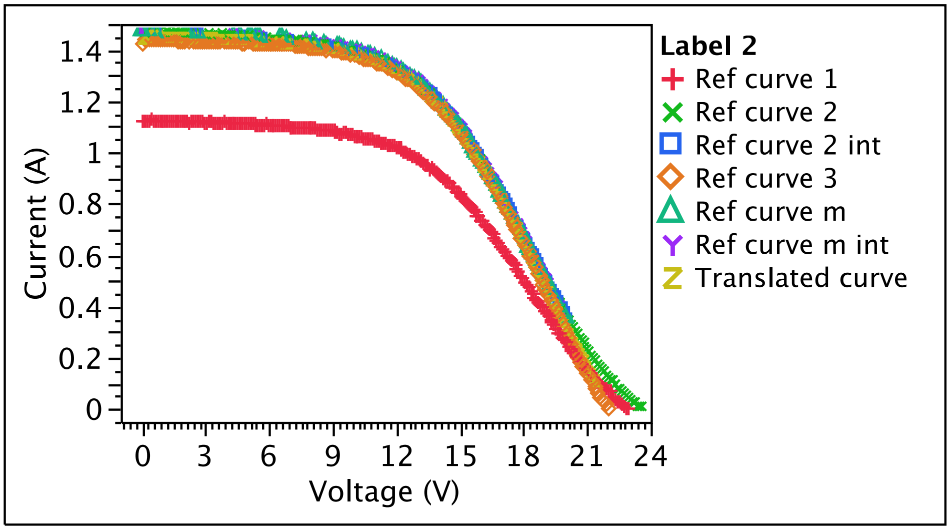


Figure 48. I-V curve translation for 264.73 W/m^2 and 48.2

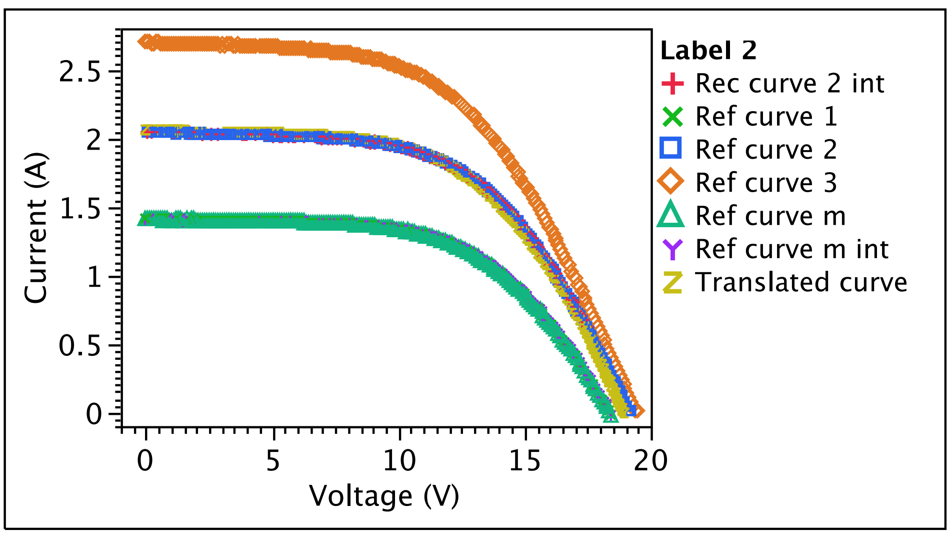


Figure 49. I-V Curve translation for 791.47 W/m^2 and 75.3C

a-Si

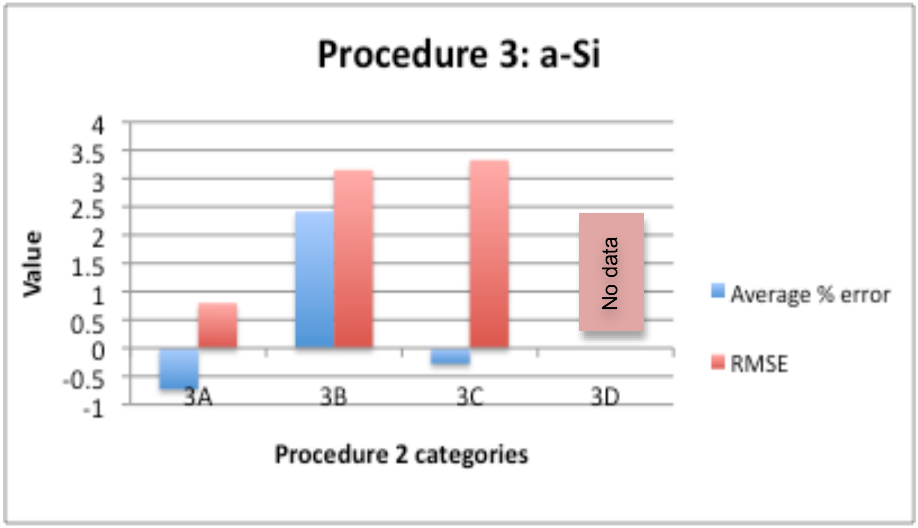


Figure 50. Procedure 3: a-Si(Average % error and RMSE)

Legend:

3A translation limit < 200 W/m^2, < 10°C (data points: 21)

3B translation limit 430.54 W/m^2, 6.9°C-75.3°C (data points: 8)

3C translation limit 99.73-430.54 W/m^2, 6.9°C-50.4°C (data points: 6)

Figure 50 shows the average % error and RMSE for three (3) procedure 3 categories. The highest average % error among the different categories is at 2.5% with an RMSE of 3.1%.

Sample curves shown in Figures 51 and 52 for different values of measured I-V curves. The curves were translated to actual measured values in which the modeled values are then compared to actual measured values.

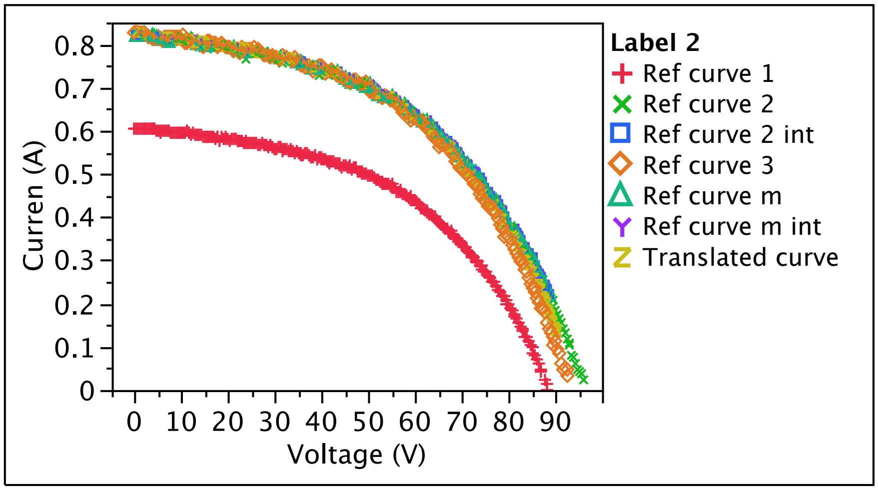


Figure 51. I-V curve translation for 1028.1 W/m^2 and 22.2°C

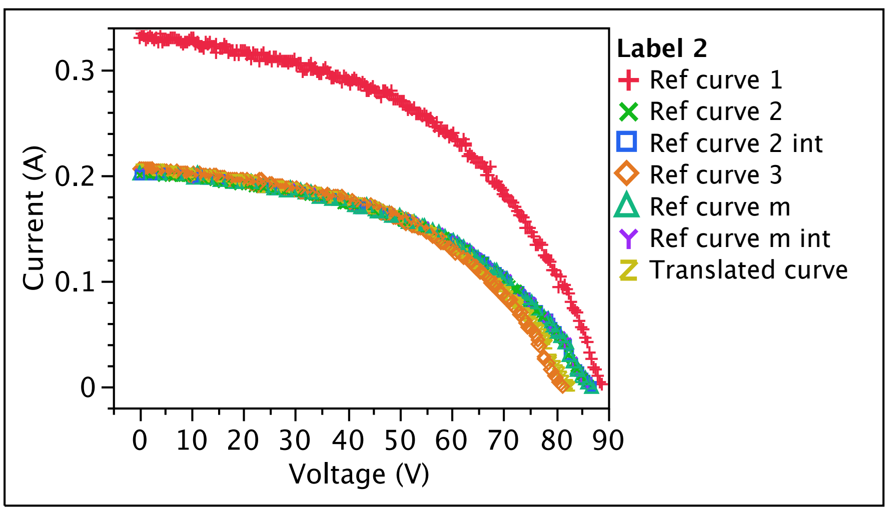


Figure 52. I-V curve translation for 265.64 W/m^2 and 21°C

CdTe

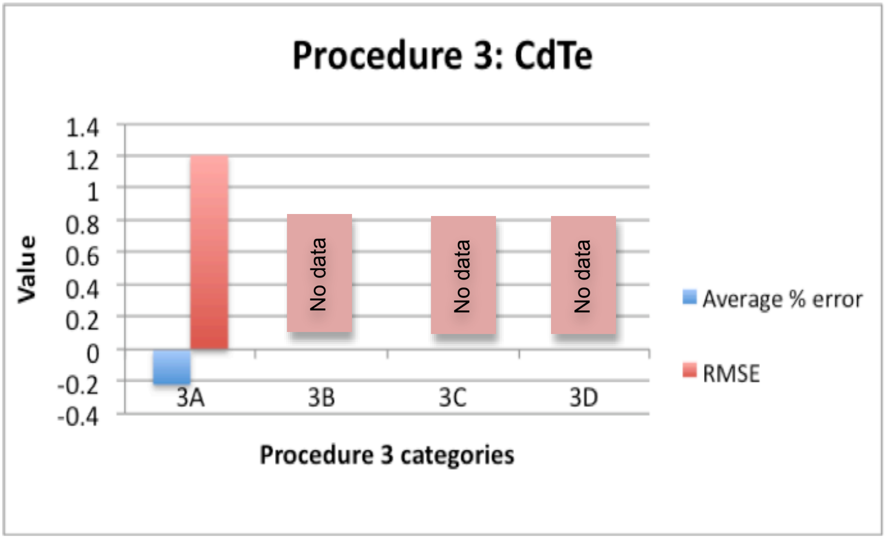


Figure 53. Procedure 3: CdTe (Average % error and RMSE)

Legend:

3A translation limit < 200 W/m^2, < 10°C (data points: 21)

Again, because of the limited data obtained from this module, the highest average % error for the tightest translation limit is 0.2% with an RMSE of 1.2%. Sample curves of this particular module is shown in figures 54 and 55.

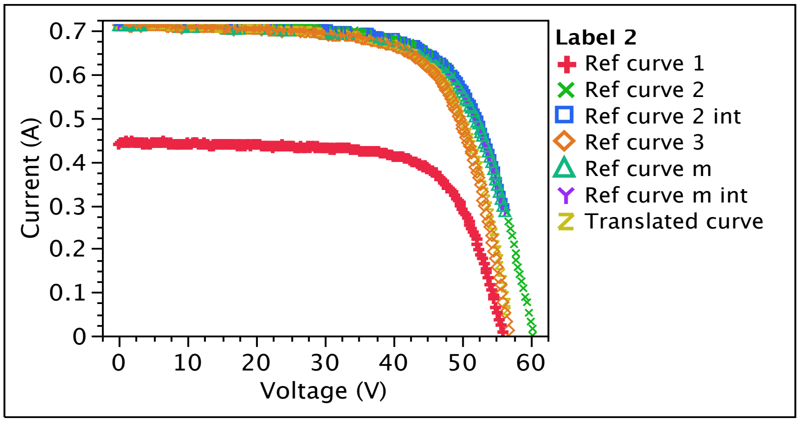


Figure 54. I-V curve translation for 425.63 W/m^2 and 34.7°C

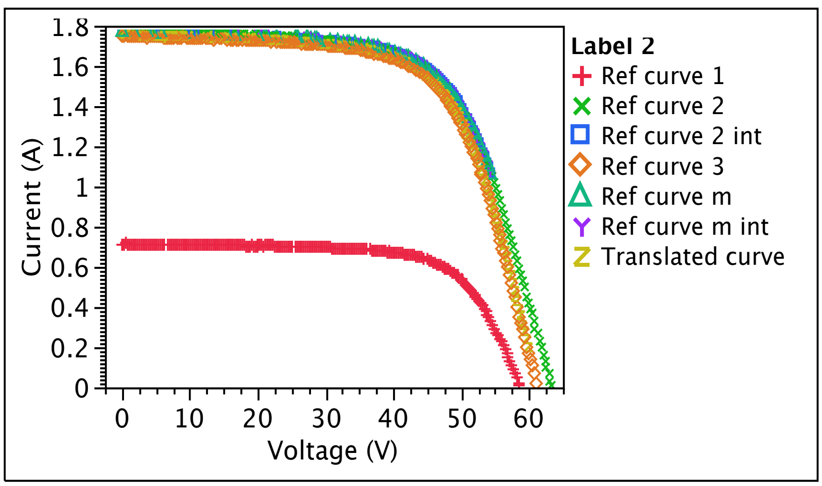


Figure 55. I-V curve translation 1024.6 W/m^2 and 27.5°C

4.2.4 NREL Bilinear Interpolation: Procedure 4

NREL method is called translation by bilinear interpolation. Four curves are used to interpolate to any irradiance and temperature conditions. It is ideal to be using interpolation as extrapolation can yield erroneous results.

The performance matrix is not obtained using NREL bilinear interpolation method so only model validation is performed to determine the accuracy of the model to the measured values. The following tables below summarize the data per module/technology. To determine the ratio of the reference curves as well as the interpolated curves several constants are to be obtained. The constants are obtained by solving nonlinear equations.

Mono-Si

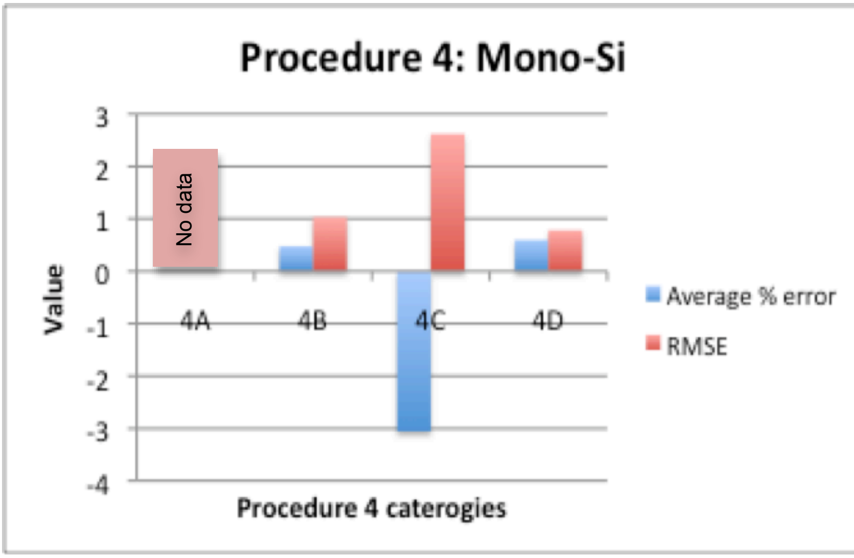


Figure 56. Procedure 4: Mono-Si (Average % error and RMSE)

Legend:

4A No data

4B translation limit 426.342-1049.5 W/m^2 ,19.9C-63.8C, (data points: 17)

4C translation limit 96.82-275.32 W/m^2, 17.3C-50C, (data points: 9)

4D translation limit 541.59-1046.3 W/m^2 , 13.5C-57.8C, (data points: 11)

For Procedure 4, the tightest range 4a was no longer tested because of the predictable outcome as seen in the previous three (3) procedures. So the testing irradiance ranges are limited to the specified ranges in the legend section for each procedure categories. For all categories the highest average % error is less than 3% with an RMSE value of less than 3% also.

Sample curves of this module are shown in figures 57 and 58.

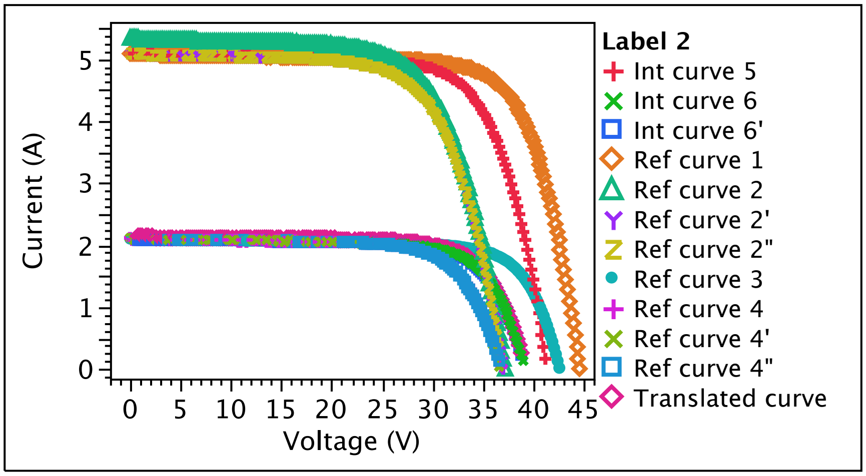


Figure 57. I-V Curve translation for 427.94 W/m^2 and 38.5°C

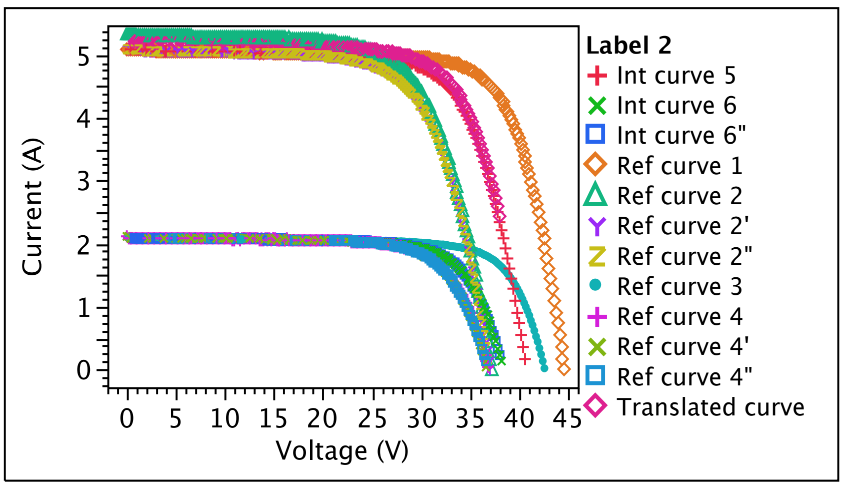


Figure 58. I-V curve translation for 1037.8 W/m^2 for 42.4°C

CIGS

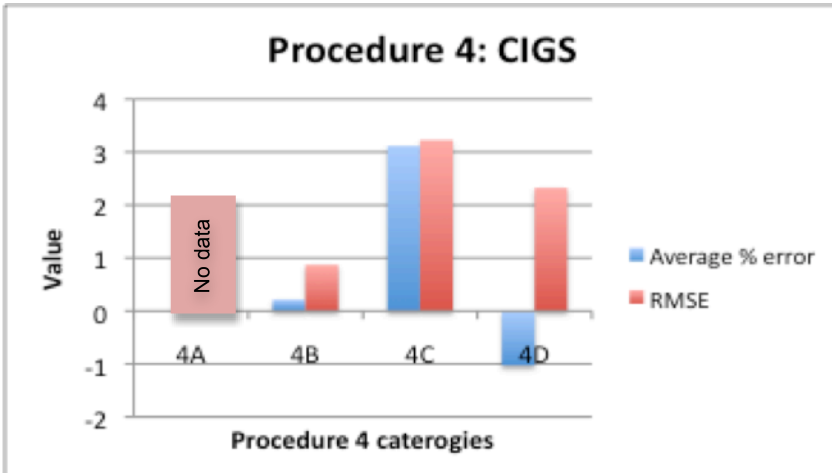


Figure 59. Procedure 4: CIGS (Average % error and RMSE)

Legend:

4A No data

4B translation limit 432.10-1034.1 W/m^2,11.2°C-74.8°C, (data points: 17)

4C translation limit 104.43-563.97 W/m^2, 16°C-49.9°C, (data points: 9)

4D translation limit 565.99-1030 W/m^2 , 8.8°C-44.6°C, (data points: 11)

Again, the highest average % error and RMSE for all of the irradiance ranges specified is at ~3%. Sample curves of this module are shown in Figures 60 and 61.

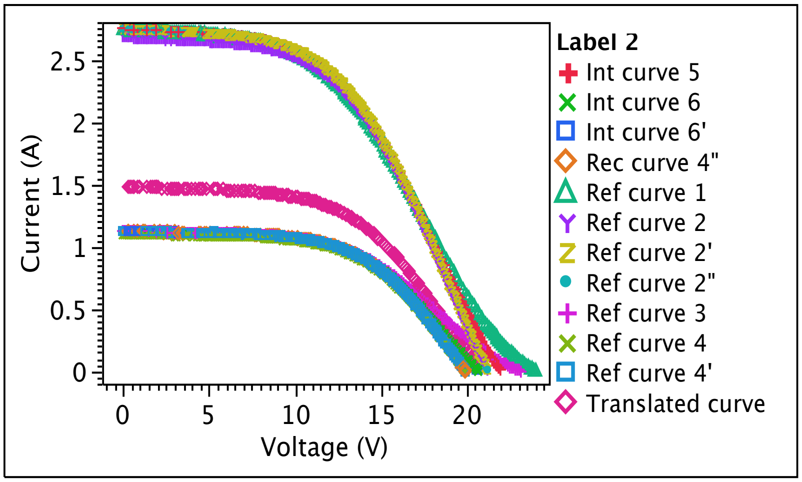


Figure 60. I-V Curve translation for 562.9635 W/m^2 and 42.4°C

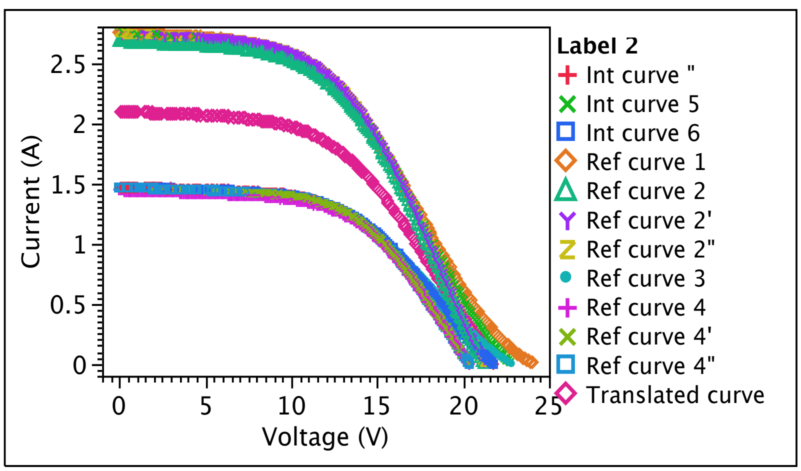


Figure 61. I-V curve translation for 792.999 W/m^2 for 32.9°C

a-Si

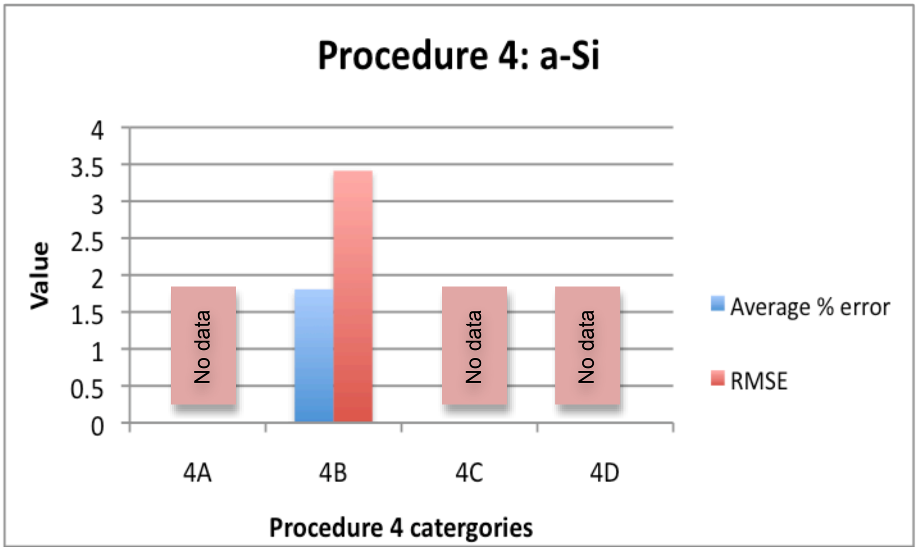


Figure 62. Procedure 4: a-Si (Average % error and RMSE)

Legend

4B translation limit 430.54-1023.6 W/m^2,6.9°C-75.3°C, (data points: 10)

Again, for a-Si module procedure 4, the highest average % error is less than 2% with RMSE value of less than 3.5%. Sample curves for this module are shown in figures 63 and 64.

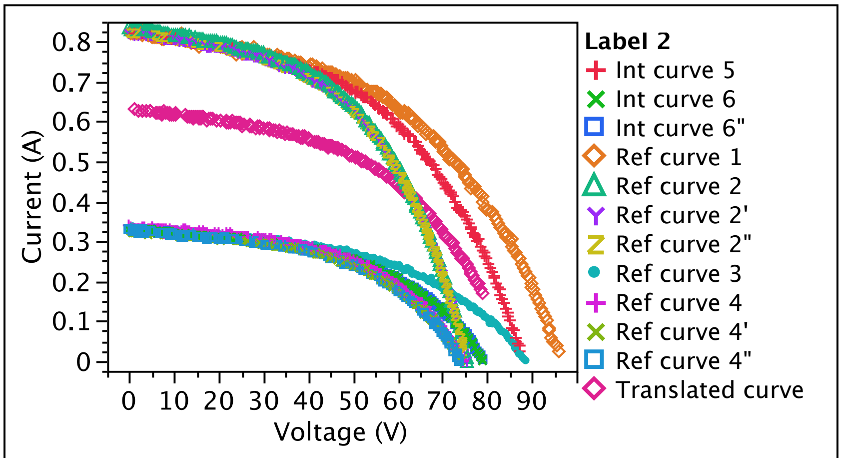


Figure 63. I-V curve translation for 782.136 W/m^2 and 38.2°C

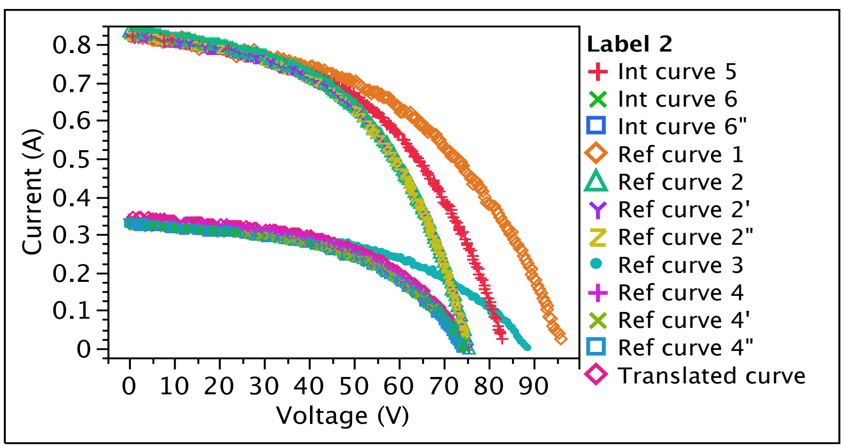


Figure 64. I-V curve translation for 428.442 W/m^2 and 49°C

To summarize the results in terms of average % error and RMSE per module or technology the following graphs below are shown.

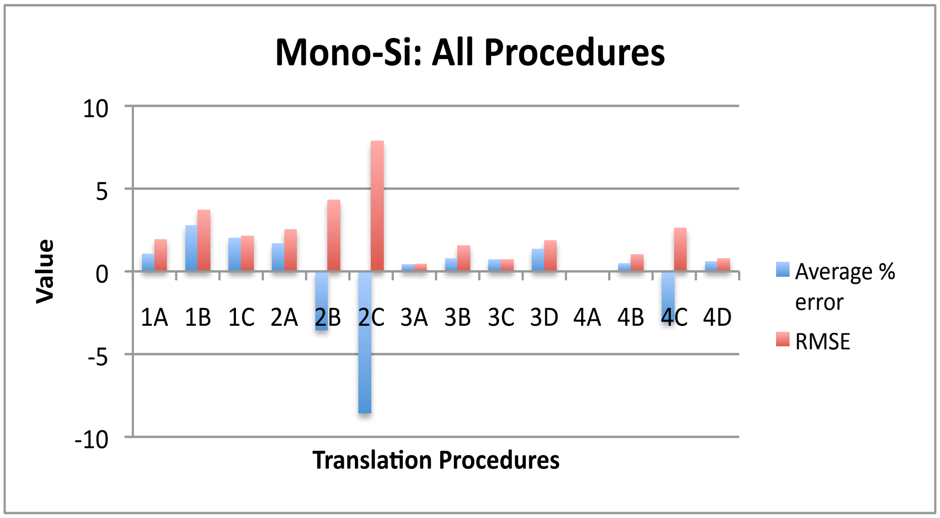


Figure 65. Mono-Si Average %error and RMSE for all translation procedures

For mono-crystalline silicon module procedures 1,3, and 4 showed less than 3% deviation from actual measured P_{max} values. Procedure 2 showed the highest at 9% for the same module. The recommendation is to revisit Procedure 2 in terms of the calculations of the constants involved in the equations.

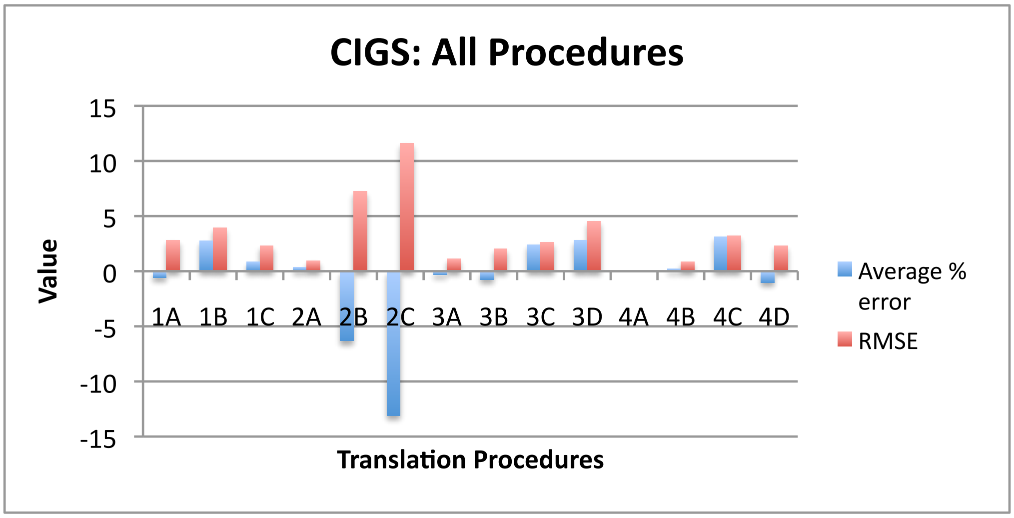


Figure 66. CIGS Average %error and RMSE for all translation procedures

For CIGS procedures 1,3, and 4 with less than 3.1% deviation from actual measured P_{max} values. Procedure 2 showed the highest % error is at 13% for the same module. The recommendation is to revisit Procedure 2 in terms of the calculations of the constants involved in the equations.

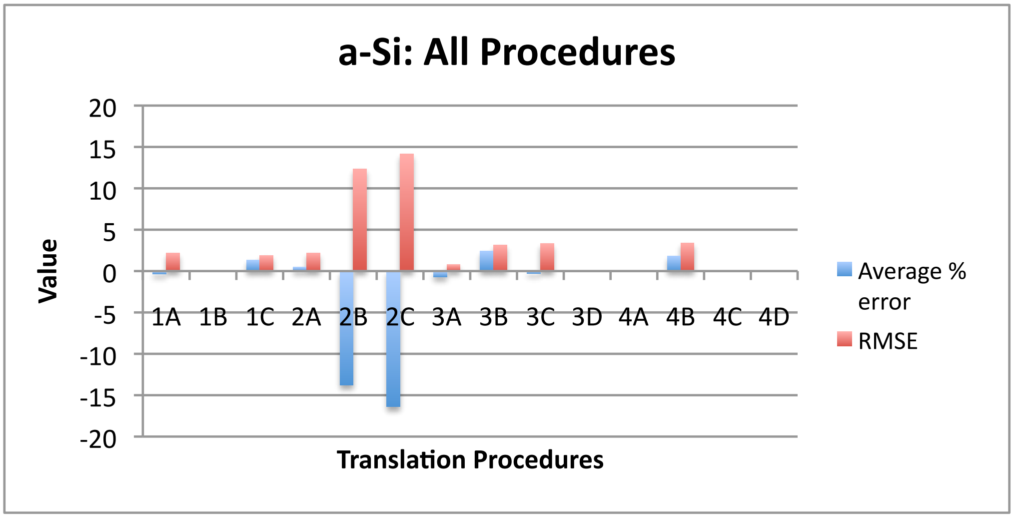


Figure 67. a-Si Average %error and RMSE for all translation procedures

For a-Si module, procedures 1,3, and 4 showed less than 2.4% deviation from actual measured P_{max} values. Procedure 2 showed the highest % error is at 16% for the same module. Again, the same recommendation is to revisit Procedure 2 in terms of the calculations of the constants involved in the equations.

The module during the year 2010 measurements broke so only a limited data was gathered for this module thus only procedures 1, 2, and 3 with limited translation ranges were compared. All of these procedures showed less than 2% error for all the P_{max} values.

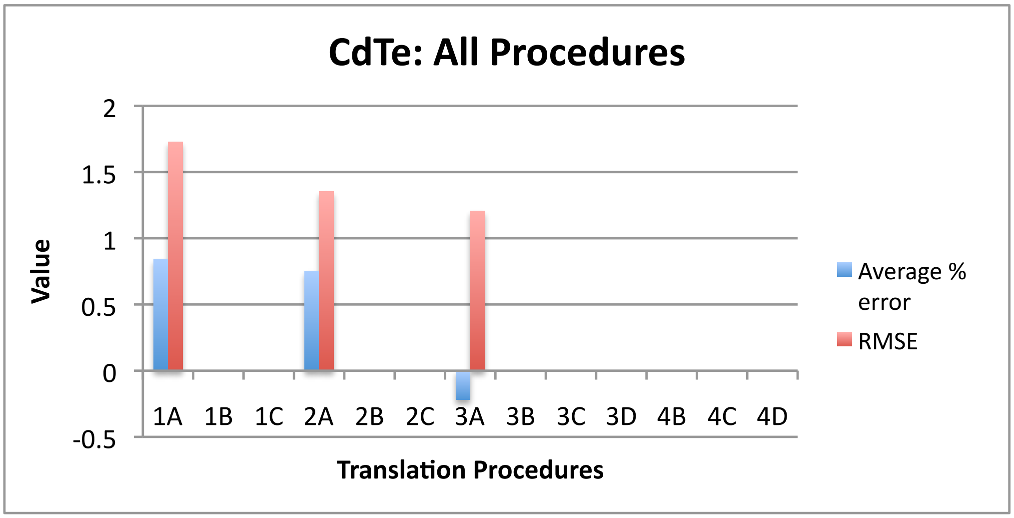


Figure 68. CdTe Average %error and RMSE for all translation procedures

4.3 Power Rating Matrix

The main goal of the translation procedures is to come up with a performance matrix for a total of 24 combinations of irradiance versus temperature without actual measurements for all of these combinations. It saves time and energy to eliminate some of the tests. The performance matrix with respect to P_{max} is summarized by the following figures below.

Mono-Si: Pmax values

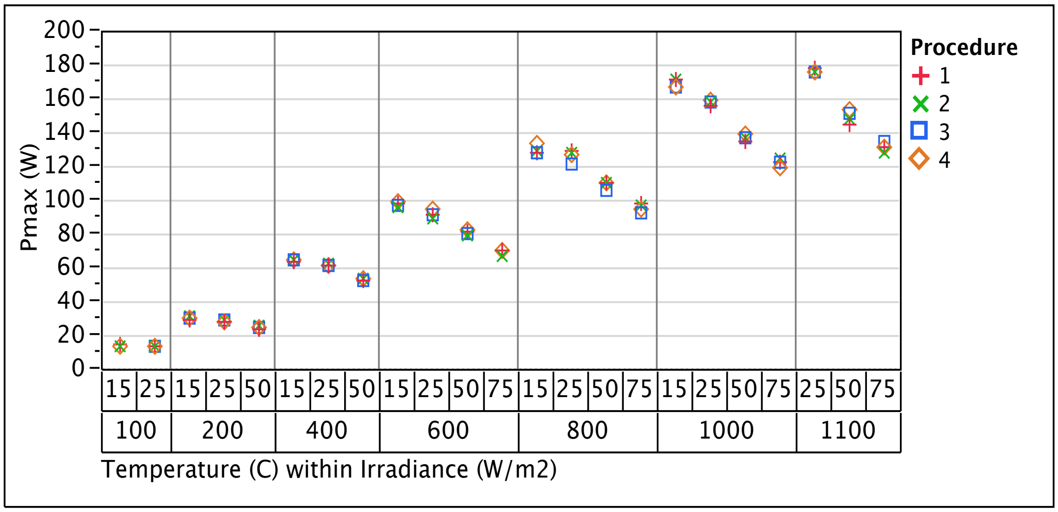


Figure 69. Mono-Si: Pmax values for all translation procedures

The graph in Figure 65 maps out all the values for all the procedures specific to the monocrystalline silicon module. It shows good correlation to the three procedures explored. The maximum P_{max} difference was 9 W at 50°C at 1100 W/m^2.

<u>CIGS: P_{max}</u>

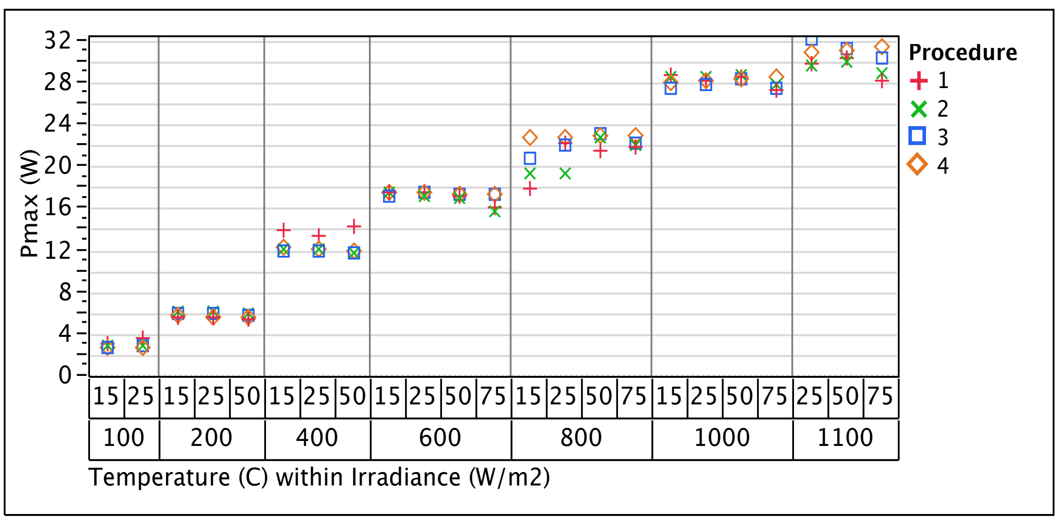


Figure 70. CIGS: Pmax values for all translation procedures

The CIGS module in Figure 66 shows good correlation among the different procedures at a maximum of 4.8 W at 15°C and 800 W/m^2.

a-Si: P_{max}

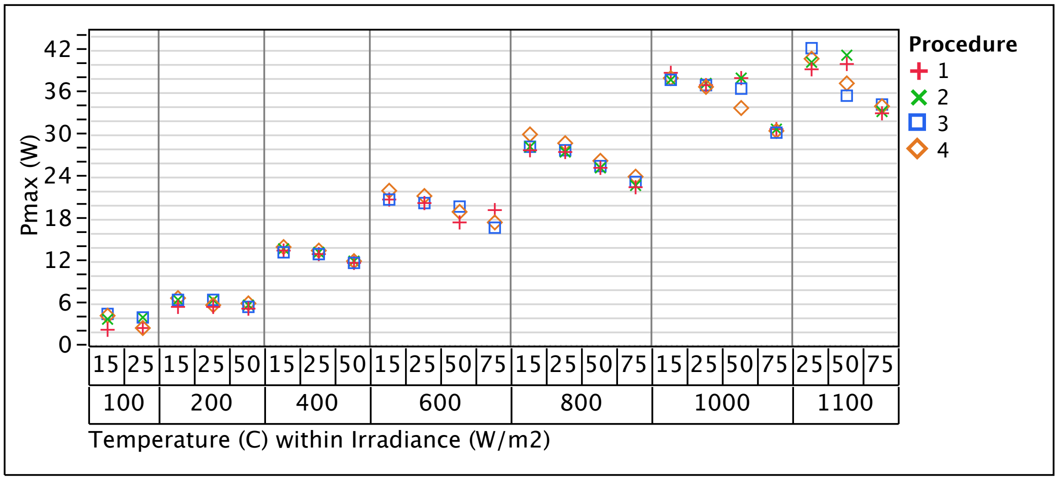


Figure 71. a-Si: Pmax values for all translation procedures

The a-Si has 5.67 W at 50°C and 1100 W/m^2 as the maximum P_{max} difference among all the temperatures and irradiances shown in Figure 71.

CdTe: P_{max} values

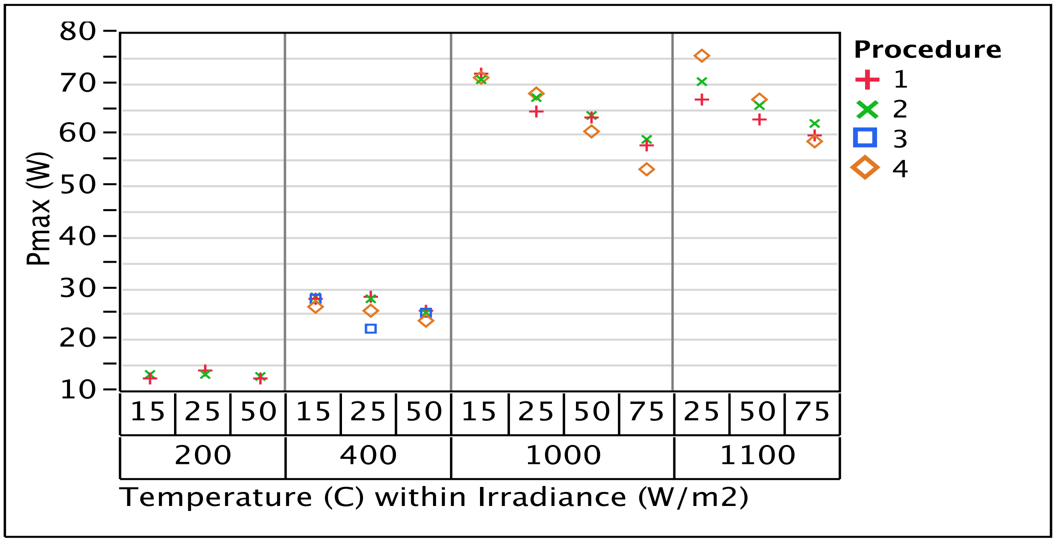


Figure 72. CdTe: Pmax values for all translation procedures

The maximum P_{max} difference is at 8.7 W at 25°C and 1100 W/m^2.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Repeatability of Measurements

The three independent experimental runs showed more than 1% error from one run to another with less than 1.5 Watts P_{max} standard deviation. The screen uniformity study using reference cells that it could be attributed to the non-uniformity across the mesh screen area. The final recommendation for further validation is to situate the reference cells outside of the mesh screen for irradiance measurements' accuracy. Also, a distance of minimum of 2 inches should be maintained between the mesh screen and PV module surface. All of these recommendations were followed when the data was collected for the validation of the translation methods.

5.1.2 Validation of the Translation Methods

The graphs below summarize all the technologies with the different translation procedures within translation categories.

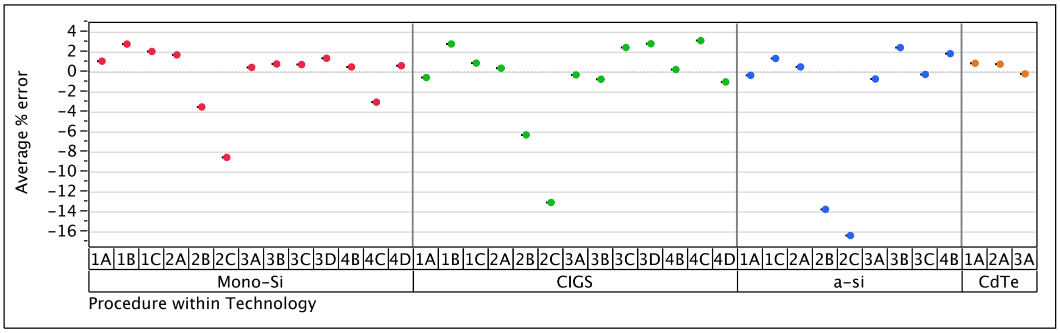


Figure 73. Average % error summary

For all of the translation procedures, disregarding procedures 2B and 2C, the average error is less than 3%. If procedures 2B and 2C are included, the highest average percent error is at ~17% which is extremely high and unacceptable.

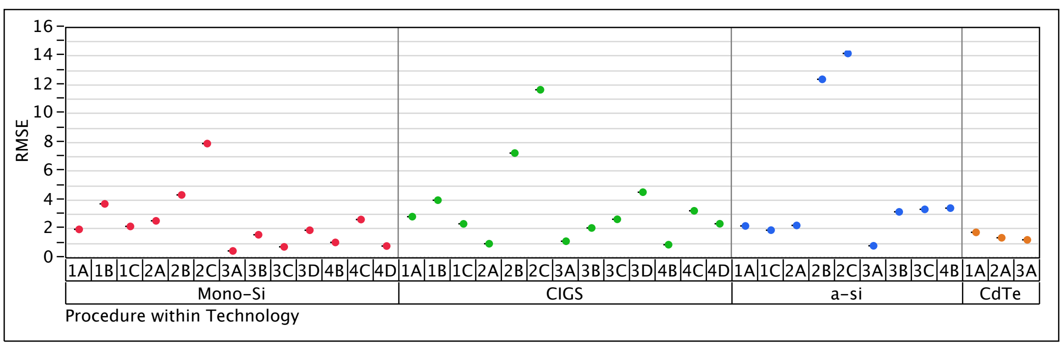


Figure 74. RMSE summary

For all of the translation procedures, disregarding procedures 2B and 2C, the highest RMSE value is at less than 4.5%. To include procedures 2B and 2C, the highest RMSE is at 14%.

5.1.3 Power Rating Matrix

All the required data of IEC 61853-1 (draft) Pmax matrix have been successfully filled for all the four technologies for the all the four translation procedures with good correlation as shown in Figures 69 to 72.

5.2 Recommendations

5.2.1 Repeatability of Measurements

There are two main factors to be revised in the current methodology. One is to place the reference cells outside of the mesh screen and the second factor is to keep the screen ~2inches from the PV module front surface. Also, to be able to achieve modules temperatures greater than 75°C an insulating material was used to cover the backside of the module during measurements.

5.2.2 Validation of Translation methods

The main recommendation is to revisit IEC60891 Procedure 2 for the accuracy of obtaining the parameter constants. All other procedures are deemed acceptable in terms of average % error and RMSE values for modeled values compared to measured values.

5.2.3 Power Rating Matrix

It is recommended to further explore the performance of CdTe module, as the data shown in this study was limited. This was due to the fact that the same module was broken during the several experiments done since last year. It is known that a frameless thin film module is challenging to handle.

REFERENCES

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APPENDIX A

MAXIMUM POWER FOR 2009 POWER RATING

Table 9. P_{max} Monocrystalline Silicon

Irradiance	20C			25C			45C		
W/m2	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100.00	NA	NA	NA	179.02	178.52	177.46	160.26	158.61	158.35
1000.00	167.21	166.78	165.71	162.89	161.66	161.20	145.59	143.77	143.97
800.00	129.48	131.90	132.08	127.16	128.50	128.37	114.78	115.52	115.73
600.00	100.74	100.39	101.01	98.29	98.11	98.09	87.52	85.89	87.87
400.00	64.10	68.60	65.53	62.25	66.48	64.15	55.76	58.13	58.58
200.00	31.37	30.26	32.43	30.43	29.70	31.75	26.11	27.56	27.16
100.00	13.86	14.13	14.05	13.61	13.67	13.85	12.43	12.94	13.32

Table 10. P_{max} CIGS

Irradiance	20C			25C			45C		
W/m2	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100.00	NA	NA	NA	31.27	29.87	29.32	32.92	31.47	30.94
1000.00	27.36	26.78	26.95	28.40	27.19	27.49	29.99	28.68	28.60
800.00	22.05	21.02	20.22	22.45	21.94	20.94	23.73	23.43	24.21
600.00	17.26	16.78	17.16	17.78	17.34	17.72	18.62	18.21	18.26
400.00	12.40	12.01	12.98	12.44	12.15	12.84	12.71	12.04	11.90
200.00	6.15	5.71	6.44	5.97	5.80	6.56	5.69	5.76	6.15
100.00	3.18	3.04	3.24	3.18	3.14	3.20	3.14	3.13	3.00

Table 11. P_{max} a-Si

Irradiance	20C			25C			45C		
W/m2	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100.00	NA	NA	NA	39.13	40.65	40.96	37.40	38.79	38.76
1000.00	36.08	37.28	37.56	35.59	36.96	37.25	33.96	35.21	35.22
800.00	28.11	28.89	29.58	27.76	28.67	29.00	26.33	27.14	26.70
600.00	20.03	21.08	21.57	19.85	20.83	21.34	19.19	19.55	20.32
400.00	12.99	14.03	13.68	12.67	13.64	13.32	11.91	12.18	12.51
200.00	4.98	5.71	5.59	4.96	5.56	5.40	4.56	5.20	4.80
100.00	2.26	2.57	2.61	2.25	2.46	2.54	2.18	2.09	2.26

Table 12. P_{max} CIGS

Irradiance	20C			25C			45C		
W/m2	Run1	Run2	Run3	Run1	Run2	Run3	Run1	Run2	Run3
1100.00	NA	NA	NA	74.47	75.29	74.83	71.48	72.15	71.90
1000.00	68.47	69.20	68.66	67.72	68.46	68.06	64.95	65.52	65.33
800.00	55.39	54.69	54.90	54.96	54.26	54.45	52.58	51.89	51.81
600.00	40.63	40.76	41.43	40.17	40.67	41.42	38.81	38.81	39.35
400.00	28.82	27.12	28.31	28.32	27.16	27.85	25.90	25.99	25.34
200.00	13.29	13.94	13.08	13.33	13.77	13.20	13.22	12.84	13.19
100.00	6.57	6.68	6.43	6.50	6.41	6.49	6.19	5.82	6.46

APPENDIX B

TRANSLATION ILLUSTRATIONS

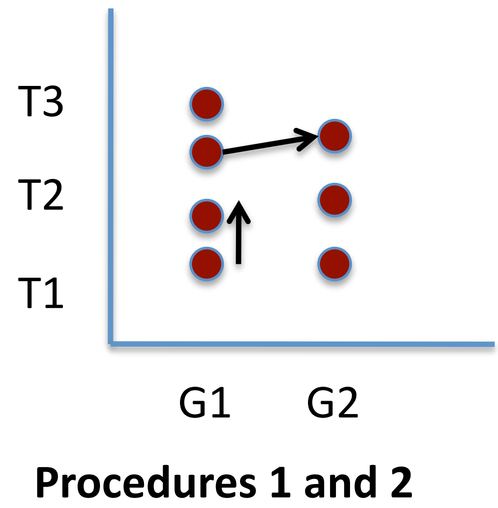

Figure 75. Procedures 1 and 2 translation illustration

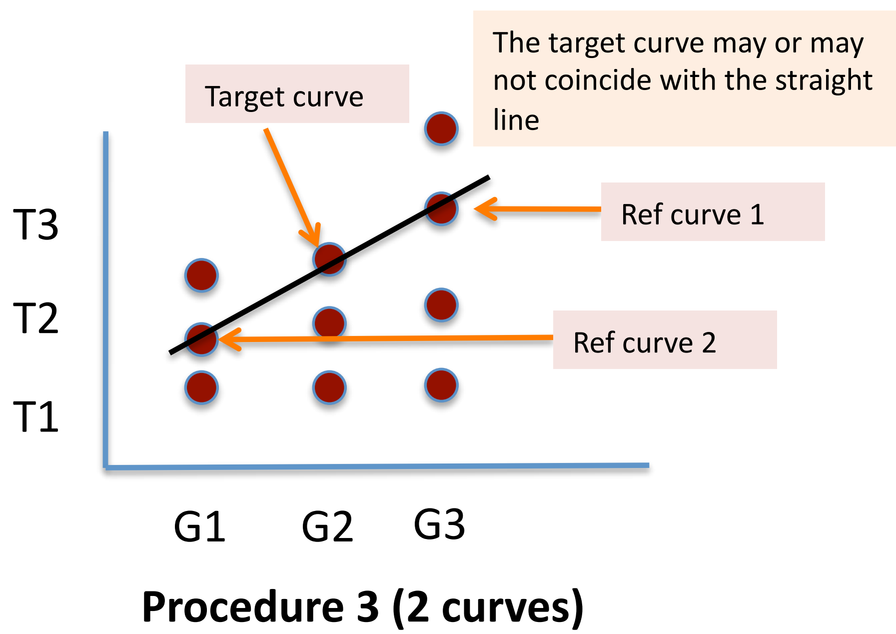

Figure 76. Procedure 3 (2 curves) translation illustration

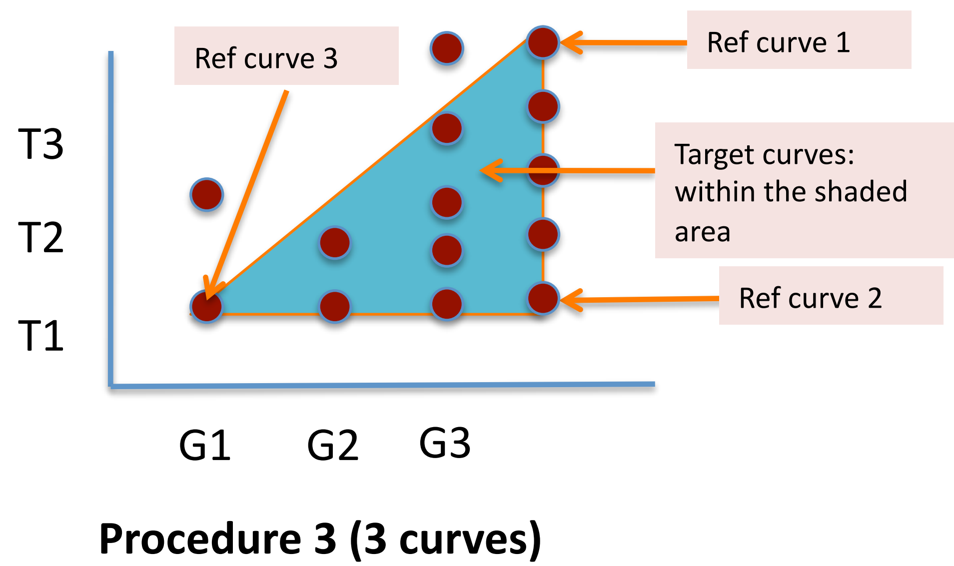

Figure 77. Procedure 3 (3 curves) translation illustration

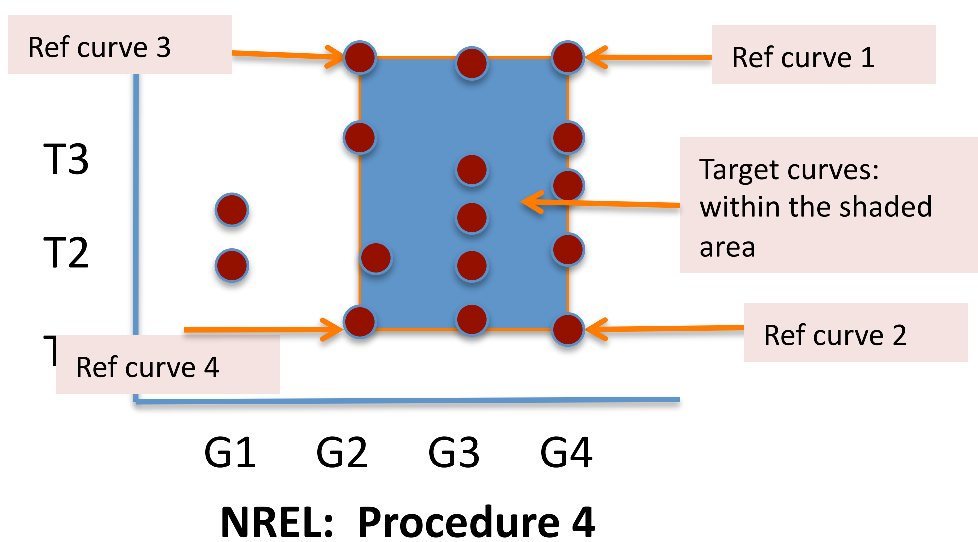

Figure 78. Procedure 4 translation illustration