Power Rating of Photovoltaic Modules Using a

New Outdoor Method

by

Meena Gupta Vemula

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Graduate Supervisory Committee:

Govindasamy Tamizhmani, Chair
Narcio F. Macia
Bradley Rogers

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ABSTRACT

Photovoltaic (PV) modules are typically rated at three test conditions: STC (standard test conditions), NOCT (nominal operating cell temperature) and Low E (low irradiance). The current thesis deals with the power rating of PV modules at twenty-three test conditions as per the recent International Electrotechnical Commission (IEC) standard of IEC 61853-1. In the current research, an automation software tool developed by a previous researcher of ASU-PRL (ASU Photovoltaic Reliability Laboratory) is validated at various stages. Also in the current research, the power rating of PV modules for four different manufacturers is carried out according to IEC 61853-1 standard using a new outdoor test method. The new outdoor method described in this thesis is very different from the one reported by a previous researcher of ASU-PRL. The new method was designed to reduce the labor hours in collecting the current-voltage (I-V) curves at various temperatures and irradiance levels. The power matrices for all the four manufacturers were generated using the I-V data generated at different temperatures and irradiance levels and the translation procedures described in IEC 60891 standard.

All the measurements were carried out on both clear and cloudy days using an automated 2-axis tracker located at ASU-PRL, Mesa, Arizona. The modules were left on the 2-axis tracker for 12 continuous days and

the data was continuously and automatically collected for every two minutes from 6 am to 6 pm. In order to obtain the I-V data at wide range of temperatures and irradiance levels, four identical (or nearly identical) modules were simultaneously installed on the 2-axis tracker with and without thermal insulators on the back of the modules and with and without mesh screens on the front of the modules.

Several issues related to the automation software were uncovered and the required improvement in the software has been suggested. The power matrices for four manufacturers have been successfully generated using the new outdoor test method developed in this work. The data generated in this work has been extensively analyzed for accuracy and for performance efficiency comparison at various temperatures and irradiance levels.

DEDICATION

I would like to dedicate this work to my parents, VenuGopal Setty and Kalavathi, and to my fiancé Preetham Kumar Duggishetti. It is only because of their support and encouragement that I can stand here today.

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Chapter 1

INTRODUCTION

Photovoltaic (PV) modules are typically rated at standard test conditions (STC) of 1000 W/m^2 and 25°C temperature and air mass 1.5 global spectrum. However, the PV modules operate in the field at various temperatures, irradiance, and spectral conditions. Recognizing this issue, the IEC (International Electro technical Commission) has released a new standard, IEC 61853-1, which explains that the module needs to be rated according to 23 element power matrix, which is shown in Table 1.

The module temperatures and irradiances vary vastly owing to location, altitude, hour of the day, season of the year, and sun intensity. As such, the power matrix is required to help analyze/decide on the number of modules to be present in the installation to drive a certain load under different climatic and variation factors.

The performance of the module depends on the Irradiance and temperature factors; it is very important to have an idea about how the power produced from PV modules changes with these factors before building a system. This can be understood as the irradiance influences the module's short circuit current directly and open circuit voltage logarithmically. At the same point, the module temperature has more effect on open circuit voltage. As the power is voltage times current, these factors affect the power extensively.

The IEC has released another standard, IEC 60891, which was released before IEC 61853-1 and it delineates three procedures which can be used in translating from one curve to the other.

Table 1. *Power Matrix as per IEC 61853-1*

Irradiance (W/m2)	**Module Temperature (°C)**			
	15	**25**	**50**	75
1100	*NA*	*1*	*2*	*3*
1000	*4*	*5*	*6*	*7*
800	*8*	*9*	*10*	*11*
600	*12*	*13*	*14*	*15*
400	*16*	*17*	*18*	*NA*
200	*19*	*20*	*21*	*NA*
100	*22*	*23*	*NA*	*NA*

The previous researchers of Arizona State University's Photovoltaics Reliability Laboratory (ASU-PRL) have validated the translation procedures of IEC 60891 by comparing it with real-time results [6].

The initial part of the project was to generate an "automation version" for the IEC 60891 procedures and the power matrix of IEC 61853-1. The three procedures of this standard were automated along with the other program, "baseline procedure" (which is not a part of the standard, but its results were used in the procedures). This part of the project was performed by the previous researcher of ASU PRL [1] who developed the software and extensive help with troubleshooting and improving the software were offered by the current researcher. This part of the project included:

- Deciding upon the requirements of the software,
- Explaining the functionality of the procedures,
- Testing and validating the software.

For data analysis, this project was conducted on Poly crystalline PV modules. This part of the project can be divided into the following stages:

- Selecting four manufacturers
- Selecting four similar or nearly-identical modules of same model from each manufacturer
- Checking the linearity of the devices
- Calibrating the meshes used in this project
- Placing each set (four modules of each manufacturer) on the two axis tracker with different setup – using mesh and insulation
- Connecting modules to the multi curve tracer to collect the data
- Collecting the data for twelve days at different irradiances and temperatures from sun rise to sun set
- Generating the power matrix according to IEC-61853-1 using IEC-60891 procedures
- Comparing three power matrices generated using the three procedures of IEC-60891
- Comparing the power matrices generated.

Chapter 2

LITERATURE REVIEW

One of the most important PV standards being developed by the IEC/TC82/WG2 Committee (International Electro technical Commission/ Technical Committee 82/Working Group 2) is the IEC 61853 standard titled *“Photovoltaic Module Performance Testing and Energy Rating” [5]*. This standard is composed of four parts:

- IEC 61853-1: It describes requirements for evaluating PV module performance in terms of power (watts) rating over a range of irradiances and temperatures.
- IEC 61853-2: It describes test procedures for measuring the effect of varying angle of incidence and sunlight spectra, the estimation of module temperature from irradiance, ambient temperature, and wind speed.
- IEC 61853-3: It describes the calculations for PV module energy (watt-hours) ratings.
- IEC 61853-4: It describes the standard time periods and weather conditions that can be utilized for the energy rating calculations.

The first part of the standard titled *“IEC 61853-1: Irradiance and Temperature Performance Measurements and Power Rating”* was published in January of 2011. This standard specifies the performance measurements of PV modules at 23 different sets of temperature and irradiance conditions, as shown in Table 1, using either a solar simulator (indoor) or the natural sunlight (outdoor). There are several indoor and outdoor techniques possible and many of those techniques are allowed by this standard. For successful implementation of this standard, these techniques need to be repeatable in the same laboratory and reproducible between different laboratories over a period of time. The power rating measurements at various temperatures and irradiance levels are more challenging under prevailing outdoor conditions as compared to controlled indoor conditions. This study report deals with two rounds of outdoor measurements and results:

- Round-1: 12 days measurements are used to find the power matrix
- Round-2: 6 days measurements are considered to compare the results with 12 days
- Round-3: 1 day measurements are considered to compare the results with 12 days

All the measurements were carried out at the air mass levels less than 2.5 and matched reference cell technologies to minimize and neglect the spectral mismatch error.

This report discusses the process carried out using the Automatic Two Axis tracker with a different set up. The data was analyzed using the four translation procedures of IEC 60891 to obtain the performance characteristics at different test conditions. This chapter will explain the mathematical equations behind each procedure.

The four translation procedures are used to translate from one curve to any other target curve. These procedures [4] can also be used to translate the measured data into the data points on the P matrix.

2.1 Translation Procedures of IEC 60891

2.1.1 Procedure 1.

2.1.1 Procedure 1. The first procedure is used to translate a single measured I-V characteristic to select temperature and irradiance or test conditions by using equations (1) and (2).

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

$$V_2 = V_1 - R_s\,(I_2 - I_1) - k\,I_2\,(T_2 - T_1) + \beta\,(T_2 - T_1) \text{ --------------- } (2)$$

Where:

I_1 (A) and **V_1** (V) are coordinates of the measured I-V curve

I_2 (A) and **V_2** (V) are the coordinates of the translated I-V curve

G_1 (W/m^2) is the irradiance measured with the primary reference cell

G_2 (W/m^2) is the irradiance at desired conditions in the matrix

T_1 (°C) is the module temperature

T_2 (°C) is the desired temperature in the matrix

I_{sc} (A) is the measured short circuit current of the test specimen for measured I-V curve

R_s (Ω) is the internal resistance of the test module

k (Ω/k) is the curve correction factor derived from measured conditions

α (A/k) and **β** (V/k) are temperature coefficients of Isc and Voc respectively

These temperature coefficients are calculated at the target irradiances. IEC 60891 describes how to determine the other parameters R_s and k, which is demonstrated in the Methodology chapter.

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

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

$$V_2 = V_1 + V_{oc1} * (\beta_{rel} * (T_2 - T_1) + a * \ln (G_2/G_1)) - R'_s * (I_2 - I_1) - k' * I_2 * (T_2 - T_1) \text{ ------- } (4)$$

I_1 (A) and **V_1** (V) are coordinates of the measured I-V curve

I_2 (A) and **V_2** (V) are the coordinates of the translated I-V curve

G_1 (W/m^2) is the irradiance measured with the primary reference cell

G_2 (W/m^2) is the irradiance at desired conditions in the matrix

T_1 (°C) is the module temperature

T2 (°C) is the desired temperature in the matrix

V_{oc} (V) is the measured open circuit voltage of the test specimen for measured I-V curve

a is the irradiance correction factor for open circuit voltage which is linked with the diode thermal voltage D of the p-n junction and the number of cell n_s serially connected in the module

R_s' (Ω) is the internal resistance of the test specimen

k' (Ω/k) is the temperature coefficient of the series resistance **Rs'**

α_{rel} (1/k) and **β_{rel}** (1/k) are the current and voltage temperature coefficients at STC (Standard Test Conditions)

IEC 60891 describes how to determine the other parameters a, R_s' and k' and is shown in the Methodology chapter.

2.1.3 Procedure 3. The third procedure is derived from linear interpolation or extrapolation of 3 curves from measured I-V values that were taken from our PV module. The irradiance (G_n) and temperatures (T_n) are also considered since they have a direct linearly effect on the current and voltage output. The values to be considered are at (G_a, Ta), (G_b, T_b) and (G_c, T_c) and they need to be selected as shown in Figure 1.

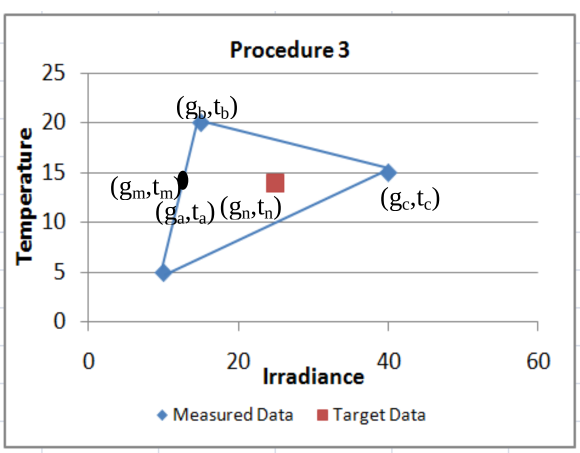

Figure 1. Curve Selection in Procedure 3

Procedure 3 requires no adjusting or fitting parameters as did procedures 1 & 2. The measured I-V curves are corrected to standard test conditions (STC) or selected temperature and selected irradiance values. The following equations are used for this procedure:

$$\mathbf{V_3 = V_1 + a \cdot (V_2 - V_1)}$$

$$\mathbf{I_3 = I_1 + a \cdot (I_2 - I_1)}$$

Where **a=** slope constant (to be used for G3, T3).

The points of (I_1, V_1) and (I_2, V_2) are chosen from measured values so that:

$$\mathbf{I_2 - I_1 = I_{SC2} - I_{SC1}}$$

Where ISC is the measured short circuit current.

The following equations are used to derive the constant ‘a’:

$$\mathbf{G_3 = G_1 + a \cdot (G_2 - G_1)}$$

$$\mathbf{T_3 = T_1 + a \cdot (T_2 - T_1)}$$

$$\Rightarrow \mathbf{a = (G_3 - G_1)/(G_2 - G_1)}$$

Using the value of ‘a,’ the new values can be used to generate the new I-V curve and the new associated irradiance and temperature plot.

2.1.4 Procedure 4. Procedure 4 is the same as Procedure 3, only the values to be considered are at (G_a, T_a), (G_b, T_b) (G_c, T_c) and (G_d, T_d)

shown in the Figure 2 and the final (G_n,T_n) are calculated in similar manner. Initially (G_x,T_x) and (G_y, T_y) are calculated and they are used to generate the (G_n,T_n) data.

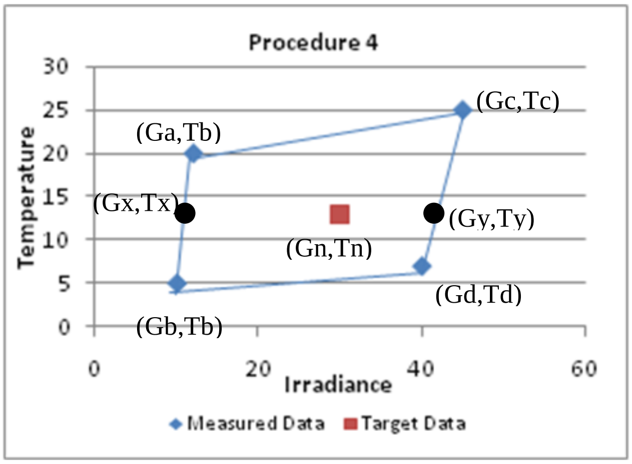

Figure 2. Curve Selection for Procedure 4

Chapter 3

METHODOLOGY

The project was planned for different test processes. They are:

- Indoor Processes – Using Solar Simulator for the data collection.
- Outdoor Process – Using real Solar power for the data collection.

The test began for the indoor process, but it was not continued. It had few setup problems for which there was need of some new equipment. With the present set up we had temperature differences seen between different locations on the module at the time of testing. The module was initially cooled/ heated to particular temperature and then the data was collected as the temperature increased/ decreased towards the room temperature. The various points at which the temperature was collected are shown in Figure 3. Where T_1 is temperature at the center and T_2 is temperature at the end of the module. As the temperature difference between T_1 and T_2 was around 10° C, it was not acceptable for the research, so different experiments were tried out to maintain the same temperature throughout the module, but it was not feasible with the methods followed. As it was not good for research to continue with the first procedure, the test was performed only with the second method.

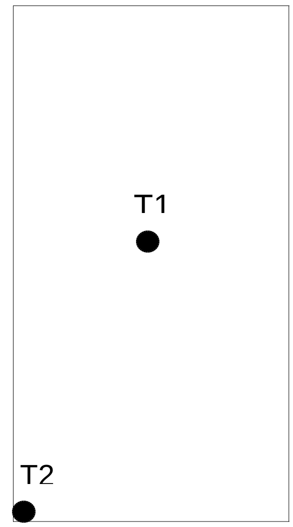

Figure 3. Thermocouple positions on the backside of PV module

The second method was to perform the same test outdoors. The outdoor measurements can be taken in different methods –

(i) Fixed tilt

(ii) Single Axis Tracker

(iii) Two Axis Tracker

a) Manual Two Axis Tracker – for which we need to check the sun direction and face the tracker towards it manually.

b) Automatic Two Axis Tracker – this one has a sensor and a controller which tracks the sun throughout the day.

In this project, an automatic two-axis tracker was used. This project was planned to use four different manufacturers and four similar modules from each manufacturer. The similarity of the modules was checked by comparing the equivalence of the temperature coefficients and different parameters at STC conditions, which will be discussed later in this chapter. The process flow of this project is shown in figure 4. The project has various stages in it as shown in figure 4. Each stage is explained briefly in this chapter.

3.1 Collecting the Data for Baseline

The data was collected at different temperatures, starting from a temperature as low as 15°C to a maximum temperature of 75 °C and irradiance from lowest to the highest irradiance values using different meshes. The data was collected at different irradiances – ~100 W/m^2 (using ~10% T meshes), ~200 W/m^2 (using ~20% T meshes), ~400 W/m^2 (using ~40% T meshes), ~600 W/m^2 (using ~60% T meshes), ~800 W/m^2 (using ~80% T meshes) and ~1000 W/m^2 (without any mesh) {where T is transmittance}.

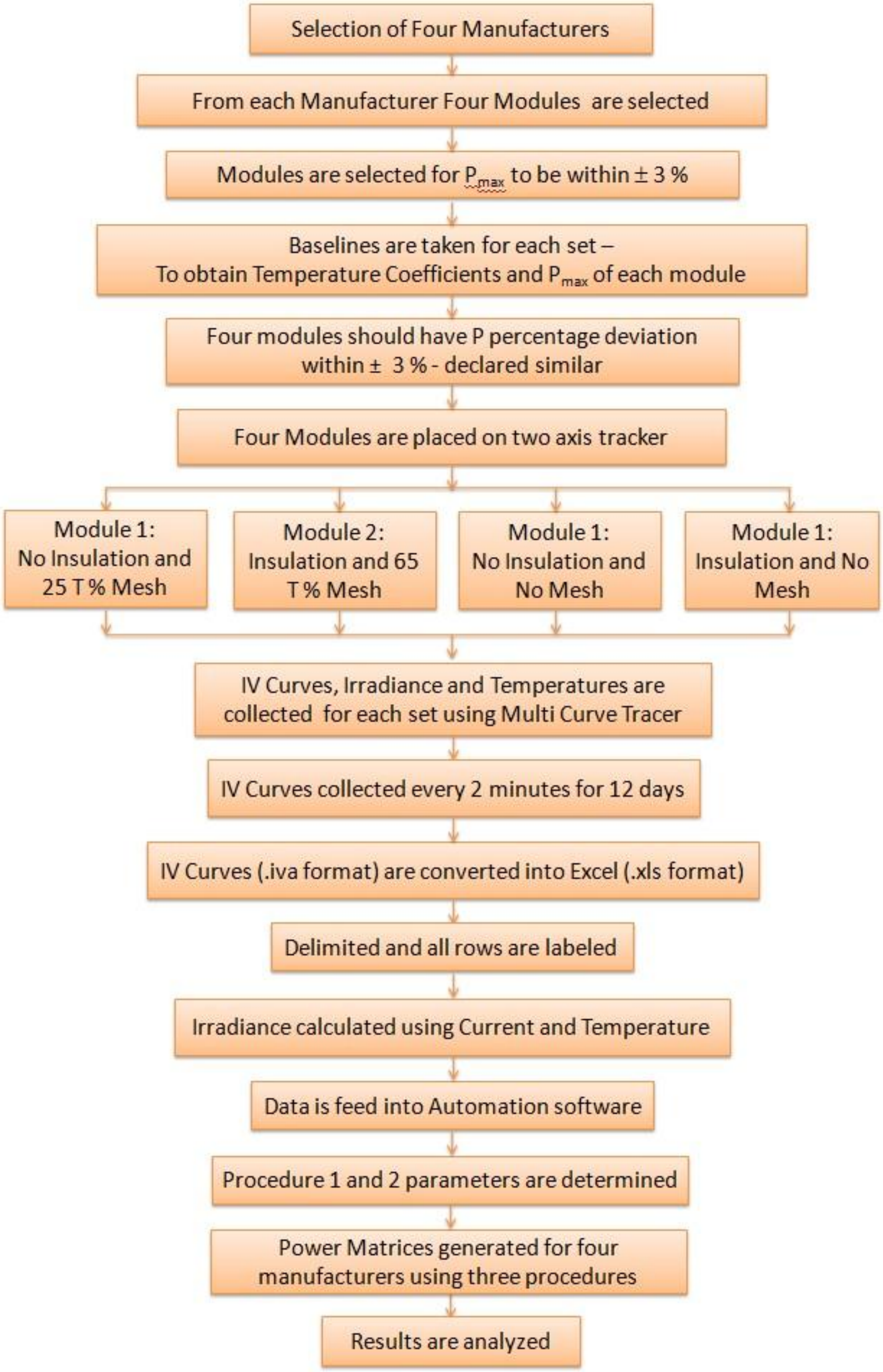

Figure 4: The process flow of the entire project

To collect data at lower temperatures, the modules were cooled to a very low temperature in an environmental chamber and then placed on the manual two-axis tracker. The tracker was set in such a way that the modules exactly faced the sun. The set up included two reference cells, test module, IV curve tracer and a computer connected to it to collect the data, thermo couples to collect the module, ambient temperature, and meshes.

The data was collected from a low temperature to a high temperature in steps of approximately 2°C with different meshes.

This data was analyzed to find the temperature coefficients which were to be used further to analyze the main data. Four modules of a manufacturer are declared as similar; when the temperature coefficients are approximately equal and IV (current – voltage) curve data at STC for all four modules needed to overlap as shown in Figure 5.

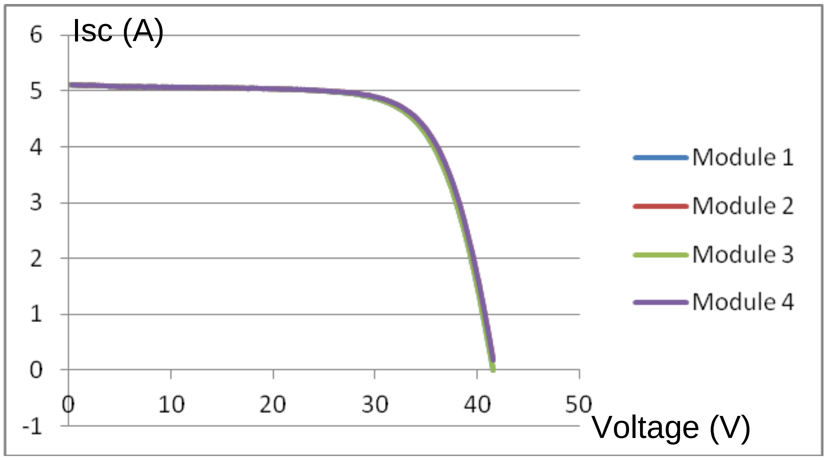

Figure 5. Four different modules data at STC

The temperature coefficients of any two modules need not be equal even if the modules belong to same model/ manufacturer/technology. The temperature coefficients vary due to the variations in the parasitic resistances. These variations in the parasitic resistances are due to the manufacturing process.

The parasitic resistances affect the power, fill factor, and efficiency of that module. The types of parasitic resistive losses are the series resistance and shunt resistance. The circuit schematic of a solar cell considering these two types of resistances is shown in Figure 6.

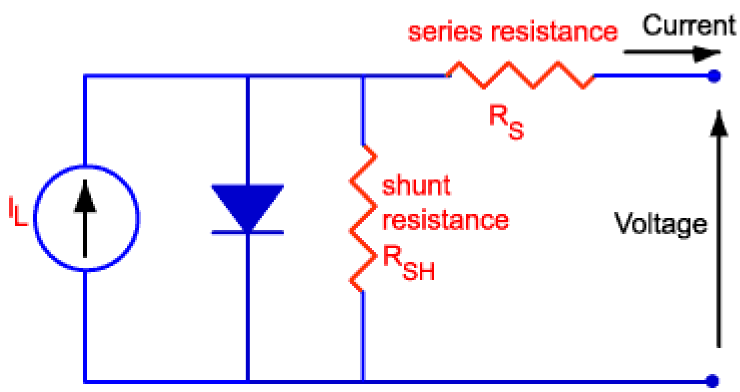

Figure 6. Series and Shunt resistances in a Solar Cell [8]

A module should have a low series resistance and high shunt resistance. The IV curve of a module will be affected by high series resistance and low shunt resistance. The series resistance effect can be seen at the higher irradiance levels and as the series resistance increases the curve looks like a triangle. In figure 7, there are two curves shown, one is a typical I-V curve shown in red color. If the series resistance is increased for the same module and I-V curve is collected, it will be as the blue curve shown in figure 7.

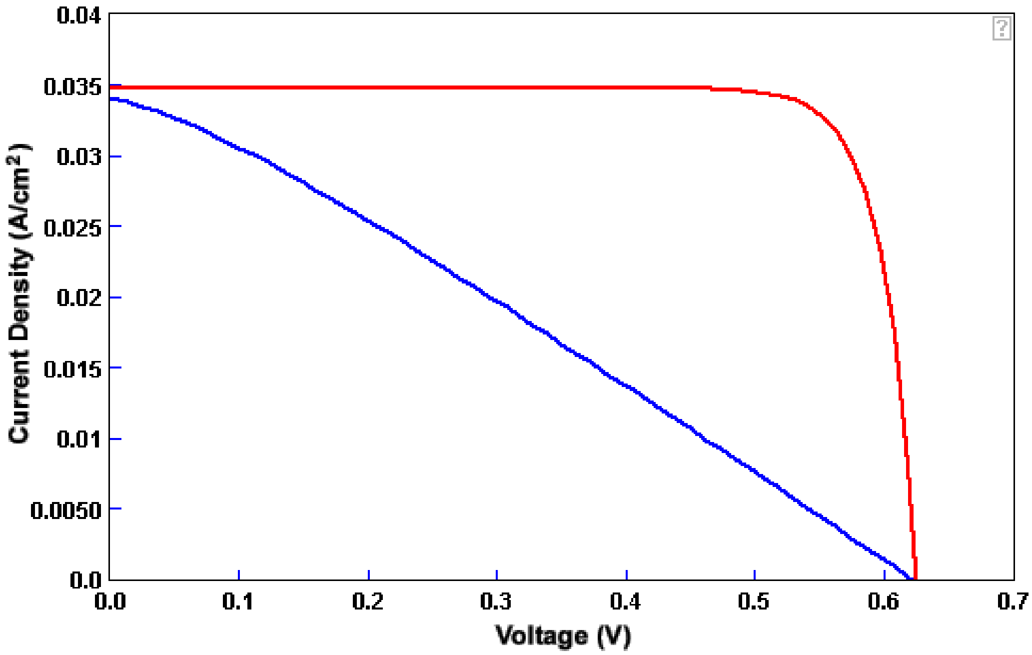

Figure 7. Series Resistance effect on Solar Cell [8]

Both series and shunt resistances affect the module's IV curve. The shunt resistance effect is seen at low irradiance levels whereas series resistance effect is seen at higher irradiance levels. Figure 8 shows two curves (blue curve with low shunt resistance and the red curve with higher shunt resistance). The IV curve will be affected as the shunt resistance decreases.

This study is performed to see how these resistances affect the module's power under different conditions in the 23 element power matrix. Chapter 4 discusses the 23 element power matrix of different manufacturers and thereby compares the effects of the above mentioned factors on the PV modules in terms of power and efficiency. It also discusses how this study is helpful for an installer or a consumer in deciding the module for installation depending on the working conditions of the place.

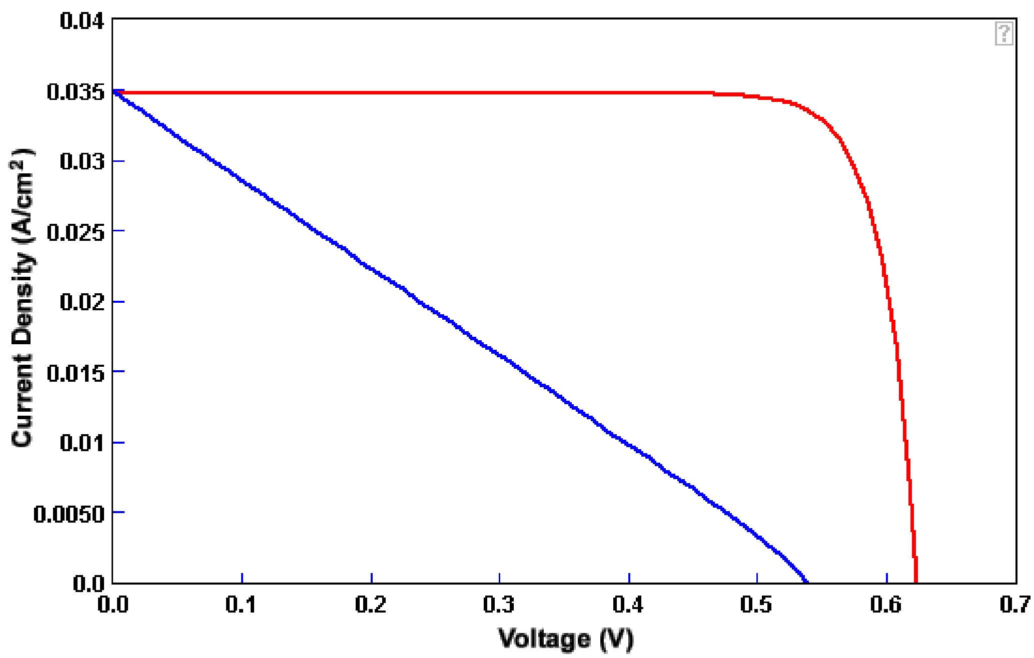

Figure 8. Shunt Resistance effect on Solar Cell [8]

3.2 Calibration of the Meshes

There are two sets of meshes used for this project:

- **Set 1 –** Meshes used to collect the baseline data.
- **Set 2 –** Meshes used to collect 12 days/4 days data which is the main required data for this research.

The meshes used for baseline measurements are approximately 10%T, 20%T, 40%T and 60%T, and they are calibrated prior to the measurements.

The meshes that are used to collect the data from four modules on two axis tracker are approximately 25%T and 65%T meshes. These meshes need to be calibrated to know exactly how much irradiance is transmitted through them.

Reference cell could have been covered with these meshes to calculate the transmittance directly. But as the meshes were not uniform throughout, reference cell being very small in size comparatively, the irradiance cannot be predicted accurately. The sensitivity to the irradiance transmitted was very high, leading it to be unusable in this procedure. This was proved by an ASU PTL previous researcher's master thesis study (Paghasian, 2010). The thesis study tells us that "to calibrate a mesh, it needs to be placed on top of the Module and the reference cell should be left uncovered" (p. #). It also says that "the mesh should be placed at least 1.5" above the module to have uniform effect" (p. 97). Therefore, in this project, the module was covered with a mesh and the reference cell was left open. IV curves were to be collected at 1000 W/m2 and with different irradiances using mesh at a constant temperature. Once the data was collected, the relation current is directly proportional to irradiance was used to determine the amount of the irradiance that was transmitted.

3.3 Linearity Check

Before performing any study on the data collected from a PV Module, we need to verify the linearity of the module. In this project linearity check has been performed on the data that was collected from four PV modules for 12 days. After collecting the data, each days data was moved into an excel sheet. Then cleanup of all the irregular data is done by using linearity process. For this two types of linearity processes were used –

a) Plotting a graph between I_{sc} vs Irradiance, this plot should be linear and should pass through the origin.
b) The second plot is between (I_{sc}/Irradiance) vs Irradiance. When a ratio between I_{sc} (Short Circuit Current) and Irradiance is taken, it gives a constant value. This is called constant because ratio remains same for any irradiance.

Therefore, from these two plots all irregular data has been cleaned up and the remaining data points were linear as discussed above.

3.4 Collecting the Data for Final Analysis

Four different manufacturer modules were used for this project. From each manufacturer, four similar modules were considered (by verifying the temperature coefficients and P_{max}). The four modules were placed on a two-axis tracker under different conditions. Two modules were insulated on the back to have high working temperature. One insulated module, one module without insulation were placed under a mesh, and a similar set was projected directly to the sun. The set up of four modules on the two axis tracker is shown in Figure 9 and the insulation on the backside of the module is shown in Figure 10.

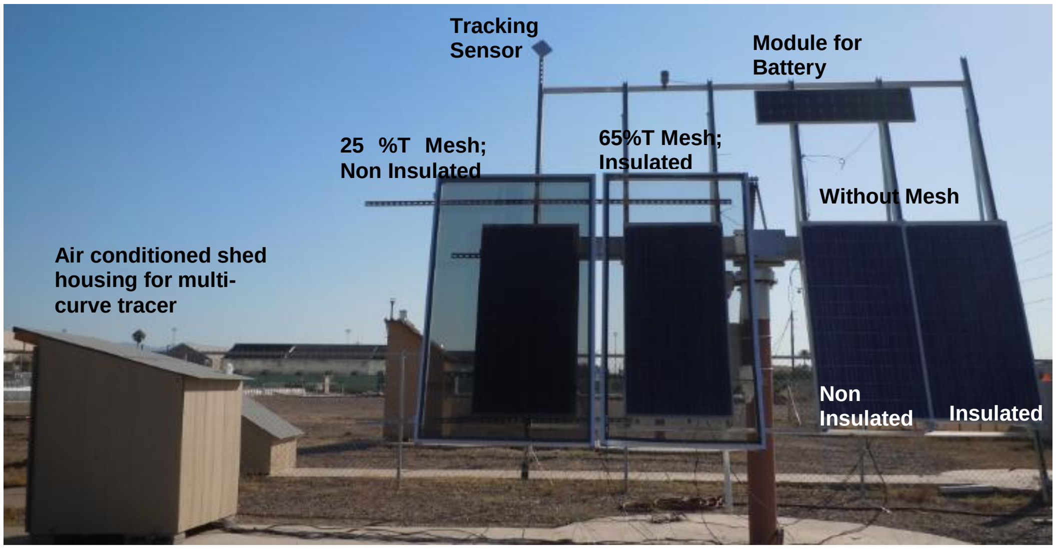

Figure 9. Setup of one set (four similar modules of one manufacturer) on two Axis Tracker platform and they are connected Multi-curve tracer

The parameters that are collected by the multi-curve tracer are:

G – Irradiance from the reference cell

T – Each Module Temperature at center and edge

I_{sc} – Short Circuit Current of each module

V_{oc} – Open circuit Voltage of each module

P_{max} – Maximum Power of each module

FF – Fill Factor of each module

I V data – A set of data points (currents and voltages) collected for each module from the short circuit current to open circuit voltage as shown in Figure 11.

Figure 10. Backside view of two modules with and without insulation on a two axis tracker

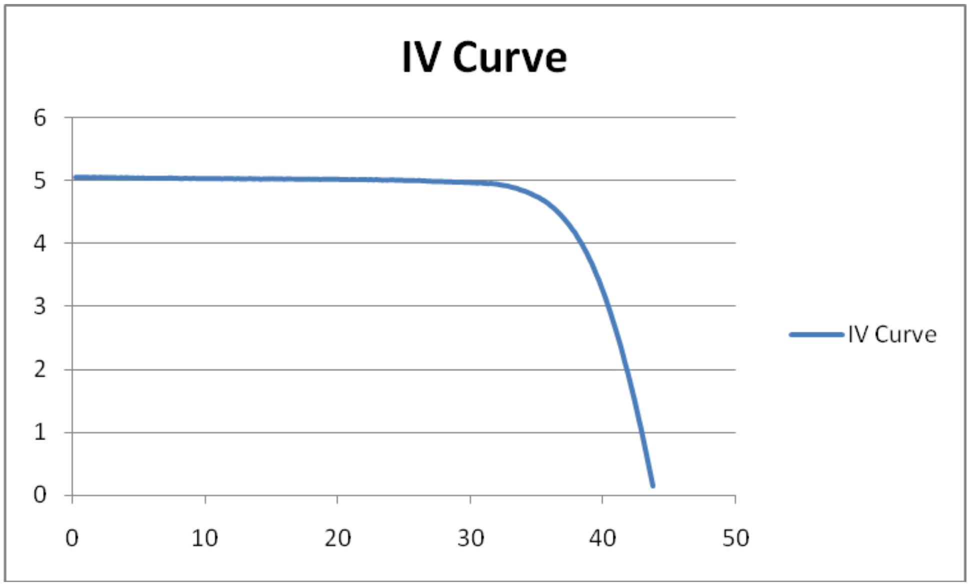

Figure 11. IV curve

Assumptions

The test station was set up at Arizona State University Polytechnic Campus, Mesa, Arizona. It constituted a two-axis tracker with a station which was built to accumulate a multi-curve tracer and an air conditioner to protect the tracer from overheating.

- All four PV modules had same length of cable and the temperature of the module was collected at two different points (Center and End).
- It was assumed that the temperature on the back skin and the cell were the same.
- The irradiance on the PV modules was assumed to be same as the irradiance measured by the reference cell, as both technologies were same and both had same superstrate (Glass). They were expected to have less mismatch between the irradiances experienced by the PV module and the reference cell as they were not expected to have the spectral mismatch as they were of same technology.

Four similar modules were placed on the two axis tracker as shown in Figure 9. The four modules were as follows:

(i) Back not insulated and with ~ 25% T mesh on the module – for low temperatures and low irradiances.

(ii) Back insulated and with ~ 65% T mesh on the module – for high temperatures at low irradiances less than 600 W/m^2

(iv) Back not insulated and no mesh on the module – for low temperatures and high irradiances.

(v) Back insulted and no mesh on the module – for high temperatures and high irradiances.

This setup allowed data collection at wider range of temperatures and irradiances. The modules with insulation and without insulation on the back side are shown in figure 10.

The data is collected for 12 days from the time the sun rises (6 AM) to the time of sunset (6 PM) after every 2 minutes. This allowed data to be collected in small variations of temperature and irradiance.

For data collection purposes, a multi-curve tracer with 16 channels (for module input), 8 Aux inputs, and 8 temperature inputs were used. The module output was connected to four channels of the multi-curve tracer and the reference cell output was fed to Aux input and the temperatures from the four modules and reference cell temperature were fed to 8 temperature inputs.

Initially it was planned to collect the data for 12 days and to analyze 12 days data for power matrix generation. But it was observed that the data was repeatable and then project included comparing the power matrices between 1 day, 6 days, and 12 days data.

3.5 Translation Procedure

This study requires the generation of power matrix at seven irradiances and four temperatures. Though the data was collected continuously throughout the day, it was still not possible to have the data at the required data point in the power matrix. To calculate the power at various test conditions with the given data, the IEC 60891 procedures are required. The standard uses four different procedures and this project analysis the data using the first three procedures of IEC 60891 [4].

3.5.1 Procedure 1. Chapter 2 shows the mathematical equations of this procedure. The temperature coefficients (α and β) were determined using the baseline procedure. It needs 10 curves for the procedure and the steps involved to determine these coefficients are shown in figure 12.

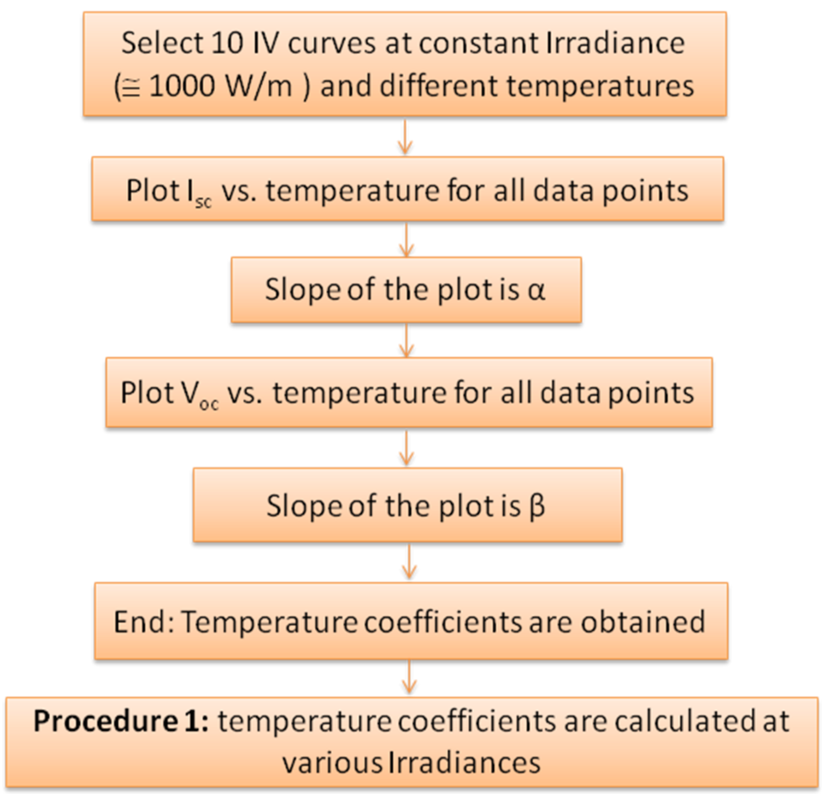

Figure 12. Procedure to obtain temperature coefficients for Procedure1

The IEC 60891 procedure 1 requires two more parameters 'R_S' and 'k' and the steps involved in obtaining 'R_S' are shown in figure 13 and 'k' is shown in figure 16.

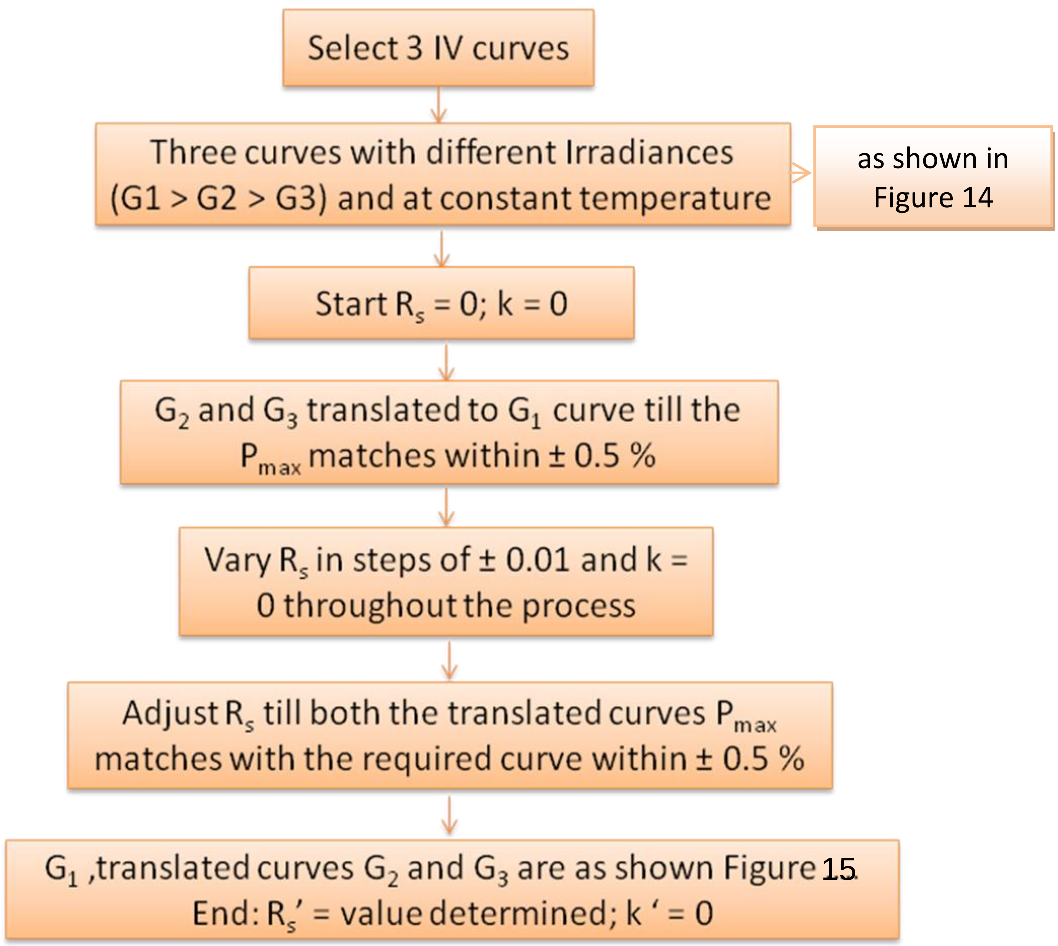

Figure 13. Steps involved in obtaining R_S of IEC 60891 procedure 1

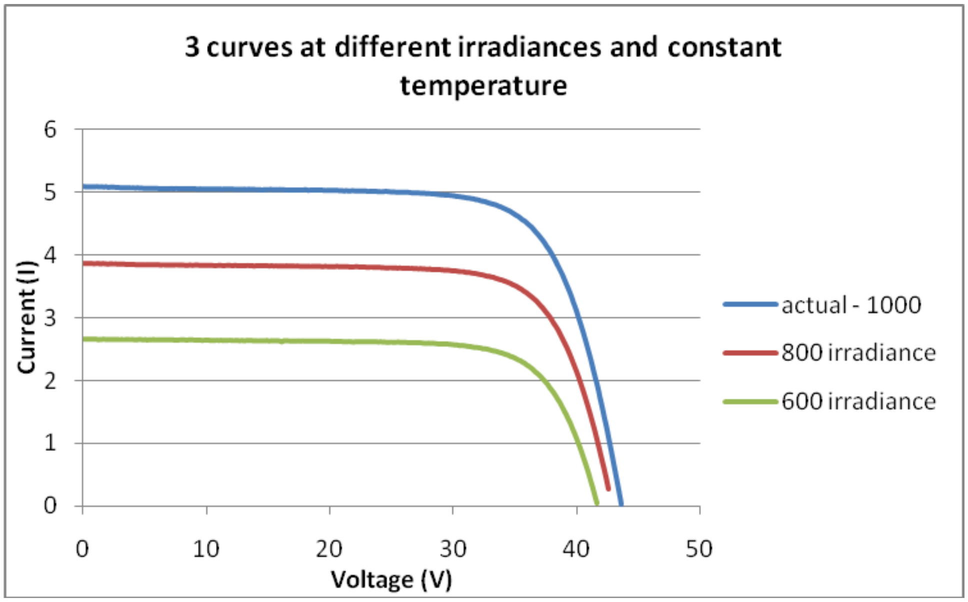

Figure 14. Three Curves at different Irradiances and constant temperature to determine “Rs” (for Procedure 2 it’s “a” and “Rs’ ”)

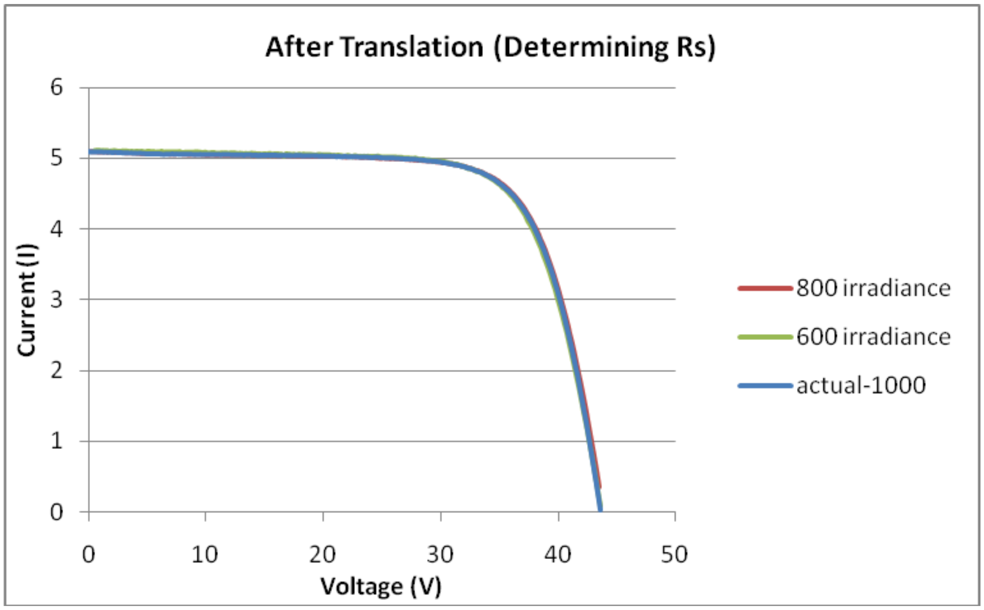

Figure 15. After determining “Rs” (for Procedure 2 it’s “a” and “Rs’ ”); the translated curves and original curve merge on each other

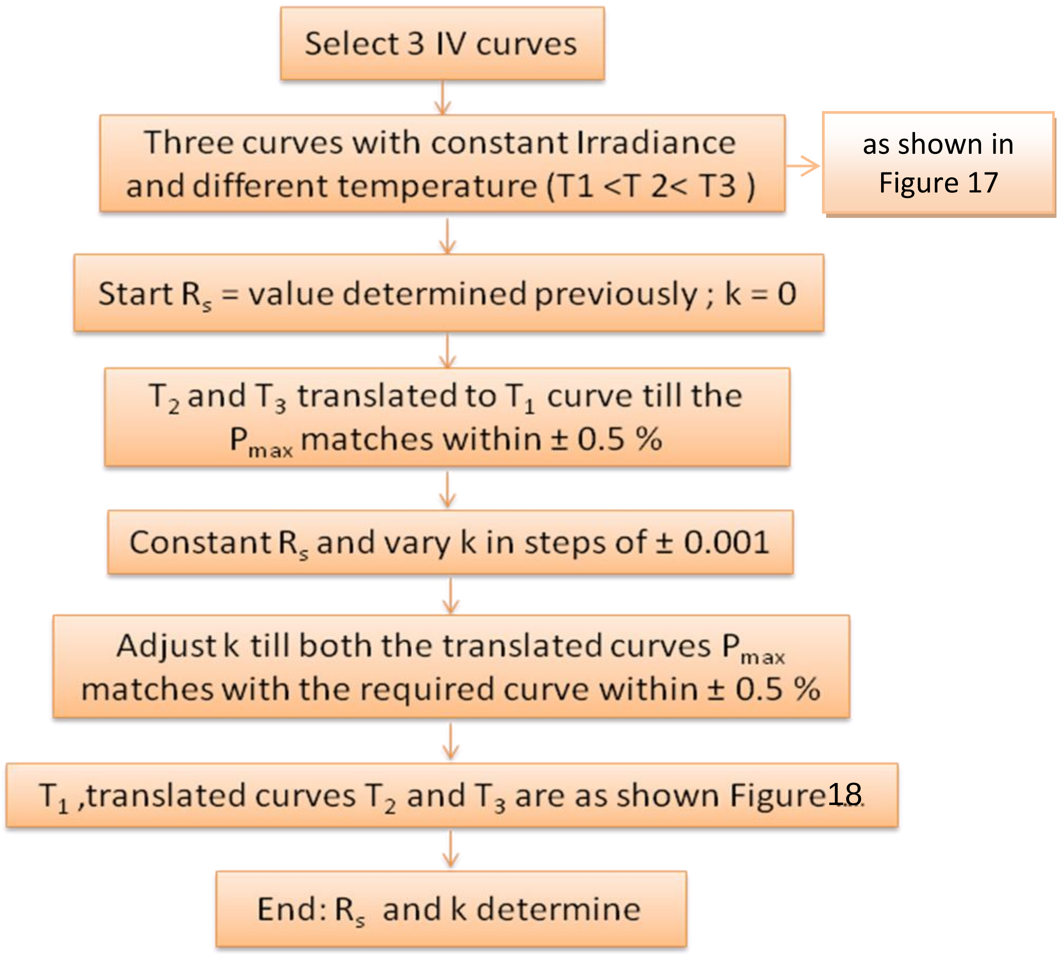

Figure 16. Steps involved in obtaining k of IEC 60891 procedure 1

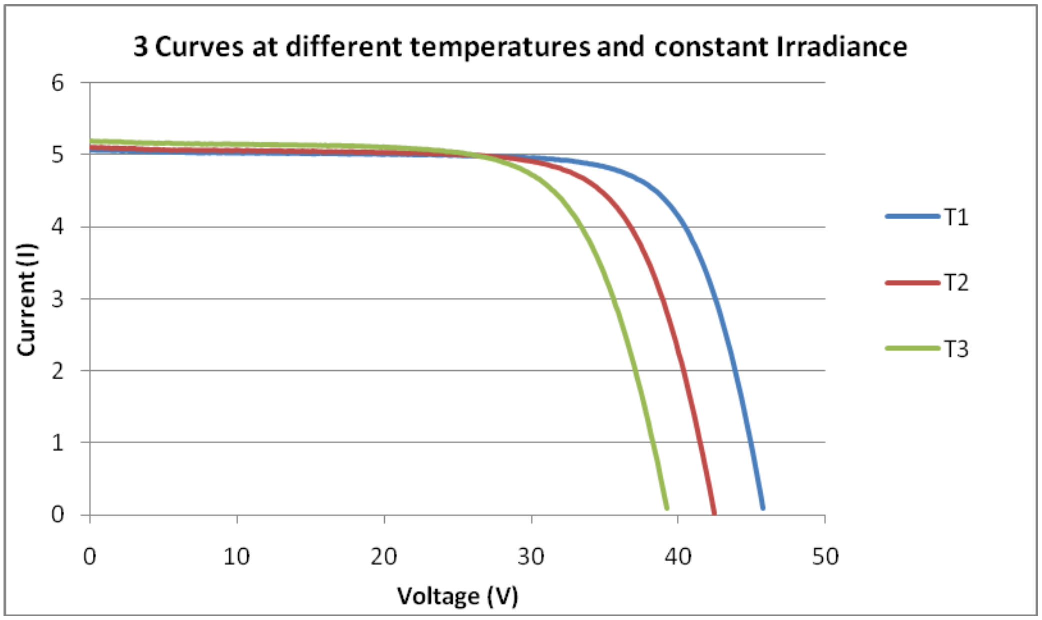

Figure 17. Three curves at different Temperatures and constant Irradiance, to determine “k”

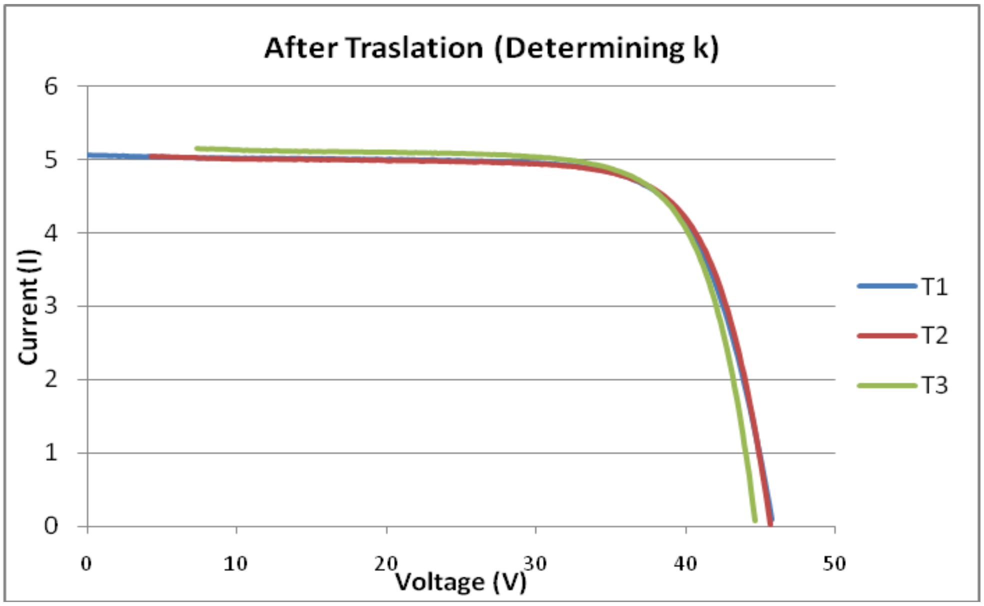

Figure 18. After determining “k,” the translated curves and original curve merge on each other

These parameters help obtain the required curve by translating any reference curve.

3.5.2 Procedure 2. Chapter 2 shows the mathematical equations of this procedure. The temperature coefficients (αrel and βrel) were determined using baseline procedure. It needs 10 curves for the procedure and the steps involved to determine these coefficients are shown in figure 19.

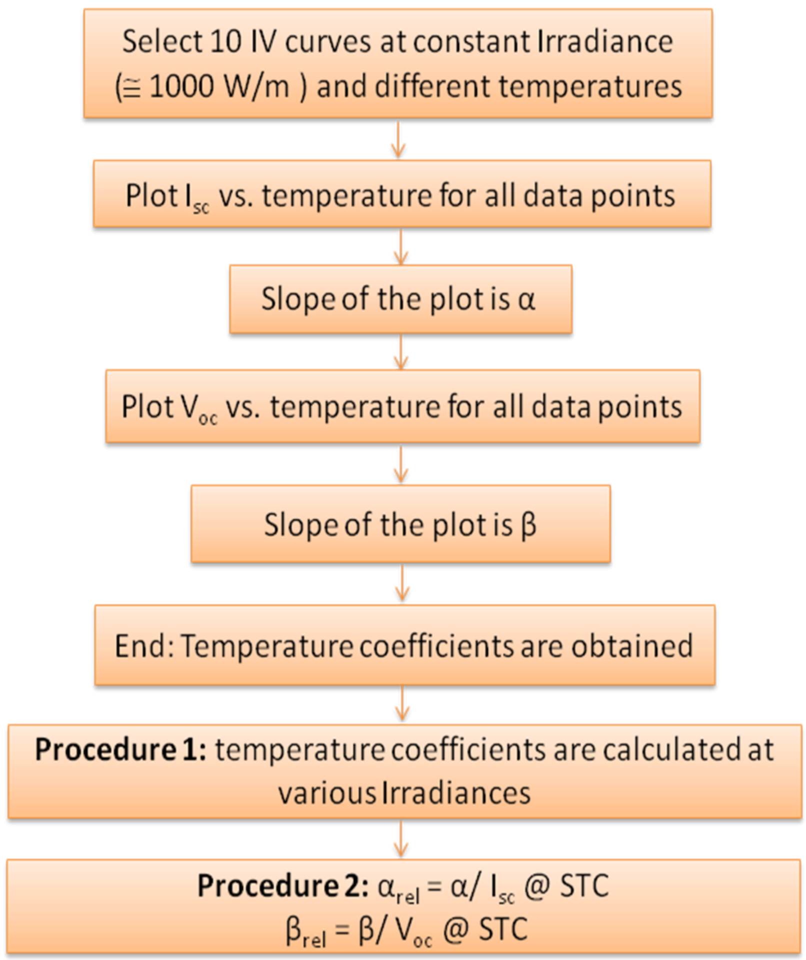

Figure 19. Procedure to obtain temperature coefficients for Procedure 2

The IEC 60891 procedure 2 requires three other parameters a, R_S' and k' and the steps involved in obtaining a, R_S' are shown in figure 20 and k' is shown in figure 21.

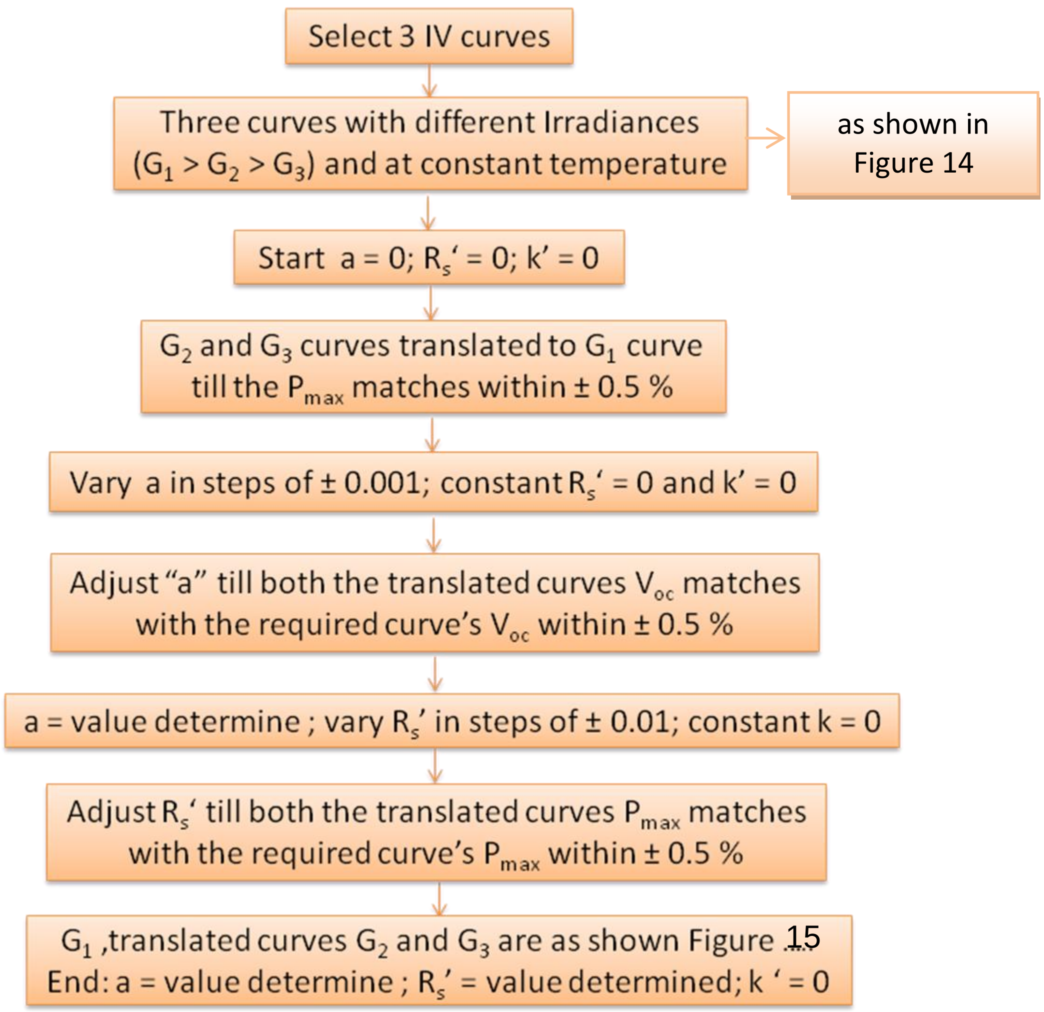

Figure 20. Steps involved in obtaining a, R_S' of IEC 60891 procedure 2

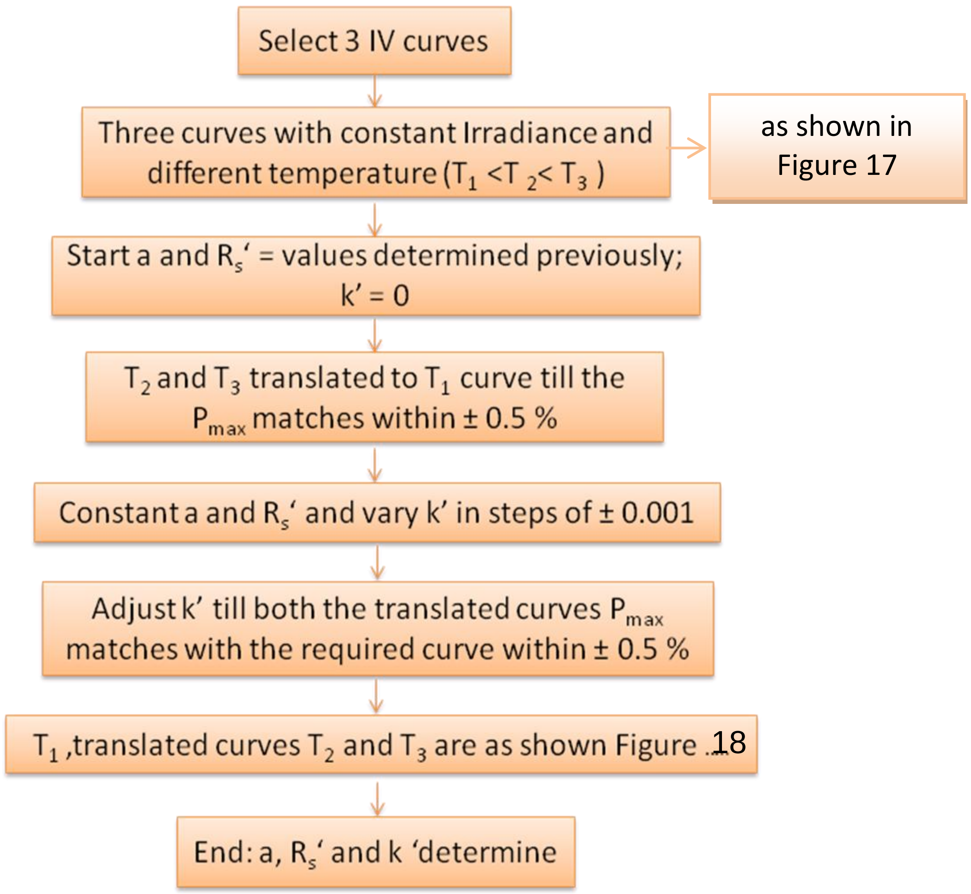

Figure 21. Steps involved in obtaining k' of IEC 60891 procedure 2

3.6 Power Matrix

The power matrix as per IEC 61853-1 [5] is shown in table 1. To translate a reference curve to a required test condition, the four translation procedures of IEC 60891 [4] are required. The power matrices generated for four manufacturers are compared to analyze their performance. This determines the capability of each manufacturer module at different irradiance levels and temperatures. The Power matrix is generated using "Automation Software" and "Hybrid method."

In the hybrid method, the power matrix uses the automation software, but the reference cell for translation is selected by manually. This method was used because the results produced by automation software had deviations when compared with the real data.

Chapter 4

RESULTS AND DISCUSSIONS

In Previous sections, the experiment setup and methodology were discussed. In the introduction it was mentioned that the project was carried out on four modules from four manufacturers. For convenience, four manufacturers are considered as four sets, each set is named as M1, M2, and M3 and M4. In each set, the modules are numbered as M1-1, M1-2, M1-3 and M1-4. The other 3 sets are numbered in similar pattern.

The results and discussions obtained at the various stages of the project are presented in this section.

4.1 Automation Software

The 23 element Power Matrix according to IEC 61853-1 had to be generated using IEC 60891 procedures. The procedures discussed in IEC 60891 have lot of math involved to obtain the required results, which needs special expertise. The calculations involved in Procedure 1 and 2 needs extreme attention and are easily prone to human errors [8]. Procedure 3 and 4 are interpolation procedures which involve a condition to select curves. Due to the above mentioned reasons, the first three procedures of IEC 60891 were automated as software [1]. This software was developed by Fernandes and was validated by the present researcher using the data collected by Paghasian [7]. The main window of the software is shown in Figure 22.

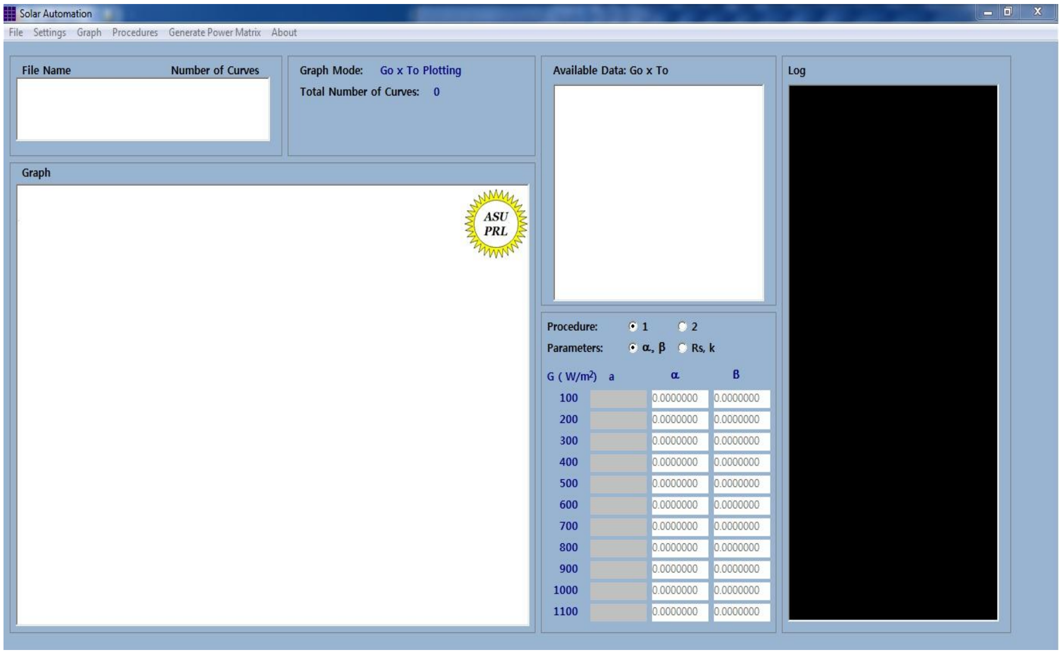

Figure 22. Automation Software Main Page

4.2 Collecting the Baseline Data

The baseline curves are collected from either three or four modules of each set. For each set of modules, 10 baseline curves were collected and computed using conventional baseline translation procedure as explained in methodology chapter. The temperature coefficients were calculated using the procedure shown in figure 23.

Apart from temperature coefficients, baseline procedure was also used to calculate various parameters at STC conditions, as shown in figure 23.

Conventional Baseline Procedure
Results of Electrical Performance and Temperature Coefficient Test

	A	B	C	D	E	F	G	H	I	J	K	L	M
6			Performance at 1000W/m^2, 25°C										
7		Date	Isc	Voc	Imp	Vmp	FF	Pm	Pm Uncertainty (25C, 95%)				
8			A	V	A	V	%	W		(W)	(%)		
9	Measured @ STC	3/13/2007	4.09	51.1	3.17	36.6	55.5	115.9		4.0	3.5%		
10	Rated @ STC		4.60	50.0	3.60	33.5	52.4	120.0					
11	Measured/Rated (%)		88.8%	102.2%	88.1%	109.1%	105.9%	96.6%					
12	Rated @ NOCT	46.0	3.59	45.1	2.83	29.2	51.0	82.6					
13	R^2 of Curve fitting		0.355	0.995	0.034	0.982	0.942	0.993					
14			Temperature Coefficients at 25°C										
15			Isc	Voc	Imp	Vmp	FF	Pm					
16			A/°C	V/°C	A/°C	V/°C	%/°C	W/°C					
17	Measured @ STC		0.0008	-0.2339	0.0005	-0.2071	-0.0687	-0.6384					
18													
19	Test Data (ATC)												
20	CurveName		GSE0973a	GSE0973b	GSE0973c	GSE0973d	GSE0973e	GSE0973f	GSE0973g	GSE0973h	GSE0973i	GSE0973j	average
21	Date		#######	#######	#######	3/13/2007	#######	#######	#######	#######	#######	#######	
22	Time		14:25	14:26	14:27	14:27	14:28	14:29	14:30	14:30	14:31	14:32	
23	Tamb (°C)		35.0	34.7	33.8	34.9	34.0	33.8	33.6	34.4	34.6	34.6	34.3
24	Tref1 (°C)		51.3	51.3	51.5	51.5	51.3	51.3	51.1	51.0	51.1	51.3	51.3
25	Tm (°C)		20.5	26.0	31.6	34.7	37.6	39.9	42.1	44.3	46.9	47.1	37.1
26	Tref2 (°C)		47.0	47.0	47.3	47.2	47.2	47.0	46.7	46.7	46.9	47.4	47.0
27	G1 (W/m^2, T)		1074.9	1076.7	1076.1	1072.1	1071.3	1069.4	1070.3	1070.9	1069.8	1074.4	1072.6
28	G2 (W/m^2, T)		1101.4	1100.6	1099.3	1099.0	1096.5	1095.4	1094.6	1095.4	1093.5	1097.3	1097.3
29	Isc (A)		4.32	4.34	4.35	4.34	4.35	4.33	4.34	4.33	4.34	4.33	4.34
30	Voc (V)		51.56	50.44	48.93	48.14	47.37	46.95	46.53	45.99	45.70	45.20	47.68
31	Imp (A)		3.36	3.34	3.42	3.36	3.35	3.40	3.36	3.33	3.36	3.36	3.36
32	Vmp (V)		36.91	36.17	34.30	34.16	33.52	32.63	32.52	32.36	31.67	31.25	33.55
33	Pm (W)		123.82	120.88	117.34	114.67	112.23	110.82	109.34	107.86	106.51	105.13	112.86
34	FF (%)		55.5	55.2	55.2	54.8	54.5	54.5	54.2	54.1	53.7	53.7	54.5
35													
36	CFref #1	38.994	ssi001			CFref #2	111.58	sx203					

PV Parameters at STC conditions

Temperature Coefficients

Figure 23. Conventional Baseline Procedure – An example

From each manufacturer, four similar modules were selected for which the parameters (Temperature coefficients, Maximum Power, Fill factor, Voc and Isc) were approximately equal. To declare four modules similar, the IV curves at STC should lie on each other as shown in figure 24.

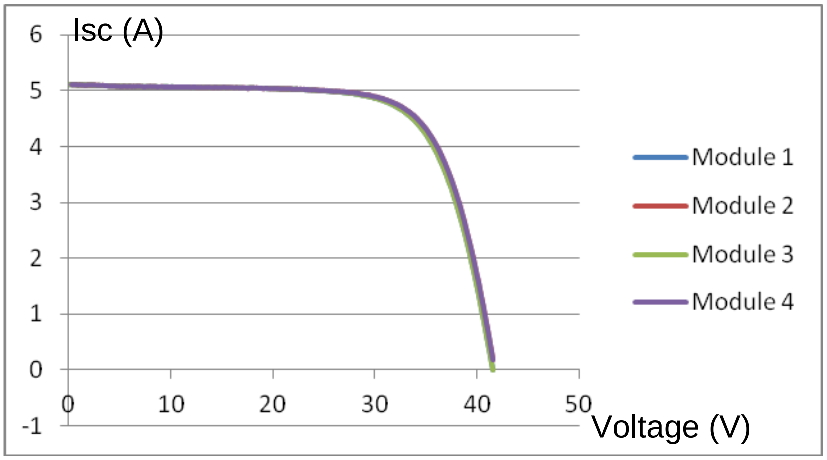

Figure 24. Baseline I-V Curves of four modules of Manufacturer A at STC

4.3 Mesh Calibration for Transmittance

The project demanded that the data had to be collected at various irradiances for which meshes were used to decrease the irradiance to the required level. Before using, the meshes were to be calibrated as discussed in methodology chapter.

The IV curves were collected at about 1000 W/m2 irradiance without mesh screen and at different irradiances by quickly placing different mesh screens at a constant stabilized temperature. Once the data collection was complete, the mesh screen was calibrated using the relation "current is directly proportional to irradiance," which determines the amount of the irradiance that was transmitted. Two sets of meshes were used in this project. Set 1 was used to collect baseline curves at different irradiances; the calibration factors for Set 1 are presented in

Table 2. The other set of meshes were used on top of the two axis tracker to obtain different irradiances in the data collection.

Table 2. *Mesh Transmittance Calibration of Set 1*

Irradiance	Trasmittance Coefficient
100	0.053
200	0.150
400	0.465
600	0.553

Table 3*. Mesh Transmittance Calibration of Set 2*

Irradiance	Transmittance Coefficient
200	0.25
500	0.65

4.4 Data Collection on Two Axis Tracker

For data collection, each set (one manufacturer of the four) was selected and three or four similar modules of the manufacturer were chosen. These three or four modules were placed on the platform of a two axis tracker. Then the output of each module was fed to the multi curve tracer, to read the I-V Curve from the module. The module temperatures (at the center and one of the ends of the module) were read using thermocouples; these thermocouples were also connected to the multi-curve tracer. Apart from these parameters the other parameters which were monitored were irradiance and temperature of the reference cell. These parameters and IV curve data were logged into a computer through the multi-curve tracer.

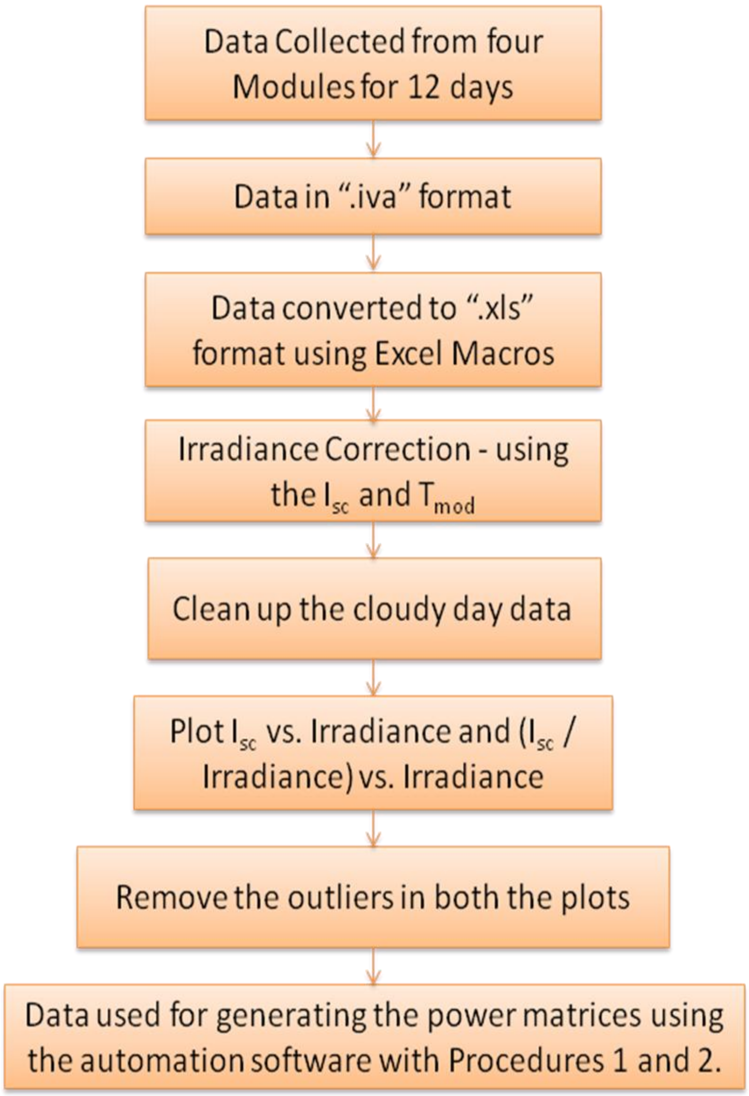

Figure 25. Steps used to cleanup and obtain quality data to use as input for the automation software

The data collected using the multi-curve tracer undergoes various processing steps before it could be used for the actual power matrix calculations as shown in Figure 25. The flow chart shows that the data collected was in ".iva" format, but in order to do the calculations, it was converted to excel format, i.e., ".xls" format. The next steps in organizing the data are discussed in the figure 25. The irradiance shown by the reference cell can be used for the calculations and when the meshes are used the irradiances can be corrected using the mesh calibration factors. But in this project, the irradiance was calculated by using the I_{sc} of the module and correcting it with the module temperature. This was done because, the modules were left on the two axis tracker for 12 days and there can be a non uniform dust accumulated on the modules or meshes. The accumulated dust affects the irradiance and could be different from the reference cell irradiance.

Once all the curves were converted, the data was fed into the automation software. The data collected on 24th November 2011 was read through the automation software and the graph with Temperature vs. Irradiance data is shown in Figure 26.

The data differs from a clear sunny day to a cloudy day; the data that is shown in Figure 26 is for a cloudy day. On a cloudy day, the data from all the four modules appear to be mixed, and one cannot differentiate the data from one module to the other module. But on a sunny day, the data will be seen as clusters. The data from each module will be seen as a group; therefore the graph will have four groups of data points, as there are four modules used in this project. The data collected from the four modules on 19th Oct 2011, which was a sunny day, is shown in Figure 27. Therefore to avoid the clusters in the graph, the experiment should be conducted on a cloudy day. This gives a high range of irradiances and temperatures

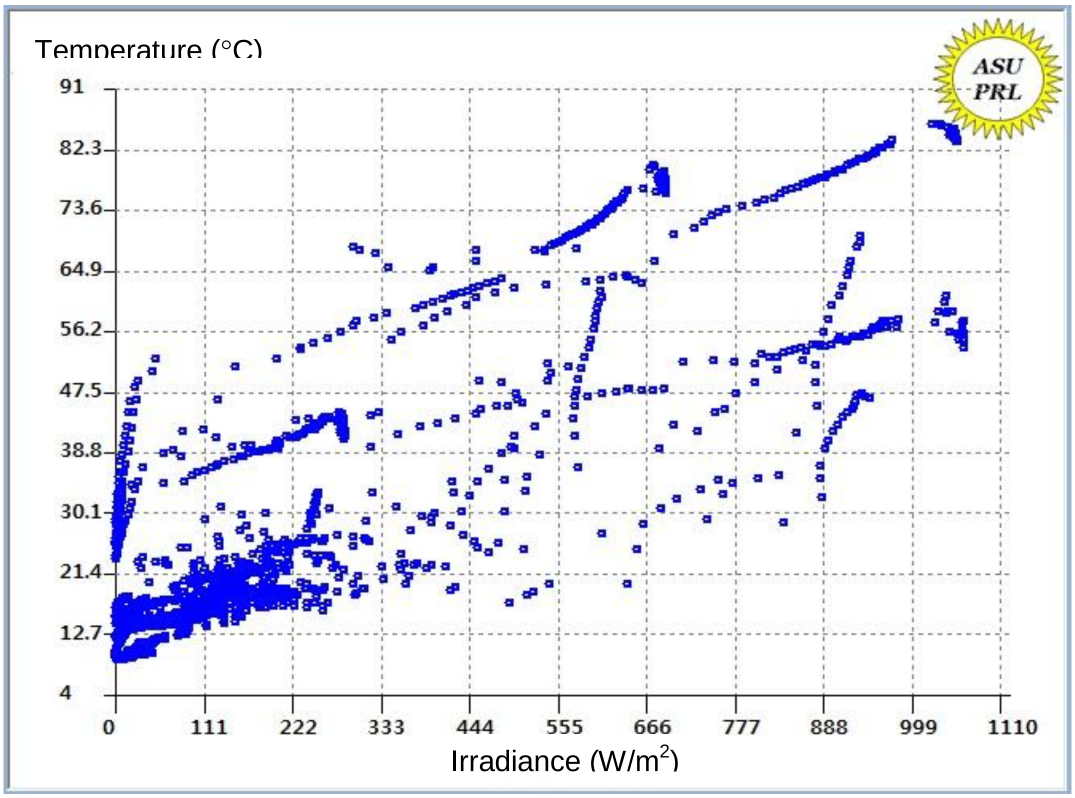

Figure 26. Figure showing the raw irradiance and module temperature data obtained on 24th Nov 2011 (partially cloudy day; fall season)– with four modules, in which two are covered with mesh screens and the other two modules with thermal insulation as explained in the experimental setup section

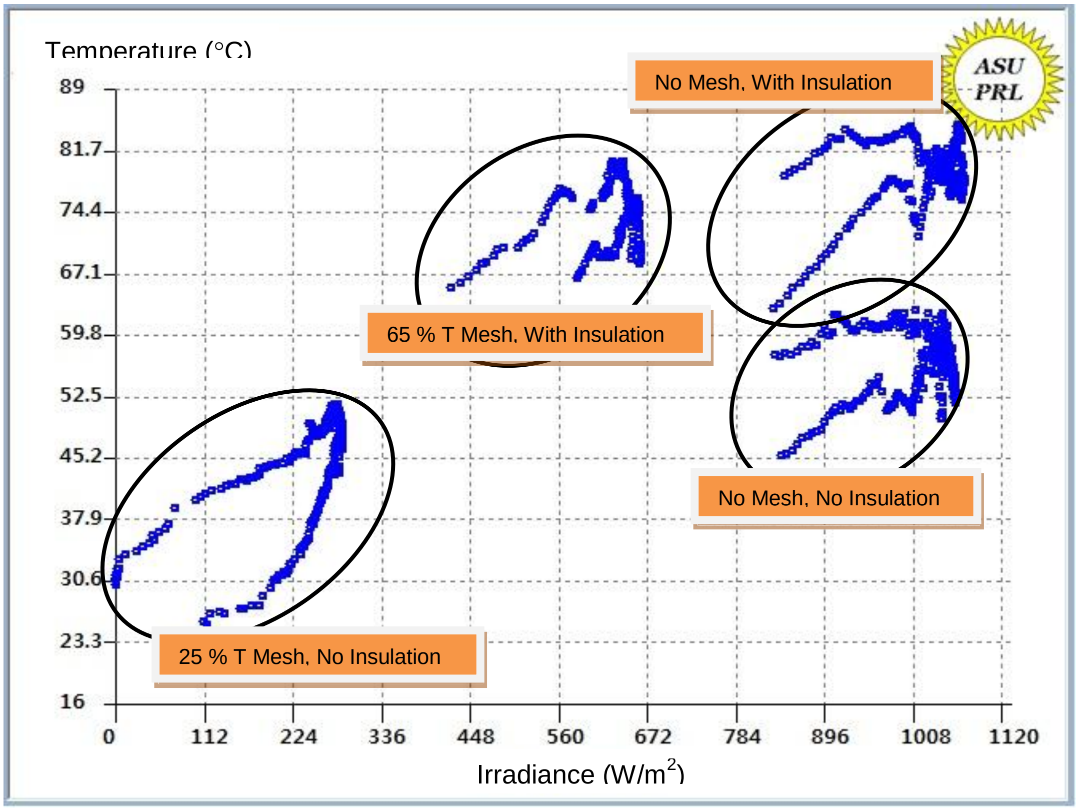

Figure 27. Figure showing the raw irradiance and module temperature data obtained on 19th Oct'11 (clear sunny day; fall season) – with four modules, in which two are covered with mesh screens and the other two modules with thermal insulation as explained in the experimental setup section

In Figure 26 and Figure 27, the graph is plotted to show the data points as "Temperature vs. Irradiance." Figure 28 (below) shows the graph of automation software which plots the data points as "Current vs. Voltage."

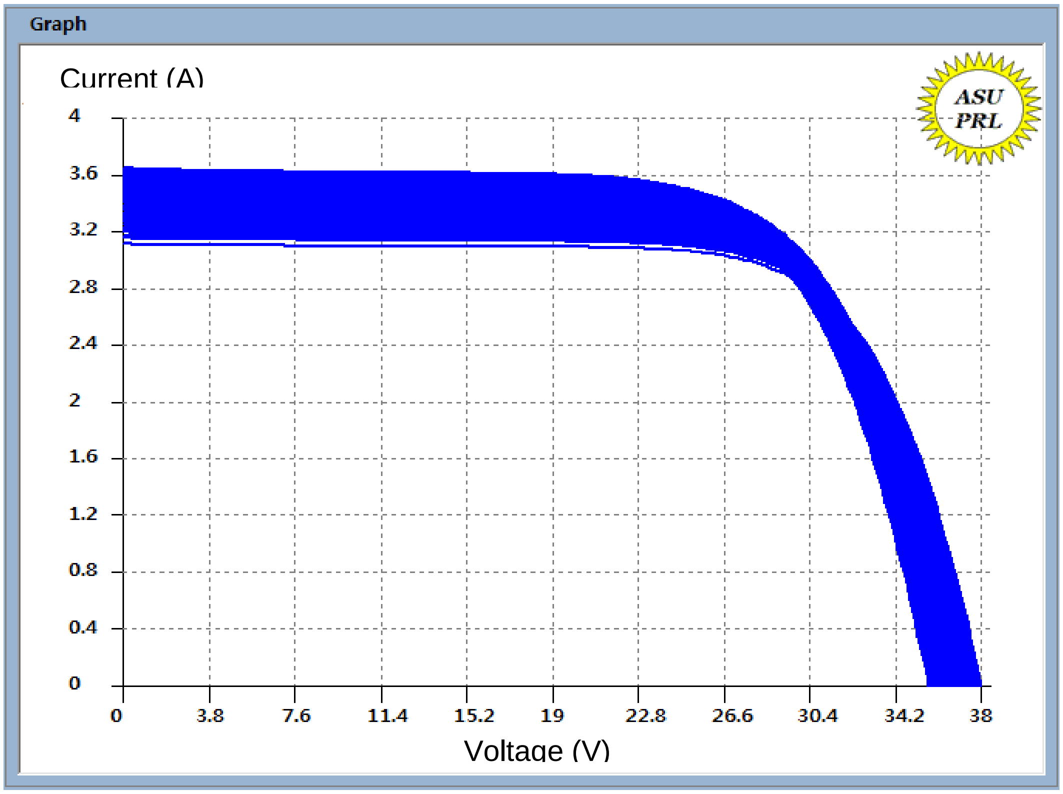

Figure 28. Data collected on 19th Oct.11 from Module 3

On a cloudy day, when there is a cloud passing at the time of I-V Curve measurement, those I-V curves would have a small drop or a shoulder in the middle of the curve. Sometimes the curve would have more than one shoulder, as shown in Figure 29. The data in the Figure 26 shows the data points on a cloudy day, so the curve shown in Figure 29 is from the set of data points of Figure 26. One I-V curve will be taken within 7 seconds, but still the module is affected by the passing cloud. If there is no cloud when the data is collected, then we get a curve, as shown in Figure 30. So from this it is clear that, when there is a passing cloud, a dip will be seen in the curve. This is similar to having a non- uniform shadow on the module.

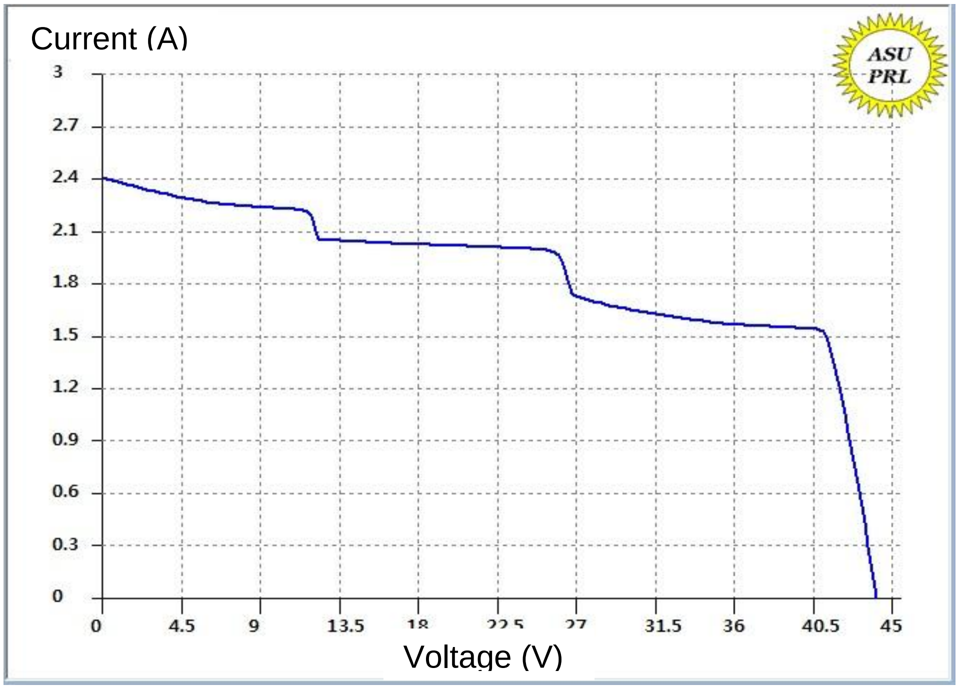

Figure 29. I-V Curve when there is a passing cloud

When the curves were observed closely, it was found that there are many curves with dips due to passing clouds. This is because the data was collected in the fall season. There is an advantage and disadvantage of collecting the curves in the fall. The advantage is that we can have a slow increase in the temperature in a day and have curves at various temperatures and irradiances. The data points spreads throughout the graph. But when it is taken on a clear sunny day, the data points will be as clusters rather than being spread throughout the graph. This was shown in Figure 29 and Figure 30.

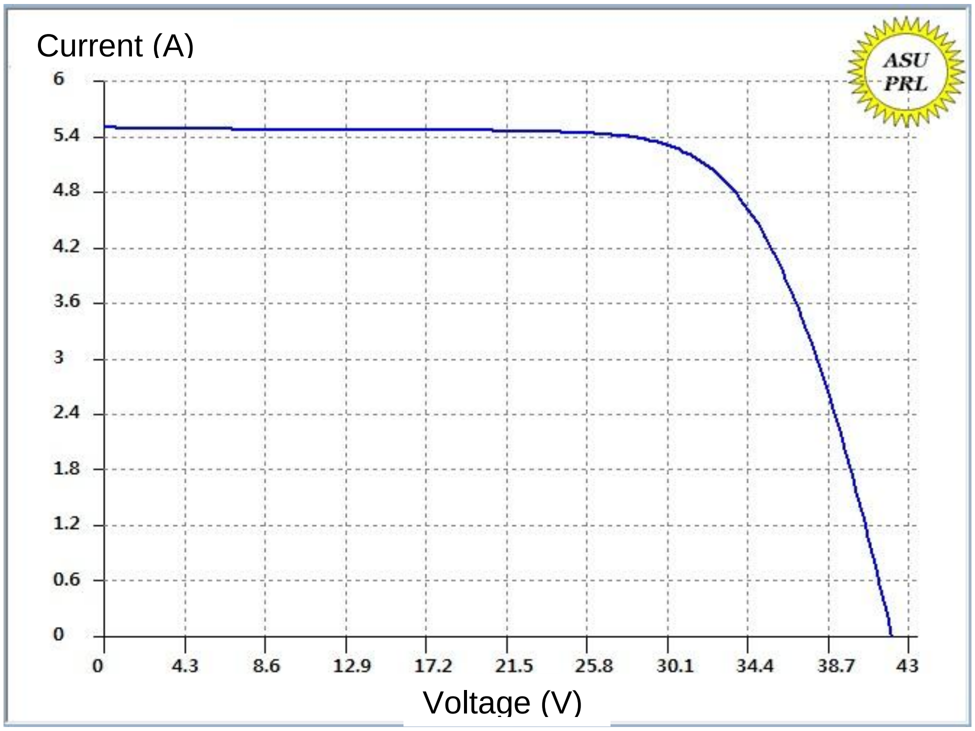

Figure 30. IV Curve taken when there is no passing cloud

It was observed that there are many curves with dips in the data collected from a single day, as shown in Figure 31. Due to the irregularity in the data which was collected on cloudy days, the linearity check was performed to remove the affected curves and have high quality data. By deleting the outliers in the data, the results produced with the new set of curves give better results.

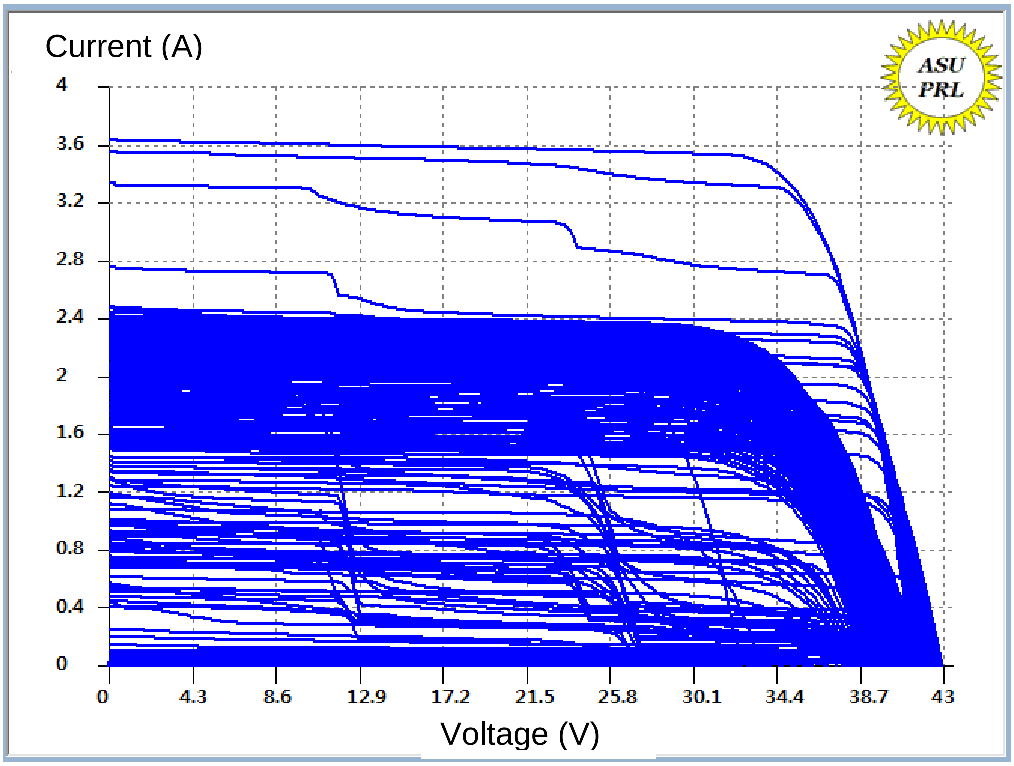

Figure 31. Single day Data set from Module 1 of M2, showing curves on a cloudy day

To perform the linearity check, various graphs are plotted – I_{sc} vs Irradiance and (I_{sc}/ Irradiance) vs Irradiance. These graphs help in removing the outlier data. Figure 32 shows I_{sc} Vs Irradiance plot and Figure 33 shows the (I_{sc}/Irradiance) vs Irradiance plot with irregular data. From Figure 32, a line can be seen, which seems to pass through origin, so any data point that was out of that imaginary line was deleted. In Figure 33, the data points seem to be constant at any irradiance point. The data point that was within the 3% limits is used for the calculations and all other data points that are outside the limits were deleted in this graph. Figure 34 shows the figure 32 data after deleting the outlier data and similarly figure 35 shows the figure 33 data after getting rid of outlier data.

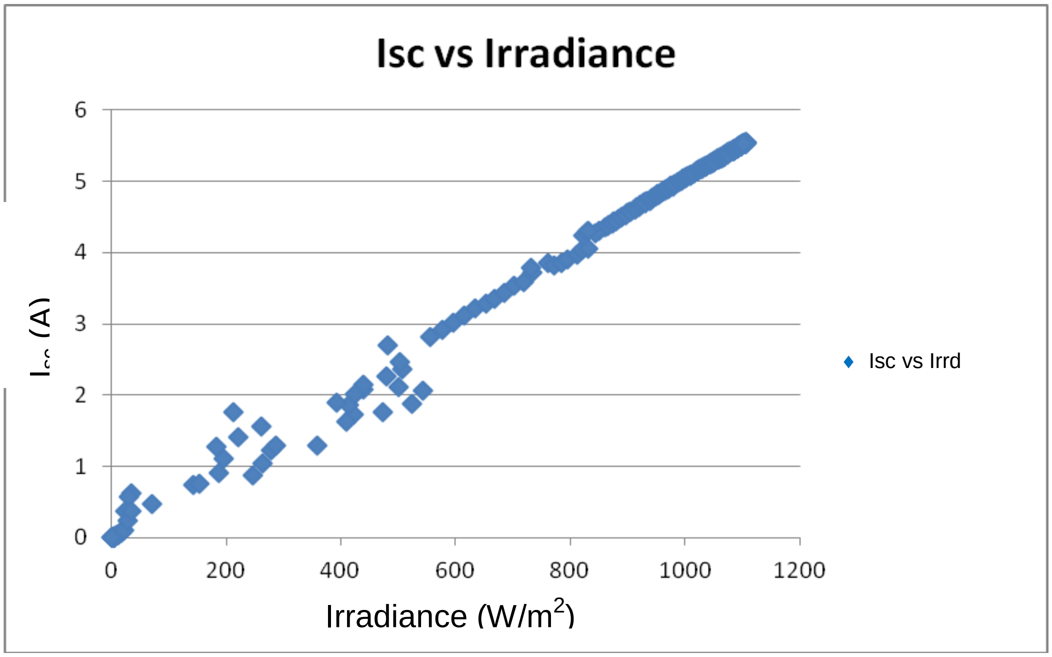

Figure 32. I_{sc} Vs Irradiance data without clearing the irregular data

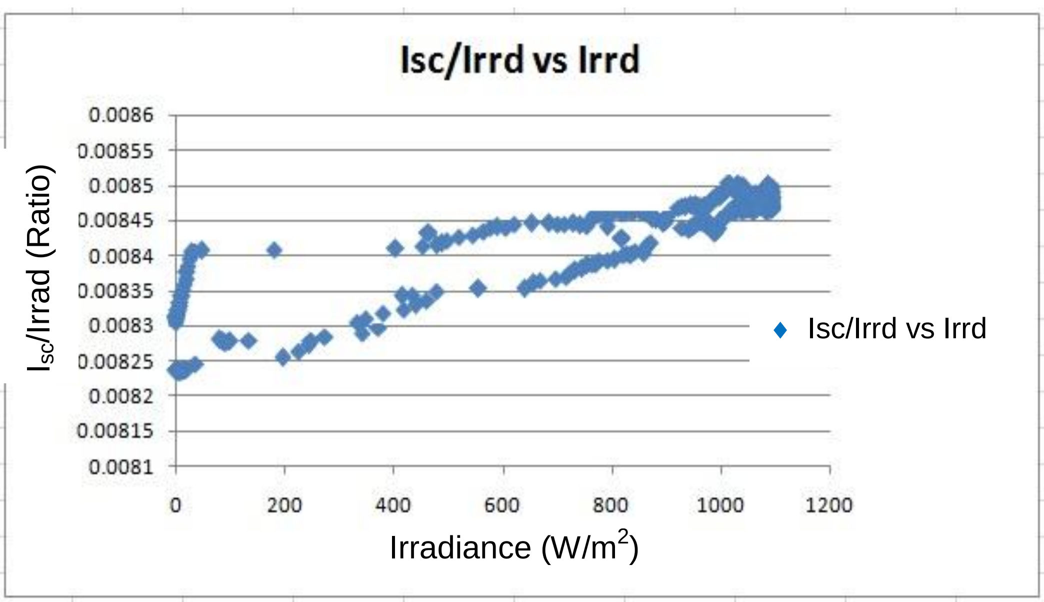

Figure 33. I_{sc}/Irradiance Vs Irradiance data without clearing the irregular data

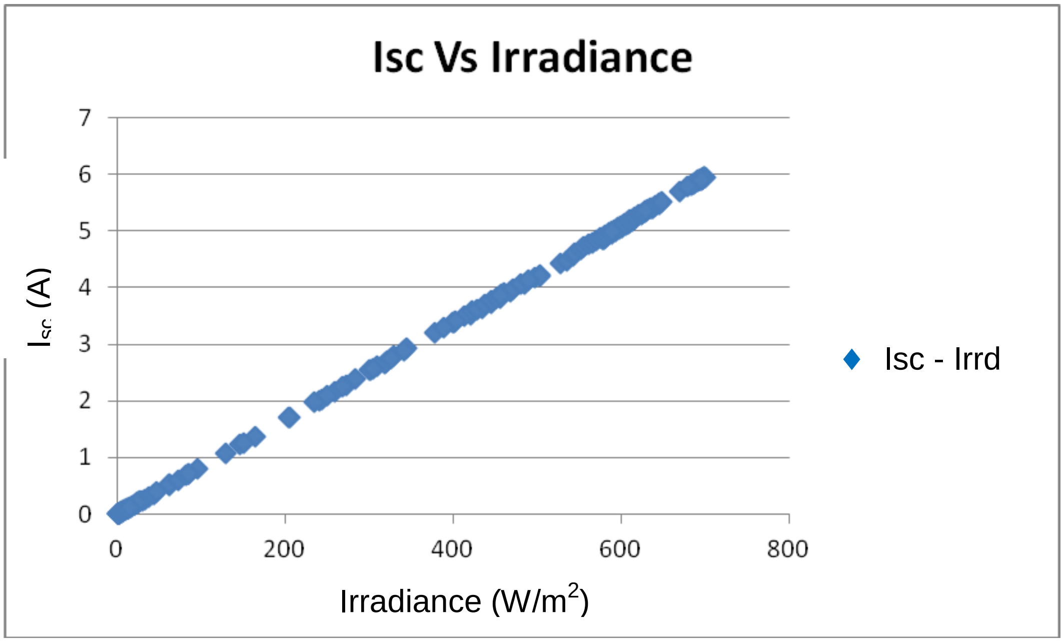

Figure 34. I_{sc} Vs Irradiance data after cleaning up the irregular data that was shown in Figure 24

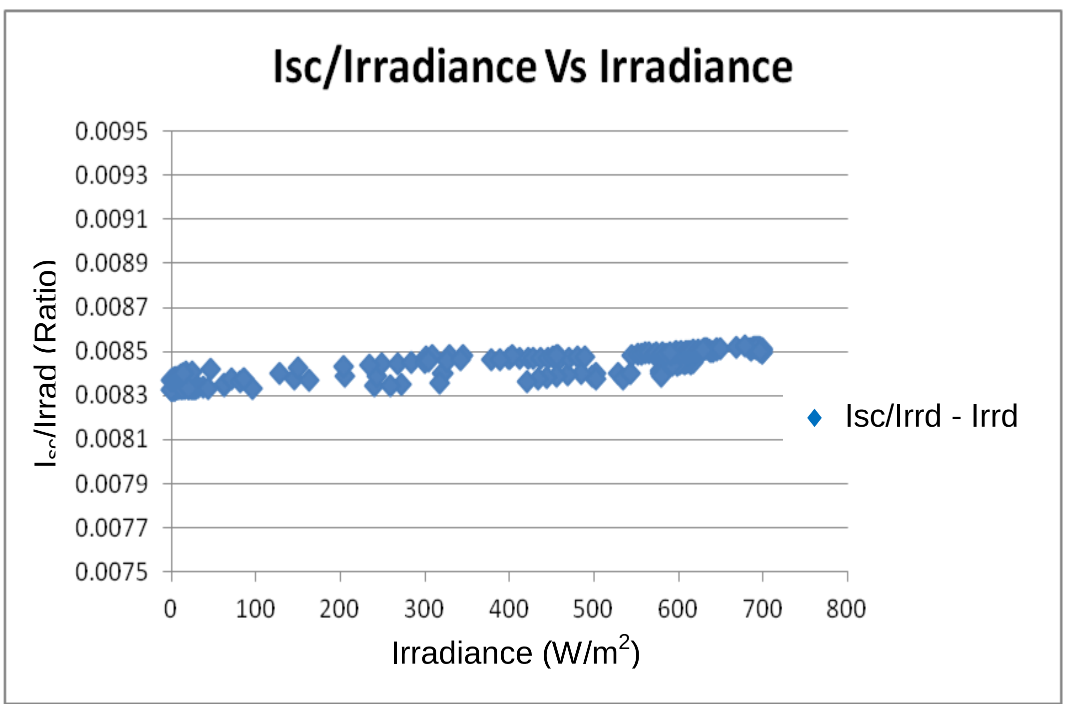

Figure 35. I_{sc}/Irradiance Vs Irradiance data after removing the outlier data in Figure 25

4.5 Parameters

After the data was cleaned up using the linearity check, the data was used for further calculations.

Each procedure has a set of parameters which need to be calculated, before the data is used to generate the Power Matrix. Temperature coefficients are calculated before any calculations are performed and this was already discussed in baseline procedure. Once the temperature coefficients are obtained the other parameters such as (R_s, k) for procedure1 and (a, Rs', k') for procedure 2 were calculated. As all the parameters were obtained the power matrices were generated using first three procedures of IEC 60891 [4]. The Power matrices for the four manufacturers were calculated and compared. . The comparison is done in terms of percentage for all the 23 elements in the power matrix.

Consider a hypothetical module of 100 W power which has constant efficiency at all irradiance levels and temperature coefficient of power as -.5%/°C. The power matrix of this module is shown in Table 4.

Table 4. *Power Matrix for hypothetical 100 W module*

Irradiance (W/m2)	Temperature (oC)			
	15	**25**	**50**	**75**
1100	N/A	110	96.25	82.5
1000	105	100	87.5	75
800	84	80	70	60
600	63	60	52.5	45
400	42	40	35	N/A
200	21	20	17.5	N/A
100	10.5	10	N/A	N/A

Note: Power temperature coefficient is - 0.5 %

The power matrix that is shown in the Table 4 is an ideal representation, where the power temperature coefficient of a particular module is -0.5%/^{o}C at all irradiance levels. But in reality, the modules of different manufacturers may have different temperature coefficients and these coefficients may depend on the irradiance levels. It is not only true for power temperature coefficients, but also for the temperature coefficients of voltage and current. In this study, four similar modules are considered from each manufacturer. When the temperature coefficients were calculated using baseline procedure, the temperature coefficients for all the four modules were not same but approximately equal. The difference in temperature coefficients for four modules of same manufacturer/ different manufacturers was due to the presence of parasitic resistances. The parasitic resistances and its effects are already discussed in the methodology chapter.

4.6 Validation of Automation Software

Automation software was developed for the translation procedures of IEC 60891 and power matrix generation of IEC 61853-1 using the first three procedures [1]. Before the automation software was used for this project, it was validated. The data used for the validation was collected on the Mono Crystalline Module [7] (Paghasian, 2010). The data was used to generate the power matrix of IEC 61853-1 using procedure 2 of IEC 60891. The power matrix was generated using both manual process using Microsoft Excel and the automation software. The percentage (%) difference between the results of manual and automation is shown in Table 5.

Table 5. *Comparison of Manual and Automation results of mono crystalline module* [7] (Paghasian, 2010)

Irradiance	**Temperature (□C)**			
	15	25	50	75
1100	N/A	-0.4%	-0.3%	-0.3%
1000	0.2%	0.2%	0.3%	-0.4%
800	-0.1%	0.1%	-0.1%	-0.1%
600	-0.5%	-0.5%	-0.6%	-0.7%
400	0.4%	0.4%	0.4%	N/A
200	1.8%	1.8%	1.7%	N/A
100	-0.1%	0.7%	N/A	N/A

4.7 Validation of First Two Procedures of IEC 60891

For each manufacturer, the data was collected as discussed in the Introduction and Methodology chapters. The setup for the data collection is shown in Figure 9. The data was collected every 2 minutes from the four modules for 12 continuous days. The power matrix was calculated for four modules at 1 day, 6 days, and 12 days. The power matrix for a particular module was calculated according to the first two procedures of IEC 60891. The percentage (%) difference between the two power values of procedure 1 and 2 of IEC 60891 was calculated for all 23 elements of a power matrix and is presented in Table 6. Whenever the percentage (%) difference was less than 3%, it was considered to be acceptable. In table 6, all the percentages are less than 3%. Therefore, to generate the 23 elements of a power matrix for any module, one can use any of the two procedures.

Table 6. *Comparison between Procedure 1 and Procedure 2 for M2 considering four modules for 12 days*

Comparison of procedure 1 & 2

Irradiance (W/m^2)	**Temperature (^oC)**			
	15	**25**	**50**	**75**
1100	N/A	-1%	0%	-1%
1000	0%	0%	0%	0%
800	1%	0%	0%	0%
600	1%	2%	1%	0%
400	1%	1%	0%	N/A
200	0%	0%	0%	N/A
100	0%	-1%	N/A	N/A

4.8 Comparison of Power Matrices of a Manufacturer at Different Conditions

The power matrices are calculated for each manufacturer at different conditions. The conditions are:

- 4 modules and 12 days
- 4 modules and 6 days
- 4 modules and 1 day
- 1 module and 12 days
- 1 module and 6 days
- 1 module and 1 day

Once the power matrix was calculated for each of the above conditions, they were compared to identify the differences between the power matrices for each manufacturer.

4.8.1 **One manufacturer, four modules.**

A single manufacturer (M3) is considered in this section. The data from four modules of Manufacturer 3 were used for the calculations and the power matrices were generated using procedure 1. In table 7, the power matrices are compared, which gives information on percentage (%) difference between the 23 elements of a power matrix generated for 1 day and 6 days. Table 8 gives the comparison between1 day and 12 days and table 9 gives the comparison between 6 days to 12 days.

Table 7. *Comparison of a power matrices generated for 4 modules of Manufacturer 3 using procedure 1 between 1 day and 6 days*

Irradiance (W/m^2)	**Temperature (^oC)**			
	15	**25**	**50**	**75**
1100	N/A	-2%	0%	0%
1000	2%	-2%	0%	0%
800	4%	2%	0%	0%
600	-3%	-2%	1%	0%
400	-3%	0%	4%	N/A
200	0%	3%	3%	N/A
100	2%	-7%	N/A	N/A

Table 8. *Comparison of a power matrices generated for 4 modules of Manufacturer 3 using procedure 1 between 1 day and 12 days*

Irradiance (W/m^2)	**Temperature (^oC)**			
	15	**25**	**50**	**75**
1100	N/A	-3%	0%	0%
1000	0%	-4%	0%	0%
800	1%	1%	0%	0%
600	-3%	-2%	1%	0%
400	0%	0%	7%	N/A
200	0%	3%	6%	N/A
100	1%	-6%	N/A	N/A

Table 9. *Comparison of a power matrices generated for 4 modules of Manufacturer 3 using procedure 1 between 6 days and 12 days*

Irradiance (W/m^2)	Temperature (°C)			
	15	25	50	75
1100	N/A	0%	0%	0%
1000	-2%	-2%	0%	0%
800	-3%	-1%	0%	0%
600	0%	0%	1%	0%
400	3%	0%	3%	N/A
200	0%	0%	3%	N/A
100	-1%	0%	N/A	N/A

From the results in Tables 7, 8, and 9 the following can be concluded –

(i) The percentage (%) differences in the power matrices are higher when compared between 1 day and 12 days as shown in figure 8.

(ii) The percentage (%) differences in the power matrices were lower than the table 8 when it is compared between 1 day to 6 days as shown in table 7, i.e., the number of points nearer to 0% is more when compared with table 8.

(iii) The percentage (%) differences in the power matrices when compared for 6 days to 12 days as shown in table 9 are within 3% and maximum points have the deviation to be zero.

(iv) This concludes that, as the number of days of data collection increases the results would be more accurate and nearer to actual value.

The power matrices generated at 1 day, 6 days, and 12 days for the 4 modules of same manufacturer M3 were considered for the next study. For the next study, these power matrices are compared with the idle power matrix, where the power temperature coefficient is -0.5% and efficiency is constant throughout the matrix. In this, each element of the power matrix was compared with the idle power at that point. The idle power at different irradiance levels was directly proportional to the irradiance.

The comparison between the calculated power and idle power is shown in terms of percentage (%) deviation. The tables 10, 11 and 12 show the percentage deviations for 1 day, 6 days and 12 days respectively of four modules of M 3 Manufacturer.

Table 10*. Comparison of idle and calculated power for 1 day data of four modules for M3*

1 day

Procedure 2 - Power Matrix (W)				
Irradiance (W/m^2)	**Temperature (°C)**			
	15	**25**	**50**	**75**
1100	N/A	0%	-2%	-1%
1000	0%	0%	0%	0%
800	0%	1%	1%	2%
600	1%	2%	4%	2%
400	1%	1%	3%	N/A
200	0%	0%	0%	N/A
100	-1%	-1%	N/A	N/A

Table 11. *Comparison of idle and calculated power for 6 days data of four modules for M3*

6 days

Procedure 2 - Power Matrix (W)				
Irradiance (W/m2)	**Temperature (oC)**			
Desired G (W/m2)	**15**	**25**	**50**	**75**
1100	N/A	0%	-2%	-1%
1000	0%	0%	0%	0%
800	0%	1%	1%	2%
600	1%	2%	4%	1%
400	1%	0%	1%	N/A
200	0%	-1%	0%	N/A
100	0%	-1%	N/A	N/A

Table 12. *Comparison of idle and calculated power for 12 days data of four modules for M3*

12 days

Procedure 2 - Power Matrix (W)				
Irradiance (W/m^2)	**Temperature (oC)**			
	15	**25**	**50**	**75**
1100	N/A	-1%	-1%	-1%
1000	0%	0%	0%	0%
800	1%	-1%	1%	3%
600	1%	0%	2%	1%
400	0%	-1%	1%	N/A
200	0%	-1%	0%	N/A
100	-1%	-1%	N/A	N/A

Tables 10, 11, and 12 clearly demonstrate which of the sets of data gives the best results. The deviations of the power matrices for the three sets of data are compared. From the deviations, it is understood that as the number of days increase, the deviation decreases. The percentage deviations are least for 12 days data.

From the above two discussions, it is clear that 12 days data produces the power that is nearer to the estimated power. The next best data is obtained from 6 days data.

4.8.2 **One manufacturer, one module (no mesh, no insulation)**.

The study discussed in the previous section was done on four modules of a manufacturer M3. In this section, the deviations were calculated in a similar manner as done in the previous section for single manufacturer, single module. In this section, one module (M3-3) of manufacturer M3 was considered. The module that was selected was without mesh and insulation on the back. This particular module was considered, as it did not have a mesh which reduces the irradiance on the module or an insulation to increase the module temperature. In this section it compares the percentage (%) deviation between the 23 elements of power matrix of calculated power for a single module to the idle power.

For this module, the power matrices were calculated for 1 day, 6 days, and 12 days. After the power matrices were generated the percentage (%) deviations were calculated between the idle power and calculated power for all the 23 elements of the power matrix. The percentage (%) deviations were calculated and projected in the Table 13 is for 1 day data, Table 14 for 6 days data and Table 15 for 12 days data.

Table 13. *Comparison of idle and calculated power for 1 day data of one module of M3*

1 day

Procedure 2 - Power Matrix (W)				
Irradiance (W/m2)	**Temperature (oC)**			
Desired G (W/m2)	**15**	**25**	**50**	**75**
1100	N/A	0%	-2%	0%
1000	0%	0%	0%	0%
800	0%	3%	1%	2%
600	-5%	-2%	4%	5%
400	0%	1%	-2%	N/A
200	-2%	-1%	-2%	N/A
100	-2%	-3%	N/A	N/A

Table 14. *Comparison of idle and calculated power for 6 days data of one module of M3*

6 days

Procedure 1 - Power Matrix (W)				
Irradiance (W/m2)	**Temperature (oC)**			
Desired G (W/m2)	**15**	**25**	**50**	**75**
1100	N/A	0%	-2%	0%
1000	0%	0%	0%	0%
800	-1%	-1%	1%	2%
600	1%	-6%	4%	5%
400	1%	0%	0%	N/A
200	-1%	-1%	-1%	N/A
100	-2%	-1%	N/A	N/A

Table 15. *Comparison of idle and calculated power for 12 days data of one module of M3*

12 days

Procedure 1 - Power Matrix (W)				
Irradiance (W/m2)	**Temperature (oC)**			
Desired G (W/m2)	**15**	**25**	**50**	**75**
1100	N/A	-1%	-2%	0%
1000	0%	0%	0%	0%
800	-1%	-1%	1%	-1%
600	0%	0%	4%	2%
400	-2%	-1%	0%	N/A
200	-2%	-1%	-1%	N/A
100	-2%	-2%	N/A	N/A

From tables 13, 14 and 15; we get the same information as in the previous section. It is once again proved that as the number of days increase, the percentage (%) deviation decreases. Therefore, the table 15 has least percentage (%) deviations compared to table 13 and 14.

4.8.3 **Comparison of 12 days data of one module (no mesh, no insulation) to four modules of same manufacturer**. It is concluded that the deviation is least when the power matrix is generated for 12 days data either with one module or four modules. In this section, the power matrices of one module and four modules are compared for 12 days of manufacturer M3. This comparison is shown in table 16, which gives information about the percentage (%) deviation of one module to four modules.

Table 16. *Comparison of Power between 4 modules data to 1 module data for 12 days of M3 manufacturer*

Procedure 2 - Power Matrix (W)				
Irradiance (W/m^2)	**Temperature (^{o}C)**			
	15	**25**	**50**	**75**
1100	N/A	0%	0%	2%
1000	-2%	0%	0%	3%
800	0%	0%	0%	4%
600	0%	0%	-2%	-3%
400	1%	-1%	3%	N/A
200	8%	0%	5%	N/A
100	9%	14%	N/A	N/A

Though the power matrix in table 15 shows that the percentage (%) deviation is low, but it is high when compared to table 12. This is because, in table 15, the power deviations are calculated in comparison with the idle power but not the actual power. The percentage (%) deviations are calculated for table 12 to table 15 is shown in table 16. The percentage (%) deviations are more than ± 3 %.

4.9 Power Matrix Generated Using Procedure 3

In the whole discussion, we considered only the first two procedures of IEC 60891 as the other two procedures of IEC 60891 were not able to generate the power for all the 23 elements of the power matrix. This was because the translation was done only by using interpolation method, but for interpolation the curves need to be outside the required curve as it was shown in methodology chapter. When the data is collected for this procedure, there was no chance to collect the data at required condition. Therefore in procedure 3, the powers were calculated only at few points, where the curves were available for interpolation as shown in figure 36.

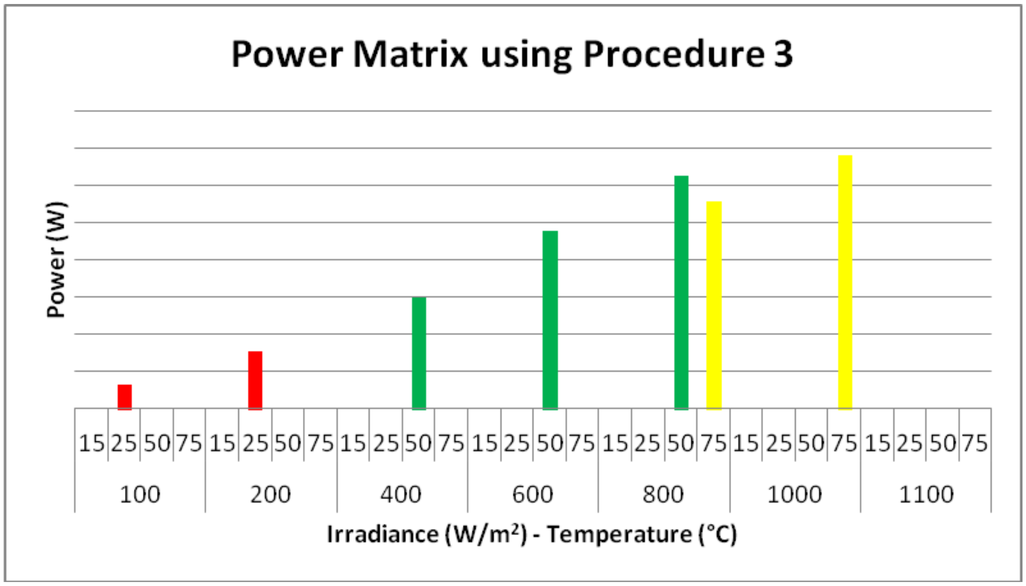

Figure 36. Power Matrix generated with procedure for four modules of M1using 12 days

The graph has various colors to differentiate the power at different temperatures. The color coding is done for each temperature.

4.10 Comparison of Efficiencies of a Manufacturer at Different Conditions

For a particular module, after calculating the Power Matrices at different conditions, the efficiency is calculated by taking its area into account. In Figure 37, we can see the efficiency of one particular manufacturer by considering the data of four modules for 12 days. Figure

37 gives information of a manufacturer at four different temperatures (15 °C, 25 °C, 50 °C and 75 °C).

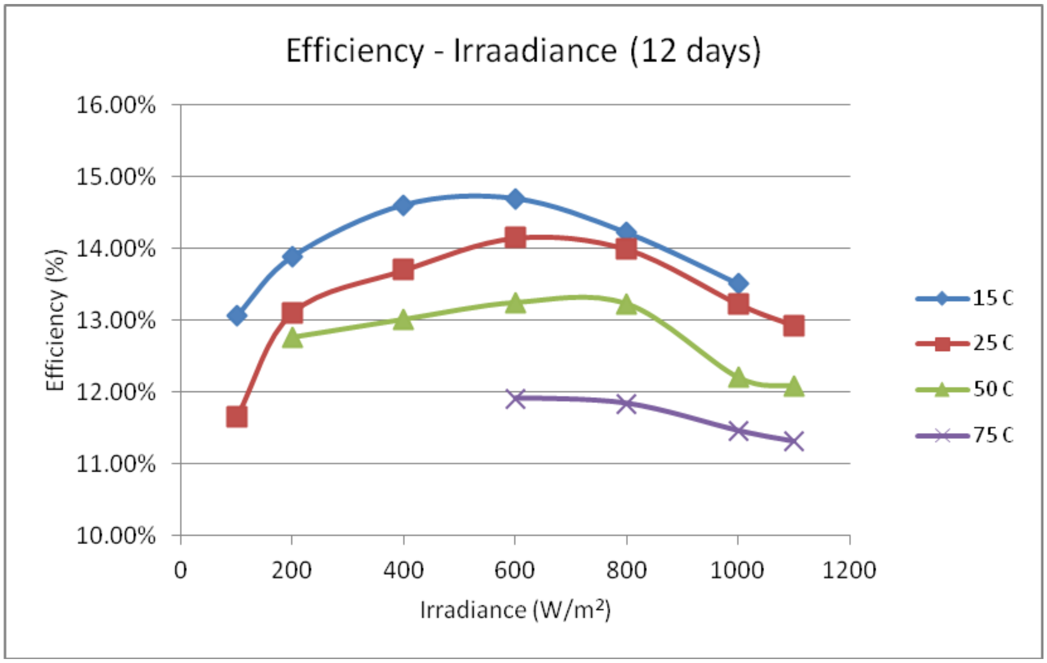

Figure 37. Efficiency of a manufacturer (4 modules and 12 days) at four different temperatures

The other three manufacturers also give a similar Efficiency (%) vs. Irradiance (W/m^2) graph. The data points considered in the Figure 37 are from the power matrix.

In the figure 37, it is seen that the efficiency of the module drops as the temperature of the module increases. Apart from that, it is also observed that as the irradiance decreases from 1100 W/m^2 towards 600 W/m^2 the efficiency increases. But after 600 W/m^2 the efficiency decreases as the irradiance decreases. The initial increase in the efficiency was due to the series resistance and later decrease in efficiency was due to the shunt resistance. The graph in figure 37 is a good example for the influence of the parasitic resistance on the efficiency of PV modules. It shows how the series resistance and shunt resistance affect the efficiency of the module (actually the power of the module). Considering the 15°C plot in the figure 37, the efficiency decreases even though the irradiance increases from 600 W/m^2 to 1000 W/m^2 because of the series resistance affect. But from 400 W/m^2 to 100 W/m^2, the irradiance decreases and efficiency also decreases. In this case the efficiency is affected by the shunt resistance. The drop is even high when compared to irradiance, as the shunt resistance is very high. Now for a single manufacturer, four modules of data are considered for 1 day, 6 days and 12 days. The efficiencies are calculated for all the 23 elements of the power matrix for the three sets of data. Figure 38 gives the efficiencies for 1 day data at seven different irradiance levels and four different temperatures. The next two figures, Figure 39 and Figure 40, give similar information but for 6 days and 12 days respectively of the same manufacturer. These three power matrices are generated using the automation software.

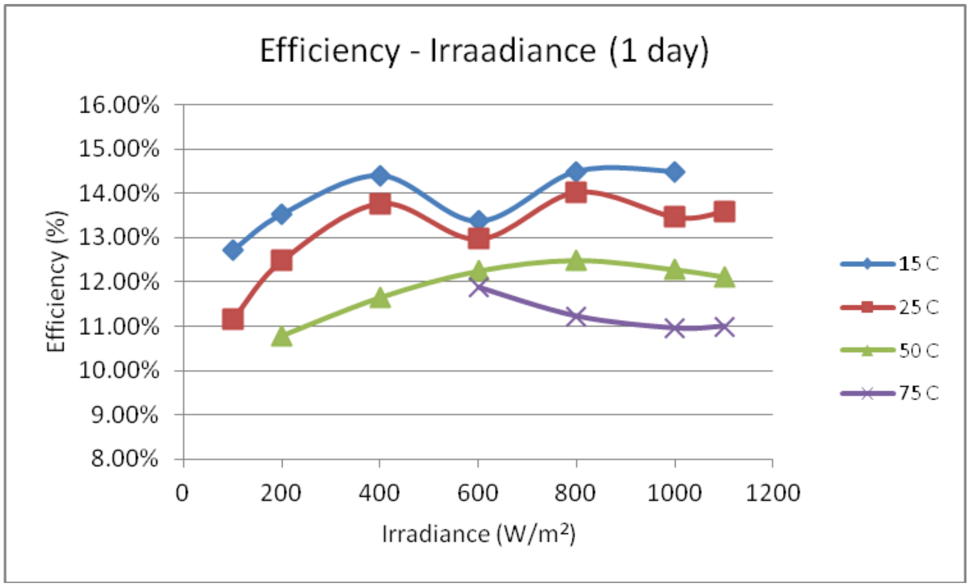

Figure 38. Efficiency of a manufacturer (4 modules and 1 day) at four different temperatures

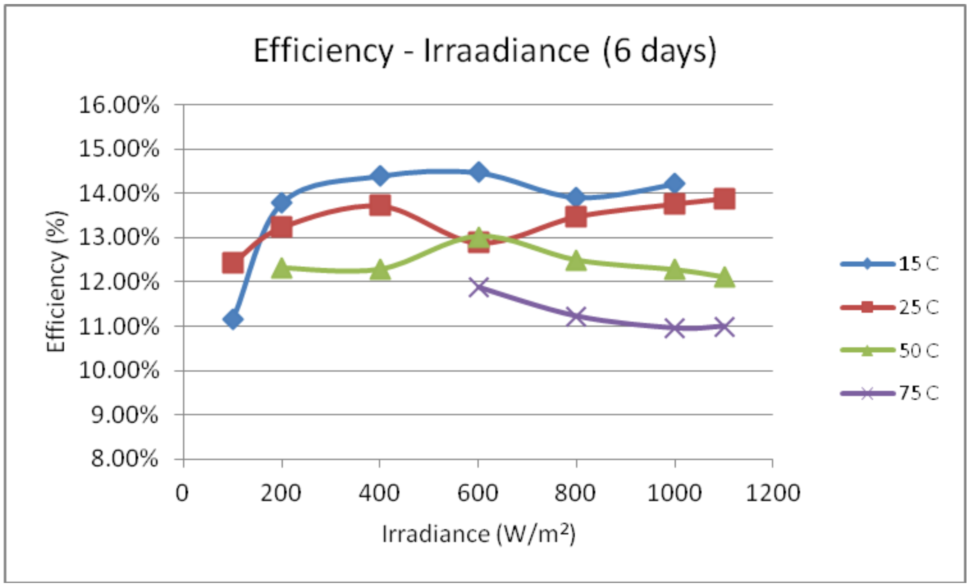

Figure 39. Efficiency of a manufacturer (4 modules and 6 days) at four different temperatures

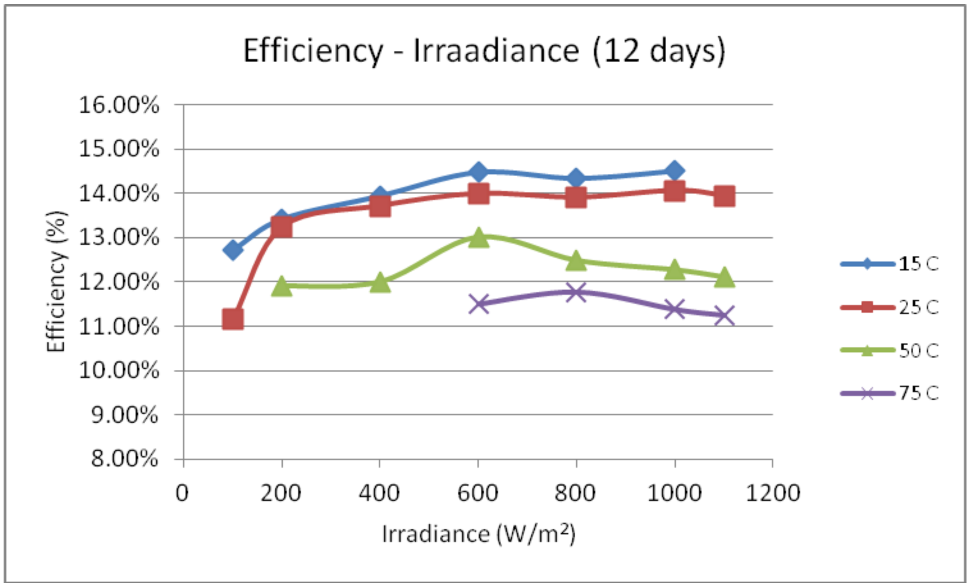

Figure 40. Efficiency of a manufacturer (4 modules and 12 days) at four different temperatures

In figure 38, the efficiency dropped at 600 W/m^2 in 15 °C and 25 °C plot. But in figure 39 the efficiency increased at 15 °C; still there is a drop seen at 25 °C. When it is seen in Figure 40, the efficiency plot is similar to the plot shown in figure 37.

From the above three figures, it is again proved that the power matrix generated for 12 days gives better results compared to the 1 day and 6 days data. In figure 38 and figure 39, a sudden drop in the graph is observed. But later in the efficiency graph figure 40 which has 12 days data, looks better. This is because when there are less data points, there is chance of not having exact or closest curve to translate it to the required data point. When the translation is done from a far data point, then the deviation is high; this is what is seen as a drop in figure 38 and figure 39.

4.11 Comparison of Four Manufacturers

The four manufacturer efficiencies are compared at different temperatures. These graphs best explain the differences in the efficiencies for four manufacturers at different irradiance levels and constant temperature. Figure 41 compares the efficiencies of four manufacturers at seven different irradiances, but at 15°C. Similar graphs are shown in Figure 42 at 25°C, Figure 43 at 50°C and Figure 44 at 75°C temperatures.

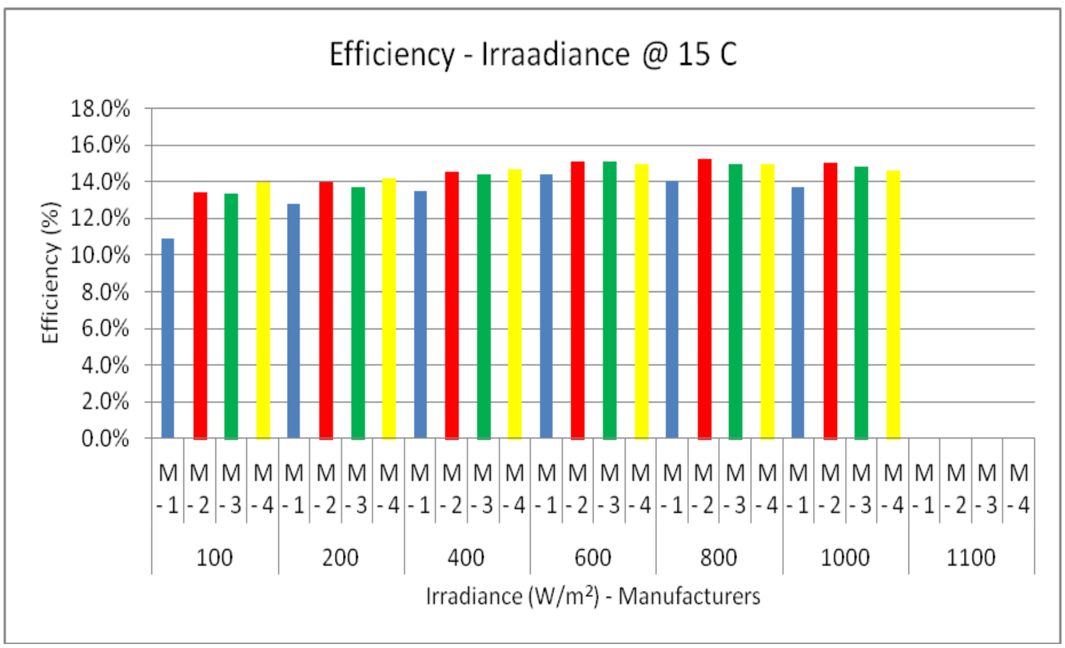

Figure 41. Comparison of Efficiencies at different Irradiance levels and at constant temperature of 15 °C

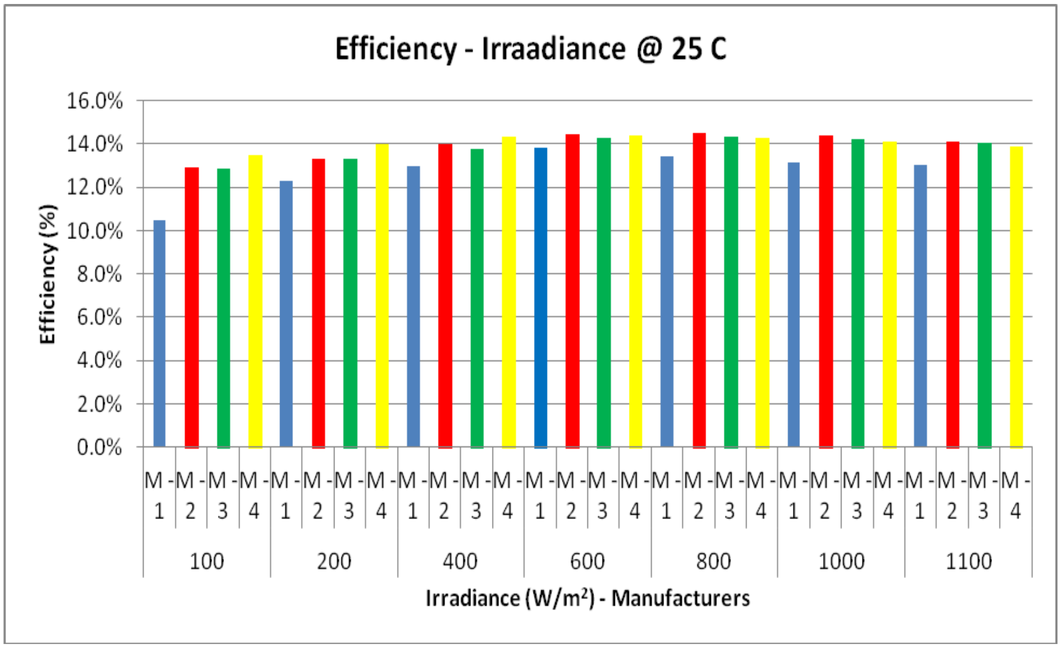

Figure 42. Comparison of Efficiencies at different Irradiance levels and at constant temperature of 25 °C

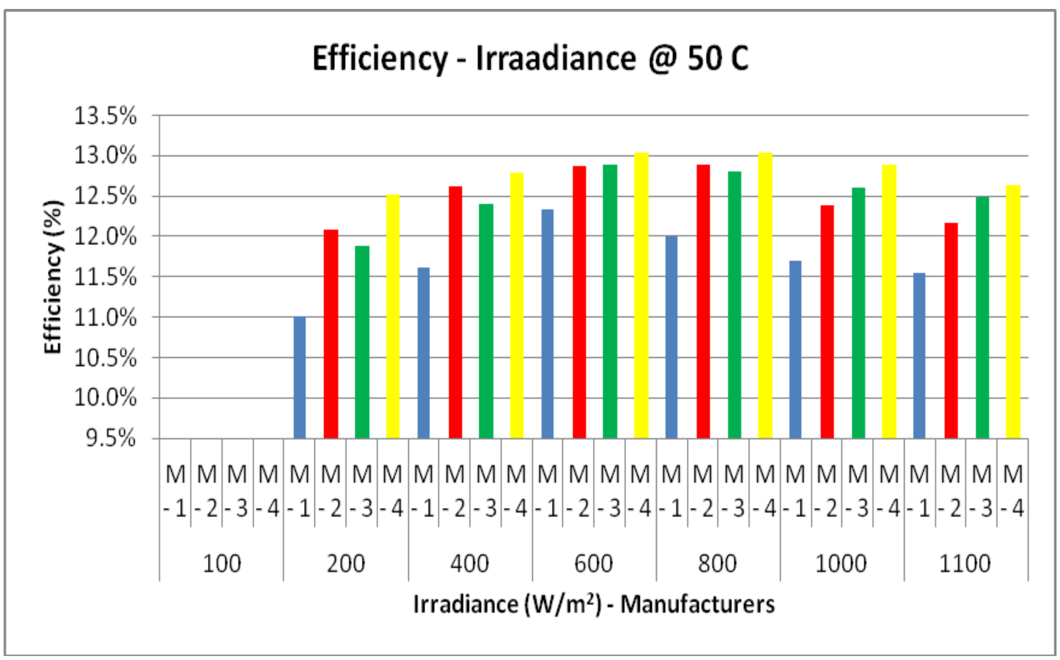

Figure 43. Comparison of Efficiencies at different Irradiance levels and at constant temperature of 50 °C

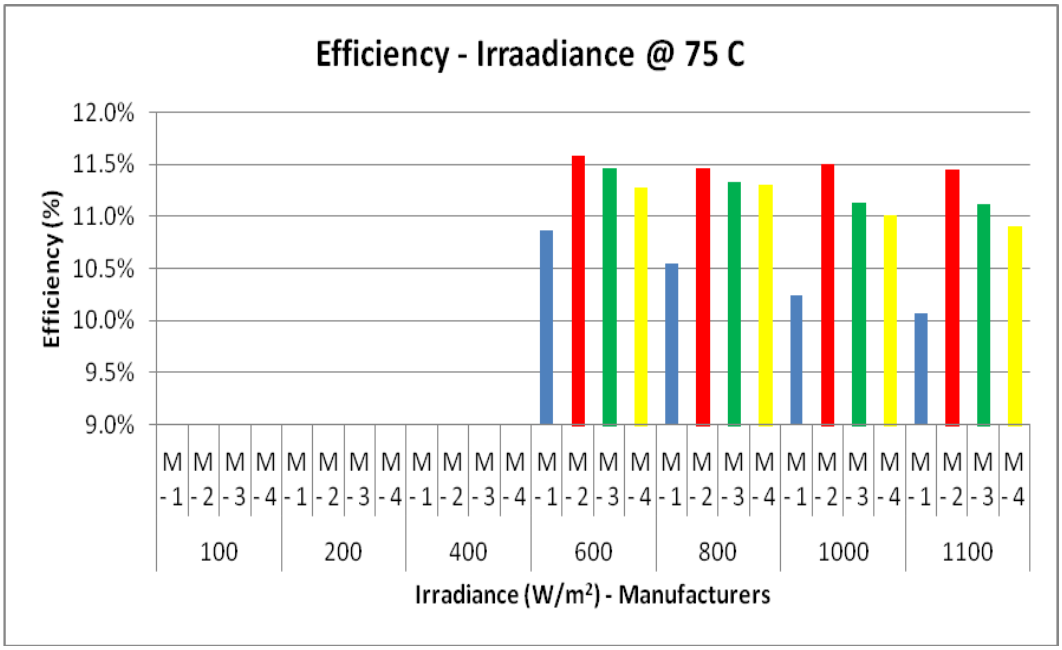

Figure 44. Comparison of Efficiencies at different Irradiance levels and at constant temperature of 75 °C

The main purpose of the comparison is to identify the best module which suits the region where the installation needs to be done. The three main required criterions are:

- Price of the Module
- Efficiency of the module
- Area required to meet the required power

The comparison is done in respect of the price of the modules. In figure 43 at 600 W/m^2 and 50 °C, the M2 and M3 have same efficiencies. Therefore the installer can choose one of them depending upon the price of the module.

The next comparison for manufacturers is for the efficiencies of the modules. The installer wants to install the modules with higher efficiency to reduce required roof/land area along with reduction of structural cost. With the old method of module rating, the efficiencies of the PV modules were labeled only at STC conditions. But in reality the modules need to be installed at different environmental conditions from that of the labeled conditions. In this case the power matrix helps the installer to select the module which has more efficiency at the required environmental conditions. In figure 42 at STC conditions the M2 manufacturer has higher efficiency compared to M4. But if the modules need to be installed at 400 W/m^2 and 25°C then M4 manufacturer is more suitable as it has higher efficiency than M2. This is the main advantage for the installer when a power matrix is used.

The next criterion for the installer is the area of the installation. To explain this, let's consider two hypothetical modules, each with 100 W/m^2 but with different areas. The one with the less area and same power occupies less space in installation. For this the module with more efficiency will occupy less area in installation. Therefore, to occupy less area the installer need to select a module with high efficiency.

The above discussion clearly explains that the installer needs to pay attention on how much power the module produces at the required test conditions. The installer can get the required power if the modules are rated according to the IEC 61853-1 (Power Matrix at seven irradiances and four temperatures).

Usually, when comparing two or more manufacturer modules, irradiance of that region is taken as a reference. This is because the irradiance effect is more when compared to the temperature of the region. The next graph shown in figure 45 compares the efficiencies of four manufacturers at different temperatures, but at a constant irradiance (1000 W/m^2).

Let's consider an installation of solar modules on a roof top at Mesa, AZ. In this region, majority part of the year the irradiance is expected to be around 1000 W/m^2. But the modules will experience more than 50°C temperatures. Therefore, figure 45 indicates that at STC conditions M2 is having higher efficiency compared to M3, but the same graph indicates that at 50°C temperatures, M3 is having higher efficiency compared to M2. This is a good example for the installer in regard to selecting a particular model for the region.

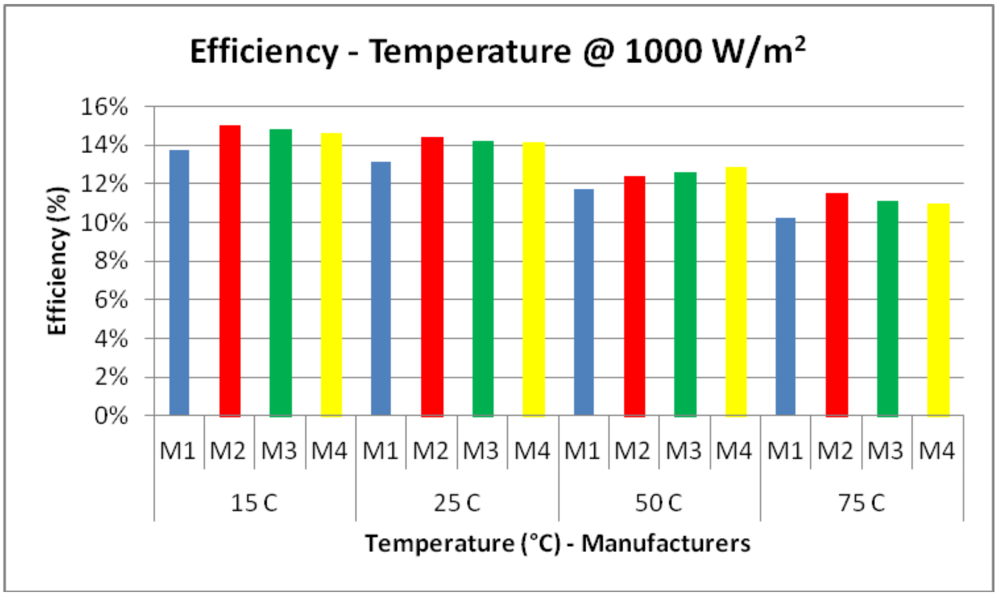

Figure 45. Comparison of Efficiencies at constant Irradiance @ 1000 W/m^2 and different temperature

4.12 Advantages and Disadvantages of Automation Software

There are various options built in to automation software. The options embedded in the automation software are:

4.12.1 Single-step automation. The data analyzer has to feed the data collected; by clicking this button, the software calculates all the parameters. The program starts its calculations with the baseline parameters and then calculates the individual parameters for each procedure. Once the required parameters are calculated, the power matrices will be calculated with provided data.

4.12.2 Multiple-step automation. The data analyzer has to feed the collected data into the automation software. Once the data is fed into the software, data analyzer next steps are:

(i) Calculate the baseline parameters

(ii) Calculate the parameters for each procedure

(iii) By clicking the multiple steps button—for example, “Multiple Steps Automation – Procedure 1”—the software uses the parameters calculated by the analyzer and produces the Power Matrix by selecting the nearest and appropriate curve.

Initially the project was started with this method for research and calculated the power matrices for all the manufacturers using Procedure 1 and Procedure 2. It was also planned to perform the analysis using Procedure 3 but, due to limitations, this procedure was not considered. The limitations will be discussed later in this chapter.

4.12.3 Hybrid method (manual + automation). The previous method had some disadvantages, therefore this method was introduced. There were limitations to the previous method. As the number of curves was more than five thousand, the system picks up the best curve for translation. But for the translations, the best curve has a different definition than what the software was designed for. The irradiance of the curve should closely match with the required condition but the temperature difference can be high. At the same time, if the irradiance is different, very little and the temperature difference is very high then the temperature parameter should be given more importance.

As the priorities are changing according to the required curve conditions, the curves need to be selected. The present software need to be modified to perform the calculations as discussed in this section. But in the available software, the analyzer can only set a ratio between the irradiance and temperature but cannot make the software to select a right curve when there is more than one curve available for translation.

As this issue sprang up in the project, the curves were to be selected manually by checking which curve fits the best for the translation. The selection is done by selecting the curve that is nearest to the required conditions and then translation is applied to that particular curve to the required condition by using either Procedure 1 or 2.

The comparison of the power matrices obtained from multiple step automation and hybrid method is shown in Table 17. In both the methods, the power matrix is obtained using procedure 2.

Table 17. *Comparison of multiple steps automation to hybrid method for M3 using procedure 2*

Comparison of Automation method to Hybrid method

Irradiance (W/m2)	**Temperature (°C)**			
	15	**25**	**50**	**75**
1100	N/A	0.1%	2.5%	-1.7%
1000	4.1%	0.5%	2.0%	-2.8%
800	3.8%	2.3%	2.0%	-4.4%
600	3.7%	1.6%	-1.5%	-0.8%
400	3.5%	1.2%	-1.2%	N/A
200	-0.2%	0.2%	-4.7%	N/A
100	-0.9%	0.4%	N/A	N/A

In Table 17, it is observed that 25% of the points in matrix have percentage deviations between two methods, either less than – 3% or more than + 3%. The other 50% have the percentage deviation either less than – 1% or more than + 1%. Therefore only 25% of the points in the matrix have the deviation percentage between ± 1%. This concludes that the deviation is high between two methods and it was observed that the power matrix generated using multiple steps automation is not meeting the conditions when cross checked with parameters such as maximum power at STC, temperature coefficients, etc.

The powers generated by the automation software and hybrid method at STC are compared with the module rated power. This comparison is shown in table 18. This table clearly explains that the hybrid method produces best results compared to the automation software.

Table 18. *Comparison of module rated power at STC with the powers calculated using automation software and hybrid method*

Rated Power	Power generated using Automation Software	Power generated using Hybrid Method
0%	-5.1%	0.1%

4.13 Comparison between Four Procedures of IEC 60891

The IEC 60891 has two procedures (Procedure1 and Procedure 2) which are based on the translation phenomenon. The other two procedures (Procedure 3 and Procedure 4) are based on interpolation phenomenon. The four procedure are discussed in the methodology chapter, where it is explained how each procedure works.

These four procedures of IEC 60891 have their own advantages and disadvantages and these are compared in table 19.

Table 19. *Comparison of four procedures of IEC 60891 from this project perspective*

	Procedure 1	**Procedure 2**	**Procedure 3**	**Procedure 4**
Temperature Coefficients	Needed at various irradiance levels	Needed only at 1000 W/m^2	Not required	Not required
No of curves required to obtain temperature coefficients	10 curves at **each** irradiance level	10 curves at 1000 W/m^2 with different module temperature	Not required	Not required
Parameters required for the usage of procedure	R_s and k	a, R_s' and k'	a	a
No of curves required to obtain parameters	Only 2 curves other than the curves available for baseline; however, long range extrapolation could lead to inaccuracy	Only 2 curves other than the curves available for baseline; however, long range extrapolation could lead to inaccuracy	Only 3 curves covering the temperature and irradiance extremes of the matrix ;For every translation the parameter “a” varies	Only 4 curves covering the temperature and irradiance extremes of the matrix; For every translation the parameter “a” varies
Method	Interpolation and Extrapolation	Interpolation and Extrapolation	Interpolation	Interpolation
Translation to a condition using the curves covering the temperature and irradiance extremes of the matrix	Done using interpolation and the entire matrix can be obtained	Done using interpolation and the entire matrix can be obtained	Done using interpolation and the entire matrix can be obtained	Done using interpolation and the entire matrix can be obtained
Translation to a condition using the curves not covering the temperature and irradiance extremes of the matrix	Done using extrapolation and the entire matrix can be obtained	Done using extrapolation and the entire matrix can be obtained	Cannot be translated and the entire matrix can NOT be obtained	Cannot be translated and the entire matrix can NOT be obtained

Procedure 1 and 2 can translate any curve to any required condition using the temperature coefficients and the parameters required for that particular procedure. Procedure 2 requires only 12 curves on total to obtain the curve at any condition. But as the number of curves increase the deviation percentage of P_{max} decreases.

But Procedures 3 and 4 have many limitations. These procedures can generate any condition in the power matrix, even if it has 4 curves covering extreme temperatures and irradiances of the matrix. However, long-range interpolation may lead to inaccurate results due to the influence of irradiance on fill factor. When having 4 curves, the below mentioned conditions are to be met –

- Irradiance less than 100 W/m^2 and at least one curve at temperature less than 15 °C and one curve at temperature more than 75^{o}C.
- Irradiance more than 1100 W/m^2 and at least one curve at temperature less than 15 °C and one curve at temperature more than 75^{o}C.

But to have these conditions, it was practically difficult with the test setup used in this study. It is possible to have such curves only by using an external heating or cooling system behind the module. Irradiance nearer to 1100 W/m^2 can frequently be obtained in summer; so to have these irradiances; the tests need to be conducted primarily in summer season. At the same time, these four curves are not enough to have accurate results. Paghasian [7] proved that to have less percentage deviation between the translated curve and actual curve, the reference curve needs to be nearer to the required condition.

As the project's main aim was to use the natural sunlight and natural heating or cooling process, the above discussed procedure is not applicable for this project

.

4.14 Power Temperature Coefficient

The module data sheet indicates the power temperature coefficient of the module at the STC conditions only. As the efficiency and power varies with the irradiance so does the power temperature coefficient. The change in the power temperature coefficient is shown in figure 46.

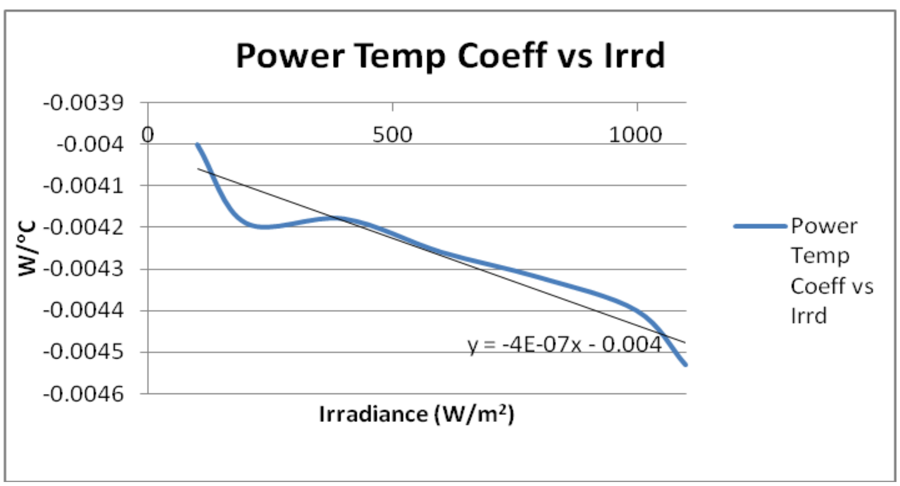

Figure 46 – Comparison of the power temperature coefficients at various irradiance levels for M1 manufacturer

From the figure explains that, the power temperature coefficient is directly proportional to the irradiance. As the irradiance decreases, the power temperature coefficient decreases.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Number of Days Required for Data Collection –

The power matrices generated using monitored data for one, six and twelve days were compared. It is concluded that the power matrix generated based on twelve days was the best, though the improvement was found to be very minimal when compared with the matrix generated based on six days.

5.1.2 Procedure selection –

Based on the test setup used in this work, the procedure 2 of IEC 60891 was selected for all data processing. This is because the procedure 1 required more number of performance parameters to be calculated as compared to procedure 2. Even though procedure 3 and procedure 4 do not require more than one parameter, they require monitored data at or above temperature and irradiance levels specified in the IEC 61853-1 standard. The experimental setup used in this work could not collect data at these extreme temperature and irradiance levels, and hence the matrix generation based on procedure 3 or procedure 4 is not included in this work.

5.1.3 Software Validation –

In this report the power matrices were generated using both the automation software developed in a previous work and the hybrid method utilized in this work.

It is demonstrated that the maximum power determined at STC conditions using the hybrid method was closer to the actual measured power using the conventional baseline method established at ASU-PRL. It was observed that the percentage deviation for automation software was as high as -5.1% and for hybrid method it was only +0.1% when compared with the actual baseline power at STC. This demonstrates that the hybrid method provides more accurate results than the automation software. The automation software needs some improvement as described in the recommendation section below.

5.1.4 New Outdoor Test Method –

For power matrix calculation, Sandia National Laboratories method requires collection of I-V curves continuously throughout a day or two from a single module mounted on a two axis tracker. Since the Sandia test setup does not use thermal insulators on the back side of the test module to obtain data at high temperatures or mesh screens in front of the test module to obtain data at low irradiances, the availability of sufficient number of data for regression analysis at low irradiances and high temperatures could be challenging depending on the season. In this research a new outdoor test setup was used, in which four similar or practically identical modules were placed on a two axis tracker to collect the data throughout the day. These four modules were set to collect data at different irradiances and temperatures. To have data at low irradiance levels, two of the modules were covered with mesh screens. At the same time two other modules were back insulated to have higher temperatures. The data collected using this new test setup covered a wide range of irradiance and temperatures required to generate the matrix of IEC 61853-1 standard.

5.1.5 Comparison of power temperature coefficient at various irradiance levels –

Whenever the module maximum power is to be calculated at different temperatures other than 25^{o}C, the power temperature coefficient obtained at a single irradiance of 1000 W/m^2 is used for the calculations. In this study it was observed that the power temperature coefficient of the module is not constant. It has a dependence on the irradiance level and hence the use of single power temperature coefficient for all irradiance levels is discouraged.

5.1.6 Comparison of Different Manufacturers –

One of the primary aims of the project was to find out the best suited module for particular field conditions using Efficiency vs. Temperature and Efficiency vs. Irradiance plots.

This study concludes that the efficiency of the PV modules is not constant at all irradiance levels and it could dramatically decrease at very low irradiance levels depending on the quality of the cells used in the module. . These variations from one cell/module manufacturer to another cell/module manufacturer have been clearly seen in this study and they are attributed to the cell parameters such as varying power temperature coefficient, series resistance and shunt resistance. Based on the test method developed in this study, a suitable module for a specific site condition could be selected by screening a large number of modules with minimal number of labor hours.

5.2 Recommendation

- In this study, procedure 3 and procedure 4 were unusable due to natural limitations on temperature controllability. Further research may be conducted with more controllability on temperature. With this improvement, all the four procedures of IEC 60891 and NREL can be used to analyze the data.

- The automation software should be improved to select a reference curve closest to the target condition; this selection was done manually (Hybrid Method which utilized the manual selection of reference curves and the automatic data processing) in this research.
- The current version of automation software generates only Pmax matrix; however, the IEC 61853-1 standard requires generation of other matrices including Isc and Voc. Therefore, the automation software should be further improved to generate all the matrices required by the IEC 61853-1 standard.

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