Photovoltaic Module Performance and Thermal Characterizations:

Data Collection and Automation of Data Processing

by

Kartheek Koka

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Graduate Supervisory Committee:

Govindasamy Tamizhmani, Chair
Bradley Rogers
Narciso F.Macia

ARIZONA STATE UNIVERSITY

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ABSTRACT

The photovoltaic (PV) modules are primarily characterized for their performance with respect to incident irradiance and operating temperature. This work deals with data collection and automation of data processing for the performance and thermal characterizations of PV modules. This is a two-part thesis: The primary part (part-1) deals with the software automation to generate performance matrix as per IEC 61853-1 standard using MPPT (maximum power point tracking) data at the module or system level; the secondary part (part-2) deals with the software automation to predict temperature of rooftop PV modules using the thermal model coefficients generated in the previous studies of the Photovoltaic Reliability Laboratory (PRL).

Part 1: The IEC 61853-1 standard published in January 2011 specifies the generation of a target performance matrix of photovoltaic (PV) modules at various temperatures and irradiance levels. In a conventional method, this target matrix is generated using all the data points of several measured I-V curves and the translation procedures defined in IEC 60891 standard. In the proposed method, the target matrix is generated using only three commonly field measured parameters: Module temperature, Incident irradiance and MPPT (Maximum Peak

Power Tracking) value. These parameters are loaded into the programmed Excel file and with a click of a button, IEC 61853-1 specified P_{mppt} matrix is displayed on the screen in about thirty seconds.

Part 2: In a previous study at PRL, an extensive thermal model to predict operating temperature of rooftop PV modules was developed with a large number of empirical monthly coefficients for ambient temperature, irradiance and wind speed. Considering that there is large number of coefficients for each air gap of rooftop modules, it became necessary to automate the entire data processing to predict the temperature of rooftop PV modules at different air gaps. This part of the work was dedicated to automatically predict the temperature of rooftop modules at different air gaps for any month in a year just using only four input parameters: Month, Irradiance, Ambient temperature and Wind speed.

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CHAPTER 1: INTRODUCTION

1.1 Overview

The performance of a photovoltaic (PV) module depends on its operating conditions. Irradiance and ambient temperature are the major climatic conditions that affect the power production of PV modules. PV modules are typically rated at Standard Test Conditions (STC) (1000 W/m², 25°C, AM1.5). These conditions vary hour-to-hour, day-to-day and season-to-season. Thus, the amount of energy produced by a PV module is heavily influenced by these climatic conditions. Apart from rating the module at STC, the industry needs a temperature and irradiance matrix to predict the energy produced by the PV module.

The performance of the modules increases as the irradiance increases and decreases as the module temperature increases. The decrease in the performance is due to the negative temperature coefficient of power output.

The temperature of PV modules is dictated by ambient conditions, such as irradiance, ambient temperature and wind speed. Based on field data acquired by Arizona State University's Photovoltaic Reliability Laboratory (ASU-PRL), the effects of wind direction and humidity on open, rack-mounted PV modules were found to be negligible [1].

The Building Applied Photovoltaic (BAPV) system, also known as the The Building Applied Photovoltaic (BAPV) system, also known as the Building Integrated Photovoltaic (BIPV) system or Rooftop Photovoltaic system, is a major application of the PV modules. In hot climatic conditions, such as those in Phoenix, Arizona, the BAPV module temperature can reach as high as 95°C during the peak ambient temperatures of summer. Considering a general 0.5%/°C power drop for crystalline silicon modules, a performance drop of about 30% would be expected during the summer months because of the difference between rated temperature (25°C) and operating temperature (~90°C). When the BAPV modules are installed on a roof, there is an air gap between the modules and the surface of the roof. The temperature of the BAPV modules is affected directly by the size of this air gap, which, in turn, affects the performance of the BAPV modules. Therefore, it is necessary to determine the optimum air-gap size in order to appropriately design a BAPV system. In addition, temperature prediction is very important in order to determine expected power output from the modules.

1.2 Statement of Work

This work deals with data collection and automation of data processing for the performance and thermal characterizations of PV modules. This is a two-part thesis: The primary part (part-1) deals with the software automation to generate performance matrix as per IEC 61853-1 standard using MPPT (maximum power point tracking) data at the module or system level; the secondary part (part-2) deals with the software automation to predict temperature of rooftop PV modules using the thermal model coefficients generated in the previous studies of the Photovoltaic Reliability Laboratory (PRL).

1.2.1 Part 1 :

A temperature and irradiance matrix of performance parameters of a photovoltaic (PV) module can be used to predict energy produced by that PV module. The temperature and irradiance matrix specified by the IEC 61853-1 standard is presented in Table 1 [2]. The matrix of these parameters is usually obtained through a series of indoor or outdoor current-voltage (I-V) measurements using temperature and irradiance controlled equipment. In the current work, the output power (MPPT, maximum power point) of module along with irradiance and module temperature are monitored frequently (every 6 minutes) throughout the year. This is done using a multi-curve tracer, on a fixed tilt module. In the current work, an Excel file is programmed to automatically generate the performance matrix by using the best fitting curve and performing interpolation or extrapolation to the required values. The translated data are compared with actual measured data for validation of the program.

Table 1[2] Temperature and Irradiance Matrix as per IEC 61853-draft standard

I_{sc}, P_{max}, V_{oc}, And V_{max} Versus Irradiance And Temperature					
Irradiance (W/M^2)	Spectrum	Module Temperature (°C)			
		15	25	50	75
1100	AM1.5	NA			
1000	AM1.5				
800	AM1.5				
600	AM1.5				
400	AM1.5				NA
200	AM1.5				NA
100	AM1.5			NA	NA
NA is not applicable.					

The PV module parameters are listed below:

Isc = Short-circuit current (A);

Voc = Open-circuit voltage (V);

Imp = Current at maximum power point (A);

Vmp = Voltage at maximum power point (V);

Pmp = Power at maximum power point (W);

FF = Fill factor (dimensionless).

This work introduces a new and inexpensive way of generating the performance matrix using conventionally monitored MPPT (maximum power point) values at the array dc level or system ac level. The advantages of the new approach include:

- Predicting module(dc) / array(dc) / system(ac) output based on the routinely monitored outdoor data of irradiance, temperature and MPPT
- Avoiding the pre-cooling of PV module for temperature control while warming up under sun
- Avoiding the mesh screens for irradiance control under sun.
- Eliminating the prolonged manual work of taking I-V curves outdoor, especially during hot summer days
- Eliminating the waiting period for a clear sunny day measurements
- Avoiding extensive and complex I-V curve translation methods

- Utilizing this spreadsheet as an online system level diagnostic tool to monitor the health of dc array (and/or ac system) over time (year over year) for performance degradation or soiling effect at any specific set of temperature-irradiance conditions.

Assumptions:

A test station is set up at Arizona State University Polytechnic Campus, Mesa,Arizona. This station has ten polycrystalline silicon PV modules whose performance is measured.

- PV module temperature is only measured at one point of PV module's backskin. This temperature is considered to be PV module's operating temperature
- Irradiance measured by reference cell is considered as the actual irradiance on the test PV module since they both are in same plane with glass superstrates (angle of incidence effect is the same for both test module and reference cell) and cell technology of PV module and reference cell are closely matched for spectral response.

1.2.2 Part 2:

There are several thermal models for open, rack-mounted PV modules, but only a few thermal models are available for BAPV modules [3]. This thermal model for BAPV modules was based on the field data from ASU-PRL, which were acquired for one year. The objective of developing a thermal model was to analyze the temperature variation and its influence on the performances of the BAPV modules with different air gaps of 0”, 1”, 2”, 3”, and 4”, respectively, on the BAPV system with respect to ambient temperature and other influencing parameters, such as wind speed, wind direction, and solar irradiance.

Twenty BAPV modules were arranged in 5 rows and 4 columns. Every column modules are installed with various air gap sizes (0,1,2,3, and 4inches). Irradiance, Ambient temperature, wind speed, wind direction and module temperature were collected for one-year period (May 2009 – April 2010).

The thermal model used is as shown in the equation below

Tmodule = E * w1 + Tamb*w2 + WS*w3 + c

where:

Tmodule: module temperature (°C);

E: irradiance (W/m^2);

Tamb: ambient temperature (°C);

WS: wind speed (m/s);

w1- w3: coefficients;

c: constant.

A linear regression fit to the data provides the required coefficients for the development of the thermal model, and the MATLAB program was used to extract these coefficients.

In the previous studies at ASU-PRL, the coefficients obtained with one-month data (May 2009; monthly coefficients) and one-year data (May 2009 - April 2010; annual coefficients) were compared and was decided to develop the coefficients for every month.

This thesis deals with automation of the thermal model by programming an Excel file using Visual Basic macros. The programmed Excel file contains a sheet where month, irradiance (W/m²), ambient temperature (°C) and wind speed (m/s) are entered. With a click of a button a column is generated which shows the predicted module temperatures of the modules.

Limitations

The mock roof construction is limited to only one pitch and one type of roof concrete tile. Even though the frames of the 0-inch air gap modules are attached to the surface of the roof, stagnant air still exists below the modules due to space between the laminate of the module and the tile.

CHAPTER 2: LITERATURE REVIEW

2.1 Energy Model

The performance of the module mainly depends on module temperature, irradiance, the spectral response of the module, and the characteristic of the module itself. Different models like irradiance model, thermal model, and spectral model are to be used for determining the module performance. Energy from the daily power production can be calculated using the equation (1) [4] given below:

$$E = \Delta t \times \sum_{i=1}^{n} P_i \qquad (1)$$

where:

E: module energy output (Wh);

Δt: data sampling interval (hours);

P*i*: power at the i^{th} sample time (W).

2.2 Power Models

There are different models for evaluating module's power output under operating conditions. In this section, the typical power models are reviewed.

2.2.1 PVUSA Model

Since 1989, PVUSA has been rating PV systems using continuous data collection and a simple regression model. The PVUSA model [5] is based on simplified assumption that array current is primarily dependent on irradiance, and that array voltage is primarily dependent on array temperature, which, in turn is dependent on irradiance, ambient temperature, and wind speed. These dependencies are combined in Equation (2).

$$P = Irr \times (A + B \times Irr + C \times Tamb + D \times WS) \quad (2)$$

where:

P = power output of module (kW);

Irr = plane-of-array (POA) solar irradiance, broadband measurement (W/m^2);

Tamb = ambient temperature (°C);

WS = wind speed (m/s);

A, B, C, D = regression coefficients.

The limitations of this model are [5]:

- It is necessary to collect the data at and above the certain rated value of irradiance, and a particular range of module temperature and wind speed.

- This model does not work for low irradiance values (usually below 500W/m^2).

2.3 Solar ABCs report - Power rating as per IEC61853-1

This study report deals with two rounds of outdoor measurements and results to realize the following five objectives.

- Identify measurement repeatability issues with a non-standardized test setup, standardize the measurement setup,
- Verify the device linearity per IEC 60904-10,
- Generate the power (Pmax) matrix per IEC 61853-1, and
- Validate four different current-voltage translation/interpolation techniques of IEC60891 and the National Renewable Energy Laboratory (NREL).

Here are the major conclusions corresponding to the five objectives:

1. Outdoor measurement repeatability issues: The repeatable power rating measurements at various irradiance levels under natural sunlight within an acceptable deviation limit of 2% could not be achieved when uncalibrated mesh screens were placed directly (0-inch distance) on the test module and reference cell.

2. Standardization of measurement setup: A standardized measurement setup was established with reference cells kept outside the calibrated mesh screens, which were placed at a 2-inch distance above the test modules.
3. Verification of device linearity per IEC 60904-10: The linearity requirements of opencircuit voltage, short-circuit current, and maximum power versus temperature are met by all four test technologies. Similarly, the linearity requirement of open-circuit voltage versus the logarithm of irradiance is also met (with two minor exceptions presumably due to some experimental errors) by all four test technologies. For the short-circuit current versus irradiance, the devices met the linearity requirement (2% deviation limit) for irradiance levels above 200 W/m2 but they surprisingly showed a higher deviation for the irradiance levels below 200 W/m2. This higher deviation was objectively attributed to some minor experimental errors related to the calibration of low transmittance mesh screens under natural sunlight.
4. Generation of Pmax matrix per IEC 61853-1: The required 23-element Pmax matrix of IEC 61853-1 was successfully generated for all four module technologies using the four translation/interpolation procedures of IEC 60891 and NREL. Unless the data processing personnel pay extreme

attention or commercial test laboratories automate the data processing, the translation procedures (1 and 2) are more prone to human error than the interpolation procedures (3 and 4). However, procedures 1 and 2 would work extremely well if multiple narrow irradiance ranges are used with individual sets of correction values for each narrow irradiance range or multiple sets of correction values are used for a single wide irradiance range.

5. Validation of procedures of IEC 60891 and NREL: An extensive validation analysis of the four translation/interpolation procedures, at both narrow and wide irradiance ranges, indicates that all four procedures are remarkably accurate within an average error of 3% and a root mean square error (RMSE) of 4.5%.

2.4 IEC 60891 translation procedures

2.4.1 Procedure 1 - IEC 60891 Method

IEC 60891 Procedure 1 [4] 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).

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

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

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

2.4.2 Procedure 2 - IEC 60891 Method

IEC 60891 Procedure 2 [4] 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.

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

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

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.

2.4.3 Procedure 3 - IEC 60891 Method

IEC 60891 Procedure 3 [4] 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.

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

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

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.

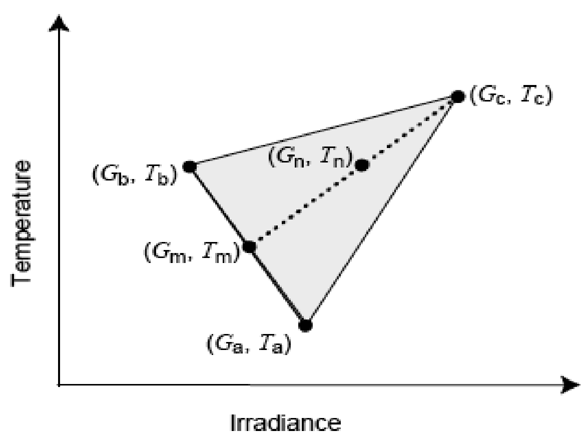


Figure 1 Procedure 3: Area enclosing interpolation range[2]

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) [4] 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).

2.5 Thermal Model

Module temperature has a major impact on the power output of the module. Voltage produced by the module decreases with increase in module temperature. Module temperature depends on following factors [6]:

1. *The equilibrium between the heat produced by the PV module.* This depends on the operating point of the module, the optical properties of the module and solar cell, and the packaging density of the solar cells in PV module.
2. *The heat loss to the environment.* Conduction, convection, and radiation are the three mechanisms through which heat loss to environment is possible. These mechanisms depend on the thermal resistance of the module, the emissive properties of the module, and the ambient conditions in which the module is mounted (roof integrated or open rack).

3. *The ambient operating temperature, irradiance, shading and wind speed.*

Different thermal models are developed in past either based on theoretical heat balance approach or on real world field data. Different thermal models are discussed as follows.

2.5.1 Simple Model

The simple model [8] was built on the fact that the operating temperature of solar cell above ambient is roughly proportional to the solar irradiance when the module is installed on the open rack and wind speed is low. The equation of module temperature prediction of simple model is given in equation (9).

$$\mathbf{T_{cell}}(°C) = \mathbf{T_{amb}}(°C) + 0.03 \times \text{Irradiance} \quad (9)$$

where:

T_{cell} = solar cell temperature (°C);

T_{amb} = ambient temperature (°C);

Irradiance = solar irradiance (W/m^2).

2.5.2 NOCT Model

PV modules when operating in field usually operates at higher temperature and somewhat lower insolation [6]. Thus, it is necessary to determine the expected operating module temperature to know the power output of the module. The

Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the conditions as listed below:

- Irradiance on cell surface = 800 W/m^2
- Ambient Temperature = 20°C
- Wind Velocity = 1 m/s
- Mounting = open back side.

Therefore, for open rack PV systems, an approximate equation for calculating cell temperature as per NOCT model [6] is given in equation (10).

$$T_{mod} = T_{amb} + (T_{NOCT} - 20°C) \times \frac{Irradiance}{800} \quad (10)$$

where:

T_{mod} = module temperature (°C);

T_{amb} = ambient temperature (°C);

T_{NOCT} = module's nominal operating cell temperature (°C);

Irradiance = solar irradiance (W/m^2).

2.5.3 Sandia Model

Sandia National Laboratories developed a simple empirically-based thermal model [7] for predicting PV module temperature. This model has been verified by

Sandia National Laboratories and has shown the accuracy of about ±5°C for predicting PV module temperature. Equation (11) [7] represents Sandia thermal model.

$$T_m = E \cdot \{e^{a+b \cdot WS}\} + T_a \tag{11}$$

where:

Tm = back-surface PV module temperature (°C);

Ta = ambient air temperature (°C);

WS = wind speed measured at standard 10m height (m/s);

a = empirically-determined coefficient establishing the upper limit for module temperature at low wind speeds and high solar irradiance;

b = empirically-determined coefficient establishing the rate at which module temperature drops as wind speed increases.

Empirically determined coefficients (Equation (11)) by Sandia National Laboratories for different PV module types and mounting configurations are given in Table 2 [7].

Table 2 Empirical Coefficients reported by Sandia National Laboratories for Sandia Thermal Model [7]

Module Type	Mount	a	b
Glass/cell/glass	Open rack	-3.47	-0.0594
Glass/cell/glass	Close roof mount	-2.98	-0.0471
Glass/cell/polymer sheet	**Open rack**	**-3.56**	**-0.0750**
Glass/cell/polymer sheet	Insulated back	-2.81	-0.0455
Polymer/thin-film/steel	Open rack	-3.58	-0.113
22X Linear Concentrator	Tracker	-3.23	-0.130

2.5.4 Tang's Model – Open Rack

Yingtang Tang's Masters' thesis, "Outdoor Energy Rating Measurements of Photovoltaic Modules," developed a thermal model using three parameters ambient temperature, wind speed, and global irradiance. This thermal model gave accurate results for predicting module temperature. Tang started off with five parameters: irradiance, wind speed, ambient temperature, wind direction and humidity. From his results, ambient temperature, irradiance, and wind speed are the major factors affecting the module temperature. Wind speed has a major effect. The module temperature decreases by about 1.5°C per m/s wind speed increase. The thermal model two developed by Tang [8] is given in equation (5).

$$\mathbf{T_{mod} = 0.943 \times T_{amb} + 0.028 \times Irradiance - 1.528 \times WS + 4.3} \quad (3)$$

where:

T_{amb}: ambient temperature (^{0}C);

Irradiance: global solar irradiance (W/m2);

WS: wind speed (m/s).

CHAPTER 3: METHODOLOGY

3.1 PART 1: Performance matrix methodology

3.1.1 Experiment Setup

An experimental setup with ten polycrystalline PV modules, a weather station, a multi-channel current-voltage curve tracer and data acquisition system (DAS) were installed at ASU Polytechnic Campus, Mesa, Arizona. These test modules were installed in open rack configuration, south facing and with latitude tilt. The data acquisition system was used for recording module temperature, weather, and performance of PV modules. Weather station monitored irradiance, windspeed, ambient temperature, wind direction, relative humidity, and rainfall. I-V (Current-Voltage) curves are taken using a Raydec Multicurve Tracer. The maximum peak power tracking (MPPT) is done by Multicurve Tracer. Two mono-crystalline silicon reference cells (EETS) and a pyranometer (Eppley PSP) were used to measure irradiance. One reference cell is at latitude tilt while the other is in horizontal position. PSP is also mounted in latitude tilt position. Thus, two values of latitude tilt irradiance and one value of horizontal irradiance are being recorded.

The complete data acquisition system is kept in an outhouse in the Photovoltaic Reliability Laboratory's (PRL) test yard. The complete setup is shown in Figure 2.

Figure 2 Experiment Setup

The output of each module is connected to IV curve tracer which in turn is connected to a data acquisition system which recorded irradiance, module temperature and MPPT as a data set. These data sets are collected for every six minutes.

3.1.2 Data Collection:

The data is obtained with one PV module. Every MPPT value with its corresponding irradiance and module temperature is considered as a dataset. To obtain datasets at nearly every degree temperature raise, the data acquisition system is programmed to collect the datasets at a high frequency of 6-minute interval. In the first approach, data (irradiance, module temperature and MPPT value) of a single module was collected for twelve continuous days and used as raw data. To minimize the number of days used for data collection, six continuous days data of the single module was used as raw data.

3.1.2 Data Entry

Irradiance in W/m^2, Module Temperature in ˚C and Module output power (MPPT) in Watts are used as raw data. This raw data has to be entered in first tab (Sheet 4) starting from cell "A6" as shown in Figure 4.

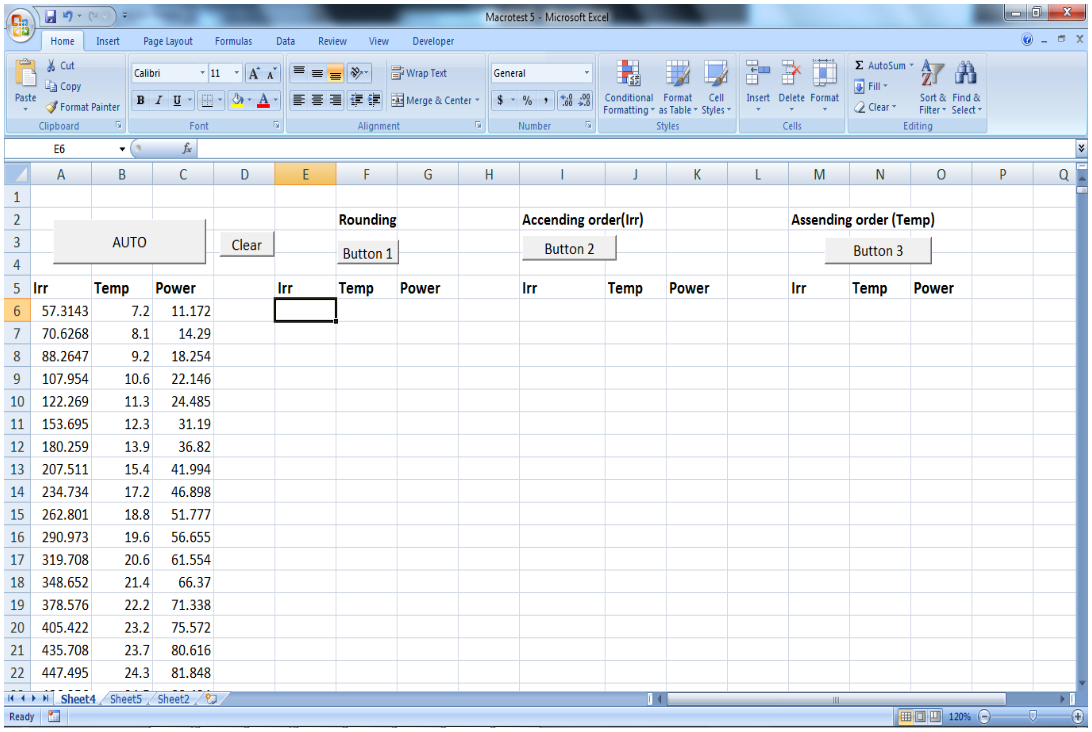


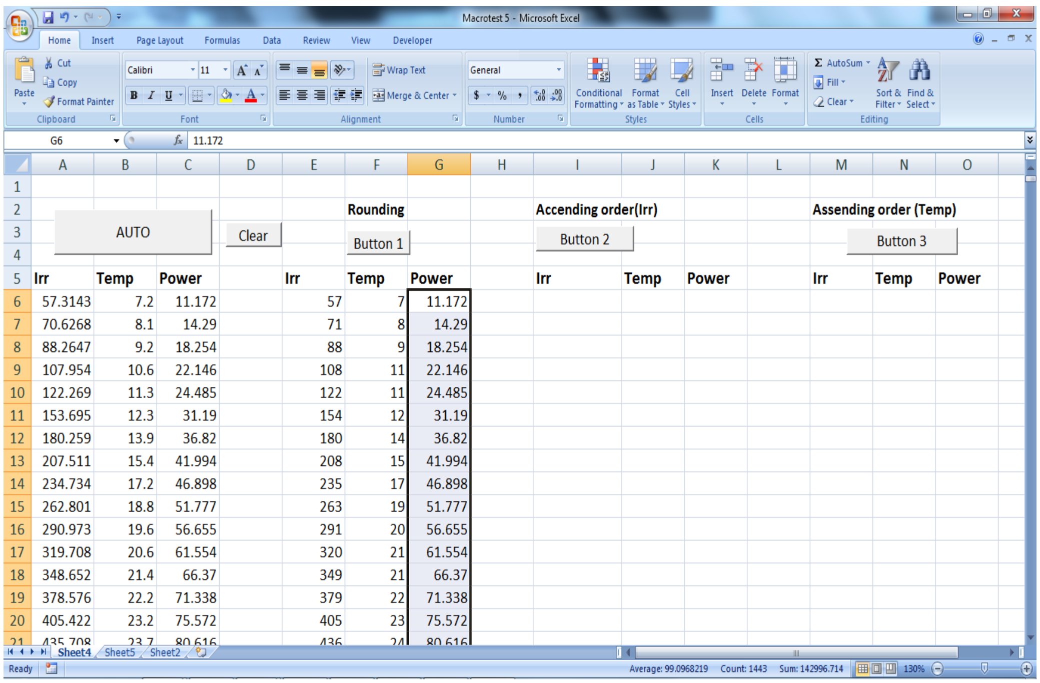
Figure 3 Screen shot of raw data in "Sheet 4"

3.1.3 Data Processing

The Excel sheet has different pre-programmed buttons for step by step processing.

1. Button 1.The irradiance data and Module temperature data are rounded to its nearest integer. Power values remain the same.

2. Button 2. The whole data is arranged in increasing order of irradiance and data sets having less than 40W/m² irradiance are deleted.



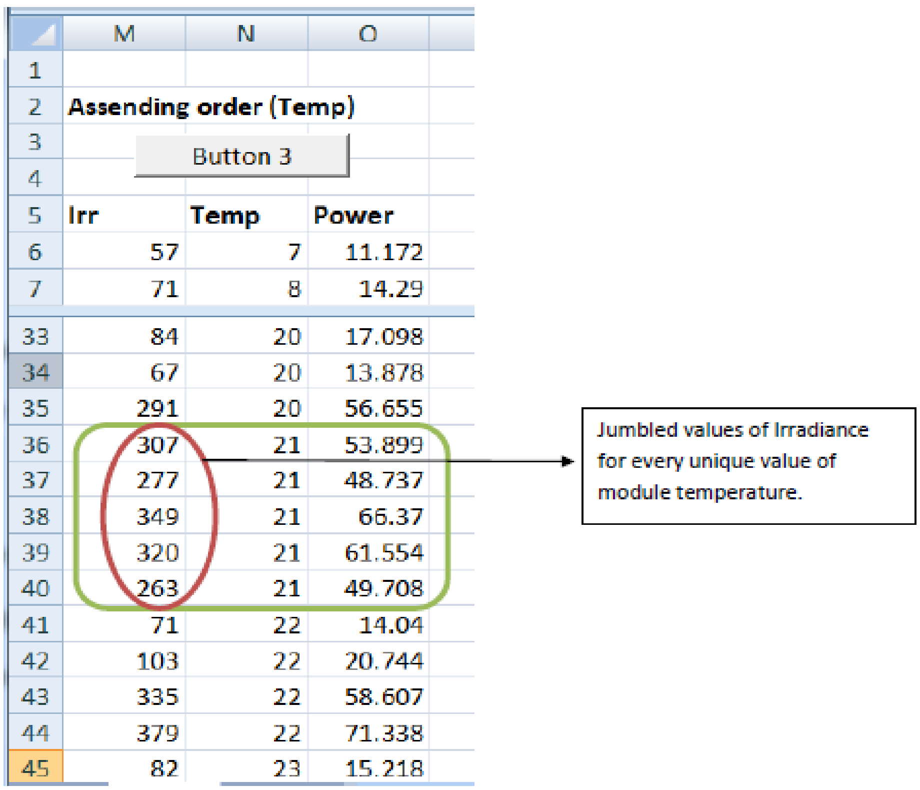
	Irr	Temp	Power		Irr	Temp	Power		Irr	Temp	Power		Irr	Temp	Power
6	57.3143	7.2	11.172		57	7	11.172								
7	70.6268	8.1	14.29		71	8	14.29								
8	88.2647	9.2	18.254		88	9	18.254								
9	107.954	10.6	22.146		108	11	22.146								
10	122.269	11.3	24.485		122	11	24.485								
11	153.695	12.3	31.19		154	12	31.19								
12	180.259	13.9	36.82		180	14	36.82								
13	207.511	15.4	41.994		208	15	41.994								
14	234.734	17.2	46.898		235	17	46.898								
15	262.801	18.8	51.777		263	19	51.777								
16	290.973	19.6	56.655		291	20	56.655								
17	319.708	20.6	61.554		320	21	61.554								
18	348.652	21.4	66.37		349	21	66.37								
19	378.576	22.2	71.338		379	22	71.338								
20	405.422	23.2	75.572		405	23	75.572								
21	435.708	23.7	80.616		436	24	80.616								

Figure 4 Data after rounding raw data

3. Button 3. The whole set of data is arranged again in increasing order of temperature.

   3.1. Reason for arranging the data by irradiance followed by temperature.

If the “Button 2” (ascending order of irradiance) is not executed before “Button 3”, sorted data would be in the format shown in Figure 6.



	M	N	O
1			
2	**Assending order (Temp)**		
3	Button 3		
4			
5	**Irr**	**Temp**	**Power**
6	57	7	11.172
7	71	8	14.29
33	84	20	17.098
34	67	20	13.878
35	291	20	56.655
36	307	21	53.899
37	277	21	48.737
38	349	21	66.37
39	320	21	61.554
40	263	21	49.708
41	71	22	14.04
42	103	22	20.744
43	335	22	58.607
44	379	22	71.338
45	82	23	15.218

Figure 5 Unsorted Data

3.2. After arranging data in increasing order of irradiance and then sorting by temperature, we get values of irradiance in increasing order for every module temperature as shown in Figure 7.

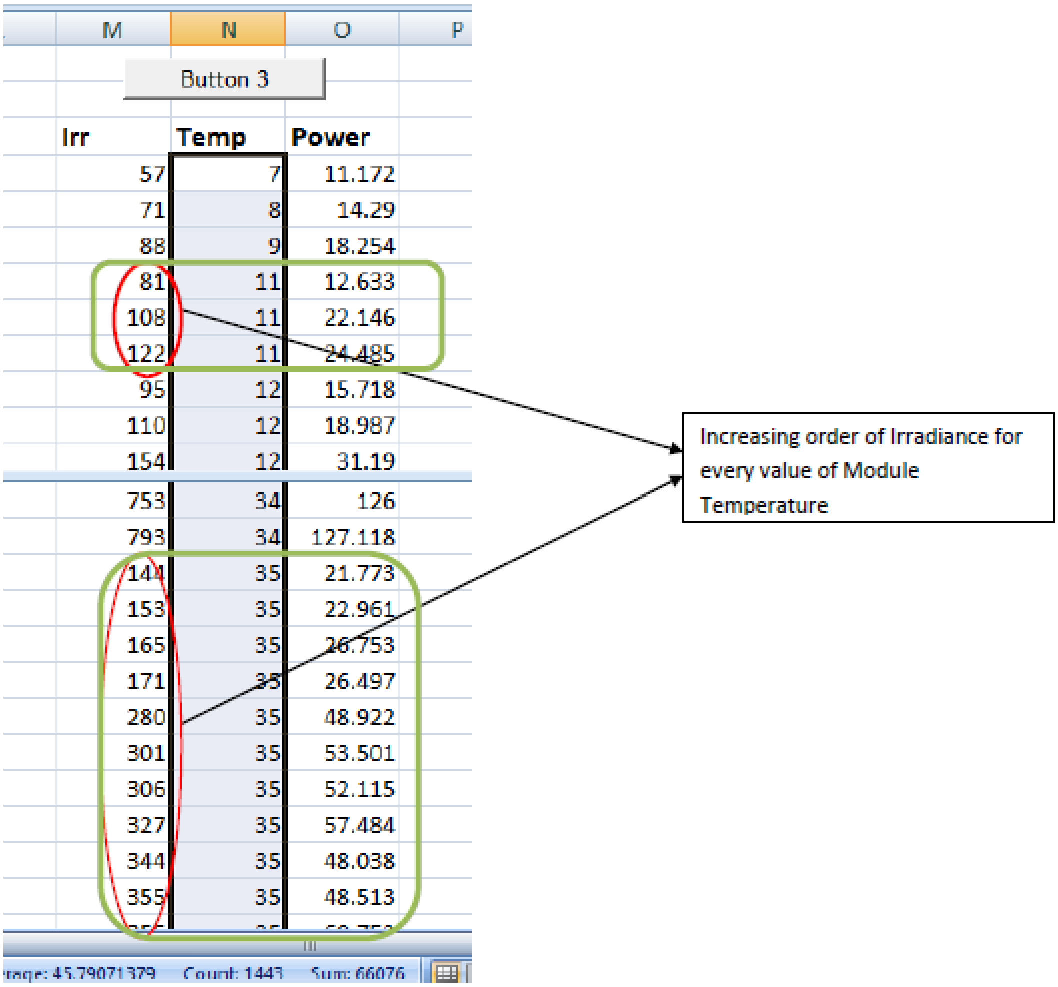


Figure 6 Irradiance values arranged in increasing order

4. In sheet 5, clicking on "*Create X and Y*" unique values of Irradiance and Temperature to form the axis are created. Here "Arranged order (Temp)"

values are selected and duplicates are removed from each row of Irradiance and Temperature. Then the Irradiance values are again sorted in increasing order.

5. Button 11 is used to filter the whole data set using 3 steps.
   - Step 1: Considering all the data points with same module temperature as a set. A trend line equation is calculated using all the data points in a set. The data points deviating more than -13% are deleted.
   - Step 2: Trendline equation is calculated again for the same set and points and values deviating more than +16% are deleted.
   - Step 3: Assuming linear behavior of the module, the P_{max} values are considered to be in increasing order with irradiance. P_{max} values which do not follow the increasing order are deleted.
   - Step 4: Trend line equation is calculated again for the same set and points and values deviating less than +0.9% are deleted.
6. By clicking “Form the axis”, axis is created in sheet2. Irradiance is in Y axis and Module temperature is in X axis.
7. Using “Create Graph” button, module output values are displayed in the cells intersecting Irradiance value(Y axis) and Module temperature(X axis). If the Excel doesn’t finds value for any combination of Irradiance and

Temperature, it prints N/A in the respective cell. Its working is given in the following flow chart.

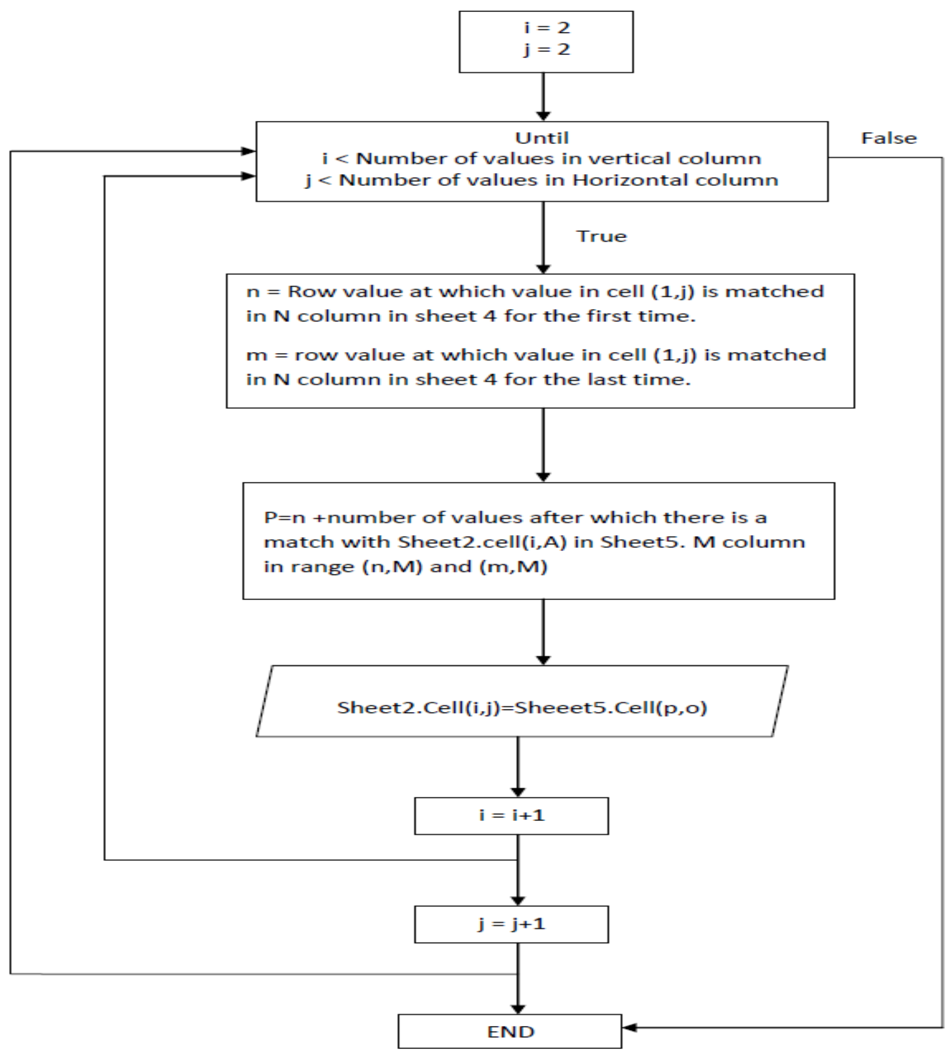
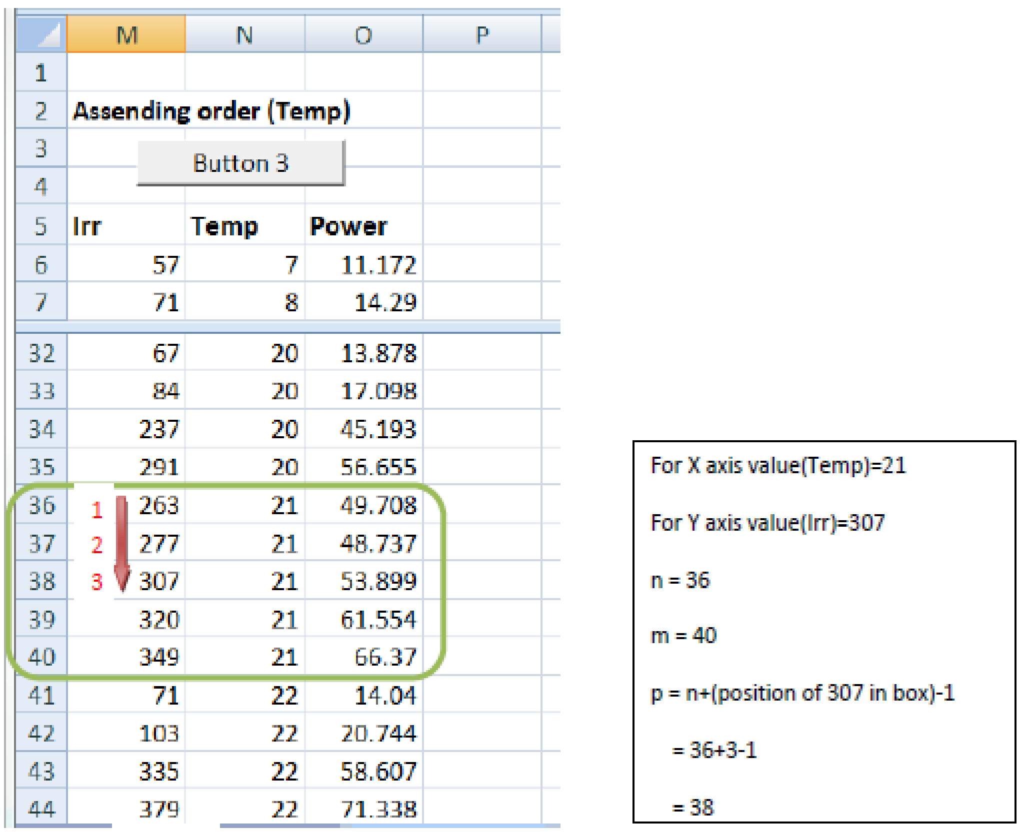


Figure 7 Flowchart for chart generation

3.1.4 Result generation

Irradiance and module temperature are entered and “Verify” button is clicked as shown in Figure 10. When Pmax of the module is required for specific irradiance(X) and module temperature(Y), the program searches for data sets having the module temperatures in the range Y +/-5 degree Celsius.



	M	N	O	P
1				
2	Assending order (Temp)			
3	Button 3			
4				
5	Irr	Temp	Power	
6	57	7	11.172	
7	71	8	14.29	
32	67	20	13.878	
33	84	20	17.098	
34	237	20	45.193	
35	291	20	56.655	
36	1 263	21	49.708	
37	2 277	21	48.737	
38	3 307	21	53.899	
39	320	21	61.554	
40	349	21	66.37	
41	71	22	14.04	
42	103	22	20.744	
43	335	22	58.607	
44	379	22	71.338	

Figure 8 Program searching for matched value

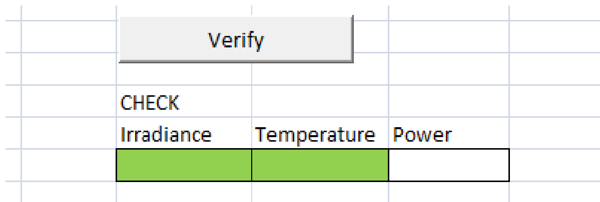


Figure 9 Screen shot of "Verify" button

In the selected group,

Pmax values are calculated for only Y˚C using temperature coefficient. Now the group has different irradiance values with one temperature value(Y) as shown in Figure 9. In this group a range of irradiance values have to be selected which can be used for generation of slope of Pmax. Depending upon the value of X, three conditions may arise in selection of irradiance range.

1. X is less than lowest irradiance value in the group.
2. X is between any of the two irradiance values in the group.
3. The value of X is greater than the highest irradiance value in a group.

Condition 1 is addressed by interpolating the lowest irradiance values close to X.

For the second condition, a graph is created for irradiance values in the range of X+100 and X-100 versus Pmax. Finally, the Pmax of the module at X irradiance and Y module temperature is calculated with the help of trend line equation.

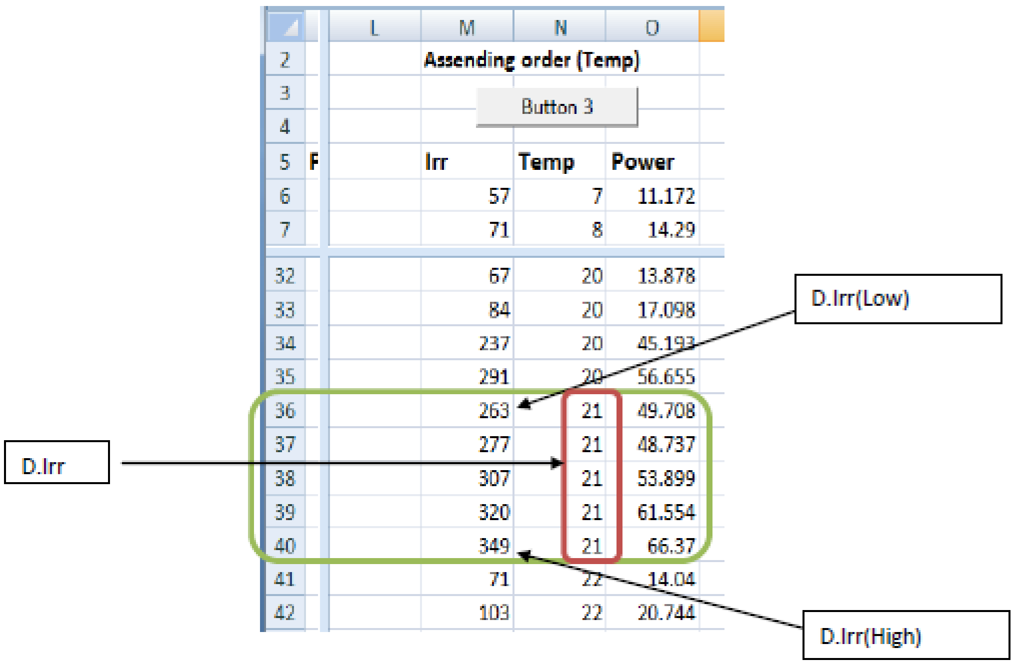
For condition 3, The Pmax value is extrapolated from the irradiance values falling under range X-100 and X. If the program did not encounter irradiance values under this range, the program searches for the same range of values at Y+1 module temperature. The program continuously searches for this range until it finds at Y+n module temperature.

The program calculates Pmax of the module at X irradiance and Y+n module temperature using extrapolation. This Pmax is translated for Y module temperature using 0.5%/˚C temperature. A flowchart description of the program is shown in Figure 7. Button 6 is used to generate the Performance matrix.

Conventions used in the flowchart

R.Irr = Irradiance at which the module output power has to be predicted.

D.Irr = Irradiance value in the data base.



	Irr	Temp	Power
6	57	7	11.172
7	71	8	14.29
32	67	20	13.878
33	84	20	17.098
34	237	20	45.193
35	291	20	56.655
36	263	21	49.708
37	277	21	48.737
38	307	21	53.899
39	320	21	61.554
40	349	21	66.37
41	71	22	14.04
42	103	22	20.744

Figure 10 Displaying conventions used-1

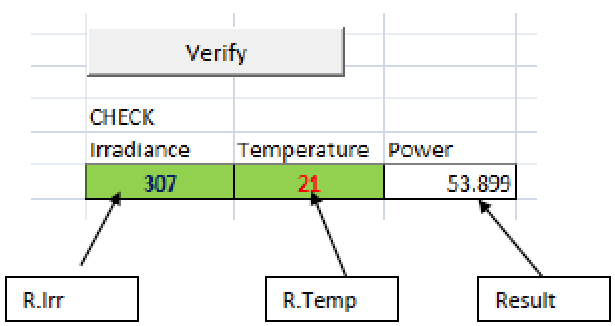
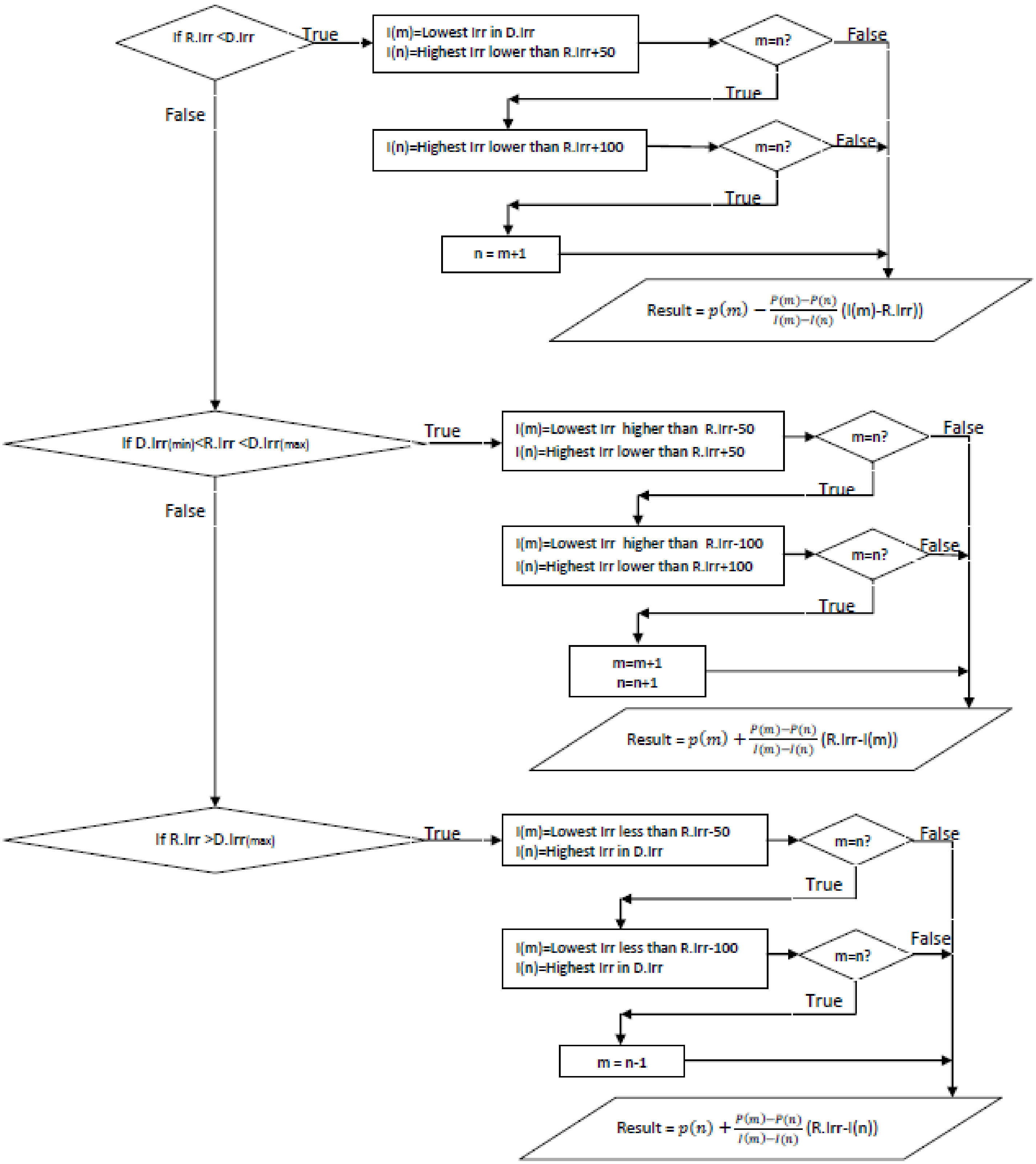


Figure 11 Displaying conventions used-2

3.1.5 Flow chart:



3.2 Thermal Model Automation (Part 2)

3.2.1 BAPV Module Installation

In order to install the BAPV modules, a mock roof was designed and constructed at Arizona State University's Photovoltaic Reliability Laboratory (ASU-PRL) in Mesa, Arizona.

The specifications of the mock roof are detailed below.

- Roof dimension: 32 x 17.5 ft
- Roof orientation: South fixed
- Roof pitch: 23° from horizontal
- Roofing materials: cement based concrete flat tiles
- Air gap spacing: 0, 1, 2, 3, and 4 inches

Twenty PV modules from four different manufacturers were selected for use in monitoring the temperatures of the BAPV modules. Crystalline silicon technology PV modules were chosen for this experiment. Ten BAPV modules were from two different manufacturers that used poly crystalline silicon (poly c-Si) technology, and the other 10 BAPV modules were from two different manufacturers that used mono crystalline silicon (mono c-Si) technology. The array configurations are detailed below, in Table 3.1 and Figure 3.1.

Test technology: poly c-Si and mono c-Si

Module electrical termination: open-circuit

Number of test modules: 20 (10 mono c-Si; 10 poly c-Si)

Array matrix: 4 columns (5 modules each) x 5 rows (4 modules each)

Column 1: poly c-Si BAPV modules [manufacturer 1]

Column 2: mono c-Si BAPV modules [manufacturer 2]

Column 3: poly c-Si BAPV modules [manufacturer 3]

Column 4: mono c-Si BAPV modules [manufacturer 4]

Row 1: 0" air gap (0 cm air gap)

Row 2: 1" air gap (2.54 cm air gap)

Row 3: 2" air gap (5.08 cm air gap)

Row 4: 3" air gap (7.62 cm air gap)

Row 5: 4" air gap (10.16 cm air gap)

Distance between modules in each column: 2 – 6 in (5 - 15 cm)

Distance between modules in each row: 1 in (2.54 cm)

Depth of module frame. ~2 in (5 cm)

Table 3 Array of BAPV modules on the mock roof

	Roof top			
	Column 1	**Column 2**	**Column 3**	**Column 4**
4" air gap	Poly c-Si	Mono c-Si	Poly c-Si	Mono c-Si
3" air gap	Poly c-Si	Mono c-Si	Poly c-Si	Mono c-Si
2" air gap	Poly c-Si	Mono c-Si	Poly c-Si	Mono c-Si
1" air gap	Poly c-Si	Mono c-Si	Poly c-Si	Mono c-Si
0" air gap	Poly c-Si	Mono c-Si	Poly c-Si	Mono c-Si
	Roof bottom			

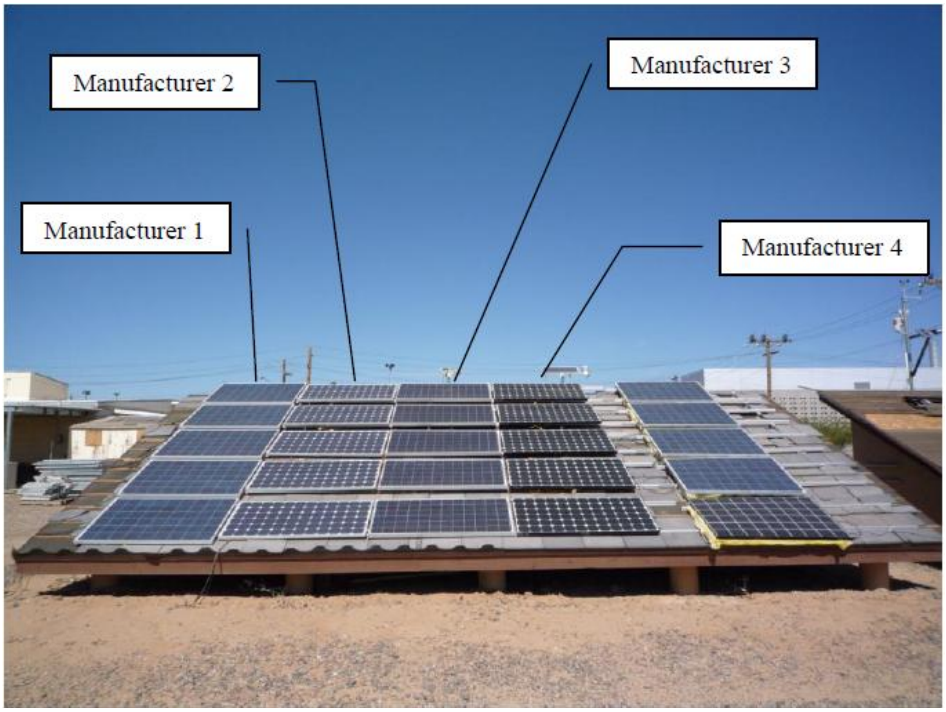


Figure 12 Array of BAPV modules on the simulated rooftop structure[3]

Figure 13 Side view of the simulated rooftop structure with installed modules[3]

3.2.2 Data Collection and Processing

A data acquisition system (DAS) was used to collect the extensive quantity of temperature data over the one-year period. For the data collection, a National Instruments data acquisition system was installed behind the mock roof. The four NI-9211 modules that were connected to the thermocouples were hard wired to the high-speed, USB DAS, which was controlled by the LabVIEW signal express program, which is a powerful and flexible graphical development environment created by National Instruments, Inc.

To analyze the temperature variation of the BAPV modules with different air gaps of 0”, 1”, 2”, 3”, and 4”, with respect to ambient temperature and other influencing parameters, such as wind speed, wind direction, and solar irradiance. The method of linear regression was chosen for this work, and MATLAB was used for this mathematical model development.

Using MATLAB coefficients of the influencing parameters were generated for every module each month. For each module, as the data collection was done over a period of one year, twelve different coefficient values of each influencing parameter were generated for a year.

For example, twelve irradiance coefficients are generated on a single module in one year. Similarly, twelve ambient temperature coefficients, twelve wind speed coefficients and twelve constants are generated over the year.

The twelve coefficients belonging to each influencing parameter are used to generate an equation using Microsoft Excel’s curve fitting.

These equations are used to program an Excel file using Microsoft Visual basic which in turn generates the coefficients from the equations and calculates module temperature using equation below.

$$T_{module} = E * w1 + T_{amb}*w2 + WS*w3 + c$$

where:

T_{module}: module temperature (°C);

E: irradiance (W/m^2);

T_{amb}: ambient temperature (°C);

WS: wind speed (m/s);

w1- w3: coefficients;

c: constant.

The results of the thermal model are presented in Chapter 4.

Results of Performance matrix generation software and Module temperature prediction software are presented in this chapter.

4.1 Automation of Performance matrix results

Different procedures are now being followed in a specific sequence to generate the performance matrix from raw data. Every procedure is allotted a separate button for its execution. The procedures with their buttons are shown below:

Table 4 Sequence of Procedures/Buttons

1	Rounding	Button1
2	Sorting in increasing order of irradiance	Button 2
3	Sorting in increasing order of module temperature	Button 3
4	Filtering	Button 11
5	Performance matrix generation	Button 6

The performance matrix is generated when these procedures are executed in the sequence shown in Table 4.

These procedures have their own execution time which depends on the number of raw data points. So, the user has to wait for the next procedure until the previous procedure completes execution.

To circumvent the process of executing each program one after the other and to avoid the waiting time after each procedure, a master button “AUTO” is now created on top left corner of Sheet4. Clicking “AUTO” button would execute all the procedures automatically in sequence generating various tables and graphs as shown below.

- IEC 61853-1 or user defined Pmppt matrix [Table 5]
- Pmppt versus Irradiance [Figure 15]
- Pmppt versus Temperature [Figure 16]
- Actual Pmppt versus Calculated Pmppt [Figure 17]
- RMSE value

A sample of energy matrix table based on 12-day datasets of a polycrystalline silicon module is presented below:

Table 5 Pmax Matrix: Irradiance vs Temperature

Button 6

IRRADIANCE (W/m²) \ TEMPERATURE (°C)	15	25	35	45	50
100	18.2	18.8	16.9	9.9	N/A
200	38.2	36.7	36.0	23.3	23.3
300	74.0	55.0	52.7	38.0	37.4
600	111.5	105.7	99.4	92.8	85.3
800	142.5	135.2	125.8	121.8	118.9
1000	167.4	160.1	152.8	148.8	144.1

Extrapolated values

The Pmax values are calculated according to flowchart provided in the methodology section 3.1.5. The generated matrix also differentiates the interpolated data (white cells) from the extrapolated data (yellow cells) as shown in Table 5.

Performance matrix with different combinations of irradiance and temperature other than IEC61853-1 standard can also be created. To generate this user defined energy matrix, required combinations of irradiance and temperature values are entered in table as shown in the Table 6. After entering the required combinations, "Button 6" is used to re-calculate the user defined matrix. The user defined matrix is as shown in Table 6 .

Table 6 User defined Pmax matrix

Button 6

IRRADIANCE (W/m²)	TEMPERATURE (°C) 20	25	30	35	40
300	55.5	55.0	53.3	52.7	N/A
350	63.7	63.6	61.5	60.4	53.1
400	72.6	71.5	69.8	68.2	62.4
450	82.5	79.6	77.5	76.0	72.2
500	95.4	87.2	86.2	84.1	81.6
1100	177.2	173.5	169.9	166.2	163.0

Extrapolated values

Graphs of Irradiance vs Output power and Temperature vs Output Power are linked to the values in the energy matrix. When the values in the energy matrix are being calculated, these graphs are automatically created. They also get automatically updated with change in the combinations of irradiance and temperature for user defined energy matrix.

Screen shot of graphs created are shown in Figure 16 and Figure 17 below.

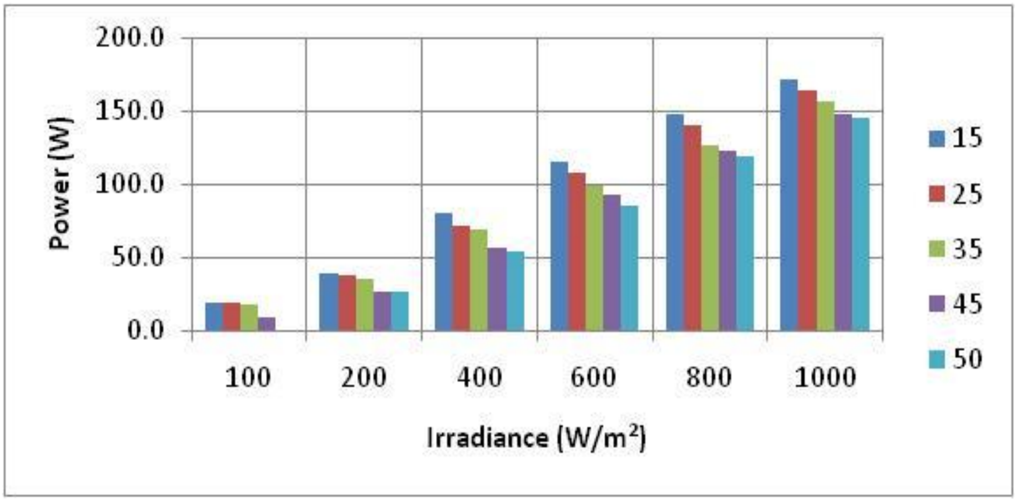


Figure 14 Irradiance vs Power

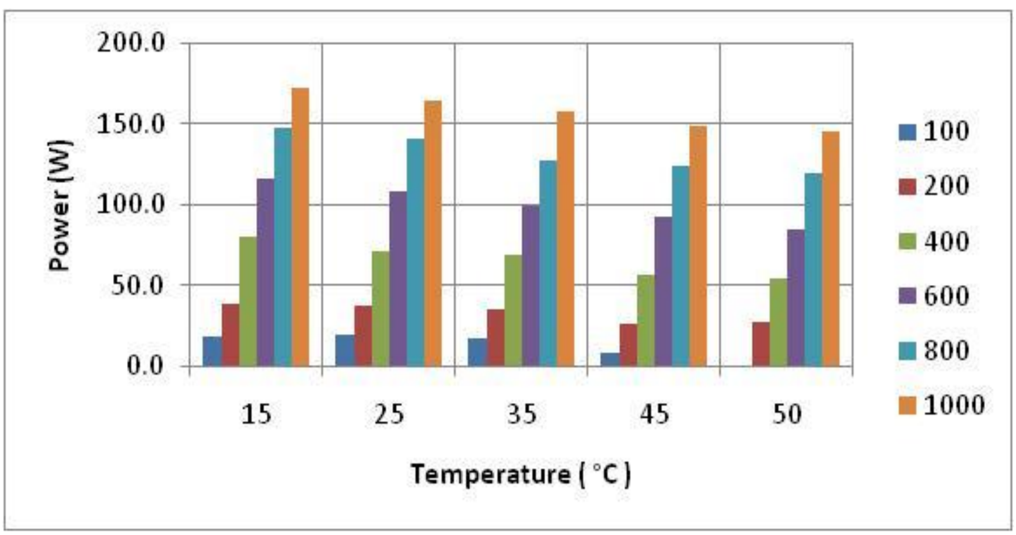


Figure 15 Module Temperature vs Power

To know the accuracy of the program for the given set of data, linearity check between raw data and calculated data can be performed. By clicking “Validate” on Sheet1, the Excel file automatically calculates the Pmax value for every combination of irradiance and temperature in the raw data set and compares with the raw(real) Pmax. A graph is plotted with real Pmax value in X axis and calculated value in Yaxis. The slope of the trend line generated shows the accuracy of the program.

Calculated data vs Real data graph is also displayed as shown in the Figure 18.

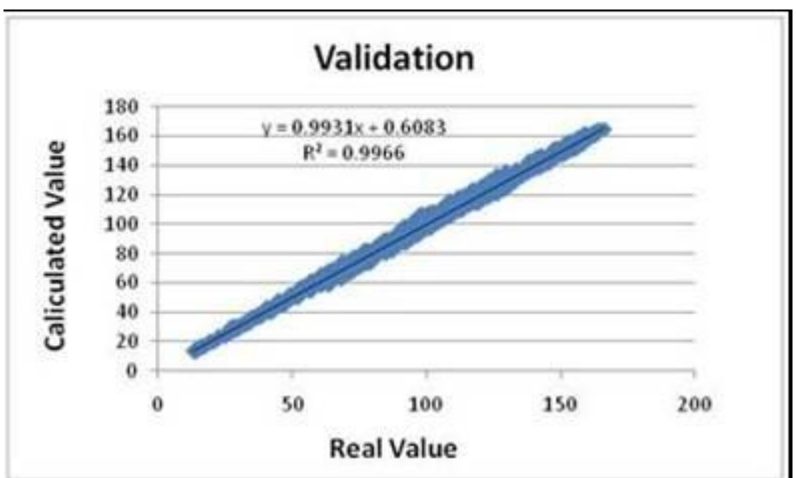


Figure 16 Validation of calculated value

4.1.1 Accuracy of MPPT Tracking by Tracer

To determine if the MPPT tracer is tracking the maximum peak power value on the IV curve, the MPPT value and Pmax value on the IV curve has been compared. The data acquisition system frequency of MPPT value generation is matched with IV curve generation frequency of 6 minutes. The two values were compared for a day and achieved a mean deviation of about 2%.

Equation used: Percentage Deviation=((Pmax-MPPT)/Pmax)*100

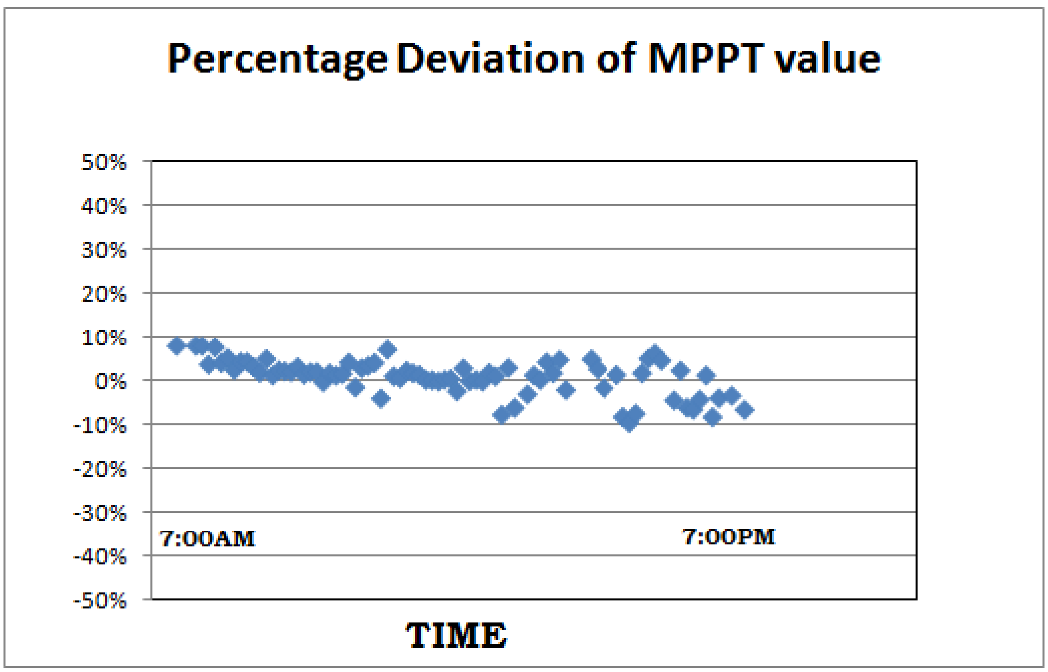


Figure 17 Comparison of Tracer MPPT values with Tracer Pmax values on a single clear day.

The MPPT values with manually calculated Pmax value in an IV curve are plotted as shown in Figures 16.

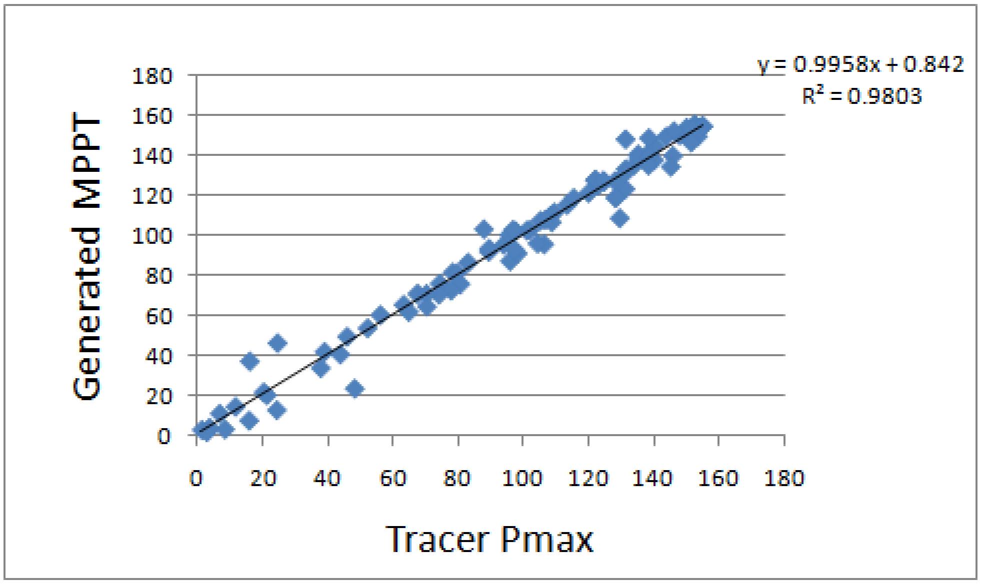


Figure 18 Comparison of Tracer MPPT Values with Generated MPPT Values on a single day

The raw data should contain datasets having all the module temperatures starting from the lowest module temperature to highest module temperature required in the performance matrix. This can be verified by carefully observing column "N" of Sheet 4. The module temperature values should be incrementing by only 1˚C till the highest module temperature available in the data set.

To achieve this raw data, the data collection frequency should be sufficient enough to record the raw data for every 1˚C raise in temperature. The module temperature rises rapidly during the morning along with the rising sun. During mid day, the module temperature remains constant with a comparatively less rate of increase in temperature. During the afternoon and into the evening, the rate of decrease in temperature decreases at a lesser pace than the corresponding increase in the morning. So to generate the matrix with minimum data points, frequency of data point collection can be increased in the mornings where the module temperature increases and decreased in the afternoons where there is less rate of change in module temperature. In this project, the data collection interval is set to 6 minutes throughout the day.

When the number of data points in raw data are reduced, the program has been unable to calculate accurate Pmax values. These Pmax values were then calculated by interpolating the raw data Pmax values in the same module temperature range. To overcome this problem, Pmax values with temperature range of +/- 5 ˚C are used for interpolation. This increased the number of data points used for calculating Pmax and decreased errors.

One of the aims of this project is to reduce the number of days of data collection. To determine the required minimum number of days to collect the datasets, different approaches were followed as delineated below.

1. 1-module 12-day approach:

   Data of a single module is collected from 7:00AM to 6:00PM for 12 continuous days every 6 minutes. Performance matrix generated using this approach is shown in Table .

   Table 7 Performance matrix using single module 12 day approach

Button 6

IRRADIANCE (W/m²)	TEMPERATURE (°C) 15	25	35	45	50
100	18.2	18.8	16.9	9.9	N/A
200	38.2	36.7	36.0	23.3	23.3
300	74.0	55.0	52.7	38.0	37.4
600	111.5	105.7	99.4	92.8	85.3
800	142.5	135.2	125.8	121.8	118.9
1000	167.4	160.1	152.8	148.8	144.1

Extrapolated values

2. 1-module 6-day approach:

Data of a single module is collected from 7:00AM to 6:00PM for 6 continuous days every 6 minutes. Matrix generated using first 6 days data and second set of 6 days are shown in Figure 20.

First 6 days

IRRADIANCE (W/m^2) \ TEMPERATURE (°C)	15	25	35	45	50
100	18.2	18.7	2.1	9.0	N/A
200	38.2	37.1	30.3	23.6	22.6
300	74.0	55.4	52.8	38.4	37.0
600	111.5	105.7	99.2	91.5	83.5
800	142.5	135.2	125.8	120.5	116.7
1000	167.4	160.1	152.8	148.8	144.0

Extrapolated values

Second 6 days

IRRADIANCE (W/m^2) \ TEMPERATURE (°C)	15	25	35	45	50
100	18.2	18.2	14.4	9.4	N/A
200	39.1	36.5	30.8	23.1	23.3
300	60.3	56.1	51.8	38.0	37.4
600	112.7	105.4	98.2	91.7	85.7
800	141.5	134.2	126.9	121.6	118.3
1000	170.0	162.7	155.4	148.1	143.2

Extrapolated values

Figure 19 Performance matrix using single module 6 day approach

Comparison of 12 day and 6 day energy matrix

Matrix generated using 6-days data and 12-days data are compared. They are found to be practically identical at all irradiance conditions except for

3 conditions. 100 W/m^2 at 35^{o}C ; 200 W/m^2 at 35^{o}C ; 100 W/m^2 at 45 ^{o}C.

The percentage deviation of the values among the first two approaches is shown in Table .

Table 8 Percentage deviation among Single module 12 day and 6 day approach

First 6 days

	15	25	35	45	50
100	0%	-1%	-711%	-9%	#VALUE!
200	0%	1%	-19%	1%	-3%
300	0%	1%	0%	1%	-1%
600	0%	0%	0%	-1%	-2%
800	0%	0%	0%	-1%	-2%
1000	0%	0%	0%	0%	0%

Second 6 days

	15	25	35	45	50
100	0%	4%	15%	5%	#VALUE!
200	-2%	1%	15%	1%	0%
300	19%	-2%	2%	0%	0%
600	-1%	0%	1%	1%	0%
800	1%	1%	-1%	0%	0%
1000	-2%	-2%	-2%	0%	1%

12 Day Approach

TEMPERATURE (°C)

IRRADIANCE (W/m²)	15	25	35	45	50
100	18.2	18.8	16.9	9.9	N/A
200	38.2	36.7	36.0	23.3	23.3
300	74.0	55.0	52.7	38.0	37.4
600	111.5	105.7	99.4	92.8	85.3
800	142.5	135.2	125.8	121.8	118.9
1000	167.4	160.1	152.8	148.8	144.1

Extrapolated values

First 6 days

TEMPERATURE (°C)

IRRADIANCE (W/m²)	15	25	35	45	50
100	18.2	18.7	2.1	9.0	N/A
200	38.2	37.1	30.3	23.6	22.6
300	74.0	55.4	52.8	38.4	37.0
600	111.5	105.7	99.2	91.5	83.5
800	142.5	135.2	125.8	120.5	116.7
1000	167.4	160.1	152.8	148.8	144.0

Extrapolated values

Second 6 days

TEMPERATURE (°C)

IRRADIANCE (W/m²)	15	25	35	45	50
100	18.2	18.2	14.4	9.4	N/A
200	39.1	36.5	30.8	23.1	23.3
300	60.3	56.1	51.8	38.0	37.4
600	112.7	105.4	98.2	91.7	85.7
800	141.5	134.2	126.9	121.6	118.3
1000	170.0	162.7	155.4	148.1	143.2

Extrapolated values

711% deviation 15- 19% deviation 3% deviation

Figure 20 Comparison of 12 day approach and 6 day approach

4.2 Thermal model automation results

The module temperature is dependent on three influencing parameters which are irradiance, ambient temperature and wind speed. The coefficients of these influencing parameters are generated for twelve months using MATLAB.

These coefficients for 5 modules are generated independently. These coefficients of a single module are sorted monthly in a table as shown in Figure 16. Coefficients of Column 3 with 4 inch air gap module are being used for explanation.

Each column of coefficients are arranged in increasing order and a third degree polynomial trend line is generated for each column as shown below.

4 in

Month	Irr	T_{amb}	WS	Constant
Jan	0.026702	0.901464	-2.23919	9.306498
Feb	0.009905	0.188984	-3.69965	41.85293
Mar	0.004721	0.142665	-2.99204	51.98393
Apr	0.028713	0.693278	-1.32363	12.17127
May	0.032625	0.58209	-1.18329	9.002892
Jun	0.019394	0.735585	-2.16576	17.00682
Jul	0.026909	0.717625	-1.57979	10.63467
Aug	0.029573	0.562439	-2.77542	17.93095
Sep	0.035325	0.599304	-2.99051	13.28023
Oct	0.020642	0.905495	-3.79304	17.33673
Nov	0.02962	0.699907	-1.88121	11.4947
Dec	0.031559	0.905684	-3.54259	11.08688

Figure 21 Coefficients of a module for an year

	4 in				
	Month	Irr	T_{amb}	WS	Constant
	Mar	0.004721	0.142665	-2.99204	51.98393
	Feb	0.009905	0.188984	-3.69965	41.85293
	Jun	0.019394	0.735585	-2.16576	17.00682
	Oct	0.020642	0.905495	-3.79304	17.33673
	Jan	0.026702	0.901464	-2.23919	9.306498
	Jul	0.026909	0.717625	-1.57979	10.63467
Column 1	Apr	0.028713	0.693278	-1.32363	12.17127
	Aug	0.029573	0.562439	-2.77542	17.93095
	Nov	0.02962	0.699907	-1.88121	11.4947
	Dec	0.031559	0.905684	-3.54259	11.08688
	May	0.032625	0.58209	-1.18329	9.002892
	Sep	0.035325	0.599304	-2.99051	13.28023

Increasing order of Irradiance coefficients

Figure 22 Sorted coefficients of irradiance

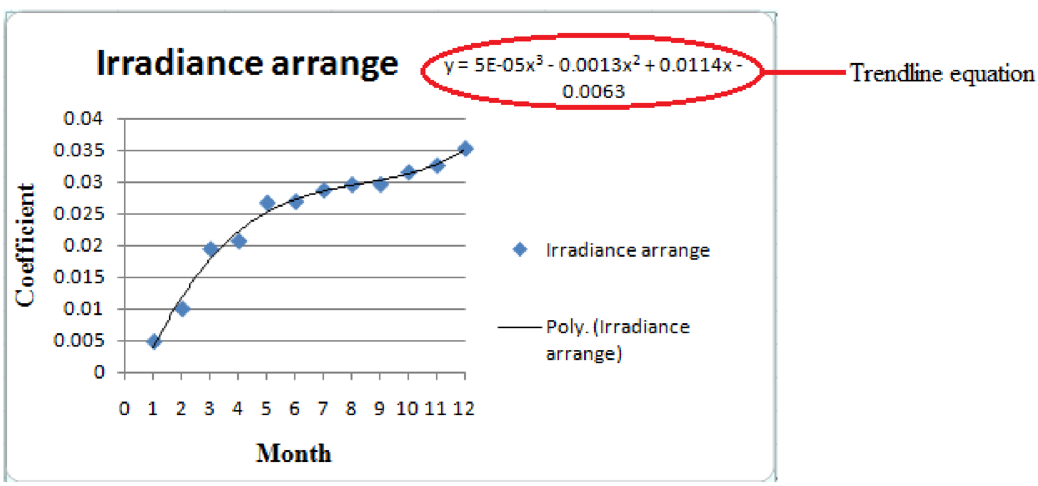


Figure 23 Trendline of irradiance coefficients

Similarly,trend line equations for coefficients of Tamb and Wind speed are generated.

Thus, for each module trendline equations for Irradiance, Tamb, Wind speed and Constant are created. For 5 modules, 5x4=20 equations are generated which are manually loaded into the Visual Basic program of the Excel file.

The Excel file is programmed to generate Thermal model which shows temperatures of five modules arranged in a column. Each cell in the matrix contains temperature of respective positioned module as shown in Figure 24.

The user needs to input irradiance, ambient temperature and wind speed at the space provided in Sheet1. The user input region is shown in Figure 21.

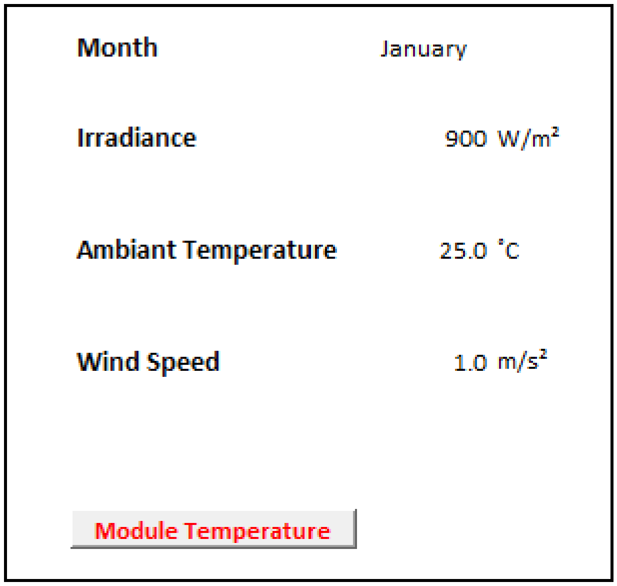


Figure 24 User Input region

Clicking "Module Temperature" generates module temperatures of all the modules in column 3. The procedure followed by the program is shown in the flowchart below.

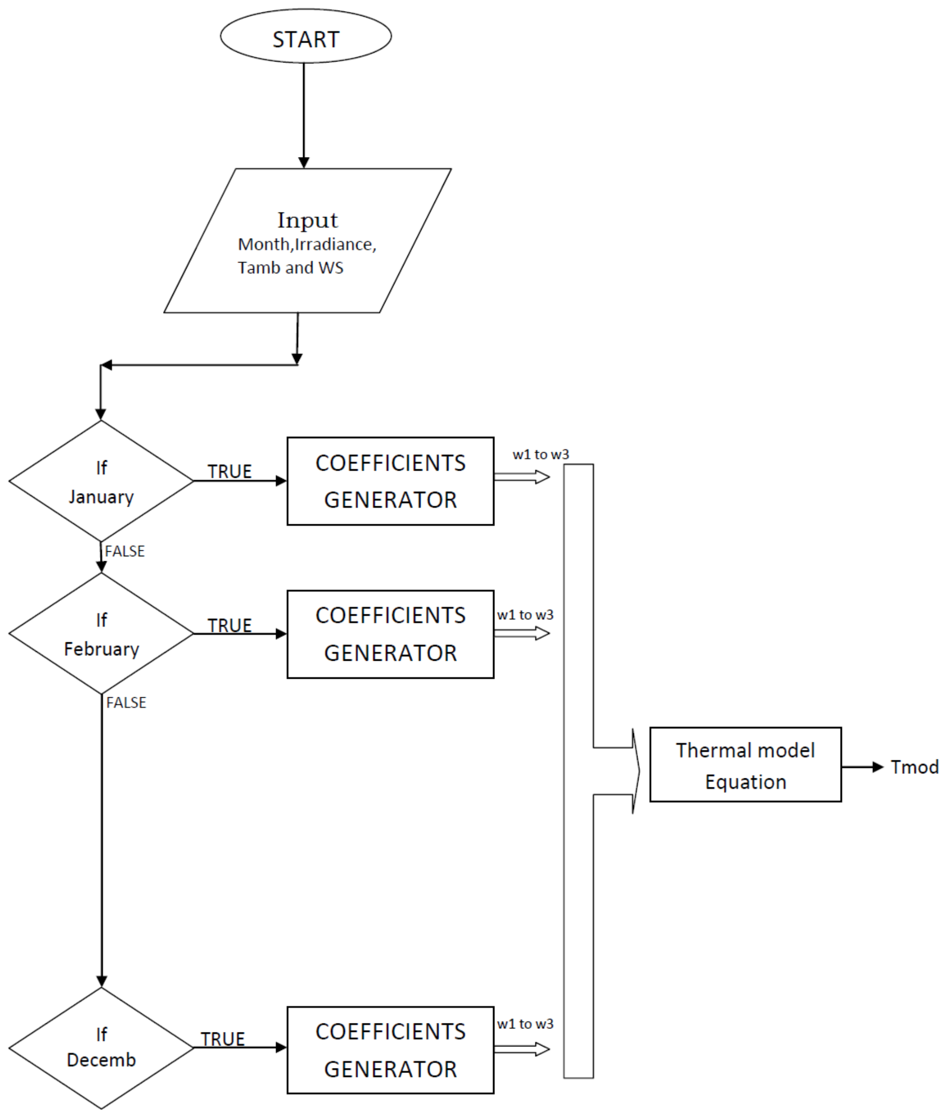


Figure 25 Flow chant of procedure

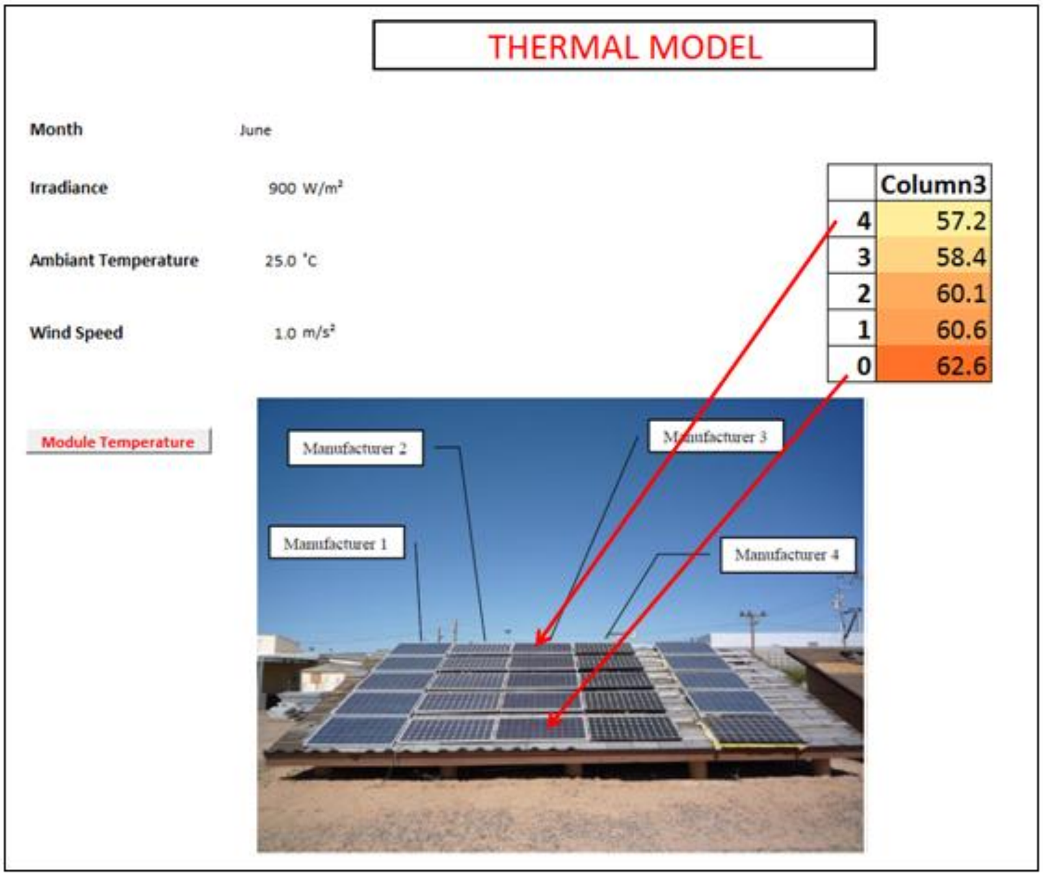


Figure 26 Thermal model result description

CHAPTER 5.CONCLUSIONS

5.1 Performance Matrix

Based on a 3-column data (irradiance, module temperature and MPPT), Pmax matrix at different irradiance-temperature sets per IEC 61853-1 standard can be generated by click of a button on an Excel spreadsheet

3. The program checks for the Pmax linearity with irradiance and temperature
4. The program checks for the data accuracy by comparing the calculated data with actual measured data
5. The proposed approach has the potential generating various user-defined plots to use as a diagnostic tool for power plant degradation or soiling effect over time

It can be concluded that the approach is feasible but the accuracy needs to be improved.

5.2 Thermal Model

Temperatures of the modules on rooftop can be predicted using the pre programmed Excel file. The coefficients of irradiance, ambient temperature and wind speed have to be initially loaded into the program. These coefficients can be generated using linear regression in MATLAB. These coefficients in turn can be used in the programming Excel to automate thermal model.

5.3 Recommendations

Following recommendations are made for improving the accuracy of results generated from the automated softwares.

- In this work, the data is collected from modules at fixed tilt. It is suggested that data from modules on two axis tracker is used as raw data for automated Excel file.
- The program uses fixed temperature coefficient. It is suggested to have dynamic temperature coefficient.
- Thermal model is automated for only a column which can be automated for entire array using the same approach. In the present work, data is sorted on a monthly basis. Coefficients of irradiance, ambient temperature and wind speed are calculated for every month assuming the wind direction is taken into account. It is suggested to sort the year round data on a wind direction basis.

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APPENDIX A

COEFFICIENTS USED IN THERMAL MODEL AUTOMATION

The monthly coefficients are calculated using linear regression analysis in MATLAB. These coefficients are arranged in increasing order and are fitted to third order polynomial curve. This curve equation is loaded in the automation program to generate the monthly coefficients dynamically. The generated coefficients are used to derive module temperature.

Month	Irr	T_{amb}	WS	Constant
Jan	0.033162	1.110866	-3.12466	6.28033
Feb	0.031625	1.25231	-3.43377	5.731947
Mar	0.022587	1.688219	-2.47409	5.562432
Apr	0.032891	0.668458	-1.81511	11.44415
May	0.03111	0.973395	-1.72626	6.146027
Jun	0.021008	1.121781	-2.99241	12.1723
Jul	0.031773	0.644791	-2.18083	22.28218
Aug	0.028345	1.126298	-3.02573	6.109041
Sep	0.033709	1.086812	-3.70162	4.93996
Oct	0.020497	1.190827	-4.14069	14.14174
Nov	0.030466	1.01499	-2.21605	7.010964
Dec	0.0311	1.220498	-3.07425	5.763836

Figure 27 Monthly coefficients of 4inch air gap module

Month	Irr	T_{amb}	WS	Constant
Jan	0.035065	1.132393	-2.68332	5.867093
Feb	0.033618	1.288313	-3.18742	5.381139
Mar	0.026103	1.639114	-2.48896	6.420418
Apr	0.033966	0.684979	-1.66053	12.89686
May	0.032883	0.985954	-1.57928	6.017808
Jun	0.022839	1.110261	-2.94166	13.24648
Jul	0.034461	0.749142	-2.07948	17.57193
Aug	0.030365	1.160896	-2.61173	4.36896
Sep	0.035299	1.126954	-3.37622	3.703687
Oct	0.021777	1.209367	-3.80762	14.10994
Nov	0.032842	1.000947	-1.87488	7.09204
Dec	0.03312	1.190294	-2.87685	6.328354

Figure 28 Monthly coefficients for 3 inch airgap module

Month	Irr	T_{amb}	WS	Constant
Jan	0.035777	1.25934	-1.69042	3.301368
Feb	0.035241	1.361433	-2.48956	3.481269
Mar	0.029395	1.627232	-2.21818	6.545146
Apr	0.0316	0.873114	-1.185	13.54058
May	0.034102	1.05487	-1.17251	3.994003
Jun	0.02458	1.164441	-2.47242	11.8736
Jul	0.039842	0.641253	-1.62703	19.75412
Aug	0.031214	1.233577	-1.64846	1.638645
Sep	0.034905	1.260183	-2.67169	0.538334
Oct	0.022641	1.260921	-2.8099	12.78689
Nov	0.03388	1.094222	-1.24562	4.649632
Dec	0.035753	1.240297	-2.19587	4.034902

Figure 29 Monthly coefficients of 2 inch airgap module

Month	Irr	T_{amb}	WS	Constant
Jan	0.033134	1.226436	-1.52873	3.909301
Feb	0.033718	1.312063	-2.29096	3.805146
Mar	0.027684	1.590719	-2.09036	6.590622
Apr	0.030799	0.855132	-1.18822	13.3989
May	0.034467	1.060138	-0.9117	3.968455
Jun	0.025616	1.144768	-2.09805	12.00784
Jul	0.032909	0.989932	-1.59477	10.26397
Aug	0.03018	1.317649	-1.7139	-1.28166
Sep	0.032548	1.274469	-2.67941	1.015996
Oct	0.021945	1.209417	-2.7406	13.57483
Nov	0.032668	1.123095	-1.08192	3.540995
Dec	0.033338	1.224656	-1.95507	4.225295

Figure 30 monthly coefficients of 1 inch airgap module

Month	Irr	T_{amb}	WS	Constant
Jan	0.035424	1.284823	-1.60393	3.65192
Feb	0.035489	1.36556	-2.27255	3.587003
Mar	0.029981	1.580238	-1.94498	6.444166
Apr	0.031852	0.830805	-0.89178	14.89952
May	0.036335	1.130828	-0.84521	1.8832
Jun	0.027147	1.180957	-2.07312	11.96629
Jul	0.033505	1.146584	-1.96607	5.399179
Aug	0.030785	1.3902	-1.77783	-3.40954
Sep	0.033356	1.350722	-2.76298	-0.9226
Oct	0.022345	1.164807	-2.93226	16.24296
Nov	0.034656	1.086845	-1.10759	4.851835
Dec	0.035707	1.287132	-1.74752	3.53023

Figure 31 Monthly coefficients for 0 inch airgap module

	Month Code (x) for Air Gap 4"			
	Irr	Tamb	WS	Const.
Jan	11	6	4	7
Feb	8	11	3	3
Mar	3	12	8	2
Apr	10	2	11	9
May	7	3	12	6
Jun	2	7	7	10
Jul	9	1	10	12
Aug	4	8	6	5
Sep	12	5	2	1
Oct	1	9	1	11
Nov	5	4	9	8
Dec	6	10	5	4

Figure 32 Month code coefficient generation for 4inch airgap module

	Month Code (x) for Air Gap 3"			
	Irr	Tamb	WS	Const.
Jan	11	7	6	4
Feb	8	11	3	3
Mar	3	12	8	7
Apr	9	1	11	9
May	6	3	12	5
Jun	2	5	4	10
Jul	10	2	9	12
Aug	4	8	7	2
Sep	12	6	2	1
Oct	1	10	1	11
Nov	5	4	10	8
Dec	7	9	5	6

Figure 33 Month code coefficient generation for 3inch airgap module

	Month Code (x) for Air Gap 2"			
	Irr	Tamb	WS	Const.
Jan	11	8	7	3
Feb	9	11	3	4
Mar	3	12	5	8
Apr	5	2	11	11
May	7	3	12	5
Jun	2	5	4	9
Jul	12	1	9	12
Aug	4	6	8	2
Sep	8	9	2	1
Oct	1	10	1	10
Nov	6	4	10	7
Dec	10	7	6	6

Figure 34 Month code coefficient generation for 2inch airgap module

	Month Code (x) for Air Gap 1"			
	Irr	Tamb	WS	Const.
Jan	9	8	9	5
Feb	11	10	3	4
Mar	3	12	5	8
Apr	5	1	10	11
May	12	3	12	6
Jun	2	5	4	10
Jul	8	2	8	9
Aug	4	11	7	1
Sep	6	9	2	2
Oct	1	6	1	12
Nov	7	4	11	3
Dec	10	7	6	7

Figure 35 Month code coefficient generation for 1inch airgap module

	Month Code (x) for Air Gap 0"			
	Irr	**Tamb**	**WS**	**Const.**
Jan	9	7	9	6
Feb	10	10	3	5
Mar	3	12	6	9
Apr	5	1	11	11
May	12	3	12	3
Jun	2	6	4	10
Jul	7	4	5	8
Aug	4	11	7	1
Sep	6	9	2	2
Oct	1	5	1	12
Nov	8	2	10	7
Dec	11	8	8	4

Figure 36 Month code coefficient generation for 0inch airgap module