CHAPTER III

RESEARCH METHODOLOGY

The work compared the name plate power output (P_{max}/ minimum P_{max} at STC) of PV modules with the present output power (P_{max} corrected to STC) by measuring the power output of selected samples from the four different lots of PV modules installed at Energy Park, SERT, Naresuan University, Phitsanulok. The main research steps for the study undertaken are as follows:

1. Selection of samples for testing from the four lots of modules.
2. Review of the Name Plate data and data sheets.
3. Testing of samples under field conditions for I-V curve characteristics and correction of measured values to STC.
4. Comparison of results with manufacturer's data and other previous similar studies.

The performance of individual PV module can be evaluated only when we have two sets of output parameters measured at similar conditions. The actual field conditions vary instantaneously so a set of conditions termed mostly as Standard Test Conditions (STC) has been defined by IEC for measurement of output parameters of PV module. A set of certain parameters had to measure under STC at production facility and hence made available for buyers as nameplate data. More over manufacturers normally make it available online along with the guarantee conditions. To evaluate the performance guarantees after certain time period under real field conditions it is necessary to measure the output parameters again under STC or measurements under field conditions should be corrected to STC using well known procedures, so that it can be compared with the nameplate data keeping in view the degradation rates guaranteed by manufacturers.

The graphical representation of methodology is as below.

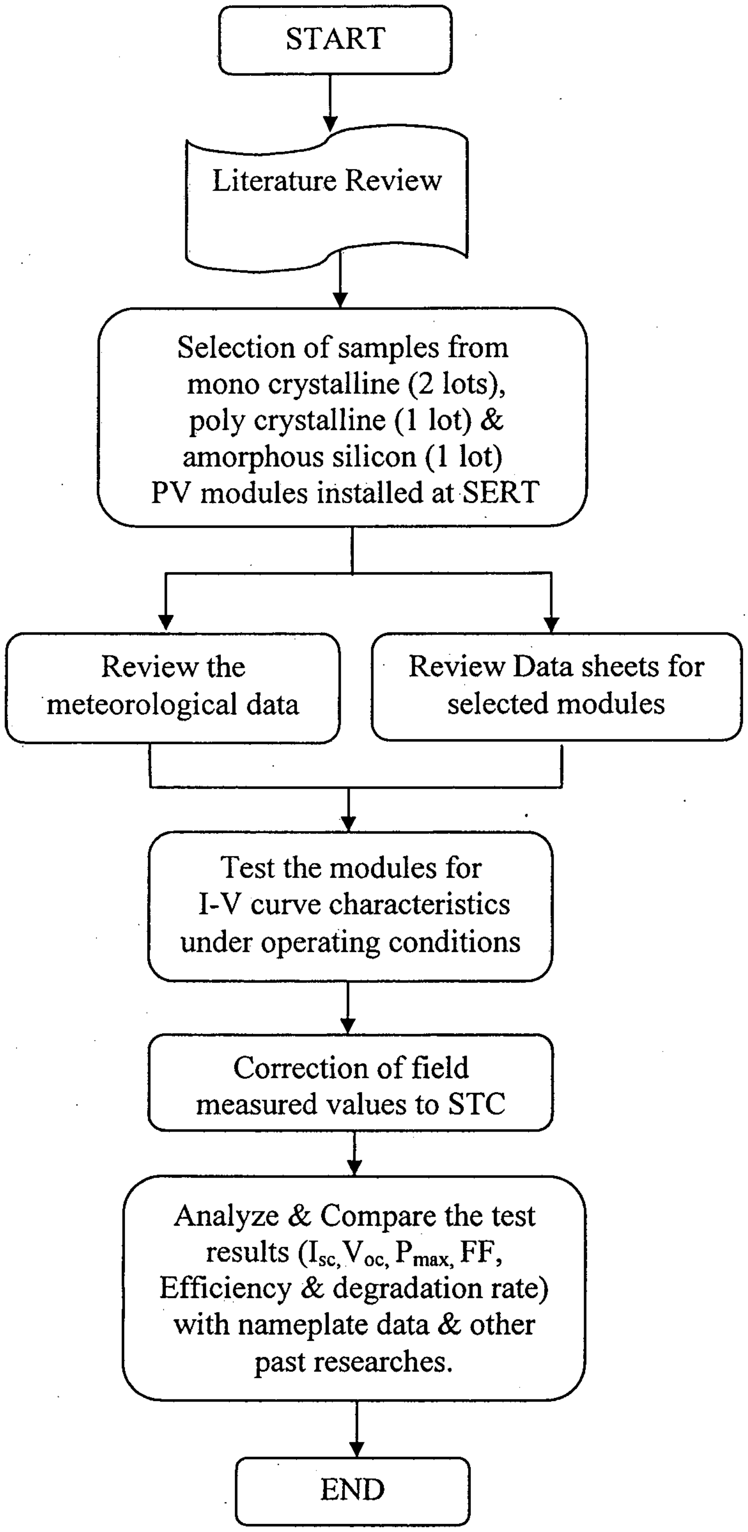


Figure 2 Flow chart of research methodology

Literature Review

Literature review briefly comprises on:

1. Photo voltaic technology.
2. Types of photo voltaic modules.
3. Efficiency of PV modules.
4. Performance of PV modules under different operating conditions.
5. Lifecycle of PV modules.
6. Guarantee conditions of modules.
7. Common reasons for performance degradation.
8. Degradation rates of different PV modules types.

Selection of samples

At the School of Renewable Energy Technology (SERT) different lots of Silicon PV modules are under operation since long time. These modules belong to relatively newer generation and were put into operation in year 2000, 2003 and 2005. As a matter of fact it was not possible to test the whole lot because of operational hurdles, so sampling was considered as an alternate option. The best technique for such a homogeneous population can be probability based simple random sampling. In this type every member of population has an equal chance of selection and thus on this bases the results can be generalized for whole population. The size of sample can be calculated using online sample size calculators or by available tables based on following formula [22]:

$$s = \frac{X^2 NP(1-P)}{d^2(N-1)} + X^2 P(1-P) \qquad (1)$$

Where

s = required sample size.

X^2 = the table value of chi-square for 1 degree of freedom at the desired confidence level (3.841).

N = the population size.

P = the population proportion (assumed to be .50 since this would provide the maximum sample size).

d = the degree of accuracy expressed as a proportion (.05).

Using the above formula and Morgan's Table, sample size for each 4 lots comes out to be 77, 24, 40, and 58 against a population of 96, 26, 45 and 68 respectively. When population is lower the sample size is very high and it decreases with the increase in population. As mentioned earlier for the testing of modules under this study it is not possible to test all or majority of modules due to operational and time constraints, so from each lot samples are to be collected at a rate of 10% whereas the minimum number should not be less than 3 to get a better representation. The selection of samples was done on simple random bases using a random number table [23].

Data Collection

The data collection nature was secondary for meteorological & module data sheets/ nameplates, however it was of primary nature for the module's output parameters measurement.

Review of name plate data and Manufacturer's data sheets

All the selected samples were located carefully in the arrays and marked. Selected modules were washed to remove dust and stains. A thorough inspection was carried out for locating any visible defects or changes in the modules. Nameplate data like short circuit current (I_{sc}), Open circuit voltage (V_{oc}), Maximum Power (P_{max}) and maximum corresponding current (I_{max}) & voltage (V_{max}) were noted for all the 4 lots under study before testing.. The guarantee conditions were also reviewed for each lot of module. Moreover the specifications sheets provided by the manufacturers of these modules were reviewed in detail.

Review of the meteorological data:

The meteorological data for last 7 years recorded by the SERT meteorological station [24] was analyzed and year 2010 was selected as typical year to represent the environmental/field conditions of Phitsanulok to which modules under test were exposed during their operation. The monthly average, maximum and minimum temperatures, humidity and wind speed (at 3m height) have been shown in the Figure 3-5 below.

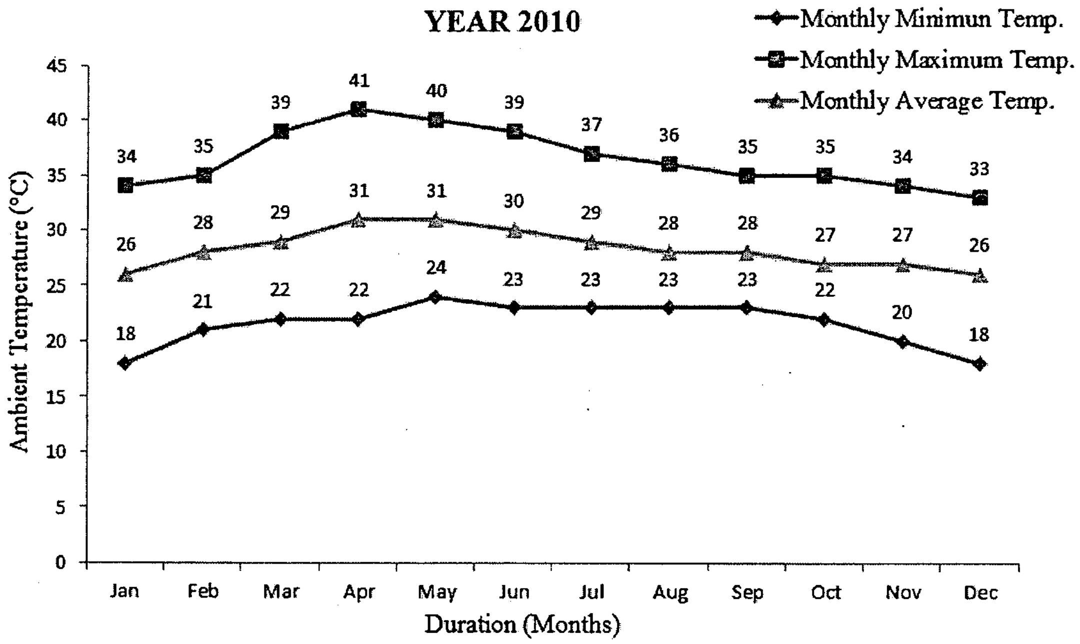


Figure 3 Monthly maximum, minimum and average temperatures (representative year 2010) for SERT Phitsanulok

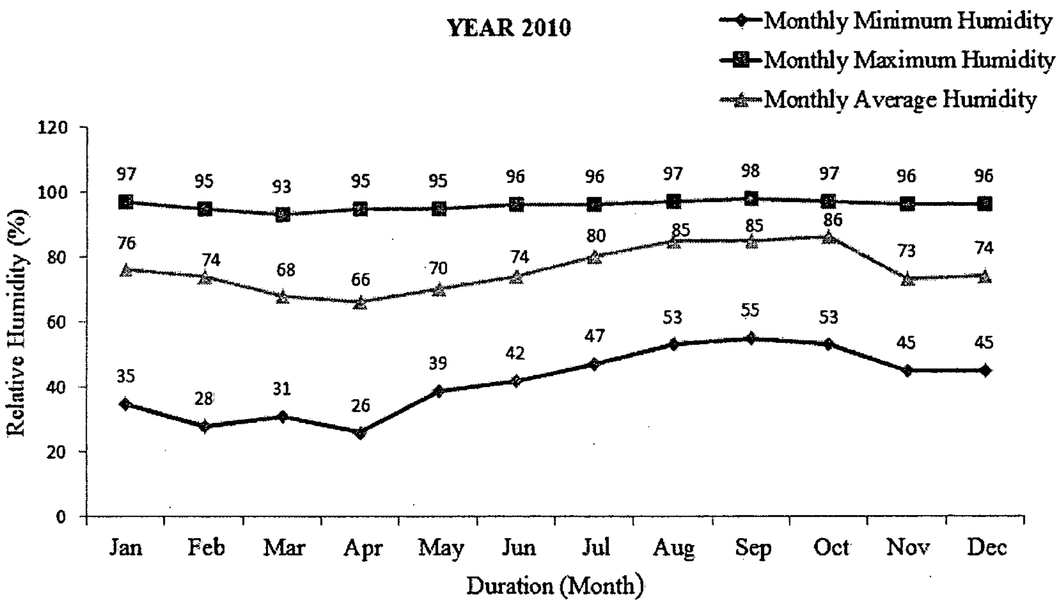


Figure 4 Monthly maximum, minimum and average relative humidity (representative year 2010) for SERT Phitsanulok .

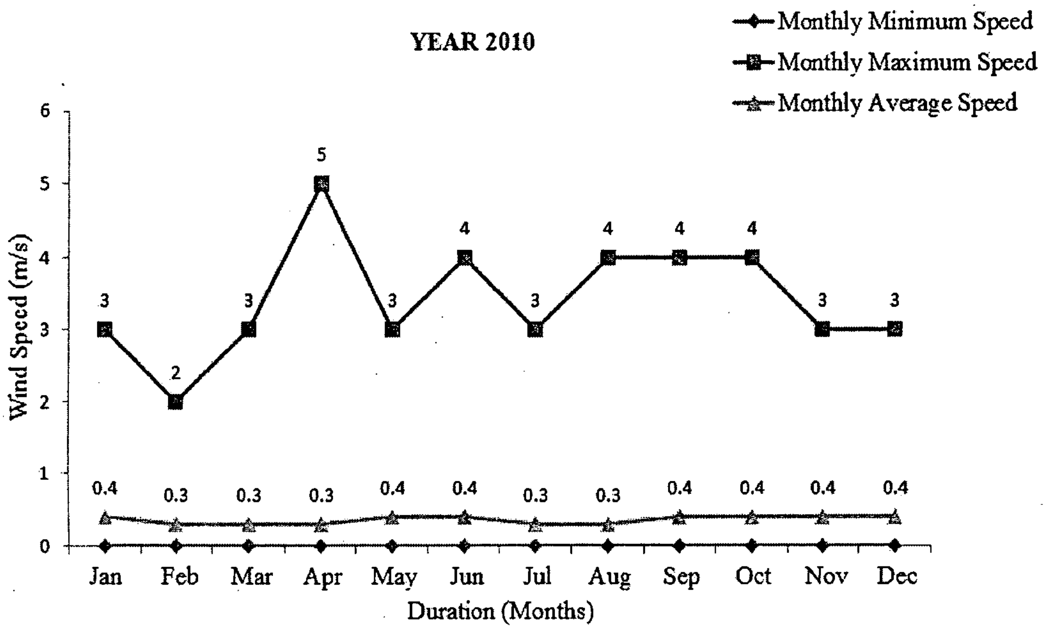


Figure 5 Monthly maximum, minimum and average wind speed at 3 meter height (representative year 2010) for SERT Phitsanulok

It should be noted that monthly *average* temperature, relative humidity and wind speed have been calculated from data sets recorded every five minutes at the station thus showing the true picture of real weather conditions. The maximum and minimum temperatures recorded during the year were 41°C and 18°C respectively, although the average temperatures have slight difference throughout the year as evident from Figure 3. The special features of Phitsanulok are its almost consistent monthly average temperature (in the order of 26-31°C) and higher humidity rates. The monthly average relative humidity recorded is between 70-86%. Moreover the monthly average wind speed recorded at 3 meter height is between 0.3-0.4 m/s. In general the weather conditions are hot and highly humid.

Equipment used for I-V curve measurement

Equipment used for I-V curve measurement in the field along with specifications is described in the table below.

Table 5 Equipment used for I-V curve measurement

I-V Checker:	
EKO I-V Checker MP-140	A device used to measure and record I-V curve characteristics for PV modules and is suitable for field measurements
Key Specifications:	
Measuring method	Condenser loading method
Range	50W to 10 kW, 25V to 350V, 2A to 30A
Data storage	Non-volatile memory, max. 70 data
Interface	RS-232C
Power requirements	20W
Measuring parameters	(P_{max}), (I_{sc}), (I_{mp}), (V_{oc}), (V_{pm}), (FF), Solar Irradiance, Ambient and PV device surface temperatures.

Source: EKO Instruments Co., ltd, Data sheet for I-V Checker [26].

Table 5 (Cont.)

Pyranometer:	
Kipp & Zonen CM 11 pyranometer	A radiometer for measuring short-wave global radiation in W/m2.
Key Specifications:	
Classification to ISO 9060:1990	Secondary Standard
Sensitivity	5.02×10^{-6} V/W/m^2
Spectral range (50% points)	285 to 2800nm
Impedance	10 to 100Ω
Expected output range (0 to 1500 W/m^2)	0 to 20 mV
Maximum operational irradiance	4000 W/m^2
Operational temperature range	-40 to 80°C
Humidity range	0 to 100% non-condensing.
Recommended applications	Meteorological networks, PV panel and thermal collector testing, materials testing.
Source: Kipp & Zonen Manual [25].	

Thermo couple:	
Type-T thermocouple	A bimetallic device used to measure temperatures
key specifications:	
Material	Copper-Constantan
Measurement range	−270 to 370 °C
Sensitivity	43 µV/°C
Accuracy standard	±1 °C or ±0.75% (whichever is greater)

Source: http://www.reotemp.com/thermocoupleinfo/type-t-hermocouple.htm [27].

Testing of selected modules under field conditions

Every module was tested in the plane of array (POA) individually for its I-V characteristics while electrically disconnecting it from the array. All the modules were facing south with a tilt angle of 17 degree.

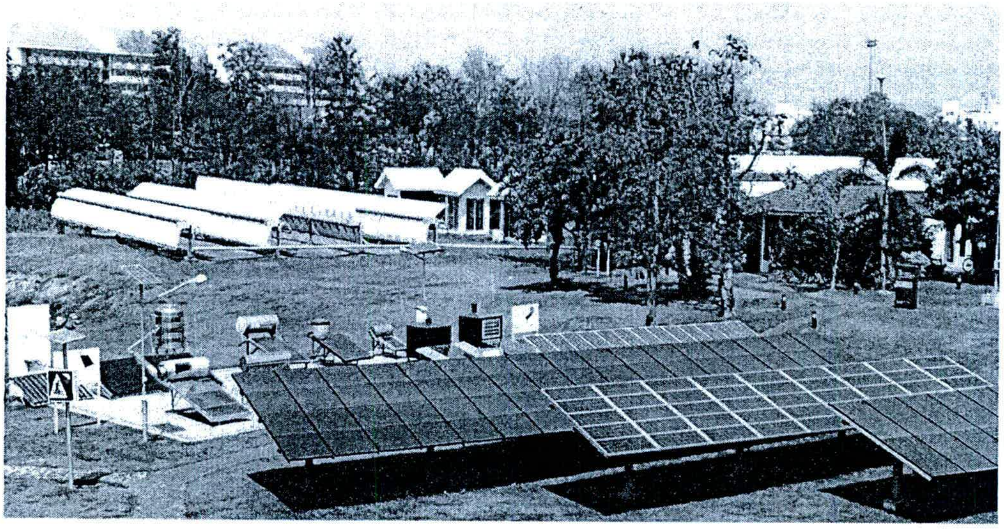


Figure 6 PV modules Lot I, II & III installations at SERT Energy Park NU Phitsanulok.

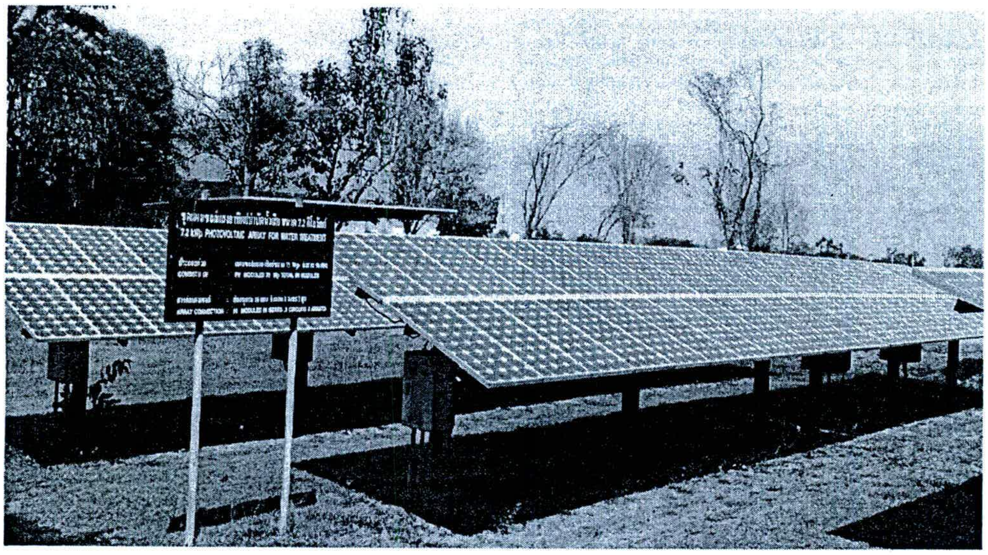


Figure 7 PV modules Lot IV installations at SERT Energy Park NU Phitsanulok.

A CM 11 pyranometer by Kipp & Zonen was used to measure solar irradiance and was placed in the plane of array during the measurement. The output of pyranometer was connected to an EKO MP140 I-V checker which was used to measure I-V curve. A *T-type* thermocouple provided with I-V checker was used to measure the module back surface temperature at the center of a cell close to module center. Moreover a similar thermo couple was used to measure the ambient temperature. A single line diagram of testing arrangements is shown in Figure 8.

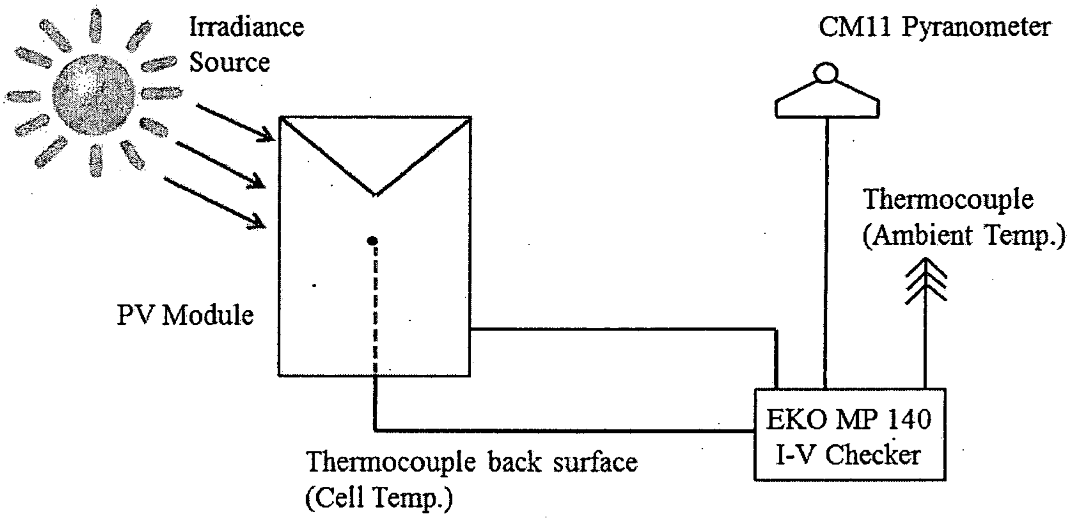


Figure 8 Single line diagram of I-V curve measurement system.

A set of three measurements were recorded for each module to ensure repeatability. All the readings were taken with in the two hours range from solar noon with all the irradiance levels above 800 W/m^2 on clear sky days. I-V curve measurement was done following the IEC Standard 60904-1[28] & 60891 [29].

I-V curve is a well-known parameter of performance measurement for photo voltaic devices. Important electrical characteristics can be derived from the I-V curve. I-V curve of a photovoltaic device is subject to change with cell temperature and intensity of solar irradiance. The typical plot of I-V curve is shown below [30].

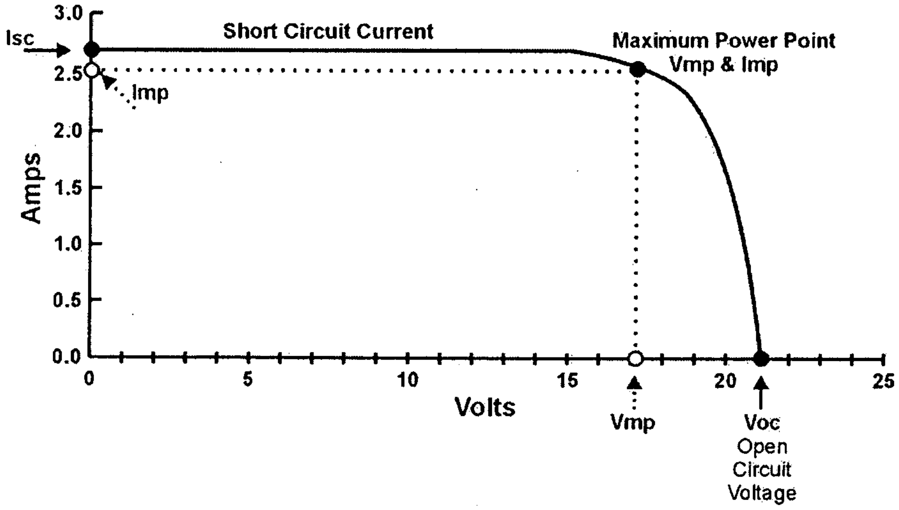


Figure 9 Typical I-V curve characteristics [30]

The current and voltage pairs are measured for PV module output, within a very short period of time with a fast variation of resistive load from Zero (short circuit) to Infinity (open circuit).

The important parameters of I-V curve are:

1. Short circuit current (I_{sc}): Output current of solar module or array with terminals short circuited with zero external resistance.

2. Open circuit voltage (V_{oc}): Voltage at the terminals of module or array with practically infinite resistance (no load).

3. Maximum power point (P_{max}): Maximum power attainable under specified operating conditions.

4. Maximum current (I_{mpp}): current corresponding to maximum power point.

5. Maximum voltage (V_{mpp}): Voltage corresponding to maximum power point.

There are some parameters which are indirectly connected to I-V curve like:

1. Fill Factor (FF): It is the ratio of the maximum power point to the product of the open circuit voltage and short circuit current, mathematically it can be represented by [31]:

$$FF = \frac{P_{max}}{I_{sc} \times V_{oc}} \tag{2}$$

2. Maximum Efficiency (η_m): It is defined as the ratio of maximum power output to the irradiance input. Mathematically;

$$\eta = \frac{P_{max}}{P_{in}} \tag{3}$$

P_{in} can be calculated by multiplying the Irradiance to the area of module. The irradiance has almost linear effect on I_{sc} of the PV device, but it has logarithmic relation with V_{oc} as shown in Figure10 below [32].

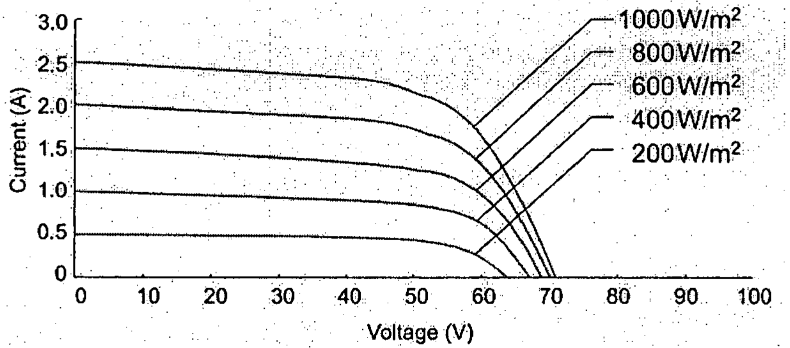


Figure 10 I-V curve characteristics at constant temperature and varying irradiances [32]

The module operating temperature has an important effect on the V_{oc}, with the increase in the temperature V_{oc} reduces considerably thus limiting the power output of device, however I_{sc} increases slightly with the rise of temperature as shown in Figure 11 below [32].

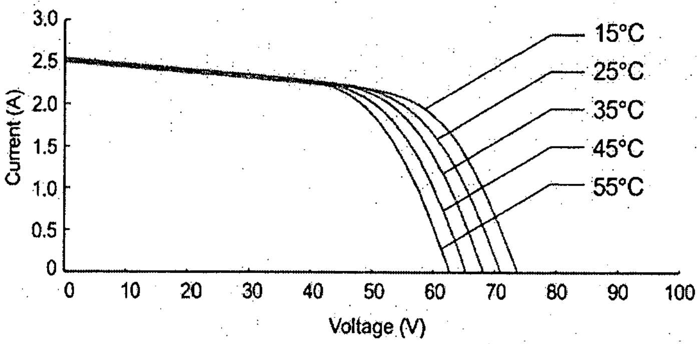


Figure 11 I-V curve characteristics at constant irradiance and varying temperatures [32]

The operating conditions for the PV generators always vary with time and location and hence the performance of PV devices, so it was very difficult for manufacturers to declare power output of modules on a common basis. Therefore it has been widely accepted that every module should be rated for output characteristics on standard test Conditions (STC) as defined in IEC Standard 60904-3 [33].

Correction of measured values to STC values

As the nameplate parameters of performance are being measured at Standard Test Conditions at manufacturer's facility, the present measured parameters under field conditions needs to be corrected to STC values for comparison. The Standard test conditions defined in IEC Standard 60904-3[33] are:

1. Solar Irradiance	1000 W/m^2
2. Cell/ Module temperature	25°C ±2°C
3. Air Mass	1.5

To correct the data measured under operating conditions to STC a comprehensive literature review has been accomplished. Literature review revealed that most of the translation equations were designed to use in the performance measuring models developed to predict the behavior of newly manufactured modules, under field conditions, thus imposing some critical measurements often impractical in the field. A limited number of researchers have been found with a primary emphasis of translation from real field conditions to STC. A summary of some important mathematical relations used by different researchers has been tabulated below:

Table 6 Different methods for correction of measured I-V curve data sets of PV modules to STC.

Group	References	Mathematical relations for Current & Voltage	Comments
A	[34]	$I_{stc} = \frac{G_{stc}}{G} I_{meas} - \mu_{I_{sc}} \left(T - T_{stc}\right)$ $V_{stc} = \frac{G_{stc}}{G} V_{meas} - \mu_{V_{oc}} \left(T - T_{stc}\right)$	It is the most basic and general form where only effect of temperature and irradiance has been accounted for in a simple way.
B	[35]	$I_{sc} = I_{sc,ref} \frac{G}{G_{ref}} + \mu_{I_{sc}} \left(T - T_{ref}\right)$ $V_{oc} = V_{oc,ref} + nT\, ln\left(\frac{G}{G_{ref}}\right) + \mu_{V_{oc}} \left(T - T_{ref}\right)$	These equations do not account for series resistance and thus cannot be used for correction of complete data sets of current and voltage. However they can be flawlessly used for I_{sc} and V_{oc} as resistance becomes irrelevant.
	[10]	$i_{sc,meas} = i_{sc,stc} \left[1 + h_f \left(T_c - T_{stc}\right)\right] \frac{G_{meas}}{G_{stc}}$ $v_{oc,meas} = v_{oc.stc} - n_s \mu_{v_{oc}} \left(T_c - T_{stc}\right) + \left(\frac{kT_c}{q}\right) ln\left(\frac{G_{meas}}{G_{stc}}\right)$	
	[36]	$I_{sc,norm} = I_{sc,meas} \frac{G_{norm}}{G} \left[1 + \alpha\left(T_{mod} - T_{norm}\right)\right]$	

Table 6 (Cont.)

Group	References	Mathematical relations for Current & Voltage	Comments
C	[37, 38, 39]	$I_{stc} = I_{meas}\left(\frac{G_{stc}}{G_{meas}}\right) + \alpha(T - T_{stc})$ $V_{stc} = V_{meas} - \beta(T_{stc} - T) - R_{s_{meas}}(I_{meas} - I_{stc}) + V_t\, ln\left(\frac{G_{stc}}{G_{meas}}\right)$	This set of equations account for temperature, irradiance and series resistance however irradiance term have very little effect on voltage especially at higher levels of irradiances.
D	[40]	$I_{stc} = I_{meas}\left(\frac{H_{stc}}{H_{meas}}\right)$ $V_{stc} = V_{meas} + \beta(T_j - T_{stc}) + V_t\, ln\left(\frac{H_{stc}}{H_{meas}}\right) - R_s(I_{meas} - I_{stc})$	Equations in [40] are similar with Group C except missing term for Δtemp. in current correction relation. Set in [41] is similar in current aspect but is quite different for voltage. The author verified results through measurement at STC and error was below 1%. The only drawback is calculation of R_{PV} which is very complex.
	[41]	$I_0 = I\left(\frac{E_0}{E_{eff}}\right)$ $V_0 = \frac{V}{1 + C_T(T_j - T_{j_0})} + V_t \frac{T_{j_0}}{T_j} ln\left(\frac{E_0}{E_{eff}}\right) - IR_{PV}\left(\frac{E_0}{E_{eff}} - 1\right)$	

Table 6 (Cont.)

Group	References	Mathematical relations for Current & Voltage	Comments
E	[29, 42, 11, 43, 44]	$I_2 = I_1 + I_{sc,meas}\left(\frac{G_{stc}}{G_{meas}} - 1\right) + \alpha(T_{stc} - T_{meas})$ $V_2 = V_1 + \beta(T_{stc} - T_{meas}) - R_s(I_2 - I_1) - KI_2(T_{stc} - T_{meas})$	The set of equations is described as procedure 1 in IEC 60891 standard. A majority of researchers have used this set of equations due to its reduced complexity and reasonable error margin.
F	[45, 46, 47]	$I_2 = I_1 + I_{sc,meas}\left(\frac{G_{stc}}{G_{meas}} - 1\right) + \alpha(T_{stc} - T_{meas})$ $V_2 = V_1 + \beta(T_{stc} - T_{meas}) - R_s(I_2 - I_1)$	It is the same set of equations described in Group E but curve correction term has been omitted due to its very low significance.

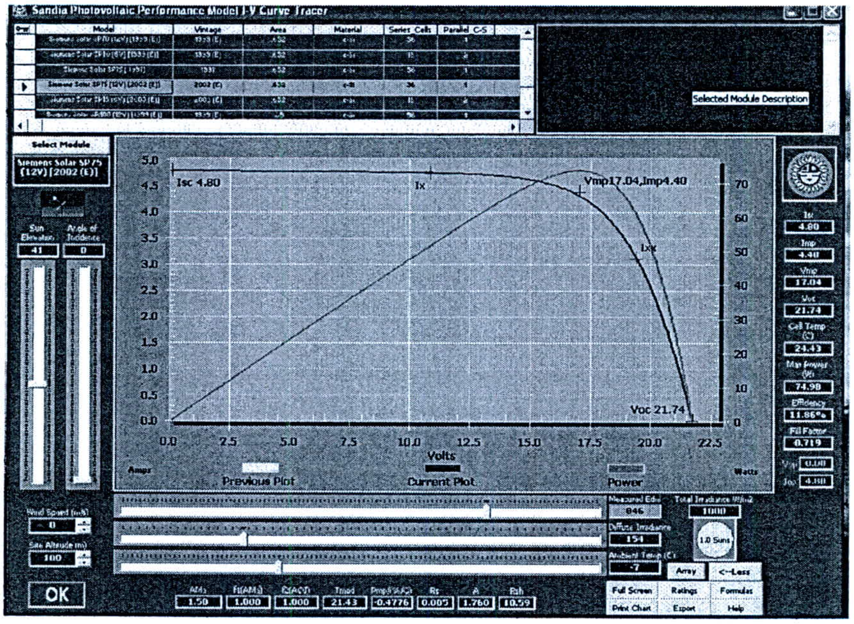
After due considerations field measured data (pairs of current and voltage) were corrected to STC values using the well-known technique inscribed in IEC 60891standard [29] and used by many researchers [11, 42, 43, 44, 45, 46, 47] with noted slight variations as in [45, 46, 47].

$$I_2 = I_1 + I_{sc,meas}\left(\frac{G_{stc}}{G_{meas}} - 1\right) + \alpha\left(T_{stc} - T_{meas}\right) \tag{4}$$

$$V_2 = V_1 + \beta\left(T_{stc} - T_{meas}\right) - R_s\left(I_2 - I_1\right) \tag{5}$$

Here I_2 and V_2 are corrected values of current and voltage respectively, while $I_{sc,meas}$ is the measured value of short circuit current, G_{stc} is the standard solar irradiance (1000 W/m^2), G_{meas} is the measured solar irradiance, T_{stc} and T_{meas} are standard temperature (25°C) and measured temperature respectively, I_1 and V_1 are measured values of current and voltage respectively, R_s is the series resistance of module and α & β are the temperature coefficients of current and voltage respectively.

In the IEC 60891 correction procedure 1, an additional term for curve correction factor "k" in connection with voltage is present, however in many studies it was ignored due to its low significance [45, 46, 47]. In this work we calculated the effect of the curve correction factor "k" using the typical value of "k" for crystalline silicon modules ($1.25\times10^{-3}\Omega/°C$ [42]) and found that it has very insignificant effect and can be ignored safely, as mentioned in [46]. Due to the limitations of field measurement and operational restrictions it was not possible to measure the series resistance so the value of series resistance was calculated using the well-known Sandia software [48] and verified through the relation $R_s = {}^{1}\!/_{40I_{sc}}$ given in [49], as it is the simple theoretical way to get authentication. The sample snapshot of Sandia software is shown in Figure 12 below. At higher irradiances as in this work, the difference between the corrected and measured currents becomes very low making the term for series resistance in equation (5) insignificant, however at lower irradiances it has significant influence. The temperature coefficients for current and voltage (α, β) were taken from the manufacturer's specification sheets for this study. Moreover variations relating to air mass at measurement time have been ignored as considered insignificant when compared to indoor simulators [50].



Sun Elevation: 41
Angle of Incidence: 0
Wind Speed (m/s): 0
Site Altitude (m): 100
Isc: 4.80
Imp: 4.40
Vmp: 17.04
Voc: 21.74
Cell Temp (C): 24.43
Max Power (W): 74.98
Efficiency: 11.86%
Fill Factor: 0.719
Measured Ed: 846
Total Irradiance W/m2: 1000
Diffuse Irradiance: 154
Ambient Temp (C): -7
AMa: 1.50
f1(AMa): 1.000
f2(AOI): 1.000
Tmod: 21.43
Rs: 0.005
A: 1.760
Rsh: 10.59

Figure 12 Sample Snapshot of series resistance (R_s) calculation through Sandia software [48].

After data correction the maximum power output (P_{max}), short circuit current (I_{sc}), open circuit voltage (V_{oc}), efficiency and fill factor (FF) were compared with the nameplate values and findings have been discussed in detail in chapter 4.

Calculation of Degradation

The percentage degradation in power output of module, over the period of operation in the field was calculated using the formula;

$$\%Degradation = \frac{P_{nameplate} - P_{measured}}{P_{nameplate}} \times 100 \tag{6}$$

Annual degradation rate in the power output of PV modules was calculated as follows;

$$Degradation\ rate\ per\ annum = \frac{\%Degradation}{No.\ of\ years\ in\ operation} \tag{7}$$

CHAPTER IV

RESULTS AND DISCUSSION

Impact of long term weathering on basic electrical parameters

The corrected values of P_{max}, I_{mp}, V_{mp}, I_{sc}, V_{oc} and calculated FF are shown in the table 7 below in comparison with nameplate values. Moreover the %degradation or escalation in each parameter is also indicated for all the 4 lots of modules under study.

Table 7 Module performance data and %change with respect to name plate

Description of lot	**Year - %diff.**	**P_{max} (W)**	**Standard Deviation of P_{max}**	**I_{sc} (A)**	**V_{oc} (V)**	**I_{mp} (A)**	**V_{mp} (V)**	**FF**
(Lot I), mono c-Si, 26 modules.	2003	75 (-7%)		4.75	21.4	4.45	17	0.74
	2013*	46.91	4.27	4.49	18.67	3.61	12.97	0.56
	%difference	-37.45		-5.47	-12.75	-18.87	-23.70	-24.32
	Annual %decrease/ Increase	-3.40		-0.49	-1.16	-1.71	-2.15	-2.21
(Lot II), poly c-Si, 45 modules.	2005	80 (-5%)		5.31	21.3	4.67	17.1	0.71
	2013*	62.11	2.95	4.91	18.83	4.34	14.32	0.67
	%difference	-22.36		-7.52	-11.59	-7.13	-16.26	-4.83
	Annual %decrease/ Increase	-2.49		-0.84	-1.29	-0.79	-1.81	-0.54
(Lot III), Thin film a-Si, 68 modules	2005	54 (**)		1.14	85	0.87	62	0.56
	2013*	55.84	1.35	1.25	72.75	1.02	54.72	0.61
	***%diff.	+3.41		+9.71	-14.41	+17.36	-11.74	+10.27
	***Annual %decrease/ Increase	+0.38		+1.08	-1.60	+1.93	-1.30	+1.14
(Lot IV), mono c-Si, 96 modules	2000	75 (-7%)		4.8	21.7	4.4	17	0.72
	2013*	31.15	5.66	4.02	18.43	2.81	11.05	0.42
	%difference	-58.47		-16.23	-15.09	-36.21	-35.01	-41.67
	Annual %decrease/ Increase	-4.18		-1.16	-1.08	-2.59	-2.50	-2.98

* Values are averaged from tested samples. **Not mentioned in data sheet.***Possible reasons have been given in the chapter ahead.

Except a-Si lot all others have shown significant degradation in each performance parameter. Thin film a-Si modules have interestingly shown good performance under hot and humid climate of Phitsanulok after 9 years of operation when compared with the poly c-Si modules during the same tenure. The comparison of corrected and nameplate parameters is given in table 7 above.

The highest degradation with respect to nominal values was recorded in the P_{max} followed by the FF. Lot IV & I showed very high %age of degradation in P_{max} (58%, 37%) and FF (42%, 24%) respectively. I_{sc} degradation was almost half of the V_{oc} degradation for both Lot I & Lot II, however degradation in I_{sc} was nearly same with V_{oc} for Lot IV. Lot III as mentioned earlier showed some increase in every parameter except voltage when compared with nominal values. The reasons behind Lot III results will be discussed later in this chapter.

Mono crystalline silicon lots (I & IV) have shown significant reduction in V_{oc} and FF, though I_{sc} also decreased as shown. Short circuit current reduction can be attributed to discoloring of EVA which blocks the irradiance to some extent and the increase in series resistance. However apparently no clear signs of series resistance increment could be found, as the connecting buses joints and terminal boxes were not found rusted or broken, though this observation is even not enough evidence for disregarding of increment possibility in series resistance. The reduction in V_{oc} can be due to drop in shunt resistance to a reasonably low value, which allows a lot of leakage hence reducing the output power on load side. Reduced shunt resistance also have a very prominent effect on FF reduction. Lot II modules have shown almost similar fashion of reduction in I_{sc} & V_{oc} but FF reduction is quite lower.

Lot III has interesting results overall power has been increased due to an increase in I_{sc} but V_{oc} reduced in a similar fashion as of other Lots. The reduction in V_{oc} indicates towards the reduced shunt resistance, showing some leakages of current through cell structure itself. However increased I_{sc} raises serious questions which we will discussed at a later stage in this chapter.

The samples tested from each group of crystalline modules have produced unpleasant results if placed alongside the warranty milestones. Unfortunately none of the samples tested could pass the winning line of warrantees for period mentioned. The corrected (to STC) results of P_{max} have been presented in the fig. 13-16, for all the samples tested, from each lot of modules.

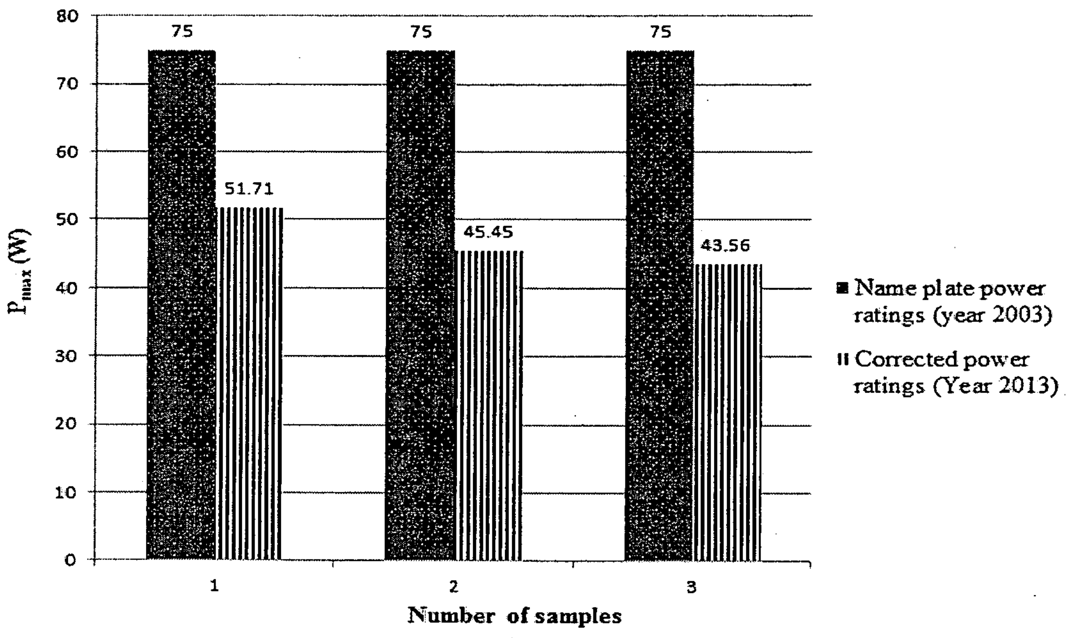


Figure 13 Corrected P_{max} vs Nominal P_{max} along with the period under operation for samples selected from Lot I.

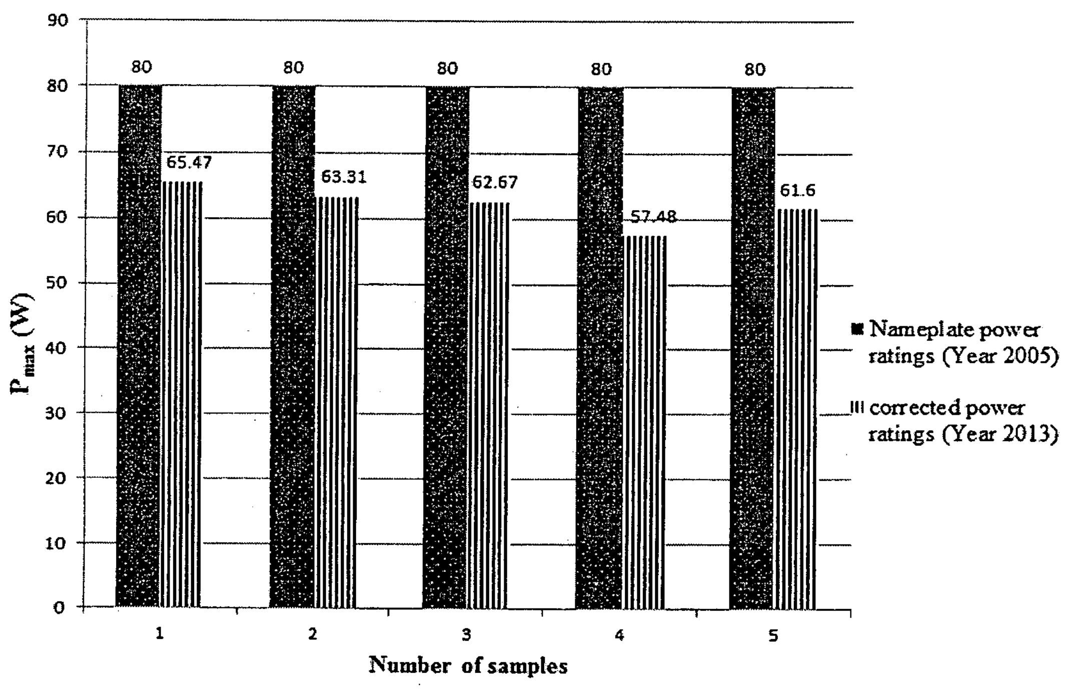


Figure 14 Corrected P_{max} vs Nominal P_{max} along with the period under operation for samples selected from Lot II.

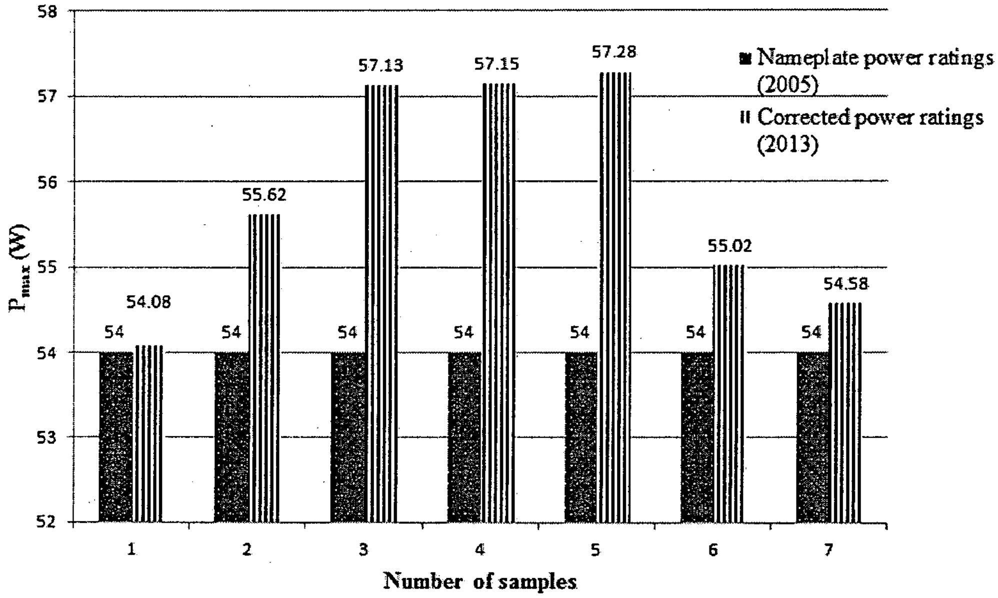


Figure 15 Corrected P_{max} vs Nominal P_{max} along with the period under operation for samples selected from Lot III.

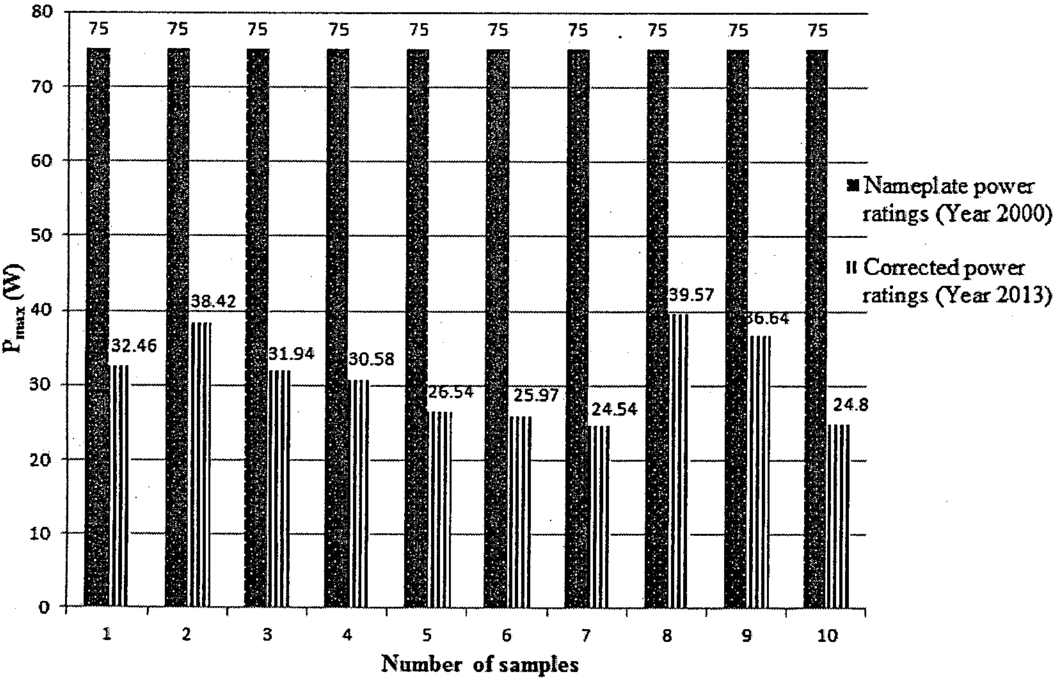


Figure 16 Corrected P_{max} vs Nominal P_{max} along with the period under operation for samples selected from Lot IV.

The measured I-V curves for all the samples were corrected to STC and results for the modules with minimum and maximum values of P_{max} in each lot are shown against the nameplate data based curve in the fig. 17-20 as follows. As the analysis of the reasons behind the modules' power reduction is beyond the scope of this study so it was considered unnecessary to reproduce all the I-V curves recorded. The three dots in each nameplate curve represent the nameplate parameters. The reduction in basic electrical parameters can be noted clearly from the curves for lot I, II & IV.

From the one diode model of PV cell we know that current of a PV cell faces resistance on its way which is named as series resistance, while voltage is related to a parallel path which provides an alternate way for leakage current, hence dropping the voltage. This is termed as shunt resistance of a PV cell. A higher value of shunt resistance ensures the proper voltage and very low value of series resistance facilitates the current. The manufacturing process of PV modules defines the shunt resistance mainly. Manufacturers try to make sure the reasonable value of shunt resistance at factory stage. The poor quality control can be a possible reason of larger drops in shunt resistance value which allows leakage currents through cells and energy loss as stray currents and heat.

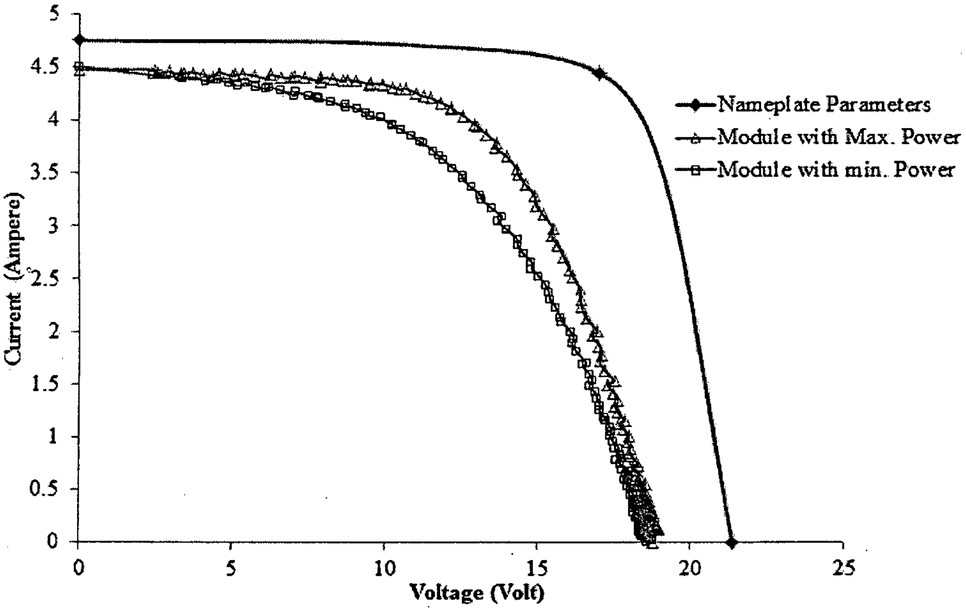


Figure 17 Corrected I-V curves for selected modules from Lot I samples

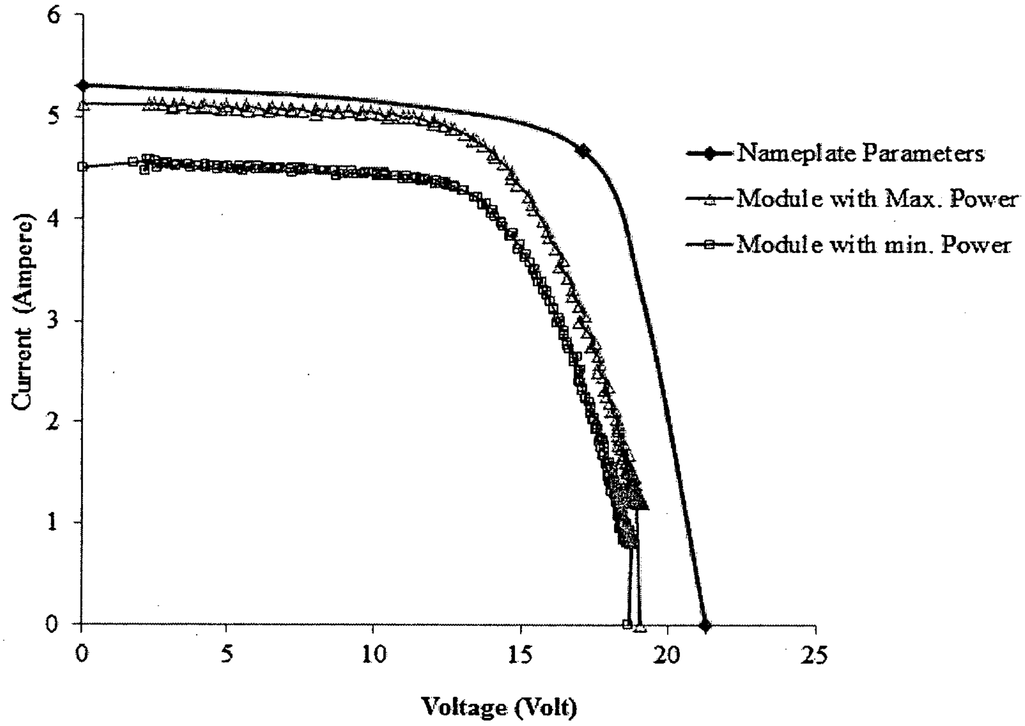


Figure 18 Corrected I-V curves for selected modules from Lot II samples

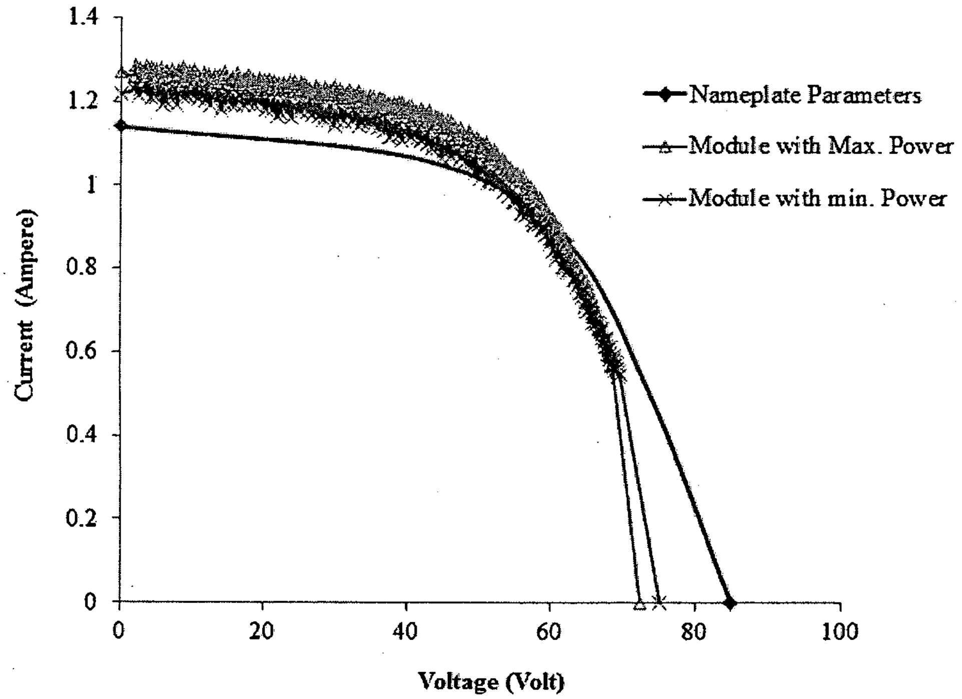


Figure 19 Corrected I-V curves for selected modules from Lot III samples

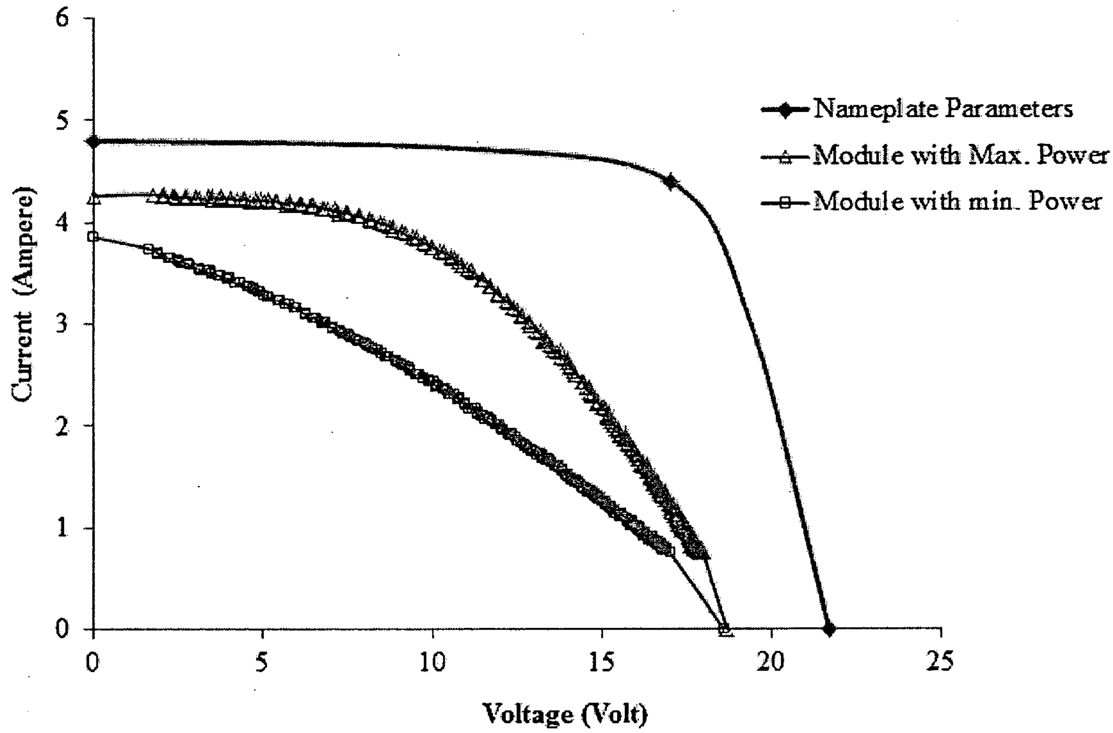


Figure 20 Corrected I-V curves for selected modules from Lot IV samples.

The representative curves from the samples reveal some interesting facts. All the curves show reduction in V_{oc} after long term use, when compared with nameplate data based curve. Drop in V_{oc} is a sign of reduction in shunt resistance of the cells. As the shunt resistance decreases voltage drops and also provides a parallel path for current. As irradiance is almost directly proportional to the current in a PV cell so the reduction in I_{sc} can be linked with the discoloring of PV cell surface. However series resistance increment also can be a reason for drop in I_{sc}. The I-V curve pattern seems similar in Lot I & II, but it is quite different in Lot III & IV. In Lot IV the curve has a trend to turn into a simple slope which results in a severe reduction of FF even though the values of short circuit current and open circuit voltage remain high. The reduction in shunt resistance or in other words increment in leakage current produces such results. The severe reduction in shunt resistance will ultimately result into a dead module, because all the current generated will be passed through leakage paths and there will be no current on load terminals.

Lot III has the most interesting results showing an increase in I_{sc} which is only possible during the stabilization stage of modules. During the field exposure theoretically there is no possibility of increment. More over there is no such evidence from literature regarding the increment in I_{sc}. We tried to find out the possible reasons and will be discussed later in this chapter.

Performance in terms of Efficiency

The efficiency of modules has been calculated using nameplate maximum power and present maximum power as well. The results are presented in Table 8 below.

Table 8 Comparasion between nominal and present Efficiency for 4 lots of modules

Description of lot	Operational duration (Years)	Nominal P_{max} (W)	Corrected P_{max} (W)	Nominal Efficiency (%)	Present Efficiency (%)	Efficiency decrease/Increase (%)
(Lot I), mono c-Si	10	75	46.9	11.9	7.5	-37.5
(Lot II), poly c-Si	9	80	62.1	12.6	9.8	-22.4
(Lot III), a-Si	9	54	55.8	6.4	6.6	+3.4
(Lot IV), mono c-Si	13	75	31.1	11.9	4.9	-58.5

*Values of P_{max} have been averaged from samples and gross area of modules has been used.

The efficiency for Lot I, II & IV decreased in the similar way as P_{max} decreased. However Lot III efficiency increased slightly. The reasons for apparent increment will be discussed in following section.

Results and Guarantee conditions

The manufacturers normally provide a warrantee for 90% P_{max} after 10 years and 80% P_{max} after 25 years of use [6, 51-53] which means a 10% & 20% degradation, will be considered normal after passing the time period mentioned against them. A new practice has been seen in recent years regarding the declaration of maximum power of a module. A term *minimum P_{max}* has been introduced in the nameplate in connection with the guarantee [6, 52]. In our study the difference between P_{max} and *minimum P_{max}* comes out to be nearly 7% for Lot I & IV and 5% for Lot II however Lot III module's nameplate and datasheet does not contain any such term. Some manufactures however mention 5% variation possibility in the P_{max} [6]. We chose to stay on the higher side of tolerance (i.e.7%) for this particular study and the degradation rates have been calculated using the 7% reduced P_{max} for the purpose of guarantee evaluations.. In addition a 3% measurement tolerance should also be considered for our measured and corrected parameters [11, 51]. Summary has been shown in table 9.

Table 9 Summary of P_{max} and annual variation rates

Description of lot	Nominal P_{max} (W)	Minimum P_{max} (W)	Corrected P_{max} (W)	*Difference (%)	Annual decrease/Increase (%)
(Lot I), mono c-Si, 26 modules, Warrantied for Power >80% after 20 years.	75	70	46.9	-33	-3
(Lot II), poly c-Si, 45 modules, Warrantied for Power >80% after 25 years.	80	76	62.1	-18.2	-2.0
(Lot III), a-Si, 68 modules, Warrantied for Power >80% after 25 years.	54	50***	55.8	+11.6	+1.3**
(Lot IV), mono c-Si, 96 modules, Warrantied for Power >80% after 25 years.	75	70	31.1	-55.5	-3.9

*Difference have been calculated using min P_{max}. **Explanation has been given in paragraph below. ***Not mentioned in data sheet taken 7% as of Lot I, IV.

Deviation trend lines have been plotted against the warrantee line for each of the four lots of modules as shown in fig. 21 below. The modules belonging to Lot I, II & IV could not conform to the guarantees due to excessive degradation. However modules from Lot III performed well above guarantee line, if compared with nameplate data showed higher value of P_{max} (dotted line) even after 9 years of field operation. As there is no evidence from the literature about the increment in the power during long term operation in any technology, so we tried to look into the history of this lot for details. Unfortunately there was no data available for individual modules, but some array data was available for the month of August 2005, nearly 3-4 months after its installation. The analysis of data showed that the output power of the array in August 2005 was higher than nominal when corrected to STC. It seems that lot III modules were stabilized in their initial months of operation at a value quite higher than nominal (115-120%). There must be some degradation after 9 years from the stabilized value but it is not possible to determine the exact value at which modules were stabilized due to unavailability of module-level measurements in that period.

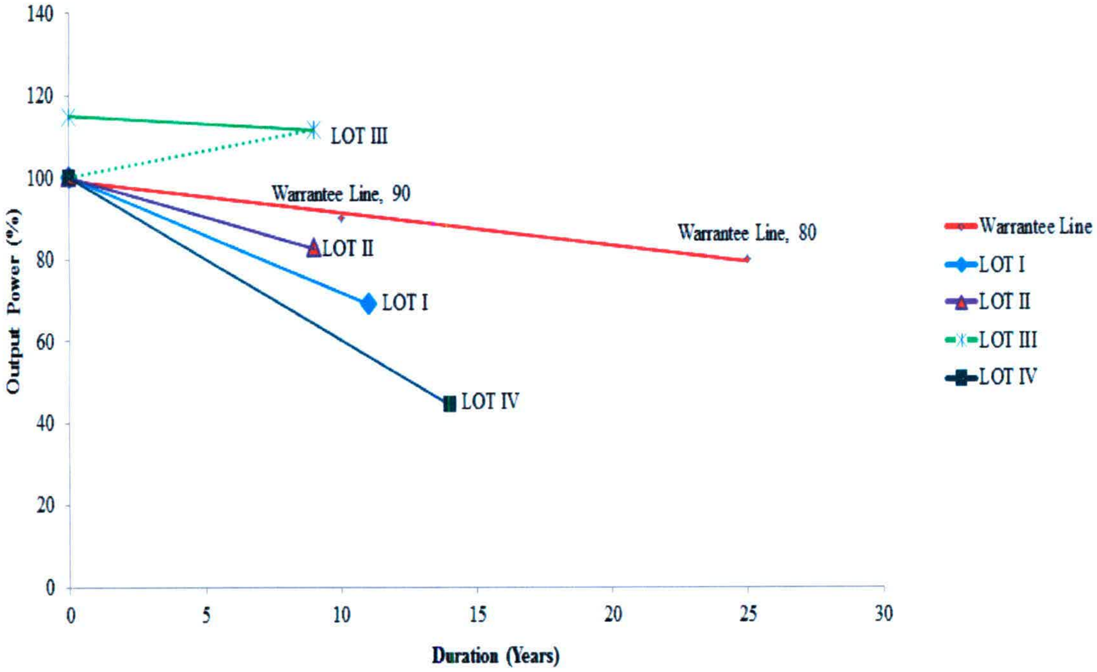


Figure 21 Comparison showing actual variations against warrantee for LOT I, II, III & IV modules.

In view of the above it is very clear that nameplate data for PV modules is subjected to various conditions and cannot be treated like any other types of generators or electrical equipment. PV modules performance depend upon a number of factors including materials, manufacturing processes, quality control, packaging, transportation, installation, and operational conditions & stresses. The actual performance of individual modules can be known only through regular periodic testing in connection with warrantees. Moreover it has been proved that mere dependence on nameplate data or warrantee certificates could lead to a false calculation and hence distrust and unpopularity of technology. Regular testing schedules will not only exhibit a true picture for user/investor but will perpetrate a pressure on manufacturers & other stake holders in the chain.

Comparison with past researches

Taking into account the initial stabilization and degradation of PV modules only a degradation rate of 0.7- 0.8% per year in output power can satisfy the guarantees. A reasonable number of studies showed the degradation rates of the order of 0.4-1% per year which can safely satisfy the guarantees provided by the manufacturers [53-56]. However there are many which do not fall in the acceptable range [13, 50, 57]. The results for three lots of crystalline silicon (mono, poly & mono) showed comparatively higher order yearly degradation rates. The average yearly degradation for Lot I, II and IV was 3, 2 and 3.9 % respectively even after considering a 7% reduction tolerance in the nominal P_{max}.

Degradation modes

Though the degradation mode analysis is beyond the scope of this study, however all the samples under test were carefully inspected visually for presence of any apparent faults. The modules are being installed well above the ground and surrounding is well kept. There were no signs of bubbles, cracks, delamination or hotspots. Additionally no rusting was found in the connection boxes. The only visible defect found was discoloring and yellowing mostly at cell centers in most of samples belonging to the three lots of crystalline modules, however a-Si lot modules were found homogeneous in color and no yellowing or discoloring was noticed.

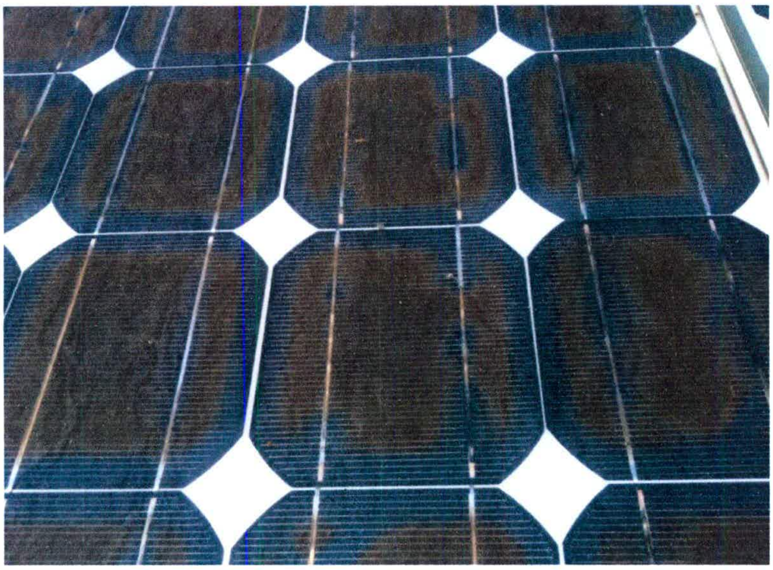


Figure 22 Discoloring at the center of each cell in almost all of the modules belonging to Lot I.

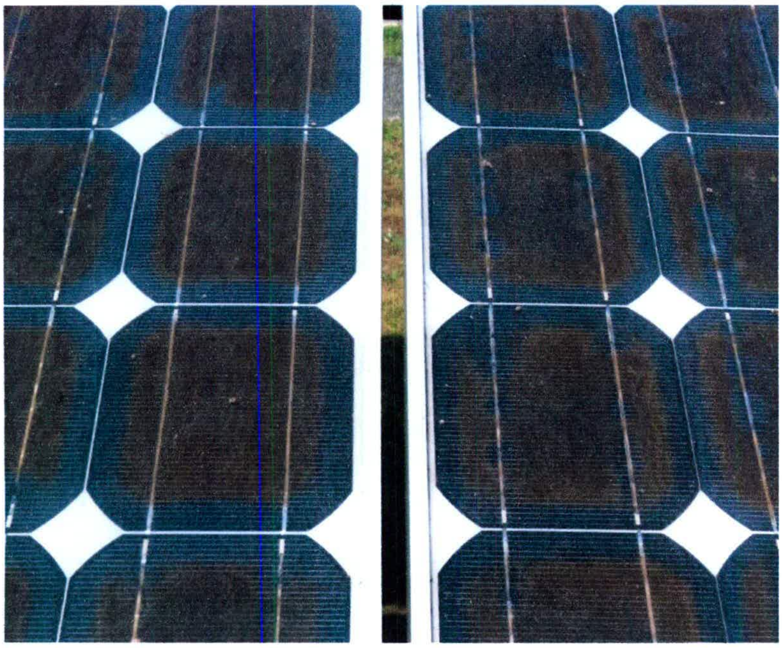


Figure 23 Discoloring pattern for Lot I modules, partial development is visible on right side module.

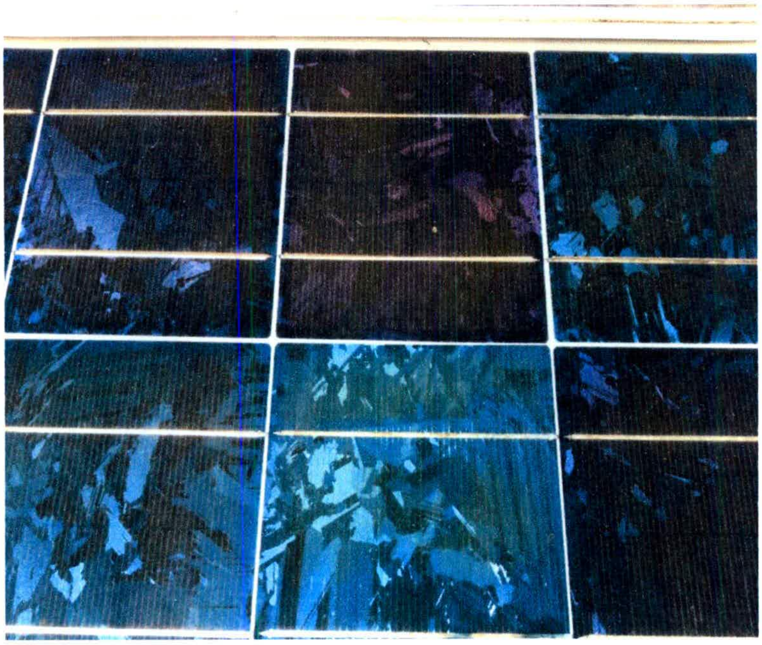


Figure 24 Discoloring pattern for Lot II modules, cell at center bottom is in original condition while others are darker.

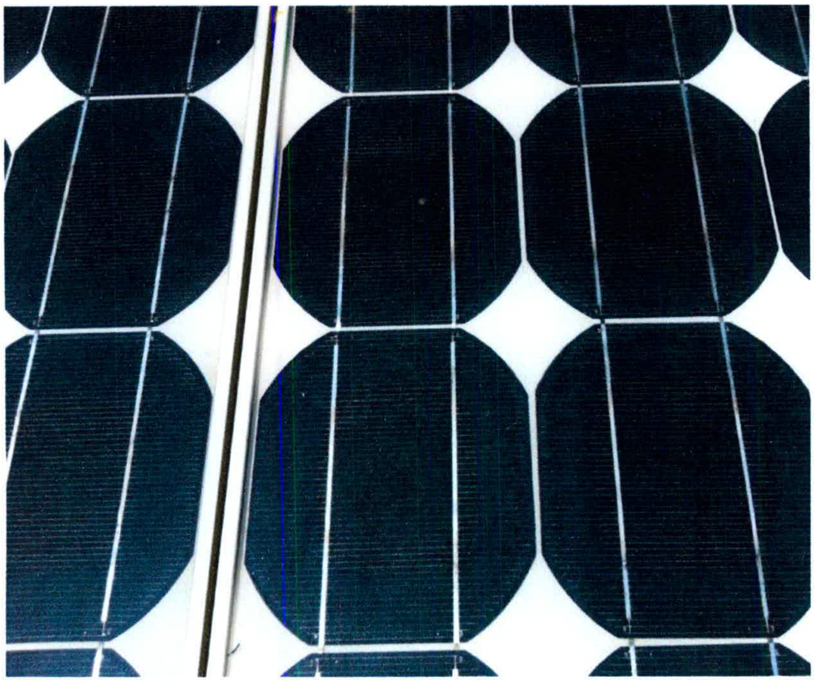


Figure 25 Discoloring pattern for Lot IV modules, cell central area has color change.

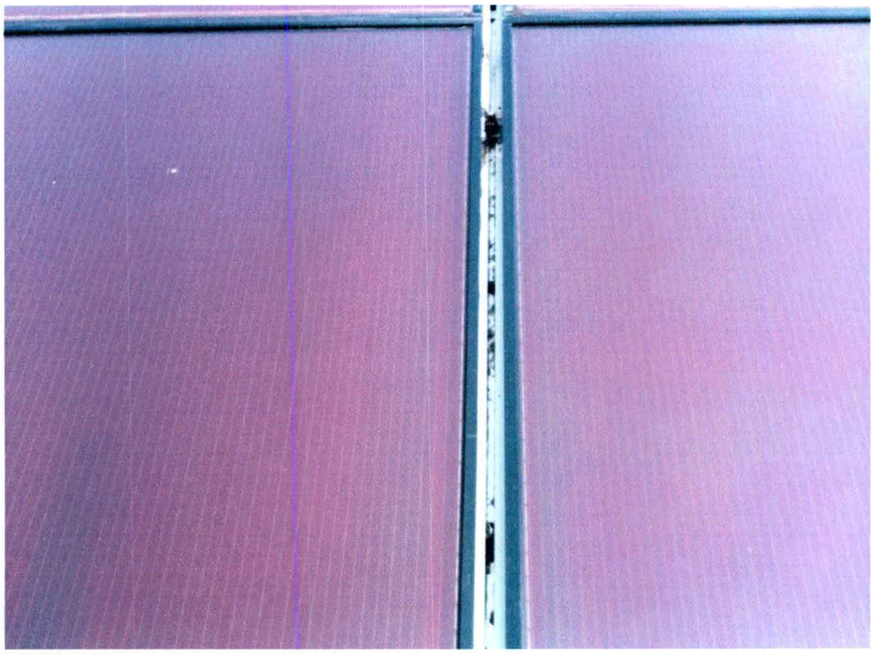


Figure 26 Lot III modules, no noticeable discoloring found.

It can be seen in fig. 22, 23 & 25 clearly that the discoloring occurred at the cell center and borders are still normal, which indicates that no moisture entered through the edges and sides of the modules. The EVA discoloring obstructs the incident irradiance and thus decreasing the photo current and hence power output.

In Lot II poly crystalline modules the discoloring can be seen for a whole cell in a uniform pattern. It should be noticed that some cells are just normal and showed no color change. The discoloring in Lot II and IV seems less severe if compared with Lot I modules, but there is no direct correlation between intensity of discoloring and power output as Lot IV modules have low intensity discoloring but high degradation in power if compared with Lot I modules. It should be considered that both Lots are mono crystalline silicon with a difference of 2 years in operational duration. Lot III modules were found in homogeneous condition if considered in terms of color and no signs of discoloring were found. The decrease in short circuit current can partially be attributed to discoloring as it obstruct the irradiance, however increase in series resistance can also be a factor.