APPENDIXES

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Determination of PV Module Power Output Degradation after Long Term Operation

Tariq Aziz, Nipon Ketjoy and Chatchai Sirisamphanwong

***Abstract*-- This work has been undertaken to examine the warranties offered by the PV module manufacturers for degradation after long term field operation under Thailand weather conditions. Samples from the four lots of PV modules comprising on mono crystalline, poly crystalline and amorphous silicon, with different duration of field operation ranging from 9 to 14 years were tested for I-V curve characteristics under field conditions and measured values were corrected to Standard Test Conditions (STC) values by using correction procedure inscribed in IEC 60891 standard. The corrected values of output power and other parameters were compared with nameplate data for calculation of degradation during the period of operation. The actual degradation in output power for two lots of mono and one lot of poly crystalline silicon was found remarkably high (3.9, 3.0 & 2%/year) when compared with the warrantees (0.8-1%/year generally). However, interestingly the lot comprising on thin film amorphous-Si modules showed higher values of output power than nameplate. There were no visible defects in the modules except yellowing and discoloring. The enhanced degradation rates can be attributed to the quality of modules along with the effects of harsh field weather conditions.**

***Index Terms*—Degradation, PV Module, Power output**

I. Introduction

RENEWABLE Energy (RE) technologies are getting attractions day by day because of their environment friendly nature and inexhaustibility. As the RE means are going to replace the conventional energy sources gradually, the reliability of RE technology is becoming an important subject in this scenario. All the future power planning and economic evaluations depend upon the consistency in performance of RE Technology over the extended periods of time. The investors and users are reluctant to proceed because of the uncertainty about the real performance of RE components when they are exposed to the operating conditions for long time.

In the case of PV modules though the performance guarantees provided by the manufacturers are very encouraging, but needs to be authenticated under the operational conditions in the different climatic conditions in various parts of the world, as it is a proven fact that PV modules Performance graph is not linear when operating environment goes under change [1],[2]. Now a day the average life of PV module is being guaranteed up to 25 years, whereas in the past its range was between 15 to 20 years. Taking into consideration the output power degradation, manufacturers are generally providing guarantees in the following fashion. A 10% decrease in the nominal power after 10-12 years of use and a 20 % decrease in the nominal output power after 25 years of operation in the field [3].

The verification work is drawing attention of researchers from all over the world. Although studies have been conducted in some areas of the world and results generally conforms to the guarantees provided by the manufacturers, but there are still a large number of climatic zones with diverse conditions in which this work needs to be done [3]. Another important aspect of this research is that there are continuous technological developments/improvements in the PV modules manufacturing, so the results of previous studies soon become obsolete [1]. Moreover the quality control of manufacturing process is not similar among all facilities so the studies play an important role for feedback. The performance guarantees mainly represented by output power needs to be authenticated after long term field operations to ensure their reliability and performance guarantees. The need for this research becomes more significant when it connects with the prevailing & prospect trends of PV Grid connected large scale Power Plants. It is very important to ensure the performance related parameters such as output power warranties. The bases for economic evaluations of PV projects must be doubt free for sustainable development of the new emerging clean energy sector.

This study was focused on the measurement of output power of selected samples from 4 lots of PV modules, among them 1 was poly crystalline (45 modules), 2 were mono crystalline (26 + 96 modules) and last was amorphous silicon (68 modules) which were exposed to hot and humid field conditions for a period ranging from 9 to 14 years in Phitsanulok Thailand (latitude16.8158° N, Longitude 100.2636° E & 45 m a.s.l). The results after correction to Standard Test Conditions (STC) were used to calculate degradation rate and were compared with the nameplate values to evaluate guarantee conditions and with previous studies as well.

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A. Tariq is MS student at School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok 65000, Thailand (e-mail: tariqaziz26@yahoo.com).
K. Nipon is Assistant Professor at School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok 65000, Thailand (e-mail: niponk@nu.ac.th).
S. Chatchai is Lecturer at School of Renewable Energy Technology (SERT), Naresuan University, Phitsanulok 65000, Thailand (e-mail: chatchais@nu.ac.th).

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II. 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 different lots of modules installed at Energy Park SERT Naresuan University, Phitsanulok. The study undertaken involved the following steps.

A. Sample Selection

Keeping in view the operational problems it was decided to test the selected samples (10% of population) from each of the four lots of PV modules, though the statistical procedure require testing of nearly whole population for such smaller populations [4]. A random number table was used to select the samples from the population [5].The detail for each lot is shown in the table I.

TABLE I
NUMBER OF MODULES IN EACH LOT & SAMPLES SELECTED

Lot number	Number of modules	Number of samples
1	26	3
2	45	5
3	68	7
4	96	10

B. Visual Inspection & Collection of nameplate data

All the selected samples 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 for all the 4 lots under study was collected before testing. Moreover the specifications sheets provided by the manufacturers of these nodules were reviewed in detail.

C. Testing 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. 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 fig. 1.

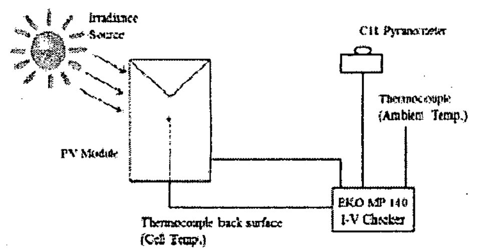

Fig. 1. Single line diagram of I-V curve measurement system

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[6] & 60891 [7].

D. Correction of data sets to STC

It is a globally agreed practice now that module's nameplate ratings base on Standard Test Conditions. To estimate any possible changes in the module ratings after long term use, the common base of conditions (i.e. STC) will be necessary. The Standard Test Conditions are given below [8]:

Solar Irradiance	1000 W/m^2
Module Temperature	25°C±2°C
Air Mass	1.5

The field measured data (pairs of current and voltage) were corrected to STC values using the well-known technique inscribed in IEC 60891standard [7] and used by many researchers [9]-[14] with noted slight variations as in [9], [14] & [15].

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

$$V_2 = V_1 + \beta(T_{stc} - T_{meas}) - R_s(I_2 - I_1) \quad (2)$$

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 [9], [14]. This study will follow the same as in [14]. The value of series resistance was calculated using the well-known Sandia software [16] and verified through the relation $R_s \cong 1/40 I_{sc}$ given in [17]. 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 (2) 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. Variations relating to air mass at measurement time have been ignored as considered insignificant when compared to indoor simulators [18].

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

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The fill factor was calculated using the following relation [19].

$$FF = \frac{P_{max}}{I_{sc} \times V_{oc}} \quad (3)$$

III. RESULTS AND DISCUSSION

A. 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 II 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. Except a-Si lot all others have shown significant degradation in each performance parameter. Thin film a-Si modules have interestingly shown excellent 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 highest degradation with respect to nominal values was recorded in the P_{max} followed by the FF. Lot IV and 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 and 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. The comparison of corrected and nameplate parameters is given in table II.

TABLE II
MODULE PERFORMANCE DATA AND %CHANGE WITH RESPECT TO NAMEPLATE

Description of lot	Year - %diff.	P_{max} (W)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF
(Lot I), mono c-Si, 26 modules.	2003	75	4.75	21.4	4.45	17	0.74
	2013*	46.91	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	5.31	21.3	4.67	17.1	0.71
	2013*	62.11	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	1.25	72.75	1.02	54.72	0.61
	%difference	+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, 56 modules	2000	75	4.8	21.7	4.4	17	0.72
	2013*	31.15	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

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. 2-5 as follows. 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.

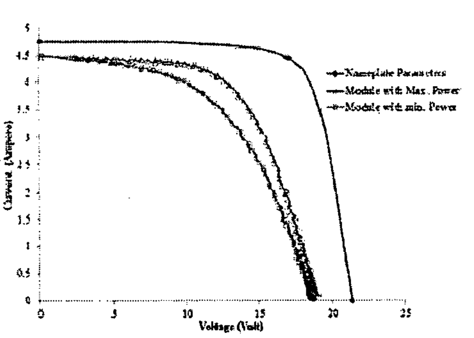

Fig. 2. Corrected I-V curves for selected modules from Lot I samples

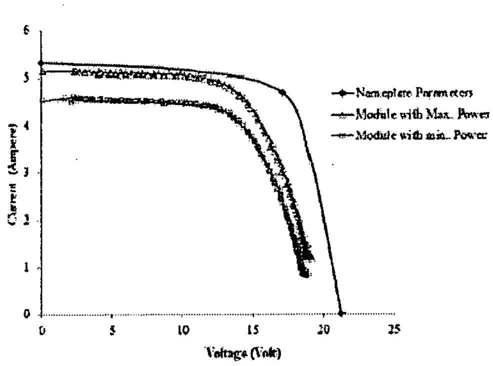

Fig. 3. Corrected I-V curves for selected modules from Lot II samples

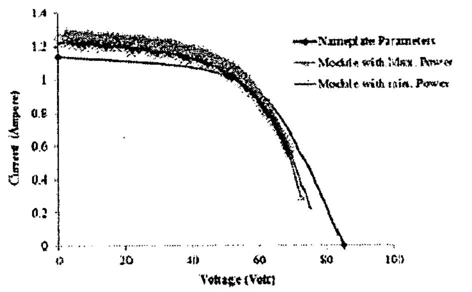

Fig. 4. Corrected I-V curves for selected modules from Lot III samples

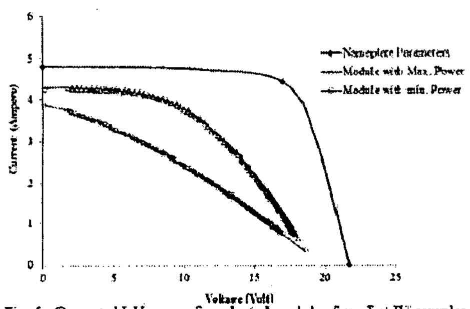

Fig. 5. Corrected I-V curves for selected modules from Lot IV samples

B. 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 [3],[20]&[21] 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 [3], [21]. 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} [3]. 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], [20]. Summary has been shown in table III.

TABLE III
SUMMARY OF P_{MAX} AND ANNUAL VARIATION RATES

Description of lot	Nominal P_{max} (W)	7% reduced P_{max} or min. 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}

Deviation trend lines have been plotted against the warrantee line for each of the four lots of modules as shown in fig. 6 below. The modules belonging to Lot I, II & IV could not conform to the guarantees due to excessive degradation. Though the measured results shown for above mentioned lots are averaged from samples but even not a single module among the samples performed within the guarantee limits.

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.

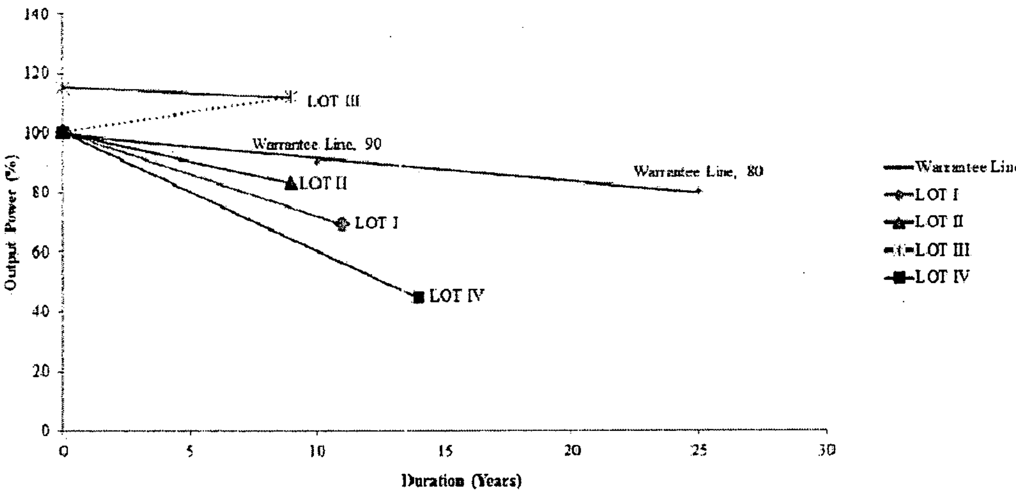

Fig. 6. Comparison showing actual variations against warrantee for LOT I, II, III & IV modules

C. In connection 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 [22]-[25]. However there are many which does not fall in the acceptable range [18], [26] & [27]. 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}.

D. About 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 in most of samples belonging to the three lots of crystalline modules.

IV. CONCLUSION & RECOMMENDATIONS

The crystalline modules degraded sharply violating the warrantee boundaries, however a-Si modules showed excellent performance over the period of operation. The modules were installed in a safe environment and were under continuous monitoring, even though the results were poor showing that only proper care and maintenance cannot make the performance better. The substandard performance can be chiefly attributed to the quality of modules and partly to the hot and humid operating conditions. The detailed study of reasons behind such higher order degradation in the modules can reveal important facts, which can help making the PV installations reliable and stable. Moreover the quality of material and processing needs to be ensured at manufacturing facilities to achieve reliability during operation. The qualification standards may be improved for varying climatic conditions as well.

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VI. REFERENCES

[1] T. Huld, R. Gottschalg, H.G. Beyer, M. Topič, "Mapping the performance of PV modules, effects of module type and data averaging," *Solar Energy*, vol. 84, pp. 324-338, 2010.

[2] K.H. Lam, J. Close, W. Durisch, "Modelling and degradation study on a copper indium diselenide module," *Solar Energy*, vol. 77, pp. 121-127, 2004.

[3] M. Vázquez and I. Rey-Stolle, "Photovoltaic module reliability model based on field degradation studies," *Progress in Photovoltaics: Research and Applications*, vol. 16, pp. 419-433, 2008.

[4] R. V. Krejcie, and D. W. Morgan, "Determining sample size for research activities," *Educational and Psychological Measurement*, vol. 30, pp. 607-610, 1970.

[5] Random Digits, (accessed on November 11, 2013), [Online]. Available: http://www.rand.org/publications/classics/randomdigits.

[6] Photovoltaic Devices – Part 1: Measurement of photovoltaic current-voltage characteristics, IEC-60904-1: Edition 2.0, 2006-09.

[7] Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics, IEC 60891: Edition 2.0, 2009-12.

[8] Photovoltaic Devices – Measurement principles for terrestrial photovoltaic solar devices with reference spectral irradiance data, IEC-60904-3: Edition 2.0, 2008

[9] C. Leboeuf and H. A. Ossenbrink, "PV module power output: sensitivity and uncertainty in non-STC measurements," in *Photovoltaic Specialists Conference, 1991., Conference Record of the Twenty Second IEEE*, 1991, pp. 614-619 vol.1.

[10] M. Kumaravel, C.R. Jeevandoss, G. Amutha and S. Veeraraghavan, "Performance Evaluation of Solar Photo Voltaic Modules Under Field Conditions Through a Quick Diagnostic Tool," in *Proceedings of ISES World Congress 2007 (Vol. I – Vol. V)*, D. Y. Goswami and Y. Zhao, Eds., ed: Springer Berlin Heidelberg, 2009, pp. 1409-1413.

[11] K. Machida, T. Yamazaki and T. Hirasawa, "Secular degradation of crystalline photovoltaic modules," *Solar Energy Materials and Solar Cells*, vol 47, pp. 149-153, 1997.

[12] K. Kobayashi, I. Takano and Y. Sawada, "A study of a two stage maximum power point tracking control of a photovoltaic system under partially shaded insolation conditions," *Solar Energy Materials and Solar Cells*, vol. 90, pp. 2975-2988, 2006.

[13] L.A. Hecktheuer, A. Krenzinger and C.W.M. Prieb, "Methodology for Photovoltaic Modules Characterization and Shading Effects Analysis," *Journal of the Brazilian Society of Mechanical Sciences*, vol. 24, pp. 26-32, 2002.

[14] R.P. Kenny, A. Ioannides, H. Müllejans, W. Zaaiman, E.D. Dunlop, "Performance of thin film PV modules," *Thin Solid Films*, vol. 511–512, pp. 663-672, 2006.

[15] G. Blaesser and E. Rossi, "Extrapolation of outdoor measurements of PV array I–V characteristics to standard test conditions," *Solar Cells*, vol. 25, pp. 91-96, 1988.

[16] Sandia Photovoltaic Performance Model I-V Curve Tracer, Maui Solar Energy Software Corporation, Haiku USA, 2001.

[17] W. Shen, H. Choo Fook, P. Wang, C. Loh Poh and Y. Khoo Sui, "Development of a mathematical model for solar module in photovoltaic systems," in *6th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2011, pp. 2056-2061.

[18] D. Berman and D. Faiman, "EVA browning and the time-dependence of I–V curve parameters on PV modules with and without mirror-enhancement in a desert environment," *Solar Energy Materials and Solar Cells*, vol. 45, pp. 401–412, 1997.

[19] S.R. Wenham, M.A Green, M.E Watt, and R. Corkish, *Applied photovoltaics*, 2nd ed. Earthscan, 8-12 Camden High Street, London, NW1 0JH, HK 2007. pp. 47.

[20] A. Skoczek, T. Sample and E.D. Dunlop, "The results of performance measurements of field-aged crystalline silicon photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, vol. 17, pp. 227-240, 2009.

[21] Siemens Solar Module SP75 Data sheet. [Online]. Available: http://www.solarcellsales.com/techinfo/docs/sp75.pdf

[22] W. Herrmann and N. Bogdanski, "Outdoor weathering of PV modules and Effects of various climates and comparison with accelerated laboratory testing," in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*, 2011, pp. 002305-002311.

[23]] J.E. Granata, W.E. Boyson, J.A. Kratochvil and M.A. Quintana, "Long-term performance and reliability assessment of 8 PV arrays at Sandia National Laboratories," in *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*, 2009, pp. 001486-001491.

[24] C.R. Osterwald, J.P. Benner, J. Pruett, A. Anderberg, S. Rummel and L. Ottoson, "Degradation in weathered crystalline-silicon PV modules apparently caused by UV radiation," in *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion*, 2003, pp. 2911-2915 Vol.3.

[25] D. Chianese, A. Realini, N. Cereghetti, A. Rezzonico, E. Bura, G. Friesen and A. Bernasconi, "Analysis of weathered c-Si PV modules." in *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion*, 2003, pp. 2922-2926 Vol.3.

[26] C. Dechthummarong, J. Thongpron, S. Thepa, D. Chenvidhya, C. Jivacate and K. Kirtikara,, "Performance assessment of PV modules after long field exposure in north eastern of Thailand," in 2011 8th International Conference on *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, , 2011, pp. 156-158.

[27] A. J. Carr and T. L. Pryor, "A comparison of the performance of different PV module types in temperate climates," *Solar Energy*, vol. 76, pp. 285-294, 2004.

VII. BIOGRAPHY

Tariq Aziz is currently doing MS in Renewable Energy at SERT Naresuan University, Phitsanulok Thailand. His focus is on Solar Energy particularly PV. He is an Electrical Engineer and working as Assistant Engineer with a Govt. owned Electricity Distribution Company in Pakistan.