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Statistical Determination of Climate-Specific Defects and Degradation Modes in PV Modules

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***Abstract*—**In the last decade, there has been a dramatic increase in the numbers of photovoltaic (PV) Systems as the world shifts toward clean and sustainable energy resources. Seeing this rise in the Solar PV market, multiple new manufacturers are seeking entry into the marketplace and the need to identify the good performance modules from the bad becomes an absolute necessity. The Performance and reliable operation of PV Modules depend on many factors including materials, manufacturing processes and environmental constraints. Even best quality PV modules and systems degrade with time. The degradation rate largely depends on field conditions and manufacturers, as well as test engineers are highly interested in accurate performance modeling of the field installed PV modules. Thus two factors have been seen to give good indications of the degradation: the Performance Ratio and the Performance Index. As a power plant in Pakistan is analyzed for its degradation using these two factors in this paper, an indication on its possible lifetime can be predicted. The performance ratio method indicated at degradation of .61% while the performance index method indicated a degradation of 1.09%.

***Keywords*—** Performance Ratio, Performance index, Degradation Rate

I. Introduction

Pakistan is a developing country and its energy crisis is one of the most burning issues it faces as there is a lack of supply of continuous energy. At the same time, increasing fuel prices is an integral factor leading to excessive load shedding. In Pakistan, sustainable energy is still immature on the commercial & industrial scale. By the end of 2050 large number of countries will set milestones of reaching 20-30% of their energy demand by utilizing renewable energy [1]. Solar energy is one of the most promising technologies among all renewable technologies. Pakistan in particular receives enough solar irradiation to fulfil its required energy demand. A large number of companies are investing in Pakistan's solar market as it is anticipated that a rush of large scale PV installation will be seen in the future. This then leads to the need of having highly precise energy forecasting and modeling methods of how these solar power plants will generate energy. Studies have indicated that relatively accurate energy Prediction can be done by calculating the trend of degradation rates of photovoltaic modules technologies and existing PV power plants [2]. This will be helpful for manufacturers as the climate specific degradation trends can be reviewed and be implemented in producing better and reliable modules. Also such forecasting studies will aid the investors have a better idea of what to expect from existing and future solar power plants. Solar energy is expected to play an important role in the energy mix of future energy scenario in Pakistan and hence, one has to see whether the country has a favorable environment where this technology can flourish. Hence this simulation can cater to the ever-increasing demand for solar energy solutions and provide an idea on the economics involved.

Performance of PV system mainly depends upon the global irradiation, selected PV technology, operating module temperature and other climatic factors [3]. Performance ratio (PR) and Performance index (PI) are key parameters to define the performance of the whole system. These indicators tell how effectively solar energy is being converted into electricity. According to the IEC 61724 standards [4] [5], PR is defined as a ratio of system yield (Y_f) to the reference yield (Y_r) at standard testing conditions or STC [6].

$$PR= Y_f / Y_r \quad (1)$$

Since,

$$Y_f = \tau_R * \sum P_A / P_o * \eta_{load} \quad (2)$$

$$Y_r = \tau_R * (\sum G_I / G_{I}, ref) \quad (3)$$

Where,

$\tau_R * \sum P_A$ = daily array energy of the system

Po = rated array power

η_{load} = efficiency with which the energy from all sources is transmitted to the loads.

$\tau_R * \sum G_I$ = daily energy incident on the system

Performance index is a more accurate dimensionless indicator that accounts for temperature, wiring and module mismatch losses.

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$$PI = Actual\ Energy / Adjusted\ Energy \quad (4)$$

Where,

Actual Energy = measured energy at any given time
Adjusted Energy = Rated Power x Loss Adjustments

When substituting in the actual loss factors that can be derived for PV systems, Equation 4 can be modified to that of Equation 5, as shown below. [7]

$$PI = (Actual\ Energy * rated\ irradiance) / (Rated\ power * Actual\ Isolation * TA * DA * SA * BOSA) \quad (5)$$

Where,
Rated Irradiance = 1000 W/m^2 for flat plate modules Rated Power = nameplate power of the array
Actual Insolation = total energy incident on the plane of array TA = Temperature Adjustment DA = DegradationAdjustment
SA = Soiling Adjustment
BOSA = Balance of System Adjustment

A systematic approach for economics analysis of a project mainly depends upon the total power delivered to the load and parameters i.e. NPV, IRR, benefit-cost ratio, Equity & simple payback period.[8][9] These parameters indicate the feasibility of the system. In this paper, techno-economic analysis of an on-grid PV system is done.

II. Power Plant Description

In the Islamic republic of Pakistan, the first on-grid photovoltaic solar power plant was commissioned near the main entrance of the government office towards the west of planning commission building, located at Islamabad with an installed capacity 178.08 kW. The project was titled "Introduction of clean energy by solar electricity generation system" and was started on May 29, 2012 & supported by Japan international cooperation agency (JICA).

A. Site and Climatic Condition

The Photovoltaic power plant is installed in Islamabad with an area of around 4108 m2 .This system is connected to the 400V side of the incoming 11kV feeder of IESCO. The remaining surplus power is flowing to the grid network of IESCO. The site specific information along with the component specification is shown in the table 1 below.

TABLE I. General Description of PV Power plant

Longitude Latitude Altitude	73.0667◦E 33.7167◦N 750 m
Avg. ambient temperature	46.6 ◦C
Maximum wind speed	20.58 m/s
Average humidity	88%
Average daily Solar Insolation	5.24 kW/m^2/day
PV MODULE SPECIFICATION	
No. of Panel/module	848 PV Solar Panel
No. of Solar Cell in each module	72 cells
Type of Module	Monocrystalline
Module Surface Area	1.28296 m^2
Total Module Area	1088 m^2
Total Land Area Used	2300 m^2
Panel Frame	Aluminum
Module eff	16.4%
PV ARRAY	
No. of sub-array	36
Module in a string	8
Total No. of strings	106
Modules in sub-array	24 x 35 set 8 x 1 set
Total PV capacity	178.08kW

III. Statistical Analysis

Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

A. Methodology

The Power plant was evaluated for performance and degradation rate calculations using two different methods. The Daily data was used which was then used to generate monthly values for both PR & PI determination.

1) Performance Ratio (PR) Analysis:
For the system under consideration, PR values were calculated by using kWh data and calculating expected energy. The Plane of array data was given by the authority of power plant and temperature model of PVSYST was used [10]. Figure 1 shows the steps followed in measuring the degradation rate. Data with irradiance values less than 50 W/m2 was filtered out. As needed, the obvious outliers were removed for a better year to year fit. The monthly average values were used as available for the PR values. The corresponding slopes for each month versus the number of years in operation was used to determine the degradation rates for each of the 12 months of the year.[7]

2) Performance Index (PI) Analysis:
PI is considered to be more accurate than PR as it incorporates the losses in the system in its measurement. For this system, the kWh data to measured energy data have been corrected for irradiance, temperature, and Module mismatch and inverter efficiency while calculating the PI values.[7] The module mismatch and the ohmic losses in the string was

assumed at 3% and 2% respectively. In PVSYST, the ohmic losses were kept at 1.5%. Figure 2 shows the methodology of PI method.

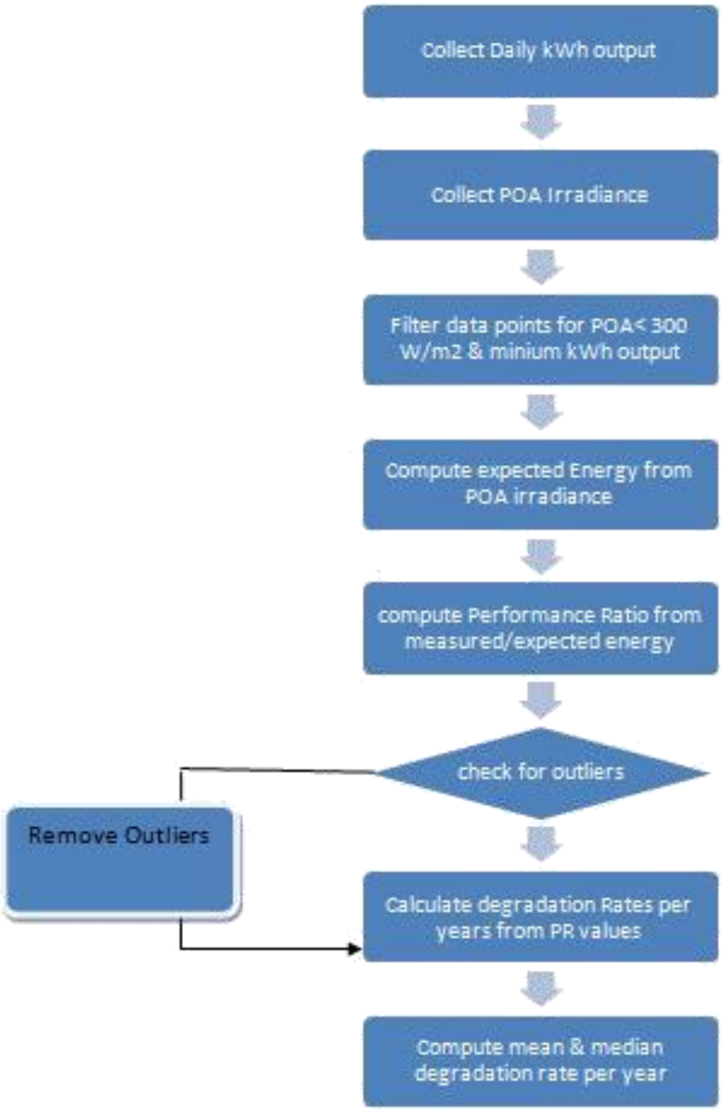

Fig.1 PR Methodology Flow Chart

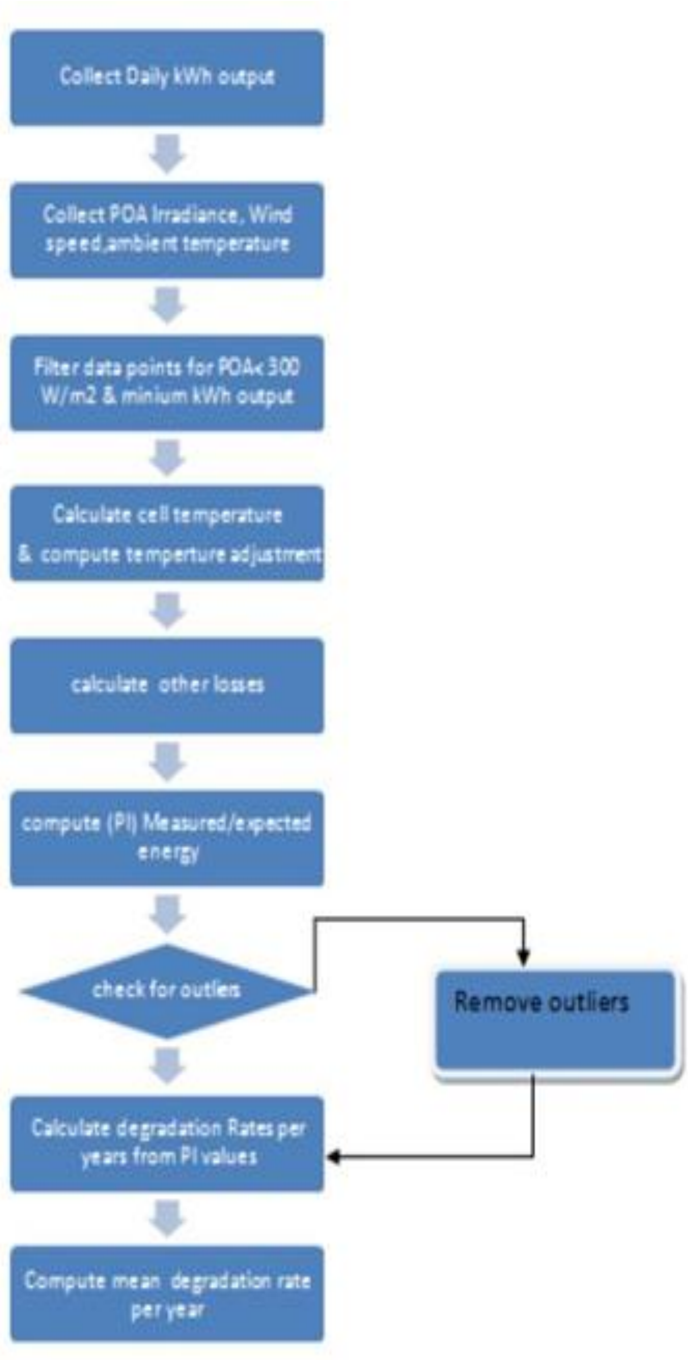

Fig.2 PI Methodology Flow Chart

IV. Results and Discussions

Performance of a system mainly depends upon variation of the solar irradiation and variety of other parameters. The metrological parameters i.e. solar irradiation, ambient temperature, and wind speed as average of every 10 minutes interval are used. Figure 3 shows the average monthly power generation from 2013 to 2016 with variation in solar irradiation.

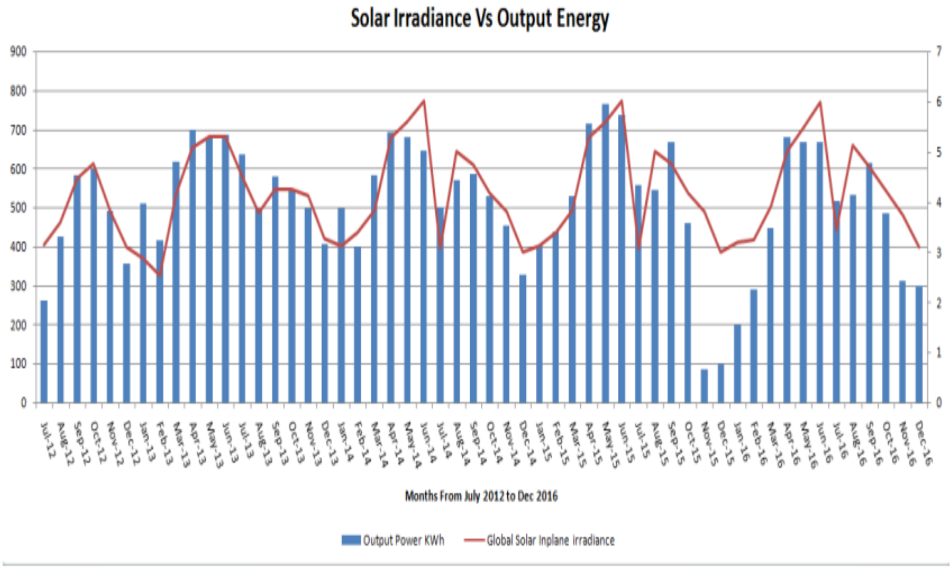

Fig.3 Solar Irradiance

From the figure 4 below, it can be seen that performance ratio of the summer months (April - August) was reduced due to the hot weather conditions leading to decrease in the module performance. From the plot it is shown that PR in year 2012 is less, this could be due to possible low irradiance conditions or component malfunctioning and replacement. The degradation rate of each month was calculated by taking slope of each PR value as shown in the table.2. The Degradation rates are shown in table

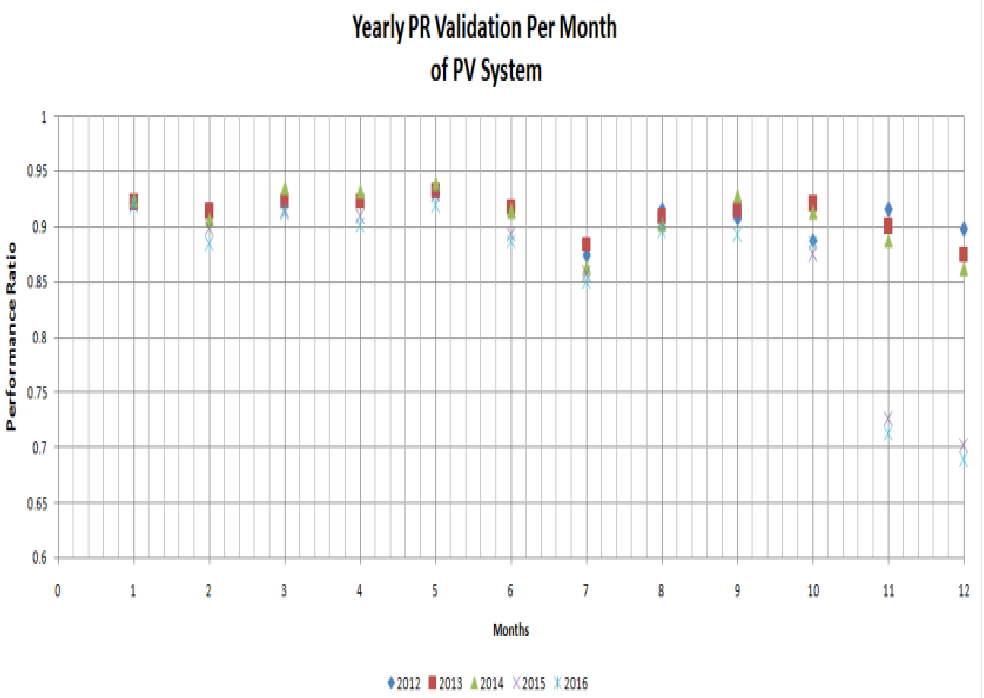

Fig.4: Monthly Average PR

Following the findings of Shrestha et al, the months with the least variation in irradiance values were considered. Hence the months of May-September were considered and the average of these months were considered as the true degradation rate. A value of 3.9% was seen to be the calculated degradation rate using the PR values determined from the measured values. The onsite degradation in the module level is hardly seen as the plant in consideration is relatively new which is verified by the IV values measured.

TABLE II MONTHLY AVERAGE DEGRADDATION RATE FROM PR

PR MONTHLY DEGRADATION RATE						
MONTHS	2012	2013	2014	2015	2016	DERGR-ADATION RATE
Jan		0.922	0.924	0.919	0.919	-0.13%
Feb		0.914	0.907	0.898	0.884	-0.99%
March		0.923	0.935	0.915	0.913	-0.49%
April		0.923	0.932	0.909	0.901	-0.87%
May		0.932	0.939	0.928	0.919	-0.49%
June		0.917	0.914	0.893	0.887	-1.13%
July	0.873	0.884	0.863	0.857	0.850	-0.73%
Aug	0.916	0.909	0.902	0.904	0.895	-0.48%
Sept	0.907	0.914	0.929	0.912	0.893	-0.30%
Oct	0.887	0.921	0.913	0.875	0.885	-0.50%
Nov	0.915	0.900	0.887	0.726	0.713	-5.79%
Dec	0.898	0.874	0.862	0.702	0.689	-5.89%

A. *Performance Index (PI)*

The performance index (PI) was used to correct for irradiance losses and other system losses (inverter efficiency losses, mismatch of the module losses, temperature loss, and wiring losses). The following plot shows that there is very less variation for the summer months that is, May-August as the PI values are calculated using the corrected vales for the high temperature months.

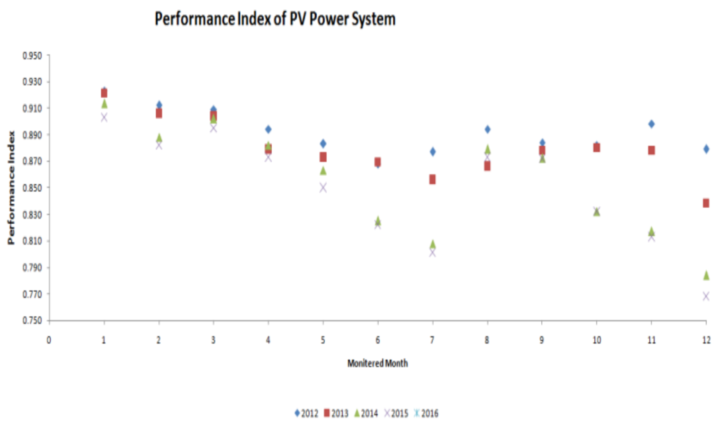

Fig. 5. Monthly Average PI

As in the case of PR, the same months with least variations in irradiance were considered and the average values were used for the determination of the degradation rates. The value thus attained is 5.83%, which show that the losses already included for the PI calculation are an accurate representation of the general losses seen by the PV system.

TBBLE III MONTHLY PI DEGRADATION

Monthly PI Degradation						
Month	2012	2013	2014	2015	2016	Degra-dation Rate
Jan		0.923	0.921	0.913	0.903	-0.68%
Feb		0.912	0.906	0.888	0.882	-1.08%
March		0.909	0.904	0.902	0.895	-0.44%
April		0.894	0.879	0.882	0.873	-0.60%
May		0.883	0.873	0.863	0.850	-1.09%
June		0.868	0.869	0.825	0.822	-1.82%
July	0.899	0.877	0.856	0.808	0.801	-2.65%
Aug	0.878	0.894	0.866	0.879	0.873	-0.25%
Sept	0.885	0.884	0.878	0.872	0.872	-0.38%
Oct	0.898	0.882	0.880	0.832	0.832	-1.82%
Nov	0.913	0.898	0.878	0.817	0.813	-2.81%
Dec	0.899	0.879	0.838	0.784	0.768	-3.57%

CONCLUSION

From the results that were discussed previously, important conclusions for failure analysis modes of modules can be drawn. The occurrences of failure modes in the power plant installed at PRL-ASU were determined. The FMEA technique was implemented on each module separately to rank the failure modes according to their impact on the performance and safety of the specific site. Weld bond weariness/breakdown with/without gridlines/metallization contact fatigue was found most dominant failure mode in PV modules. The rise of approx. 20% to 40% in series resistance even in the best modules is generally associated with failures. The degradation and weld bond weariness issues in due course could lead to breakdowns and hotspot and burning of backsheet, which could be proved catastrophic to plant.

From the analysis and result discussion of photovoltaic system performance evaluation, some conclusions are drawn. The performance models used, performance Ratio, performance index and kilowatt hour methods, which also showed difference in the calculated degradation rates. Since it is known that the best method to calculate is I-V method. Hence, after comparing different calculated values of degradation rates from this research with the values of I-V method of state-of-the-art systems of same climatic conditions found in literature, performance index degradation rate is chosen most accurate for both systems installed in Islamabad. The degradation rate of systems in Islamabad is calculated 1.09% per year. The degradation rates could be attributed to an improvement in the quality of modules that are being installed in newer system.

The trend and rate of degradation for crystalline silicon PV systems was found linear. The graphs presented in earlier sections help support the idea of linearity in the degradation rate. Prospect of solar industry seems promising in Pakistan due to good profile of the existing photovoltaic systems performance. Overall performance ratio o the PEC systems is 86.01. Comparison of these values with the other state-of-the-art- systems were made which proves that the performance of system is viable for future solar energy prospect.

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