Performance Analysis of First Grid Connected PV Power Plant in Subtropical Climate of Pakistan

Afshan Qamar[1],Adit Patankar[2], Muhammad Raza Kazmi[3]
U.S - Pakistan Center for Advanced Studies in Energy (USPCAS-E) National University of Sciences and Technology,Islamabad, Pakistan[1,3]

Photovoltaic Reliability Laboratory Arizona State University Arizona, USA[2]
afshanqamar90@yahoo.com[1], Adit.Patankar@asu.edu[2], razakazmi@uspcase.nust.edu.pk[3]

Abstract—**With the increasing penetration of both grid connected and standalone photovoltaic (PV) systems in Pakistan to cater the shortfall of energy, it is necessary to determine the performance and durability of already installed PV systems in different climates of country. This work aims to analyze the performance of first grid connected PV power plant located in Islamabad, Pakistan. The performance degradation of PV plants primarily depends on PV modules type (technology and design), regional climatic factors and field operating conditions. In this paper, performance ratio (PR) and degradation rate have been calculated from meteorological and performance data of plant to investigate the energy efficiency and modules quality over the course of operational years. Temperature losses due to module operating temperature were also estimated that primarily contribute to overall energy losses. This evaluation is of paramount importance for estimating the cost effect of the performance, identification of the underlying performance degradation and energy losses mechanisms, that help investors to choose climate specific modules technology and design for future plants and also to make efficient scheduling for preventive maintenance.**

Keywords—Photovoltaic (PV) system, performance ratio (PR), climatic factors, performance index (PI), degradation rate analysis, energy losses,

I. INTRODUCTION

The market of PV systems is expanding rapidly in Pakistan due to available high potential of solar energy and falling cost of PV units. Recently, a large number of studies were conducted in Pakistan regarding to available potential of renewable sources, cost evaluation of renewable power plants, design, potential and prospect of PV power plants [1]–[4]. However, the awareness of performance, losses, and reliability of existing solar power plants is very low, that can lead to risk of new investments. Major factors that influence the production of PV system are; shading and soiling of PV array, inverter efficiency, mismatch and wiring losses, module operating temperature losses and degradation due to aging of system components. Typically, PV manufacturers promise a 20 years warranty of PV modules assuming a linear degradation rate of 1%/year but the actual life of a PV power plant depends on the in-field degradation of performance parameters owing to the environmental affects and loss mechanisms. It was evaluated by researchers that regardless of module material and operating conditions, performance behavior and degradation rate of PV system are also location dependent [5]–[8]. Various studies have been conducted in different climates of different countries to report the performance of PV systems. A 58 KW on-grid system was analyzed in India [9] on the basis of performance indicators such as performance ratio, total and specific yield. Another study of 20 MW plant in Hami, China [10] was performed to calculate performance ratio, power degradation, system losses and inverter efficiency to determine the prominent influencing factors. A comprehensive comparison of module efficiency, energy yield and PR of three PV technologies (Mono c-Si, Poly c-Si and micromorph c-Si) were performed to determine the suitable technology for tropical Indonesia [11]. The impact of varying insolation and temperature on performance parameters was studied in [12] and [13], respectively. These studies shows that, it has become crucial to track performance characteristics and parameters influencing the energy yield of PV systems in multiple climates for the development of PV technology. Particularly, for a Commercial-scale PV energy system, it is essential to measure the actual performance over the years for better planning of future deployment. On May 29, 2012 Japan International Cooperation Agency (JICA) installed first grid connected, mono c-Si technology PV power plant of capacity 178.08 KW in parking area of Pakistan Engineering Council (PEC) building Islamabad, Pakistan. This project was established under the grant aid named Program Grant Aid for Environment and Climate Change, whose purpose was to mitigate the GHG emission, create awareness of the PV system and reduction in electricity cost by providing PV system and related equipment to under developed countries. This paper discusses the performance of aforementioned plant by using performance indicators such as PR, energy degradation rate (%/year) and output energy loss due to module operating temperature.

II. PV POWER PLANT SITE AND SYSTEM PROFILE

This plant was deployed in humid and hot weather of Islamabad (Latitude:33.6°N, Longitude: 73.1° E, Altitude:1667 ft) where ambient temperature varies from minimum 3.9°C (winter) to maximum 48.6°C (summer). Total 848 mono-crystalline silicon PV modules were installed in 3 arrays, each array further split into 7 sub arrays. These sub arrays consist of total 106 strings where each string had 8 modules. The output power from each array is; Array-1: 136.50 kW, Array-2: 26.88 kW and Array-3: 14.7 kW, respectively. To ensure the quality of electric power supply and system protection from faults 18 power conditioning units (each of capacity 10 KW) were installed. Three phase supply from system was connected to 11 kV feeder of Islamabad Electric Supply Company (IESCO) through junction boxes. All the modules were mounted on open rack at fixed 30° tilt angle to optimize the collection of input irradiance. Modules specifications and electrical parameters at standard test condition (STC): Air Mass close to 1.5 spectrum, irradiance 1000 W/m^2 and cell temperature 25°C, are given in Table I. All weather parameters: ambient temperature, humidity, wind speed, wind direction, horizontal irradiance and In-plane

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irradiance, are monitored by using thermometer, anemometer and two pyranometer (one is mounted horizontal and other one on the module tilt angle). Modules output electrical parameters: AC voltage and current of all Power conditioning unit, DC voltage and current of all Power conditioning unit, total generated DC and AC power and total supplied AC power to 400V distribution side, are logged in a data logger.

Fig. 1. View of PEC Solar Power Plant

TABLE I. MODULE SPECIFICATIONS

Type of module	Mono c-Si
Total modules area	1088 m^2
No of cells in one module	72 cells
Surface area of module	1.28296 m^2
Dimensions of module	1.58m x 0.812m x 0.035m
Module efficiency	16.4 %
Module weight	15 kg
Module frame	Aluminum
Peak power (P_{max})	210W
Short circuit current (Isc)	5.57A
Open circuit voltage (Voc)	50.9 V
P_{max} current (Impp)	5.09 A
P_{max} voltage (Vmpp)	41.3V
System maximum open circuit voltage	600V DC

III. PERFORMANCE AND ENERGY LOSS ANALYSIS

The purpose of this study was to initiate the importance of health analysis of PV power plants in Pakistan. In order to achieve this purpose, we examine plant performance and environmental data, monitored since 2012, to track its output energy, performance degradation and losses against the rated capacity.

A. Performance Ratio (PR) Analysis

The metric of performance ratio is defined by IEC 61724 standard in which the approach for analyzing a photovoltaic system has been discussed [14]. Performance ratio is the ratio of real and theoretical conceivable output energy. It is an important parameter to estimate the efficiency of plant. It is also known as ratio of system yield (Y_f) to reference yield (Y_r) and indicate the quality of plant. It measures, how efficiently PV plant convert the input irradiance into output AC energy delivered to grid. It does not depend on the location, direction and collected irradiance of PV system, therefore, PR is a useful parameter to determine the performance of solar PV plants on different locations over the globe. PR is calculated by using (1), (2) and (3).

$$Y_f = \tau_R * \frac{\sum P_A}{P_{STC\,rated}} \quad (1)$$

$$Y_r = \tau_R * \frac{\sum G_I}{G_{I\,ref}} \quad (2)$$

$$PR = \frac{Y_f}{Y_r} \quad (3)$$

Where, $\tau_R * \sum P_A$ is the daily array output energy of the system and $\tau_R * \sum G_I$ is the daily incident input energy on the system. $P_{STC\,rated}$ and $\sum G_{I\,ref}$ are STC rated power and reference irradiance i.e. 1000 W/m^2.

PR values improved over the years, generally efficient plants touching more than 80% these days. However, weather influence the PR values by affecting the module temperature, PR values swing over a day and year due to weather variations. For example, same site provide higher PR values in colder season as compared to hotter season [15]. Thus, it may over-estimate the performance and may not allow the investors to access the impact of regional climate on expected performance.

B. Degradation Rate Analysis

Degradation rate is a key variable to precisely predict the stability and longevity of PV system over years. Accurate degradation analysis to measure actual lifetime is necessary to enhance system production and reliability, lower cost and raise financiers and consumer confidence. Different methods and techniques used to calculate degradation rate of in field PV power plants are reviewed in [16]. However, every method yield slightly different results due to varying measurement uncertainty and different data filtration and trend estimation method [17]. In-field IV measurements under natural sunlight provides more accurate information of underlying degradation rates followed by Performance Index (PI) method if the weather and plane of array (POA) irradiance data are available from locally deployed ground mounted station [18]. In this research, we calculate degradation rate (%/year) by using Performance Index (PI) method as it shows less discrepancy to outdoor IV measured degradation rates. PI is a more accurate measurement of performance and incorporate system losses such as temperature, soiling, inverter efficiency, wiring, balance of system (BOS) and module mismatch [19]. It provides a clearer representation to all losses being faced by PV power plant. It is known as the ratio of actual energy and adjusted energy.

$$PI = \frac{Actual\ energy}{Adjusted\ energy} \quad (4)$$

In (4), actual energy is measured energy (KWh), and adjusted energy is:

$$Adjusted\ energ = P_{STC\ rated} * \frac{G_I}{G_{I\ ref}} * loss\ adjustment$$

Where, $\frac{G_I}{G_{I\ ref}}$ is ratio of input irradiance to rated irradiance and loss adjustments includes degradation, soiling, BOS and temperature adjustment. Temperature adjustment was done according to (5) and module temperature was calculated by using (6), Faiman module temperature model [20]:

$$T = 1 + \beta\ (T_{module} - 25) \quad (5)$$

$$T_{module} = T_{ambient} + \frac{E_{POA}}{U_0 + U_1 * WS} \quad (6)$$

In (6), T_{module}, $T_{ambient}$, E_{POA} and WS represents module temperature (°C), ambient air temperature (°C), plane of array irradiance (W/m^2) and wind speed (m/s), respectively. U_0 (W/°Cm^2), U_1 (Ws/°Cm^3) are constant heat transfer and convective heat transfer component, respectively.

The values of parameters U_0 and U_1 were calculated for modules of different technologies under different climatic conditions in [21]. The average values of U_0 and U_1 evaluated from the six months of measurements were 35.9 and 4.46, respectively. Inverter efficiency was taken from data sheet, mismatch losses (3.3%) and wiring losses (1% for smaller plants used in PVsyst) were assumed constant. Steps shown in Fig. 2 are used to calculate degradation rate by using PI method.

IV. Thermal Energy Losses

Expected output energy decreases due to conversion losses and degradation of system. Conversion losses varies seasonally due to ambient temperature variations. Module operating temperature is a crucial parameter that affects the module performance. Increase in module temperature leads to decrease in the voltages and also reduces the band gap of a semiconductor thereby affecting semiconductor material parameters. Increase in solar irradiation leads to increase in module operating temperature which causes decrease in output power and hence reduce the overall system efficiency. Modules temperature losses primarily account more than any other loss over the year in overall energy losses. We observed the effects of temperature losses on the PV power plant energy that is lost monthly and annually due to module operating temperature.

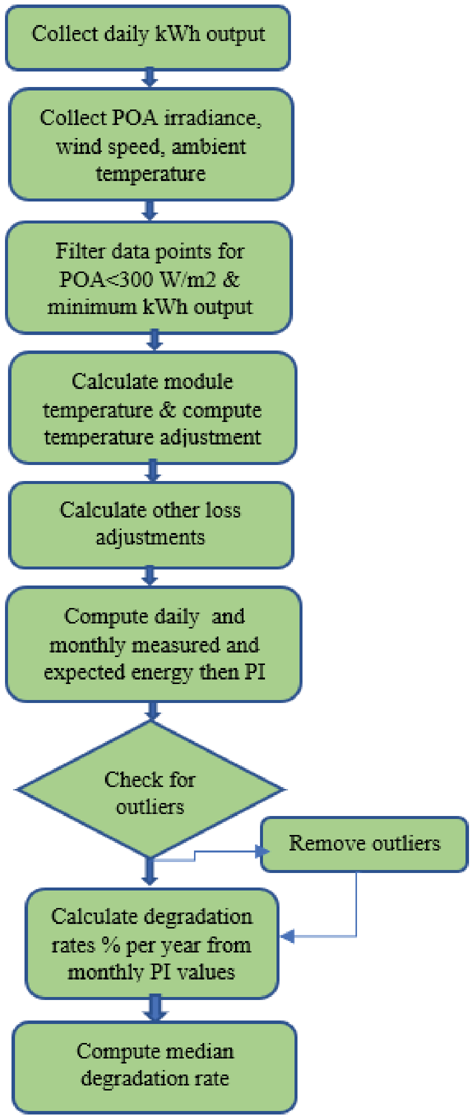

Fig. 2. Steps to calculate degradation rate by using PI method

V. Results and Discussion

PR values for 365 days of every year was calculated by using (3) from KWh and plane of array (POA) irradiance data of plant. For monthly PR values, first outliers were filtered from each month then median of daily PR values of that particular month was taken. The plot of monthly PR values from May-2012 to June-2018 is given in Fig. 3. It is noticeable from the Fig. 3 that the PR during summer months (May - July) has lower value as compared to the remaining months. This can be ascribed to the fact that the operating temperatures are not adjudged in hot and humid climate of Islamabad, module temperature can be as high as 60°C on open rack system. These rise in operating temperature cause severe losses in modules and resulting reduction in performance of the whole system. Typically, on average 0.83 to 0.76 performance ratio values are observed in winter months whereas 0.75 to 0.69 are observed in summer months over the course of operating period of plant. This plot also shows that the performance ratio value for each month gradually decreases from 2012 to 2018 due to system degradation.

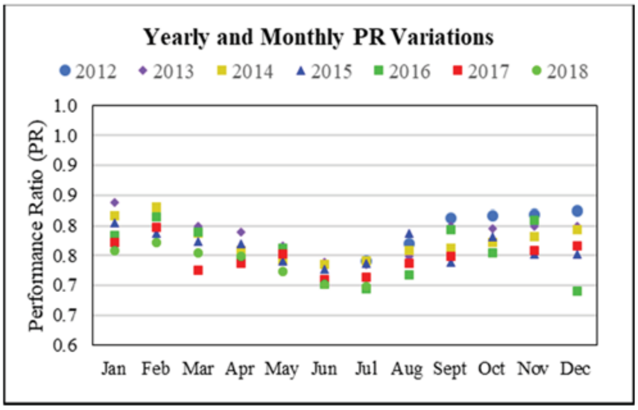

Fig. 3. PR values of six-year-old PEC solar power plant

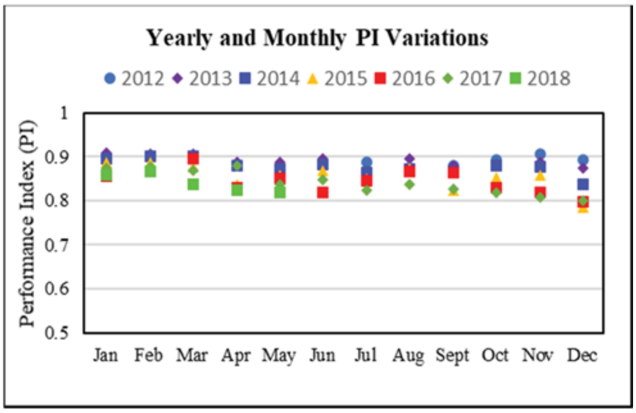

Fig. 4. PI values of six-year-old PEC solar power plant

To calculate degradation rate, we follow the instructions given in flowchart shown in Fig. 2. First, PI values of total operational days were calculated by using (4) then outliers were filtered for each month. For monthly PI values, median of daily PI values of that particular month was taken. PI values of total operational months were calculated then degradation rate (%/year) was computed by taking the same month slope of monthly median PI values over the field operating years. Total 12 degradation rates (%/year) were computed for 12 months then median degradation rate was calculated. Monthly PI values and computed degradation rate (%/year) are given in table II and plotted in Fig. 4. According to the meteorological data of Islamabad, consistency of irradiance that hits the Islamabad metropolitan area has high and low variance months, six months of lowest irradiance variations from April to October were selected to take median values of degradation rate. The value was found to be 1.15 (%/year).

TABLE II. MONTHLY PI VALUES AND COMPUTATED DEGRADATION RATE

Monthly Performance Index (PI) Degradation Rate							
	2012	2013	2014	2015	2016	2017	2018	Degradation Rate (%/year)
Jan		0.91	0.90	0.89	0.86	0.88	0.86	-1.01%
Feb		0.91	0.90	0.89	0.87	0.88	0.87	-0.83%
Mar		0.91	0.90	0.88	0.90	0.87	0.84	-1.20%
Apr		0.89	0.88	0.84	0.83	0.88	0.83	-0.94%
May		0.89	0.88	0.86	0.85	0.84	0.82	-1.29%
Jun		0.90	0.89	0.87	0.82	0.85		-1.35%
Jul	0.89	0.87	0.87	0.85	0.85	0.83		-1.12%
Aug	0.88	0.90	0.88	0.88	0.87	0.84		-0.75%
Sep	0.88	0.88	0.87	0.83	0.87	0.83		-1.00%
Oct	0.89	0.88	0.88	0.86	0.83	0.82		-1.58%
Nov	0.91	0.89	0.88	0.86	0.82	0.81		-2.05%
Dec	0.90	0.88	0.84	0.79	0.80	0.80		-2.14%

Deviation of degradation rate from industry standard i.e. 1 (%/year) in hot and humid environment of Islamabad can be ascribe to corrosion and thermal fatigue that leads to rise in series resistance (Rs).

However, this value is still consistent with c-Si degradation rate found in literature; 1.06 (%/year) in hot and humid climate of Texas, 1.55 (%/year) in hot and dry climate of India [8],[7] . PI values shown in Fig. 4 have less variations as compared to PR values because it accounts for all known losses and predict actual degradation rate. Figure. 5 shows the monthly and annual expected energy lost due to rise in module operating temperature. This system lost minimum 2% during coldest months and 12-13% during hottest months, while annually it lost an average 6.7% of expected energy due to performance loss because of varying temperature. This graph gives a distinct picture to system investors that help them to understand the variation and loss of expected energy that can occur monthly and yearly in Islamabad. Below mentioned pie chart shows the contribution of individual losses and actual performance of plant. Degradation rate (1.15 %/year) accounts for 6.9 % of total losses over the period of six years. System losses as mentioned above, accumulating of inverter loss, mismatch and wiring losses (3.3%, 1%) accounts for 7.8% of total losses. Energy lost due to thermal losses includes 6.7% of expected energy. The unknown losses can be attributed to soiling loss, over/under assumption of inverter efficiency or mismatch and wiring losses. However, this overall picture of performance is constructed by using; calculated (PR, degradation rate, thermal loss) values and assumed values (mismatch loss, wiring loss, soiling loss) from literature, to present the overall effect of parameter on system.

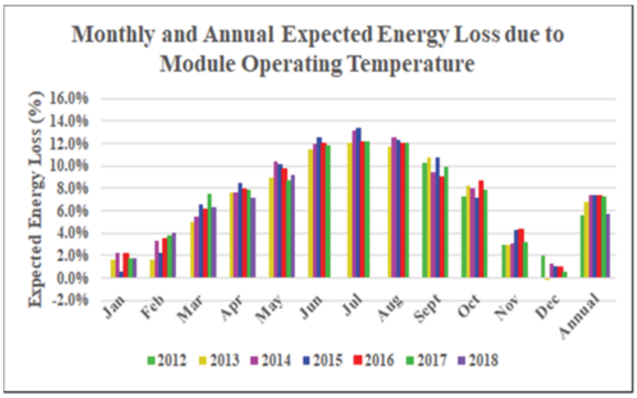

Fig. 5. Percent of expected energy loss due to variations in module operating temperature. Losses increase during summer month due to higher module temperatures.

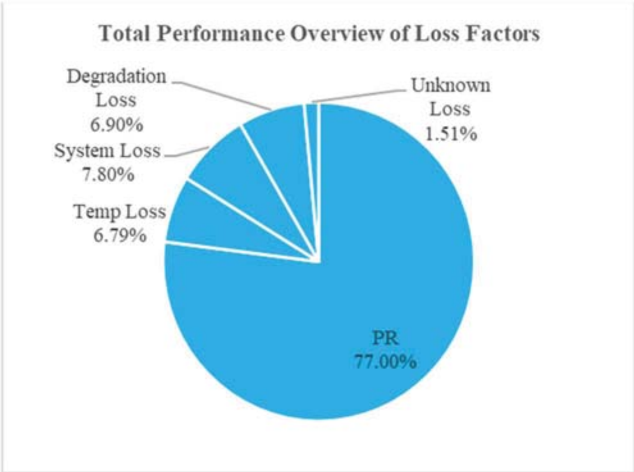

Fig. 6. Performance overview of PEC solar power plant

VI. CONCLUSION

A 178.08 KW first grid connected PV power system located in Islamabad, Pakistan was analyzed by using plant monitored meteorological and electrical data from May-2012 to June-2018. Performance ratio values indicate better performance of plant; however, it shows variations due to pronounced subtropical weather seasonality. Plant shows slightly higher degradation rate 1.15% as compared to temperate climate (less than 1% for c-Si) that can be attributed to hot and humid weather of Islamabad and low accuracy of monitored performance data due to sensors drift, poor performance of data acquisition system, and frequent downtime during load shading. Fluctuations in modules operating temperature cause energy losses over the year, evaluated thermal losses help investors and designers to install system that can cater the impact of highest and lowest temperatures. Analysis of PEC power plant will provide valuable insights to owners and manufacturer about underlying degradation and losses in subtropical, hot and humid environment of Pakistan.

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