Research Article

Comparison of Performance Measurements of Photovoltaic Modules during Winter Months in Taxila, Pakistan

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This paper presents the comparative performance evaluation of three commercially available photovoltaic modules (monocrystalline, polycrystalline, and single junction amorphous silicon) in Taxila, Pakistan. The experimentation was carried out at outdoor conditions for winter months. Power output, module efficiency, and performance ratio were calculated for each module and the effect of module temperature and solar irradiance on these parameters was investigated. Module parameters showed strong dependence on the solar irradiance and module temperature. Monocrystalline and polycrystalline modules showed better performance in high irradiance condition whereas it decreased suddenly with decrease in irradiance. Amorphous solar module also showed good performance in low irradiance due to its better light absorbing characteristics and thus showed higher average performance ratio. Monocrystalline photovoltaic module showed higher monthly average module efficiency and was found to be more efficient at this site. Module efficiency and performance ratio showed a decreasing trend with increase of irradiance and photovoltaic module back surface temperature.

1. Introduction

The performance testing of PV modules at outdoor conditions is required to have an accurate estimation of output of PV modules under specific climate. The rated values of PV modules provided by the manufacturer are based on the standard test conditions (i.e., irradiance 1000 W/m^2 , module temperature 25°C , and AM 1.5) which do not meet operating outdoor conditions due to the varying outdoor parameters [1].

Different researches and scientists have worked on the performance evaluation of photovoltaic system under different climates. Amin et al. [2] conducted an experimental study to evaluate the performance of four PV modules (monocrystalline, polycrystalline, amorphous silicon, and copper indium diselenide (CIS)) in Malaysia for three consecutive days. The results showed that CIS module has higher performance ratio while c-Si module has high module

efficiency among all the modules tested. Carr and Pryor [3] evaluated and compared the performance of five different PV modules using an outdoor facility in the climate of Perth for one year. They found that amorphous silicon module has highest performance ratio with maximum energy produced at that site. Akhmad et al. [4] investigated the outdoor performance of polycrystalline and amorphous silicon module and found that amorphous silicon module has better efficiency and output power in summer. A similar study was conducted at the site of Norway [5] to investigate the performance of three PV modules (monocrystalline, polycrystalline, and triple junction amorphous silicon). They concluded that monocrystalline module was better in terms of module efficiency and overall power production. According to the installation environment, PV power generating systems can be divided into independent PV systems and grid-connected PV systems. Grid-connected solar PV system is the fastest growing power generating technology [6].

Module temperature affects the output of PV modules. The temperature effect of the module output has been reported by different researchers [7–10]. Sanusi et al. [11] investigated the effect of ambient temperature on PV modules for three years and found a linear behaviour between output power and ambient temperature. One important factor associated with the amorphous silicon module is the effect of photodegradation. The a-Si modules undergo some degradation resulting in a decrease in module performance [12–14]. The solar irradiance effect on the output of PV modules was also investigated by the different researchers [15, 16]. Some unavoidable environmental factors including wind speed and direction, dust accumulation, humidity, and ambient temperature also effect the performance of PV modules [17, 18]. Catelani et al. [19] investigated the effect of dust and pollution on PV module performance using statistical approach. From the statistical hypothesis test, the maximum power showed decrement with the dust accumulation on panel surface. A theoretical model was proposed by Cristaldi et al. [20] to predict the impact of dust from economical point of view. The mathematical model takes into account both the cost due to reduction of the energy production and the maintenance operation cost. This model allows defining the suitable maintenance and monitoring policy for a specific plan. An investigation of dust effect on the performance of PV modules was performed by the Catelani et al. [21] by using method of a Failure Modes, Effects, and Criticality Analysis (FMECA). Mekhilef et al. [22] investigated the effect of dust, humidity, and air velocity simultaneously. They concluded that effect of each parameter should not be studied separately during estimating the cell efficiency by ignoring the other factors.

A handful number of research reports of solar energy potential in Pakistan have been reported in open literature. The average daily sunshine hours in most areas of country are 7–8 [23]. The annual sunshine hours are about 3000–3300 [24]. The daily average global solar irradiance is 19–20 MJ/m²/d and mean annual solar irradiance is 15–21 MJ/m² in Pakistan [25]. Bashir et al. [26] reported experimental data for different PV modules for January and found monocrystalline module more efficient (this data will be used in the analysis of present investigation for the sake of completeness of data).

The aim of present study is to evaluate the performance of commercially available PV modules over the winter months and to analyze the effect of temperature and solar irradiance on their output parameters.

2. Experimental Setup and Methodology

Three commercially available PV modules (monocrystalline, polycrystalline, and single junction amorphous silicon modules) used in this study were placed on a south facing structure at a fixed tilt angle of 48°C with horizontal plane (Figure 1). Table 1 shows the technical specifications and physical dimensions of PV modules used in this study. Each of the PV modules was connected with the temperature sensors and digital multimeters.

The global solar radiation (GSR) in plane with the PV modules was measured using a pyranometer TBQ-2 (sensitivity 11.346 $\mu\text{V}/\text{Wm}^{-2}$, spectral range 280–3000 nm) along with a solar radiation monitoring system (range 0–2000 W/m², accuracy error <2%, resolution 1 W/m²) which records data and transfers it into PC. The K-type thermocouples were used for module temperature measurement connected with digital multimeters and attached at the middle of each module with the help of heat conducting paste. A schematic of experimental setup is shown in Figure 2. Digital multimeters (Agilent 34401 A) were used to measure the current and voltage of PV modules. An electronic load was connected to PV modules to vary the output of the PV modules from zero to maximum. The module parameters (P_{max} , I_{max} , V_{max} , I_{sc} , and V_{oc}) were obtained from I – V curve drawn through measured current and voltage data.

The experiments were performed in Taxila, Pakistan (Latitude 33.7 N, longitude 72.8 E). Measurements were taken for alternative days on hourly basis from 8 am to 5 pm. The performance related parameters of PV modules were calculated using following equations.

Maximum power:

$$P_m = V_m \times I_m. \quad (1)$$

Fill factor:

$$\text{FF} = \frac{(V_m \times I_m)}{(V_{\text{oc}} \times I_{\text{sc}})}. \quad (2)$$

Normalized power output efficiency:

$$\eta_p = \left(\frac{P_{\text{mea}}}{P_{m(\text{STC})}} \right) \times 100. \quad (3)$$

Module efficiency:

$$\eta_{\text{mod}} = \left(\frac{P_{\text{mea}}}{(E \times A_a)} \right) \times 100. \quad (4)$$

Performance ratio:

$$\text{PR} = \frac{(P_{\text{mea}}/P_{m(\text{STC})})}{(E/1000)}. \quad (5)$$

Direct solar irradiance:

$$E_H = E_D \times \cos \delta. \quad (6)$$

The output power of PV modules used in this study was not the same so for comparison purpose we have normalized the output power of PV modules with their output power at STC.

The module efficiency depends upon the active area of the modules. Active area is the actual area of the module in which photovoltaic process takes place. The PR is the performance of modules at actual operating conditions compared to their performance at STC.

FIGURE 1: Positioning of photovoltaic modules showing direction towards sun and tilt angle.

TABLE 1: Physical dimensions, rated technical specifications, and measured values of photovoltaic modules.

	c-Si	p-Si	a-Si
Dimensions			
Module dimension (mm $\times$ mm)	690 $\times$ 540	690 $\times$ 455	1250 $\times$ 640
Cell dimensions (mm $\times$ mm)	156 $\times$ 52	156 $\times$ 45	1220 $\times$ 610
No. of cells (in series)	4 $\times$ 9	4 $\times$ 9	1
Total cells area (m ²)	0.292	0.2527	0.7442
Rated values			
Maximum power, $P_{\max}$ (W)	45	40	40
Maximum current, $I_{\max}$ (A)	2.2	2.3	0.47
Maximum voltage, $V_{\max}$ (V)	18.2	17.4	30.4
Short circuit current, I_{sc} (A)	2.7	2.66	0.65
Open circuit voltage, V_{oc} (V)	21.6	21.6	54.8
Temp. coefficient of I_{sc} (%/ $^{\circ}$ C)	+0.05	+0.06	+0.09
Temp. coefficient of V_{oc} (%/ $^{\circ}$ C)	-0.35	-0.36	-0.29
Temp. coefficient of P_M (%/ $^{\circ}$ C)	-0.45	-0.5	-0.20
Measured values			
Avg. global solar irradi. (W/m ²)	625.7	625.7	625.7
Avg. ambient temp. ($^{\circ}$ C)	18.1	18.1	18.1
Avg. module temp. ($^{\circ}$ C)	28.5	28.1	27.2
Avg. module current (A)	1.4	1.2	0.5
Avg. module voltage (V)	21.1	20.8	57.1
Avg. module power (W)	23.4	19.7	22.2
Avg. power output Eff. (%)	52	49.2	55.5
Avg. module efficiency (%)	13.1	12.5	5.5
Avg. performance ratio	0.85	0.8	1.03

FIGURE 2: Schematic diagram of experimental setup.

3. Results and Discussion

The data of alternative days of winter months was recorded and comparison was made. During the study, the month of February was cloudier as compared to other months. The data of two days in February could not be taken due to heavy rain.

Figure 3 shows the hourly average global solar radiation during the study. The monthly average global solar radiation was 569, 591, and 713 W/m^2 for January [26], February, and March, respectively. The hourly average output power of PV modules for winter months is shown in Figure 4. The output power has shown a linear behavior with solar irradiance and maximum output power was found to be at 12 pm corresponding to maximum solar irradiance.

The variation of daily average output power is shown in Figure 5. At higher solar irradiance (above 400 W/m^2), c-Si module has shown higher daily average output power but a-Si module has better output power at low solar irradiance (below 400 W/m^2) due to its better light absorbing characteristic, also found by Munoz-García et al. [27]. This is also clear from Figure 6, where a-Si shows better normalized output power efficiency at low solar irradiance which becomes less than crystalline silicon modules at high solar irradiance.

Table 2 shows a good comparison of average horizontal GSR of clear sky days measured in this study and already published data [28] of Islamabad for the months of January, February, and March.

3.1. Temperature Analysis. Module temperature depends upon solar irradiance as well as ambient temperature. The variation of hourly average ambient and modules temperature is shown in Figure 7. The modules temperature stays above to the ambient temperature for all three months. This is because of heat production during photovoltaic process. The a-Si module has shown lowest average module temperature. This is due to its large surface area which causes more heat convection between the module surface and surrounding air resulting in the cooling of module. The module temperature showed an increasing trend with solar irradiance. After 4 pm, the module temperature becomes lower than the ambient temperature due to sudden decrease of solar irradiance which slows down the photovoltaic process and module temperature decreases. The average module temperature is higher in March due to high average solar irradiance.

The output power of PV modules increased with module temperature but has shown a decrement from linear trend at high module temperature as shown in Figure 8. This effect is due to decrease of modules open circuit voltage V_{oc} at high module temperatures as reported by Sze [29]. The output power of a-Si module was higher for temperature range of 21 to 28°C but afterward decreased at high module temperature.

The module efficiency decreases with increase in module temperature as shown in Figure 9. The average module efficiency decreases by about 8.85%, 5.25%, and 26% for c-Si, p-Si, and a-Si modules, respectively, with the increase of module temperature from 22 to 33°C. Due to high module temperature, the monthly average module efficiency in March is lower than the other two months (Figure 12).

FIGURE 3: Bar diagram showing the hourly average global solar irradiance for January [26], February, and March.

FIGURE 4: Bar diagram of hourly average output power of monocrystalline, polycrystalline, and amorphous silicon modules measured for January [26], February, and March.

FIGURE 5: Variation of daily average output power of all days of study.

TABLE 2: Comparison of present global solar irradiance with Akhter et al. [28].

	Average global horizontal irradiance (W/m^2) of clear sky days					
	Measured values			Akhter et al. [28]		
	9:00 am	12:00 pm	3:00 pm	9:00 am	12:00 pm	3:00 pm
January [26]	315	612	324	277	651	409
February	432	625	445	341	674	516
March	494	711	394	461	762	424

FIGURE 6: Scattering plot of normalized output power efficiency of monocrystalline, polycrystalline, and amorphous silicon modules versus global solar radiations measured from 8 am to 5 pm.

FIGURE 7: Variation of hourly average module and ambient temperatures from 8 am to 5 pm.

Like module efficiency, performance ratio also showed a decreasing trend with module temperature (Figure 10), also reported by Rehman and El-Amin [10]. The c-Si, p-Si, and a-Si module have shown average PR decrement of about 5.6%, 9.3%, and 22.6%, respectively, for increase of module temperature from 22 to 33°C. The a-Si module has much higher PR as compared to crystalline modules for low

FIGURE 8: Scattering plot of hourly average output power versus the module temperature of monocrystalline, polycrystalline, and amorphous silicon modules measured from 8 am to 5 pm.

temperature range and shows a sharp decrease at high module temperature.

3.2. Module Efficiency Analysis. The module efficiency of PV modules at outdoor conditions is different from STC due to varying outdoor conditions. The hourly average module efficiency of three modules is shown in Figure 11. The module efficiency has shown inverse relation with the solar irradiance (also reported by [9, 30, 31]). At 12 pm, efficiency of modules was lowest corresponding to the highest solar irradiance. The decrease in average module efficiency was 7.8%, 8.2%, and 22.1% for c-Si, p-Si, and a-Si modules, respectively, with 175% increase of average global solar radiation from 8 am to 12 pm for three months. At 5 pm, sudden decrease in irradiance lowers the module efficiency. The c-Si module is well known for high module efficiency and has shown high module efficiency than p-Si and a-Si modules. The c-Si module has shown 37% and 134% higher average module efficiency than p-Si and a-Si modules, respectively, as shown in Figure 12. The lowest efficiency of a-Si module is due to its large module area compared to crystalline silicon modules as shown in Table 1.

3.3. Performance Ratio Analysis. The performance ratio PR represents the performance of the PV modules at outdoor

FIGURE 9: Variation of hourly average module efficiency with the module temperature of monocrystalline, polycrystalline, and amorphous silicon modules measured from 8 am to 5 pm.

FIGURE 10: Scattering plot of hourly average performance ratio versus the module temperature of monocrystalline, polycrystalline, and amorphous silicon modules measured from 8 am to 5 pm.

conditions compared to their performance under STC. It is observed that PR has a decreasing trend with the increase of global solar radiation and modules have lowest average PR at highest average global solar radiation as shown in Figure 13. It was found that average PR decreased by 5.68%, 9.3%, and 22.6% for c-Si, p-Si, and a-Si module, respectively, with increase of average solar irradiance of 175% from 8 am to 12 pm for winter months. The a-Si module due to its better performance in low light condition showed much higher PR than the crystalline silicon modules at low irradiance; however, it decreased sharply with increase in solar irradiance. The c-Si module, however, showed better performance at high irradiance with a PR close to a-Si module at this condition. It can be seen from Figure 14 that a-Si module is superior in terms of average PR due to its better performance and better light absorption at low light conditions. The a-Si module has

FIGURE 11: Variation of hourly average module efficiency of monocrystalline, polycrystalline, and amorphous silicon modules from 8 am to 5 pm.

FIGURE 12: Average module efficiency of monocrystalline, polycrystalline, and amorphous silicon modules (January, February, and March).

shown 21.2% and 28.7% higher average PR than c-Si and p-Si modules, respectively. The PR of p-Si module was lowest, close to the c-Si module.

4. Conclusion

Within the scope of this research, the hourly output power, module efficiency, and performance ratio of three modules were measured and variation of these parameters with solar irradiance and backside surface temperature of PV modules was investigated. The study concluded that output power of modules increases linearly with increase of solar irradiance. The c-Si module has shown high average output power but a-Si has shown higher normalized output power efficiency due to its better performance in low irradiance condition.

The overall average module efficiency of c-Si module was 13.01%, which is higher than average module efficiency of other two modules. Results depict that module efficiency shown a decreasing trend with increase of solar irradiance

FIGURE 13: Variation of hourly average performance ratio of monocrystalline, polycrystalline, and amorphous silicon modules from 8 am to 5 pm.

FIGURE 14: Average performance ratio of monocrystalline, polycrystalline, and amorphous silicon modules (January, February, and March).

and module temperature. The average module efficiency decreased by about 8.85%, 4.5%, and 26% for c-Si, p-Si, and a-Si modules, respectively, with the increase of module temperature from 22 to 33°C.

Due to light absorbing characteristic, a-Si module has shown higher average PR. The PR also showed a decreasing trend with solar irradiance and module temperature. The c-Si, p-Si, and a-Si module have shown average PR decrement of about 5.6%, 4.8%, and 25.8%, respectively, for increase of module temperature from 22 to 33°C.

Nomenclature

AM: Air mass
 A_a : Active area of module (m^2)
 a-Si: Amorphous silicon module
 c-Si: Monocrystalline silicon module
 GSR: Global solar radiation (W/m^2)
 E : Solar irradiance (W/m^2)
 E_D : Direct solar irradiance (W/m^2)

E_H : Solar irradiance at horizontal surface (W/m^2)

I_m : Maximum current (A)

I_{sc} : Short circuit current (A)

POA: Plane of array

PR: Performance ratio

P_m : Maximum power (W)

P_{mea} : Measured power output (W)

PV: Photovoltaic

p-Si: Polycrystalline silicon module

STC: Standard test condition

V_m : Maximum voltage (V)

V_{oc} : Open circuit voltage (V)

δ : Zenith angle

η_p : Normalized power output efficiency

η_{mod} : Module efficiency.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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