

OUTDOOR TESTING OF PHOTOVOLTAIC MODULES DURING SUMMER IN TAXILA, PAKISTAN

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An experimental study has been carried out to measure the performance of commercially available photovoltaic modules during summer months in the climate of Taxila, near the capital of Pakistan. The modules used in the study are monocrystalline silicon (c-Si), polycrystalline silicon (p-Si) and single junction amorphous silicon (a-Si). The analysis has been focused on the measurement of module efficiency, performance ratio and temperature of each module at actual operating conditions using outdoor monitoring facility. The measured results are compared with the already published data of peak winter month at the same site. Overall, the monocrystalline module showed high average module efficiency while amorphous silicon module was better in term of average performance ratio. Furthermore, the module efficiency and performance ratio has shown decreasing trend with increase of module temperature. It was found that modules have much higher temperature in summer months (about 20°C higher) and showed low efficiency and performance ratio than peak winter month. The average ambient temperature varied from 18.1°C to 38.6°C from winter to summer.

Keywords: *Photovoltaic modules, Photovoltaic performance analysis, Outdoor testing, Temperature dependence*

1. INTRODUCTION

At present, the energy crisis is the most crucial issue. Renewable energy is a viable source of energy that can be used to meet the energy needs of global population and to avoid adverse environmental effects caused by the use of fossil fuels. Photovoltaic technology is one of the promising applications of renewable energy technologies, widely used in urban areas and remote locations.

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The performance of photovoltaic modules depends on the environmental conditions and seasons of year. Previous research depicts that modules of different technologies have shown particular behavior for a specific climate. Amin et al. [1] investigated the performance of four different types of solar panels including mono crystalline, multi-crystalline, amorphous silicon and copper indium diselenide (CIS) in outdoor conditions of Malaysia. Results showed that the performance of mono-crystalline and poly-crystalline panel was better at high temperature but amorphous silicon performed better in cloudy weather. Pavlovic et al. [2] compared the outputs of one axis and dual axis tracking solar plants in Serbia. Results showed that as compared to fix PV solar plant, electricity generation increased 20.14% and 22.06% by using one axis and dual axis tracking system respectively. Carr et al. [3] performed experiments on five different PV modules in Perth, Western Australia and analysed that triple junction a-Si produced 8% more energy in winter and 15% more in summer than other modules. Midtgard et al. [4] described the performance of three different types of solar panels (mono crystalline, multi crystalline and amorphous silicon PV modules) in the climate of Norway. It was found that mono-crystalline was better in terms of average output power and module efficiency compared to polycrystalline and amorphous silicon modules.

The rated values of photovoltaic modules provided by the manufacturer are based on standard test conditions (global irradiance of 1000 W/m², module temperature of 25°C and air mass 1.5). These values may not agree with the measurement in actual operating conditions due to varying environmental parameters [5]. The efficiency of modules decreases with the increase of module temperature [6],[7], therefore for high performance, cooling is required at high temperatures[8]. The a-Si modules undergo photovoltaic degradation when exposed to sunlight [9],[10]. There are certain other unavoidable factors affecting on the performance of the PV modules such as dust accumulation, wind speed and direction [11]. Jiang et al.[12] performed experiments on three solar cells in a laboratory with sun simulator and test chamber and concluded that output efficiency decreased up to 26% when dust deposition density increased up to 22 g/m². Akhter et al.[13] measured the solar radiation data for Islamabad over a year. According to their study, the month of May, June and July have average 79%, 87%, 60% clear sky days and 12.3, 11.6 and 12.7 sunshine hours/day respectively in Islamabad. Bashir et al. [14] reported the performance data for different PV modules (monocrystalline, polycrystalline and amorphous silicon) for January in the climate of Taxila and found that monocrystalline module was more efficient showed average module efficiency of 13.01%. The a-Si module showed average PR 1.03 and performed better than other two modules at that site. Furthermore, module efficiency and PR showed decreasing trend with the increase of solar irradiance and module temperature. (This data will be used for the purpose of comparison with the present investigation).

This paper presents the performance measurement of commercially available PV modules over the three summer months. The results are compared with the already published data of peak winter month (January) [14] at the same site. The effect of temperature and solar irradiance on the output of PV module is analyzed and compared.

2. METHODOLOGY AND EXPERIMENTAL SETUP

An outdoor measurement system was installed at the building of Mechanical Engineering Department, University of Engineering & Technology, Taxila, Pakistan. The PV modules were placed on a structure at the top floor facing toward south. The PV modules were tilted at a fix angle of 12° with horizontal [Fig. 1]. The modules specifications and measured values are summarized in Table 1.

The same experimental setup has already been used for an already published work [14] for the month of January. The calibration of all instruments was entrusted to the Pakistan metrological department (PMD) Islamabad at the beginning of work. The solar radiation monitoring system having a pyranometer TBQ-2 (sensitivity 11.346 μ V/Wm⁻², spectral range 280~3000 nm) was used to measure the solar irradiance in plane with the PV module. The solar irradiance was recorded after every 30 sec. The module temperature was measured using K-type thermocouples attached to the central cell of each PV module with heat conducting paste. The characteristic parameters of PV modules were obtained from I-V curve, drawn by using variable resistance and multimeters as described by Bashir et al. [14]. The performance related parameters are calculated using following equations,

Table 1- Modules Specifications and Measured Values

	c-Si	p-Si	a-Si
Module Dimensions			
Module Dimensions mm x mm	690x540	690x455	1250x640
Cell Dimensions (mm x mm)	156x52	156x45	1220x610
No. of cells in series	4x9	4x9	1
Cell area (m ²)	0.292	0.2527	0.7442
Rated Values			
Maximum Power, P _{max} (W)	45	40	15
Maximum Current, I _{max} (A)	2.2	2.3	0.42
Maximum Voltage, V _{max} (V)	18.2	17.4	30.04
Short Circuit Current, I _{sc} (A)	2.7	2.66	0.62
Open Circuit Voltage, V _{oc} (V)	21.6	21.6	54.7
Measured Values			
Avg. Ambient Temp. (°C)	36	36	36
Avg. Module Temp. (°C)	41.8	41.7	41.5
Avg. Module Power (W)	21.5	18.3	8.2
Avg. Module Efficiency (%)	11.3	10.9	2.0
Avg. Performance Ratio	0.7	0.7	0.9

Maximum Power:

$$P_{\max} = V_{\max} \times I_{\max} \quad (1)$$

Module Efficiency:

$$\eta_m = \left(\frac{P_{mea}}{IrrxA} \right) \times 100 \quad (2)$$

Normalized Power Output Efficiency:

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

Performance Ratio:

(4)

$$PR = \left(\frac{P_{mea}}{P_{STC}}\right) / \left(\frac{Irr}{1000}\right)$$

Horizontal Solar Irradiance:

$$E_H = E_D \times \cos\alpha \tag{5}$$

The experiments were performed at Taxila, Pakistan (latitude 33.74 °N and longitude 72. 83 °E) for three months of summer (May, June and July). The measurements were taken hourly from 7 am to 6 pm for three days of a week. The measured data of summer months are compared with the already published data of winter month (January) [14], at same site. The purpose of this comparison was to analyze the effect of module temperature (which was significantly higher in summer compared to winter) on its performance parameters.



Figure 1- Orientation of PV Modules

3. RESULTS AND DISCUSSION

During this study, most days were sunny having average daily solar irradiance above 500 W/m². The measurements for two days of July could not be taken due to bad weather. Fig. 2 shows the variation of hourly average solar irradiance of three months. The Solar irradiance increases linearly up to 1:00 pm and then decreases in the evening. The maximum average solar irradiance was between 12:00 pm and 1:00 pm. The monthly average solar irradiance of summer months was higher than January [14] as shown in Fig. 3. The average solar irradiance was 16.3%, 19.6% and 10.2% higher for May, June and July respectively compared to January [14]. Table 2 shows a good comparison of clear day horizontal solar irradiance measured in this study and already published data [13] of Islamabad for summer months.

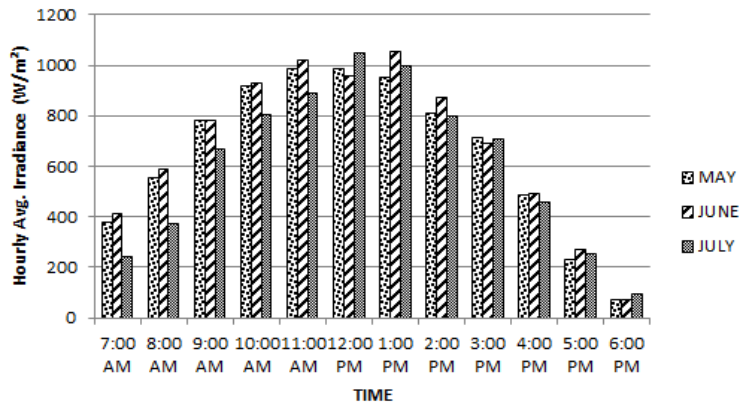


Figure 2- Hourly Avg. Solar Irradiance for Summer Months

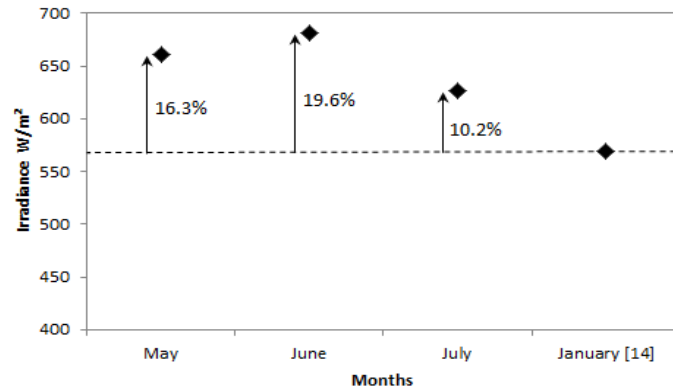


Figure 3- Monthly Avg. Solar Irradiance of Summer Months In Comparison with January

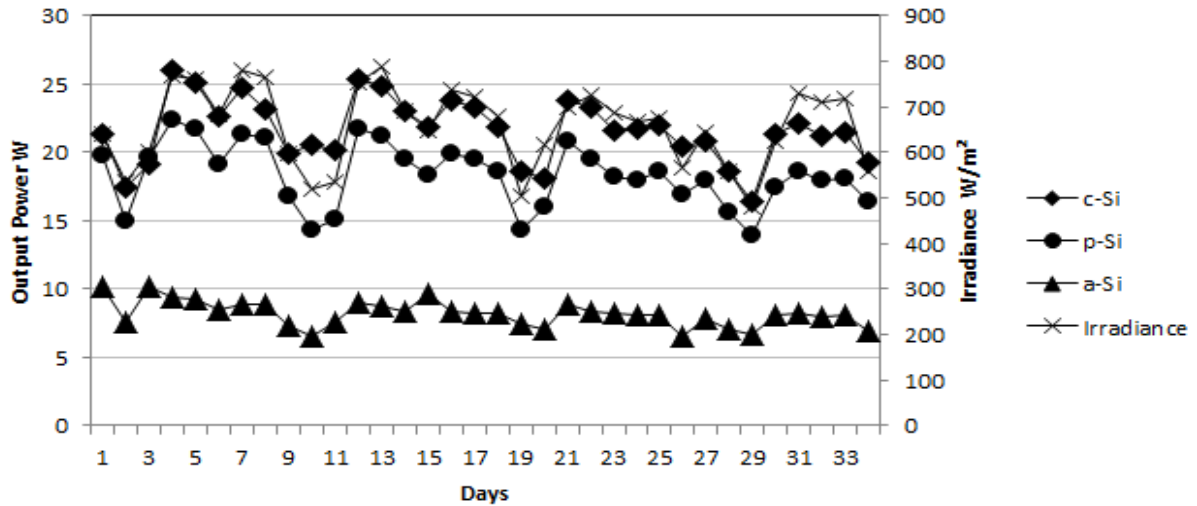


Figure 4- Variation of Avg. Output Power of All Days

The variation of daily average output power of modules over the course of this study is shown in Fig. 4. Crystalline silicon modules are more sensitive to the incident light showing sudden decrease of output power at low light conditions (low irradiance). The output of a-Si module is more stable as it performs better in low light as well. This is further clear from Fig. 5 where a-Si module shows high average normalized output power efficiency than crystalline modules at solar irradiance below 800 W/m².

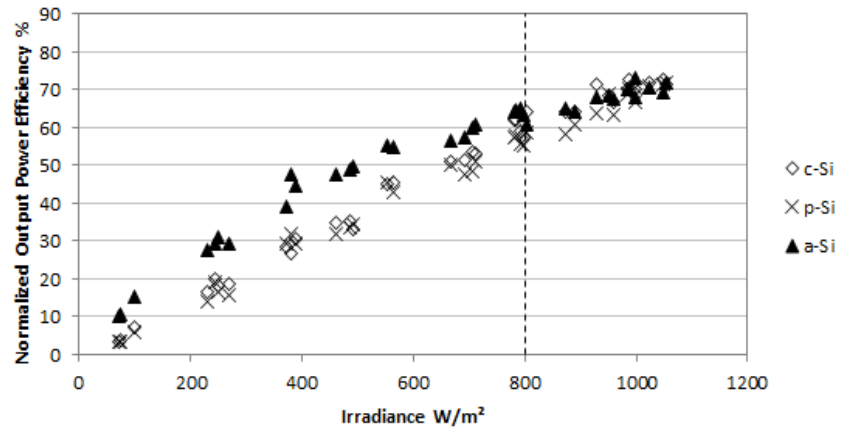


Figure 5- Daily Avg. Normalized Output Power Efficiency vs. Irradiance

Table 2- Comparison of Measured Avg. Global Horizontal Solar Irradiance with Akhter et al. [13]

	Average Global Horizontal Solar Irradiance (W/m ²) of Clear Sky Days								
	May			June			July		
Time	09:00 am	12:00 pm	03:00 pm	09:00 am	12:00 pm	03:00 pm	09:00 am	12:00 pm	03:00 pm
Average Measured Values	796	964	722	747	954	679	677	998	704
Akhter et al. [13]	663	928	781	647	897	805	655	912	778

3.1. Module Efficiency Analysis

Module efficiency is the energy output by the module to the energy input from the sun. The varying environmental conditions cause module efficiency at actual operating conditions lower than STC. The hourly average module efficiency is shown in Fig. 6. The module efficiency showed decreasing trend with the increase of solar irradiance. The lowest module efficiency was at 1 pm corresponding to the highest solar irradiance. The average module efficiency of c-Si, p-Si and a-Si modules decreased about 14.9%, 12.28% and 36% respectively with 355 W/m² increase of average solar irradiance from 7 AM to 1 PM.

Fig.7 shows the comparison of monthly average modules efficiency of summer months with already published data of January [14]. It is clear that all modules showed lower module efficiency in summer months compared to the January despite the fact that summer months have higher solar irradiance in comparison to January (see Fig. 3). However, the decrease of module efficiency in summer months was due to the reason of higher module temperature (15-20°C) in summer (see Fig. 10 & 12). Higher module temperature adversely effects on the efficiency of PV technology [6], [8].

The c-Si module is superior in terms of average module efficiency. The monthly average module efficiency of c-Si module was 14.7%, 17.6% and 15.2% lower in May, June and July respectively compared to January [14]. The p-Si module showed 14.6%, 17.8% and 15.3% decrease of module efficiency in May, Jun and July respectively compared to January [14]. The a-Si module showed low average module efficiency as its rated power is about 3 times less than the rated power of crystalline modules and has large module area. The module efficiency of a-Si was 7.4%, 13.4% and 9.7% lower in May, June and July respectively compared to January [14]. For a-Si module, less difference in the module efficiency between January and summer months confirms that output of a-Si module is more stable against the change of solar irradiance. Furthermore, all modules showed lowest module efficiency in June due to high average solar irradiance in this month (see Fig. 7).

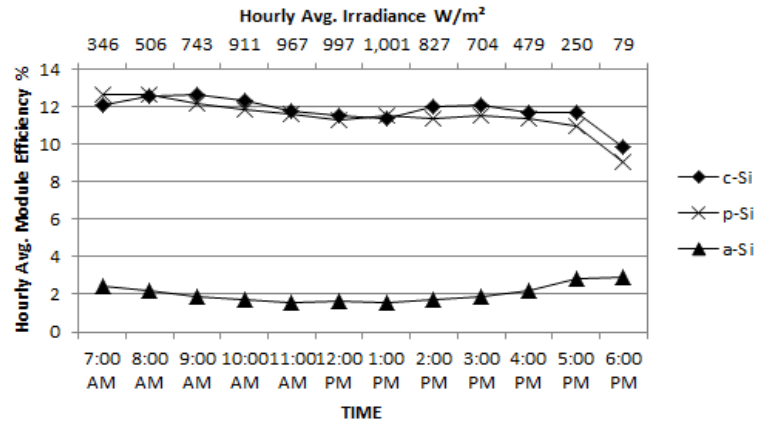


Figure 6- Hourly Avg. Module Efficiency of Three Summer Months with Time

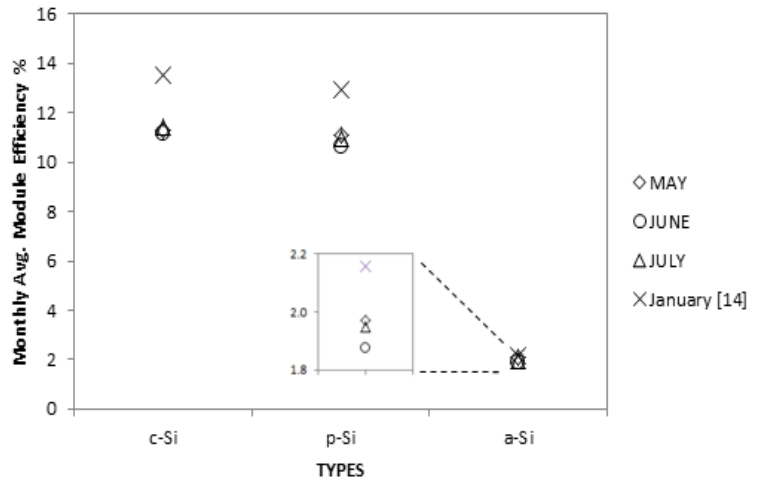


Figure 7- Comparison of Monthly Avg. Modules Efficiency of Summer Months with January [14]

3.2. Performance Ratio analysis

Performance ratio analysis determines the performance of PV modules in actual climate compared to their performance at STC. PR may have value more than 1 because average irradiance in actual operating conditions is lower than STC value (1000 W/m^2). Fig. 8 shows the variation of hourly average PR of modules for three months. Like module efficiency, decrease in PR was recorded with the increase of solar irradiance. The PR of c-Si, p-Si and a-Si modules decreases 9.1%, 12.3%, 33.3% with 355 W/m^2 increase of solar irradiance from 7 to 1 pm. a-Si module showed higher average PR at low solar irradiance and it decreased sharply with increase of solar irradiance.

The variation of monthly average PR for summer months and the month of January [14] is shown in Fig. 9. It can be seen that like module efficiency, average PR of summer months is lower than the January due to much higher module temperatures ($15\text{-}20^\circ\text{C}$) in summer months as described earlier.

The c-Si module has shown average performance ratio less than 1. The average PR of c-Si was 17%, 18.1% and 18.2% lower in May, June and July respectively compared to January [14]. The average PR of p-Si module was lower compared to other modules and is close to the PR of c-Si module. As shown in Fig. 9, the average PR of p-Si module was 15.7%, 19.3% and 18.1% less in May, June and July respectively compared to January [14]. The a-Si module was found to perform better in this climate having higher average PR than the crystalline modules. The same pattern of variation of PR can be seen from January to summer months. The average PR of a-Si module was found 9.3%, 13.1% and 14% lower in May, June and July respectively compared to January [14]. The higher average PR of a-Si module is due to its better light absorbing characteristic and thus performs better in low irradiance conditions [3].

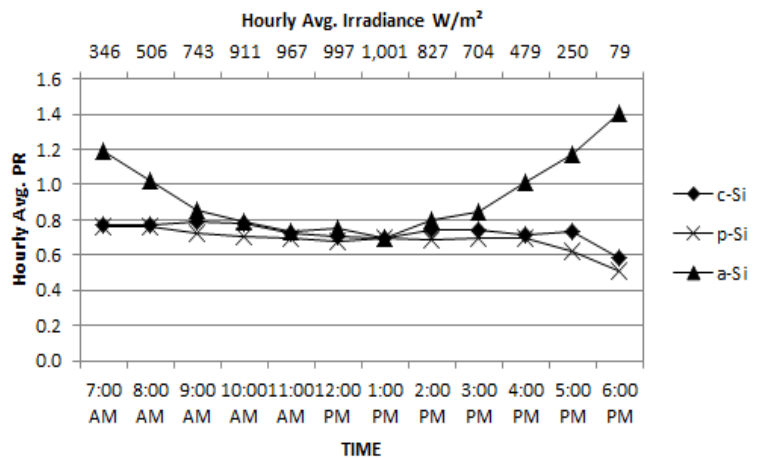


Figure 8- Hourly Avg. PR of Three Summer Months with Time

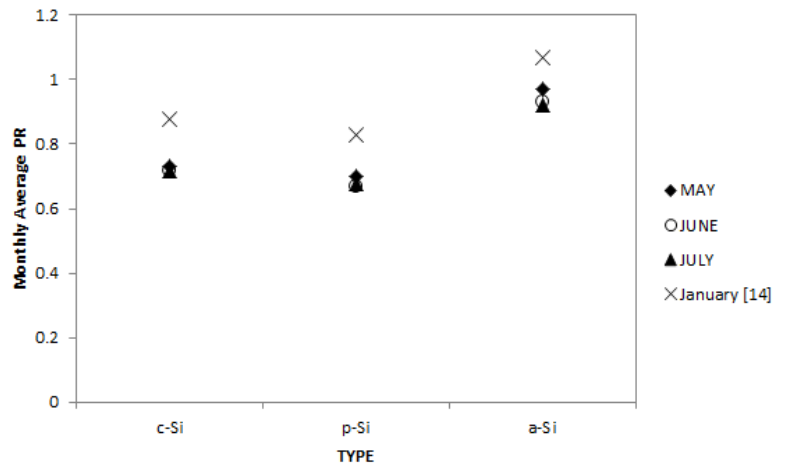


Figure 9- Comparison of Monthly Avg. PR of Summer Months with January [14]

3.3. Module Temperature Analysis

Fig.10 shows the variation of hourly average temperatures of all three months (May, June and July). The temperature data of summer months were compared with the hourly average temperature of January [14]. From this pattern of variation, it is seen that module temperature is higher than the ambient temperature for all months (Fig. 10). After 5 pm, the module temperature decreased and became less than the ambient temperature due to sudden decrease of solar irradiance. Furthermore, temperature shows direct proportionality with the solar irradiance.

The temperature in summer months was much higher than the temperature in January [14] due the high average solar irradiance in summer. The monthly average ambient temperature showed an increment of 134%, 113.4% and 93% from January to May, June and July respectively. Likewise module temperature has high values in the months of summer than January. The module temperature in January [14] ranges from 20°C to 31°C where as in summer months it ranges from 34°C to 50°C.

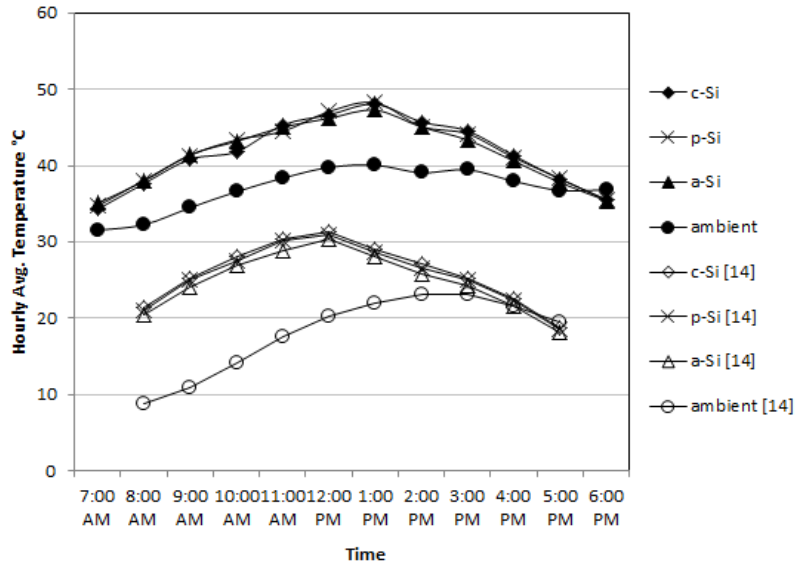


Figure 10- Hourly Avg. Temperatures of Summer Months and January [14]

Fig.11 shows the variation of average module efficiencies of the summer months and January [14] with the module temperatures. As the hourly average module temperature increased, a corresponding decrease in module efficiency was recorded for all months. However, the rate of decrease in module efficiency slows down after 45 °C. At lower module

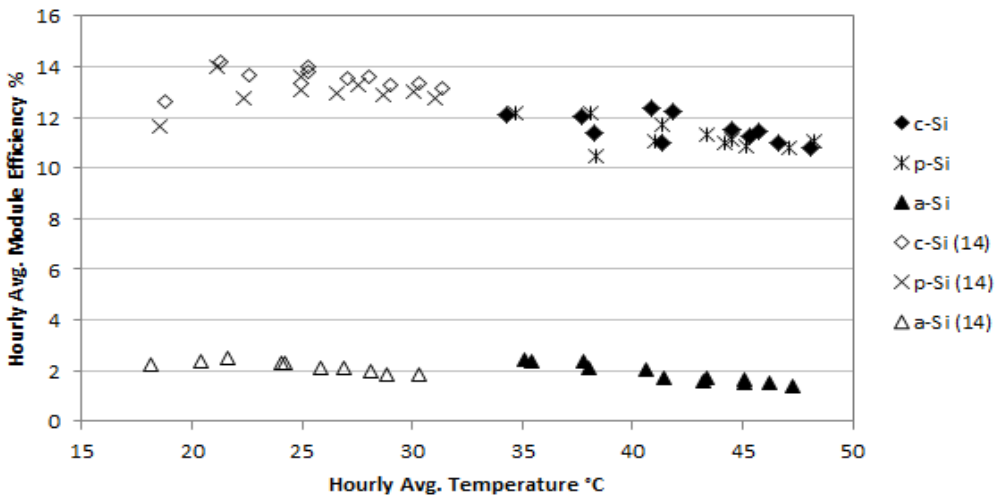


Figure 11- Hourly Avg. Module Efficiency vs. Avg. Module Temperature (Summer Months and January [14])

temperature in the month of January [14], the module efficiencies was higher than the summer months. The average module efficiency of c-Si, p-Si and a-Si modules was 19.8%, 18.7% and 14.8% higher respectively for January as compared to the average module efficiency of three summer months as shown in Fig. 12. The average module temperature was increased by 68.3% from January to summer months.

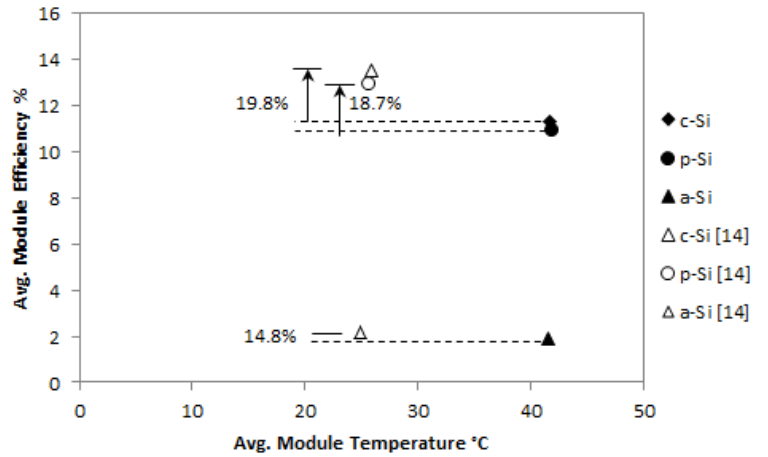


Figure 12- Average Module Efficiency of Summer Months and January [14] vs. Avg. Module Temperature

A similar trend can be seen for PR of modules in Fig. 13. The hourly average PR shows a continuous decrement with increase of module temperature. As expected, the a-Si module has much high PR at low module temperature and it decreases suddenly with the increase of module temperature. The PR of c-Si, p-Si and a-Si modules in January was 20.5%, 20.3% and 13.8% higher compare to the average PR of summer months with 68.3% increase of average module temperature as shown in Fig. 14.

As expected, the a-Si module has much high PR at low module temperature and it decreases suddenly with the increase of

module temperature. The PR of c-Si, p-Si and a-Si modules in January was 20.5%, 20.3% and 13.8% higher compare to the average PR of summer months with 68.3% increase of average module temperature as shown in Fig. 14.

As the performance of PV modules decreases with the increase of module temperature, a suitable cooling system may be used to reduce the module temperature. One of the most popular system used now a days is photovoltaic thermal (PV/T) solar system, increasing the solar cells output up to 50%.

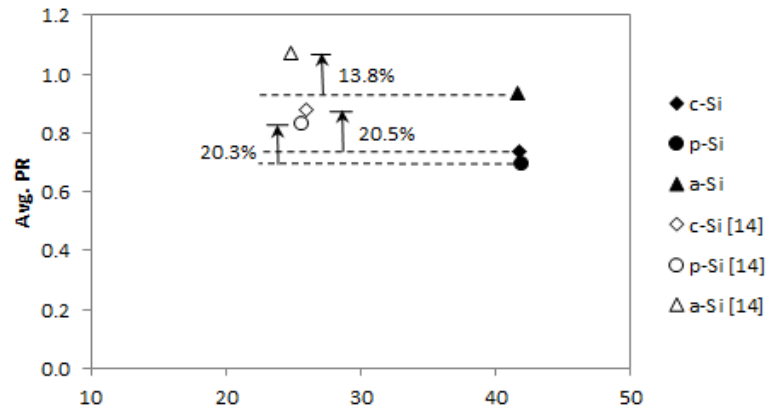


Figure 14- Average PR of Summer Months and January [14] vs. Avg. Module Temperature

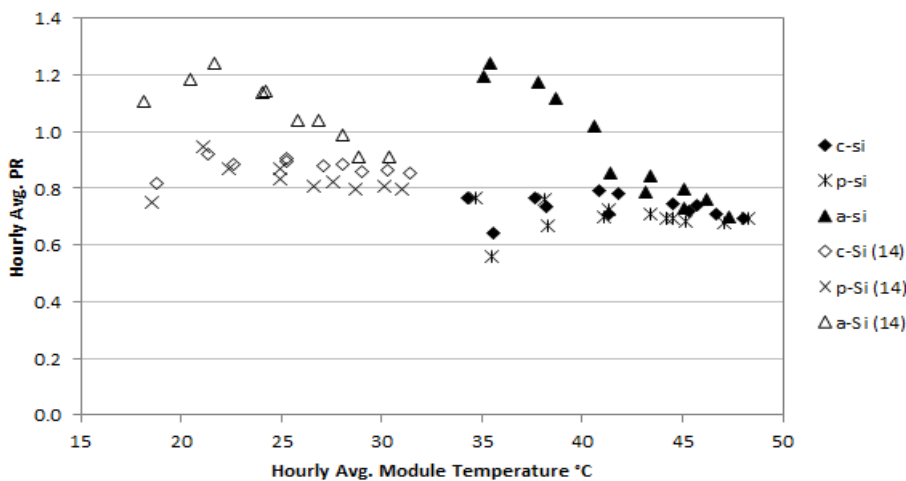


Figure 13- Hourly Avg. PR vs. Avg. Module Temperature (Summer Months and January [14])

4. CONCLUSIONS

The hourly performance data of three commercially available PV modules are reported for three summer months and are compared with the already published data of peak winter month for the same site. It was found that module temperature has significant effect on the output of PV modules. In the analysis of summer months, c-Si module showed average module efficiency of 11.4% which is higher than the other modules used in this study. The a-Si module showed low module efficiency but has shown higher average performance ratio. The module efficiency and performance ratio of PV modules decreased with the increase of solar irradiance and module temperature. The average module efficiency of c-Si, p-Si and a-Si modules decreased about 14.9%, 12.28% and 36% respectively with 355 W/m² increase of average solar irradiance from 7 am to 1 pm. Similarly, average PR of c-Si, p-Si and a-Si modules decreased 9.1%, 12.3% and 33.3% respectively from 7 AM to 1 PM.

In comparison with January [14], the average solar irradiance was much higher in summer months. The avg. solar irradiance was 16.3%, 19.6% and 10.2% higher in May, June and July respectively compared to January [14]. The average module temperature was increased by 68.3% from January to summer months. The module temperature in January [14] ranges from 20°C to 31°C where as in summer months it ranges from 34°C to 50°C.

The average module efficiency of c-Si, p-Si and a-Si modules was 19.8%, 18.7% and 14.8% higher for January [14] as compared to the average module efficiency of three summer months respectively. Similarly, the PR of c-Si, p-Si and a-Si modules was 20.5%, 20.3% and 13.8% higher in January [14] compared to the average PR of summer months with 68.3% increase of average module temperature.

Nomenclature

<i>a-Si</i>	amorphous silicon module
<i>c-Si</i>	mono crystalline silicon module
E_D	direct solar irradiance [Wm ²]
E_H	solar irradiance at horizontal surface [Wm ²]
I_{max}	maximum current [A]
<i>Irr</i>	solar irradiance [Wm ²]
I_{sc}	short circuit current [A]
<i>PR</i>	performance ratio
P_{max}	maximum power [W]
P_{mea}	measured power output [W]
<i>PV</i>	photovoltaic
<i>p-Si</i>	poly crystalline
<i>STC</i>	standard test condition
V_{max}	maximum voltage [V]
V_{oc}	open circuit voltage [V]
η_m	module efficiency
α	angle of tilt with horizontal

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