AN EXPERIMENTAL INVESTIGATION OF PERFORMANCE OF PHOTOVOLTAIC MODULES IN PAKISTAN

by

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An outdoor experimental study was carried out to investigate and compare the performance of three commercially available photovoltaic modules (monocrystalline, polycrystalline, and single junction amorphous silicon) under the weather at Pakistan for the month of January. Power output efficiency, module efficiency, and performance ratio are calculated for each module and comparison is presented. Results have shown that monocrystalline and polycrystalline modules perform better at high irradiance and show poor performance in low irradiance conditions. Amorphous solar module has shown better light absorption characteristic and performs better in low irradiance i. e. in cloudy and diffuse sunshine conditions. Monocrystalline photovoltaic module is found to be more efficient, having module efficiency of 13.5% which is higher than the other two modules. Furthermore the power output of monocrystalline and polycrystalline modules has shown a higher decrement at higher module temperatures compared to the amorphous solar module. Because of better performance in low solar irradiance, amorphous solar module has shown monthly average performance ratio of 1.07 which is higher than other photovoltaic modules under study.

Key words: *photovoltaic modules, photovoltaic performance, outdoor testing, performance ratio*

Introduction

The basic requirement of photovoltaic (PV) power generation system of any geological location is to have accurate estimation of its performance at outdoor operating conditions. The information given by the manufacturer of a PV module is based on standard test condition (STC) (irradiance 1000 W/m^2, module temperature 25 °C, and air mass 1.5). The STC results may not agree with the actual operating conditions due to the variation of environmental parameters Fuentes *et al*. [1]. In order to install a PV system at a specific location an accurate and trustworthy performance data are required. The basic types of commercially available PV modules are crystalline silicon and thin film PV modules. Crystalline silicon modules have high effi-

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ciency but thin film modules have advantage of low cost and better light absorbing characteristics. The previous research has shown that the PV modules of different types have different pattern of behavior for specific climates. Carr and Pryor [2] reported the performance comparison of five different types of PV modules including crystalline silicon (c-Si), c-Si module with laser grooved buried contact, polycrystalline silicon (p-Si), triple junction amorphous silicon, and copper indium diselenide (CIS) in the climate of Perth city, Australia, for a year. Results showed that thin film PV modules have high performance ratio (PR) and produce most energy at that site. Amin *et al*. [3] investigated the performance of monocrystalline, polycrystalline, amorphous silicon and CIS PV modules for three consecutive days in Malaysia. They found that CIS module has PR of 1.09 which is the highest amongst four tested PV modules. However, the module efficiency of c-Si module is better than all other modules. A performance measurement of three different PV modules including monocrystalline, polycrystalline, and triple junction amorphous silicon modules in Norway [4] shows that monocrystalline PV module performs best in terms of maximum efficiency and overall energy production at that region. Ahmed *et al.* [5] investigated the outdoor performance of amorphous silicon and p-Si modules and concluded that amorphous silicon has high efficiency and output power during summertime and it was opposite for p-Si module. The module temperature affects the characteristics parameters. It is well researched fact that at high temperature, the output voltage drops and hence efficiency of PV module decreases [6]. Therefore, a cooling mechanism is required at high solar insulation [7]. The PV modules exposed to sunlight in actual operating conditions for long time do not maintain their initial operating conditions. Modules undergo some degradation and hence module performance decreases [8, 9].

The performance of PV module is affected by environmental factors including wind speed and direction, dust accumulation, humidity, *etc*. [10] reported the 32% reduction in performance of PV module in KSA during 8-month due to the dust accumulation. Jiang *et al.* [11] investigated the effect of dust deposition using a test chamber and solar simulator in lab and found a decrease in module efficiency up to 26% for dust accumulation of 22 g/m^2. Goossens and Kerschaever [12] investigated the effect of airborn dust and wind speed on the performance of PV modules. They found that these factors have significant effect on the PV module performance.

Due to current energy crisis, solar energy has immense importance in Pakistan, having high insulation and long sunshine hours. In most areas of country the daily Sun shines are 7-8 hours [13] and about 3000-3300 sunshine hours per year [14]. The mean annual solar irradiation is 15-21 MJ/m^2 and average daily global irradiance is 19-20 MJ/m^2 per day [15]. These conditions make Pakistan most suitable region for solar energy utilization. In Pakistan, however no subsequent research has been conducted related to PV technology.

This paper presents the measurement and analysis of results obtained by outdoor testing of monocrystalline, polycrystalline, and single junction amorphous PV modules for the month of January (coldest month of the year). The aim of this study is to evaluate the performance of commercially available PV modules in real weather conditions of Pakistan and to decide which type of PV technology is more suitable for these conditions. As reported by Ulfat *et al*. [14], the months of December and January have the lowest average global solar irradiation in Islamabad city. The measurement of PV modules during these months has therefore great importance.

The present investigation was conducted at the site of Renewable Energy Research and Development Center, UET Taxila (Latitude 33.74 °N, longitude 72.83 °E) situated near to Islamabad, in north Pakistan.

Methodology

Three commercially available PV modules including monocrystalline silicon (c-Si), polycrystalline silicon p-Si and single junction amorphous silicon (a-Si) were used in this study (fig. 1). Table 1 shows the specifications and characteristic parameters of all modules used in this study. Rated values are given by the manufacturer of PV modules at STC and actual values are measured values at outdoor conditions. The a-Si module was purchased a few years back and has very low output power than rated values. The rated maximum power output was 40 W but the recent STC measurement performed has shown the output power near to 15 W. Low output power may be due to the light induce degradation (Steabler-Wronski effect) as reported in [16].

Figure 1. Photovoltaic modules

Table 1. Modules specification and characteristic parameters

	c-Si	p-Si	a-Si
Dimensions			
Module dimensions [mm × mm]	690 × 540	690 × 455	1250 × 640
Cell dimensions [mm × mm]	156 × 52	156 × 45	1220 × 610
No. of cells (in series)	4 × 9	4 × 9	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	0.622
Open circuit voltage, V_{oc} [V]	21.6	21.6	54.7
Measured values			
Avg. ambient temperature [°C]	18.1	18.1	18.1
Avg. module temperature [°C]	25.9	25.6	24.9
Avg. module current [A]	1.4	1.2	0.5
Avg. module voltage [V]	21.1	20.8	57.1
Avg. module power [W]	22.3	18.7	8.3
Avg. power output eff. [%]	49.56	46.7	55.1
Avg. module efficiency [%]	13.5	13.0	2.8
Avg. performance ratio	0.87	0.83	1.07

Experimental set-up and procedure

The experiments were performed at the roof top of Mechanical Engineering Dept. UET Taxila in northern Pakistan (Latitude 33.74 °N, longitude 72.83 °E). Measurements were taken for alternative days of the month of January. The readings were taken hourly from 8.00 a. m. to 5.00 p. m. The three modules under study were mounted on a south facing rack at a fixed tilt angle of 48° with horizontal (at a nearly optimum tilt angle at this site during January). The plane of array global solar irradiance was measured using a pyranometer TBQ-2 (sensitivity 11.346 μV/Wm^2, Spectral range 280~3000 nm) connected with a solar radiation monitoring system which records and stores data after every minute. The pyranometer TBQ-2 and solar radiation monitoring system (range 0-2000 W/m^2, accuracy error < 2%, resolution 1 W/m^2) were calibrated by Pakistan Meteorological Department at Islamabad before the start of experimentation.

Each PV module was connected to two digital multimeters (Fluke 179, True RMS, accuracy: ±1% for DC current and ±0.09% for DC volt) for the measurement of voltage and current. A high power multiturn variable resistance, 100 W, was connected in series in the circuit to vary the output of the module from zero to maximum. Each PV module was connected to a separate circuit and measurements of all modules were taken at the same time. The I_{max}, V_{max}, and P_{max} were obtained from *I-V* and *P-V* curves drawn from measured data. There was not much variation of solar irradiance during measurement in sunny days. To estimate the error in global irradiance during the measurement time, the average of all the global irradiance values recorded by solar monitoring system during that measurement was used. The module temperature was measured using K-type thermocouples embedded with digital multimeters (Fluke 179). The K-type thermocouples were attached at the middle of each module with the help of heat conducting paste.

The other related parameters including P_{max}, fill factor, normalized output efficiency, module conversion efficiency, and PR are calculated to understand the behavior of solar modules using the equations:

– maximum power

$$P_{\max} = V_{\max} \cdot I_{\max} \tag{1}$$

– fill factor

$$\mathrm{FF} = \frac{V_{\max} \cdot I_{\max}}{V_{\mathrm{oc}} \cdot I_{\mathrm{sc}}} \tag{2}$$

– normalized power output efficiency

$$\eta_{\mathrm{p}} = \frac{P_{\mathrm{mea}}}{EA_{\mathrm{a}}} 100 \tag{3}$$

– module efficiency

$$\eta_{\mathrm{m}} = \left(\frac{P_{\mathrm{mea}}}{EA_{\mathrm{a}}} \right) 100 \tag{4}$$

– performance ratio

$$\mathrm{PR} = \frac{\dfrac{P_{mea}}{P_{\max(\mathrm{STC})}}}{\dfrac{E}{1000}} \tag{5}$$

– direct solar irradiance

$$E_{\mathrm{D}} = \frac{E_{\mathrm{H}}}{\cos \delta} \tag{6}$$

The comparison of modules cannot be made by output power of module as all modules have different rated power, so for comparison of modules power output efficiency normalized to its value at STC is used.

The module conversion efficiency is the ratio of measured power output recorded to the power input from the Sun. The power input is the product of total solar irradiance and the active area of the module. The active area is the actual area of the module which receives the incoming solar irradiance and undergoes PV process.

The PR is calculated for direct comparison for the modules of different technologies. It gives the performance of PV modules at outdoor conditions relative to their performance at STC.

Results and discussion

During the study, the variation in daily average irradiance is shown in fig. 2. The irradiation was measured in plane with the PV modules. The average, maximum and minimum irradiance of experimentation days were 569 W/m^2, 787 W/m^2, and 215 W/m^2, respectively. Figure 3 shows the hourly average irradiance of all days. The average irradiance is maximum at 12:00 p. m., corresponds to the peak output power of solar modules.

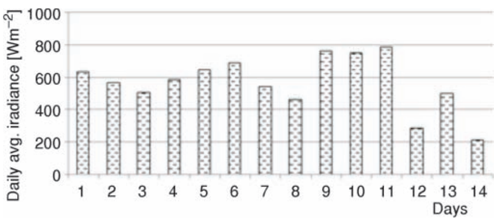

Figure 2. Daily avg. irradiance of all days

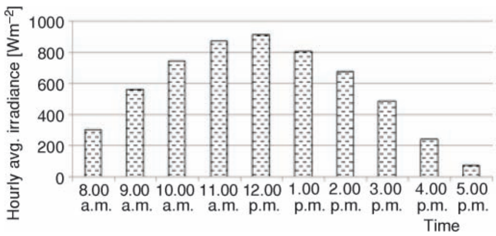

Figure 3. Hourly avg. irradiance *vs.* time

Table 2 shows the clear sky day values of average global normal irradiations measured in this study and previously published data by Akhter *et al.* [17] for Islamabad for the month of January, a close agreement can be seen. It can be seen from fig. 4 that output power of the solar modules increases with the increase in solar irradiance and decreases in the evening, this trend is also reported by Maluta [18]. At high irradiance more heat is produced by the PV modules due to high energy absorption. In this study c-Si PV module has shown highest power output (Wp) and a-Si has shown the lowest (fig. 4). This is due to the high install capacity of c-Si and low install capacity of a-Si module. It is better to examine the variation in output of modules with irradiance due to the fluctuation of irradiance. Figure 5 shows the variation of power output per unit area (W/m^2) of modules with irradiance. It can be seen that output power of a-Si is lower than the c-Si module but it performs better than crystalline modules in low light condition (fig. 8). This is due to the better light absorbing characteristic

Table 2. Comparison of present global normal irradiance with Akhter *et al.* [17] for January

	Average global normal irradiance of clear sky days [Wm^{-2}]		
Time	9:00 a. m.	12:00 p. m.	3:00 p. m.
Measured values	793	968	799
Akhter *et al.* [17]	730	941	819

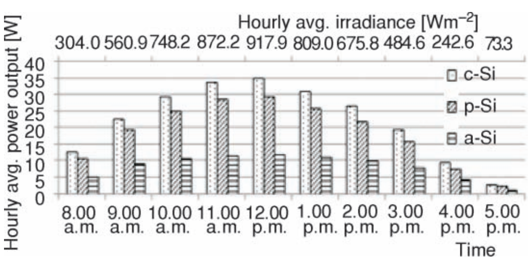

Figure 4. Hourly avg. power output *vs.* time

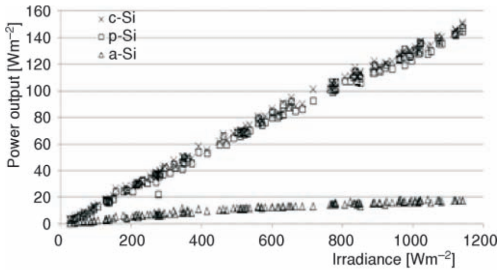

Figure 5. Output power [Wm^{-2}] *vs.* irradiance

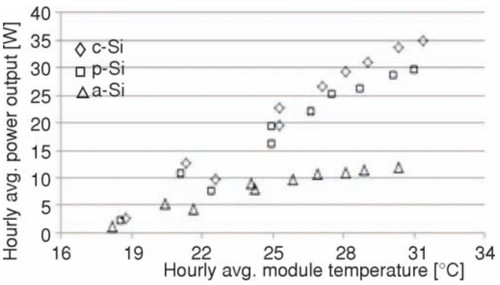

Figure 6. Hourly avg. power output *vs.* module temperature

of a-Si module than bulk crystalline modules as reported by Munoz-Garcia *et al.* [19]. It is further clear from fig. 8 where a-Si module shows high power output efficiency at low irradiance level. Furthermore, output power of a-Si gets stabilized at higher irradiance and does not vary much linearly with irradiance as it can be seen from fig. 5.

Figure 6 shows the variation of hourly average power output with module temperature. The output power of c-Si and p-Si modules at high module temperature shows a higher deviation (decrement) from linear trend than a-Si module. This shows that a-Si module withstands better at high module temperature than crystalline module.

Analysis of normalized power output efficiency

For comparison purpose, we have used the output power of all modules normalized to their power at STC. Figure 7 shows the hourly average normalized power output efficiency of modules under study. The normalized output efficiency increases steadily with increase in irradiance. The maximum power output efficiency was at 12.00 p. m. corresponding to the maximum irradiance.

As shown in fig. 7, c-Si has better power output efficiency at high irradiance condition but it drops sharply at low irradiance. This is due to the reason that c-Si has poor performance at low light conditions [3]. The a-Si module shows different behavior as it performs better in low light conditions as well. At 8.00 a. m., the avg. power output efficiency of a-Si is 23% higher than c-Si and at 12.00 p. m. it is only 1.7% high. At 5.00 p. m. there is lowest average irradiance, the output power efficiency of a-Si is 38% higher than c-Si module (fig. 7). It is also clear from fig. 8 that a-Si performs better in low light conditions than c-Si module. At high irradiance level, c-Si module shows high power output efficiency but a-Si module shows decrease in power output efficiency at this irradiance level (fig. 8).

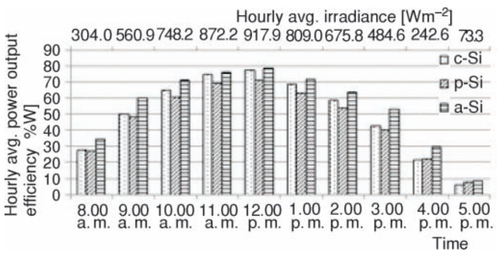

Figure 7. Hourly avg. normalized power output efficiency *vs.* time

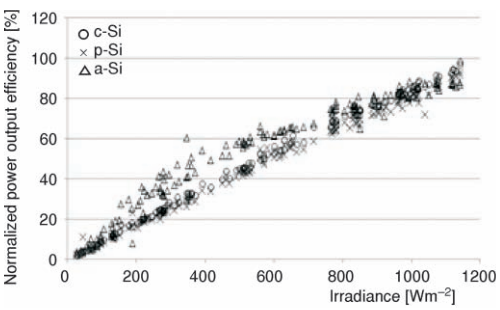

Figure 8. Normalized power output efficiency of each module *vs.* time

Figure 9 shows that the monthly average normalized output efficiency of a-Si is highest. It has 11% higher power output efficiency than c-Si module although having much lower installed capacity. The p-Si module shows lowest power output. The lower efficiency of p-Si module is due to its lower output power at outdoor compare to the STC values. Output efficiency of c-Si module is in between the other two modules.

Module efficiency analysis

Module efficiency is the ratio of total output energy of the module to the total solar energy incident on a module surface based on its total active area. The module efficiency of modules is lower at outdoor conditions as compare to their values at STC due to varying environmental conditions. Average hourly module efficiency is shown in fig. 10. It shows that all modules have high module efficiency at low irradiance and it decreases with the increase of solar irradiance and module temperature (also reported by Rodriguez *et al.* [7], Markvart [20], and Stone [21]). The a-Si module shows the high decrease in module efficiency at high irradiance. This is due to less variation and stabilization of output power at high irradiance level as described earlier. The lowest average module efficiency was examined at 12.00 a. m. corresponding to peak irradiance level. This is due to the fact that with increase in module temperature V_{oc} of PV module decreases, I_{sc} slightly increases and resulting power output decreases (see also [22]). Figure 11 shows the variation of modules efficiency with the irradiance. As shown in fig. 11. The a-Si shows better efficiency at low irradiance level. It is clear from fig. 11 that at irradiance level below the 500 W/m^2, a-Si shows most of its module efficiency values higher than its mean value and it gets stabilized after the irradiance of 800 W/m^2. This effect was also reported by Midtgard *et al*. [4].

As shown in fig. 12, c-Si module is the superior in term of monthly average module efficiency and a-Si shows the lowest module efficiency. The p-Si shows module efficiency near to c-Si module due to less power output but has module area close to the c-Si module. The a-Si module shows 84% less efficiency than c-Si module. The reason is that a-Si has 66.6% less rated power and large area than c-Si module. This finding is in line with published results, for instance Amin *et al.* [3]. Figure 13 shows the change of hourly average module efficiency against module temperature. The trend shows that modules efficiency decreases with the increase of module temperature. The same effect was also reported by Singh *et al*. [6].

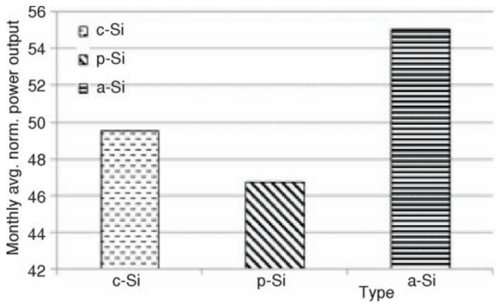

Figure 9. Monthly avg. normalized power output efficiency of each module

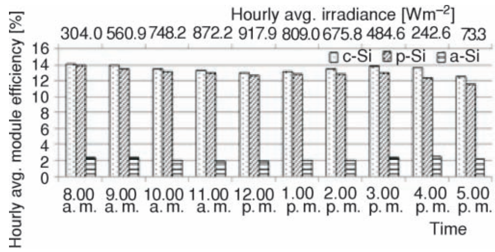

Figure 10. Hourly module efficiency *vs.* time

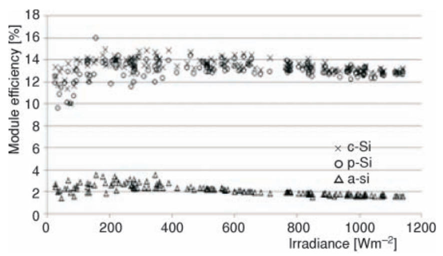

Figure 11. Module efficiency of each module *vs.* irradiance

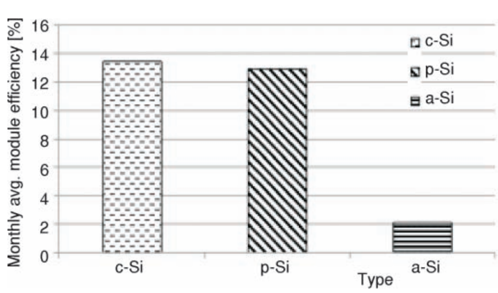

Figure 12. Monthly avg. module efficiency of each module

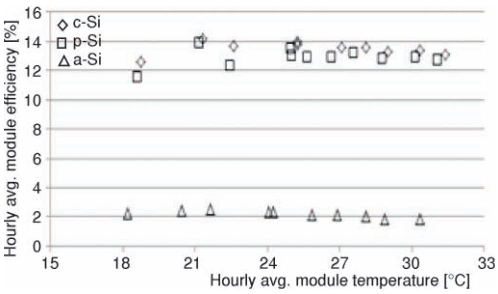

Figure 13. Hourly avg. module efficiency *vs.* module temperature

Performance ratio analysis

In order to determine the behavior of different PV modules, hourly PR of modules has been examined in this study. Figure 14 shows the hourly PR ratio of three modules under test. In general, the PR decreases with the increase in solar irradiance however, the rate of decrease in PR with irradiance is significant for the case of a-Si. At 12:00 p.m., modules have lowest PR corresponds to high solar irradiance. The a-Si module shows better performance at low irradiance and has shown large decrement in PR with increase in irradiance. Figure 15 shows that monthly average PR of a-Si is 1.07 which is 22% higher than c-Si module and 29% higher than p-Si module. The high PR of a-Si is due to the better performance in low light conditions [2, 3].

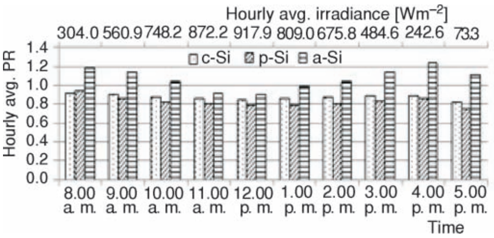

Figure 14. Hourly avg. PR *vs.* time

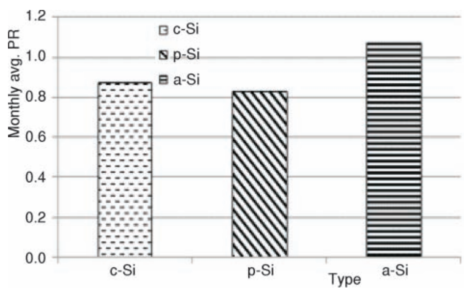

Figure 15. Monthly avg. PR of each module

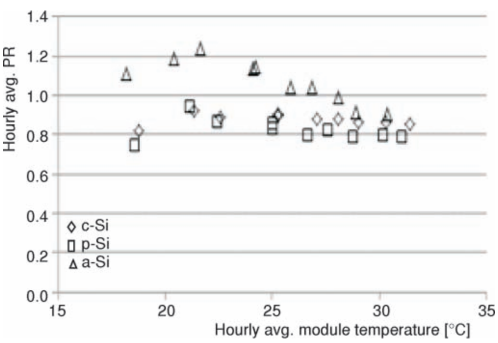

Figure 16. Hourly avg. PR *vs.* module temperature

The value of PR module may be greater than one because average outdoor irradiance level is much lower than the irradiance at STC *i. e.* 1000 W/m^2. The PR of c-Si and p-Si modules at outdoor is less than the STC value while a-Si has PR higher than STC value. These results were also found by Minemoto *et al.* [23].

Figure 16 shows variation of hourly average PR with module temperature. a-Si module has much higher PR at low module temperature which decrease with increase in temperature. This is due to the fact that output power of a-Si module does not much vary with the increase of module temperature.

Module temperature analysis

Figure 17 shows the variation in module and ambient temperature with time. The temperature of all three modules stays above the ambient temperature unless near the evening and increases with increase in irradiance. The increase in module temperature with irradiance is due to the production of heat during the PV reaction. In the evening after 4.00 p. m., the module temperature reaches below the ambient temperature. This is due to the fact of sudden decrease in irradiance which significantly slows down the PV process and hence decreases the module temperature. Furthermore, c-Si shows the highest average module temperature. Module temperature of p-Si is very close to c-Si temperature. The a-Si module shows lowest module temperature. This is due to the low output power value of a-Si module and also due to the large available area more heat convection takes place between the module surface and surrounding air.

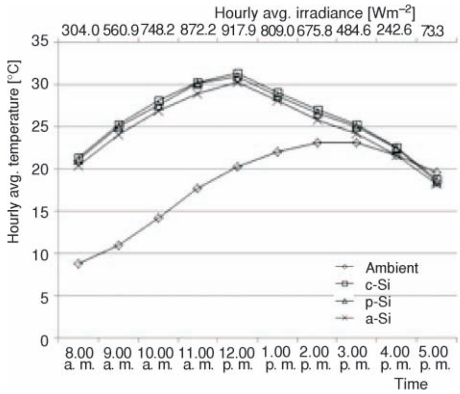

Figure 17. Hourly avg. temperature of each module

Conclusions

Three different commercially available PV modules have been tested at outdoor conditions in city of Taxila, Pakistan during the month of January. A custom made set-up was used to determine the characteristic parameters of PV modules under study. The results have shown that output power of modules varies linearly with the irradiance. The a-Si module has shown 29.3% higher monthly average normalized output efficiency than the c-Si module due to the better at low irradiance condition, although having much lower installed capacity than c-Si module.

The average module efficiency of c-Si module was 13.5% which was higher than other two modules under study. The measured module efficiency of all the modules was less than their STC values. Furthermore, results depict that the module efficiency decreases with increase in module temperature. The a-Si module has shown the highest PR of 1.07.

Pakistan has favorable climate for the implementation of PV technology with long sunshine hours and high insolation level. Due to the capability of better perform in low light condition and having high PR, a-Si module is found to be most suitable and should be preferred for implementation in Islamabad and its surrounding regions.

Nomenclature

A_a – active area of module, [m^2]
a-Si – amorphous silicon module
CIS – copper indium diselende
c-Si – monocrystalline silicon module
E – solar irradiance, [Wm^{-2}]
E_D – direct solar irradiance, [Wm^{-2}]
E_H – solar irradiance at horizontal surface, [Wm^{-2}]
I_{max} – maximum current, [A]
I_{sc} – short circuit current, [A]
PR – performance ratio
P_{max} – maximum power, [W]
P_{mea} – measured power output, [W]
PV – photovoltaic
p-Si – polycrystalline silicon module
STC – standard test condition
V_{max} – maximum voltage, [V]
V_{oc} – open circuit voltage, [V]

Greek symbols

δ – angle of tilt with horizontal
η_p – normalized power output efficiency
η_m – module efficiency

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