Contents list available at IJRED website
Int. Journal of Renewable Energy Development (IJRED)
Journal homepage: http://ejournal.undip.ac.id/index.php/ijred

Research Article

Performance Evaluation of Various Photovoltaic Module Technologies at Nawabshah Pakistan

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ABSTRACT. The purpose of this study was to evaluate the influence of module temperature on the efficiency of polycrystalline (p-Si), monocrystalline (m-Si), amorphous (a-Si) and thin film photovoltaic modules at the outdoor environment of Nawabshah city Pakistan. The experimental setup was made and installed over the top roof of departmental building. Weather conditions, such as global solar radiation, ambient temperature, wind speed and relative humidity; power output and temperature of all selected four types of module technologies were measured at the site by logging data. Then, the power output of the modules was normalized because of different rated power of photovoltaic modules for comparison purpose. Results revealed that less temperature impact was noted from thin film module and thus it gave more normalized power with 45.6% among other examined modules. On the basis of overall efficiency, p-Si, m-Si, a-Si and thin film modules gave 92.4%, 93.7%, 94.4% and 95.4% yearly average normalized efficiencies respectively. It was found that temperature has more impact on the efficiency of other examined modules compared to thin film modules. Thus, it is concluded from the study that thin film module is better at the outdoor environment of Nawabshah.

Keywords: weather conditions, normalized power output, module temperature, temperature coefficients, efficiency of photovoltaic modules

Article History: Received: 20th August 2020; Revised: 12th October 2020; Accepted: 21st Oct 2020; Available online: 29th Oct 2020
How to Cite This Article: Jatoi, A.R., Samo, S.R., and Jakhrani, A.Q. (2021) Performance Evaluation of Various Photovoltaic Module Technologies at Nawabshah Pakistan. *International Journal of Renewable Energy Development*, 10(1), 97-103
https://doi.org/10.14710/ijred.2021.32352

1. Introduction

The efficiency of commercial polycrystalline (p-Si) cell is around 12-13%, monocrystalline (m-Si) 14-15% and amorphous (a-Si) 6-7% at STC (Kalogirou 2014). Photovoltaic (PV) modules give maximum power output at STC (Duffie and Beckman 2013; Kalogirou 2014; Jakhrani *et al.* 2014). Meanwhile these conditions are hardly prevailing at outdoor environments (Schwingshackl *et al.* 2013; Ali *et al.* 2017). Still, some factors affect the power of PV modules, such as solar radiation, ambient temperature, cell temperature, tilt angle, shading, cell materials (Jatoi *et al.* 2018; Lee *et al.* 2011; Hasan and Sumathy 2010; Coskun *et al.* 2017; Malik and Chandel 2020) and dust deposition (Tripathi *et al.* 2017). These factors alone as well as in combination with each other affect the efficiency of photovoltaic modules (Coskun *et al.* 2017). The power output of modules decreased due to less solar radiation and maximum temperature gained by photovoltaic module at outdoor conditions (Maghami *et al.* 2016). After solar radiation, module temperature is one of the major factors that adversely affect the power of PV modules (Jatoi *et al.* 2018; Duffie and Beckman 2013; Kalogirou 2014; Jakhrani *et al.* 2014).

The PV module temperature coefficients reported by different researchers and manufacturers for polycrystalline modules were minus 0.40 %/°C (King *et al.* 2002) and 0.64 %/°C (Perraki and Kounavis 2016). Whereas, for monocrystalline modules were minus 0.39 %/°C (Perraki and Kounavis 2016) and 0.50 %/°C (King et al. 2002). Similarly, for amorphous modules were minus 0.10%/°C (Gaur and Tiwari 2014) and 0.25 %/°C (King *et al.* 2002), and for thin module was minus 0.24 %/°C (Clean Energy Project Analysis 2004).

Increase of PV module temperature lowers the power output of cell or module (Jatoi *et al.* 2018; Duffie and Beckman 2013; Jakhrani *et al.* 2012; Jatoi *et al.* 2016). Akhmad *et al.* (1997) investigated the performance of different cell technologies in outdoor condition and found that amorphous has better performance than polycrystalline in summer months. Jatoi *et al.* (2018) revealed that amorphous (single junction) photovoltaic module produces 5.7%, 2.7% and 15.0% more yearly average open-circuit voltage (V_{oc}) than p-Si, m-Si and thin film modules at outdoor condition of Nawabshah. Bashir *et al.* (2015) reported that the monocrystalline module was more efficient with 13.5% than polycrystalline and amorphous modules in Taxila, Pakistan. Ali *et al.* (2017) noted that monocrystalline module gave 11.4% efficiency which was higher than the other studied modules in summer months. Milosavljevic *et al.* (2015) revealed that the increase of 1°C in ambient temperature, decreases 0.3% of monocrystalline module efficiency. Harijan *et al.*

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(2015) concludes that annually 455.3 GWh of electricity could be generated Pakistan from standalone PV systems. The reduction of 22%, 16% and 18% of average power is noted in June, July and August months due to accumulation of dust on the surface of PV modules by Abbas *et al.* (2017). Besides that, the overall 3% power reduction was noted for p-Si module after three months of environmental exposure. Mekhilef *et al* (2012) examined the influence of humidity, dust accumulation and air velocity, and concluded that the effect of each influencing parameter is not an easy task and should not be considered separately.

It is a fact that the indoor (controlled) conditions are totally different than that of outdoor conditions due to unlike atmospheric and topographic conditions of the locations. Therefore, this study was conducted to compare the daily average power output of different photovoltaic modules in actual environmental conditions and to analyze the impact of module temperature on the efficiency of photovoltaic modules at outdoor conditions of Nawabshah, Sindh, Pakistan.

2. Methodology

2.1 Experimental setup

In this work, the performance of four PV module technologies, viz; p-Si, m-Si, a-Si and thin film were examined. Three of them (p-Si, m-Si and a-Si) were of 40W rated power, and only thin film was of 50W (Jatoi *et al.* 2016). The system was mounted towards true south at a slope of 12° over the roof top of departmental building at QUEST Nawabshah, Sindh, Pakistan. The installed PV system is shown in Figure 1.

2.2 Data logging

One-year data of weather conditions, photovoltaic power output and module temperature were recorded and considered for analysis. Weather parameters, such as G_{sr}, T_a, W_v and R_h were measured with HP-2000, power output of PV modules with Prova-210 and the module temperature with Prova-830 data logger. All system components were interconnected with computer for analysis and interpretation of data. PV modules were cleaned early in the morning before data recording.

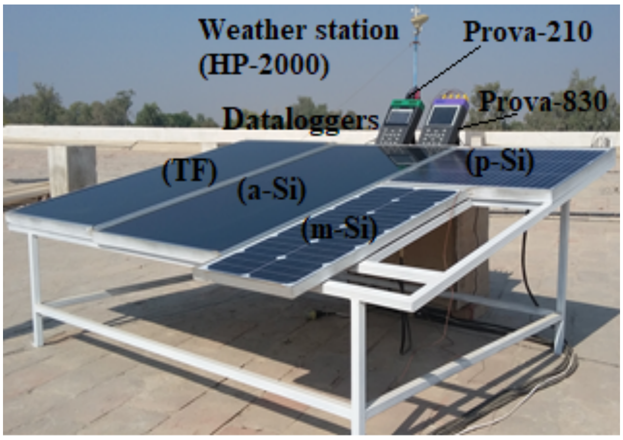

Fig. 1 Experimental setup

2.3 Normalized power output of modules

In this section, the PV power output was normalized due to their unequal rated power output. As three PV modules have rated power of 40W (p-Si, m-Si and a-Si) and only thin film was of 50W. Therefore, the equation (1) was used to normalize the measured power output of each photovoltaic module for the purpose of comparison and performance analysis. This methodology was followed as reported by (Bashir *et al.* 2014; Jatoi *et al.* 2019).

$$P_n = \left(\frac{P_{\max}}{P_{\max-STC}} \right) \times 100 \quad (1)$$

where, P_n, P_{max} and $P_{max\text{-}STC}$ are the normalized power output of modules, measured maximum power output of modules in actual condition (outdoor) and power output of module at STC.

2.4 Estimation of photovoltaic modules efficiency

For photovoltaic modules efficiency, the basic equation (2) is used for computing the impact of module temperature on the efficiency of each photovoltaic module. The equation was used by most researchers with some variation (Skoplaki and Palyvos 2009; Evans 1981).

$$\eta_m = \eta_{m-STC} \left[1 - \mu_m \left(T_m - T_{m-STC} \right) \right] \quad (2)$$

where, η_m, $\eta_{m\text{-}STC}$, μ_m, T_m and $T_{m\text{-}STC}$ are the efficiency of PV modules, efficiency of PV modules at STC, temperature coefficient, measured module temperature and module temperature at STC.

For solving the equation (2), the temperature coefficient (μ_m) and module temperature (T_m) were the main parameters. For that, different power bins were made with global solar radiations of 1000 W/m^2 and module temperature of 50°C to 70°C as reported by Yusoff *et al.* (2016), Technical brief (2017), Wilcox (2012), Field and Gabor (2002), Assoa *et al.* (2018), and Cebecauer *et al.* (2011) with consideration of ± 5W/m^2 in radiation and ±0.5°C in module temperature. The details are available in Jatoi *et al.* (2019).

Furthermore, photovoltaic module temperature coefficients (μ_m) were estimated using equation (3) as reported by (Shaari *et al.* 2009; Malik *et al.* 2010).

$$\mu_m = \left(\frac{P_{\max} - P_{STC}}{T_m - T_{STC}} \right) \quad (3)$$

where, μ_m, P_{max}, P_{STC}, T_m and T_{STC} are the temperature coefficient, measured maximum power output of module, power output of module at STC, measured module temperature and module temperature at STC respectively.

3. Results and Discussion

3.1 Weather conditions

Four important weather parameters, namely daily average measured data of global solar radiation (G_{sr}), ambient temperature (T_a), wind speed (W_v) and relative humidity (R_h) were considered in this study and plotted in Figures 2-5. Figure 2 displays the daily average values of G_{sr}. The maximum G_{sr} was found 1125 W/m^2 in June. Whereas, maximum and minimum daily average values of G_{sr} were noted with 756.98 W/m^2 and 239.86 W/m^2. On yearly average basis, G_{sr} was 0.5184k W/m^2 during study period. The daily average T_a for the similar time period is depicted in Figure 3. The maximum T_a was observed 49.2°C in June. While, minimum to maximum range of daily average T_a were found 15.58°C to 41.12°C, although its yearly average was noted as 30.10°C. Similarly, the daily average W_v for the similar time period are summarized in Figure 4. The maximum gust of W_v was recorded 15.7 m/s in January. On daily average basis, the maximum W_v was recorded as 6.14 m/s and minimum with 0.33 m/s with yearly average of 2.13 m/s. Figure 5 illustrated the daily average of R_h data. The minimum to maximum range of daily average R_h was 11.33% and 70.16% respectively. Moreover, the yearly average value of R_h was noted as 42.66%.

It was discovered from results that maximum daily average of G_{sr} and T_a were observed in June and wind gust in the month of January. Maximum R_h was noted in January and minimum in May. It is revealed that January month is calm and May & June months are the hottest. It was found from analysis, that G_{sr} and T_a were rising from morning till noon, and then falling slowly in the evening. The maximum R_h was noted when G_{sr} and T_a were low, and vice versa.

3.2 Normalized power of photovoltaic modules

The rated power output of the examined PV modules was not same. Therefore, the power output of modules was normalized for the comparative analysis and discussed as yearly average basis.

In Figure 6, the comparison of daily average normalized power output of all four examined modules is depicted. It was found that p-Si, m-Si, a-Si and thin film modules gave 55.31%, 54.24%, 49.45% and 60.43% of maximum daily average normalized power of their rated power in June. Whereas, the minimum daily average normalized power output was noted from polycrystalline with 14.24%, monocrystalline with 13.67%, amorphous with 12.69% and thin film with 16.81% in January.

It was found that p-Si module produced 43.97%, m-Si 41.61%, a-Si 36.78% and thin film 45.61% yearly average normalized (maximum) power output as illustrate in Table 1.

In the comparison of crystalline and noncrystalline photovoltaic modules, the p-Si gave 2.36 more percentage of normalized power than m-Si. Similarly, the thin film generates 8.82 more percentage of normalized power than a-Si.

In over all, thin film produced 1.64, 4.00 and 8.82 more percentage of average normalized power output than p-Si, m-Si and a-Si modules. It is discovered from analysis that the polycrystalline module gave maximum daily average normalized power than other PV modules from December to February months and thin film from March to October months than other modules. The output trend of polycrystalline and monocrystalline were found close to each other. It is revealed that the performance of thin film module was best among the examined modules on yearly average basis. If the mounting space is no limits, the thin film module technologies are the best option as others because it gives maximum performance in hot months than calm months.

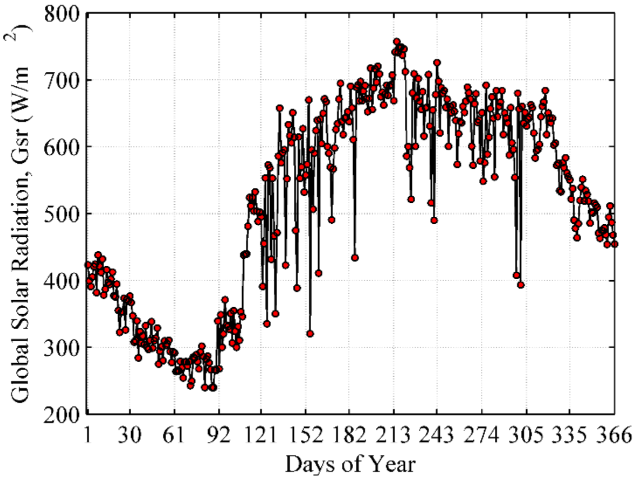

Fig. 2 Daily average global solar radiations.

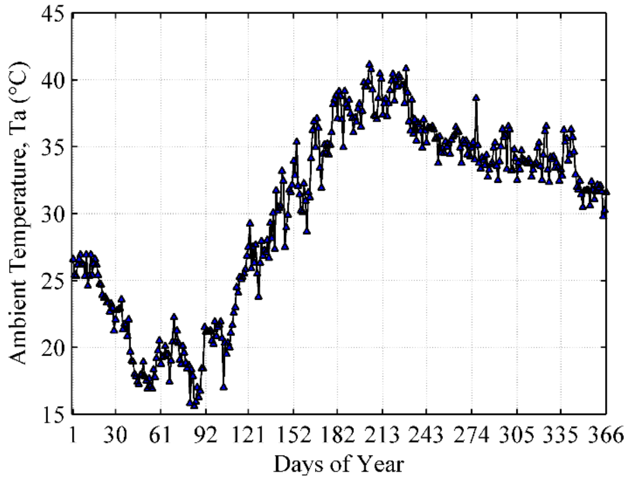

Fig. 3 Daily average ambient temperature.

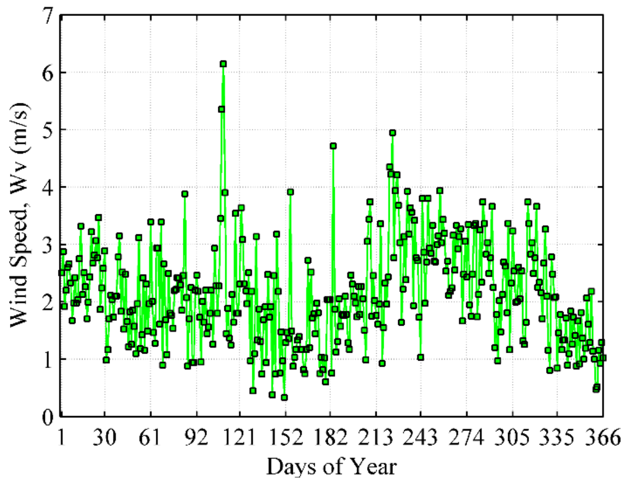

Fig. 4 Daily average wind speed.

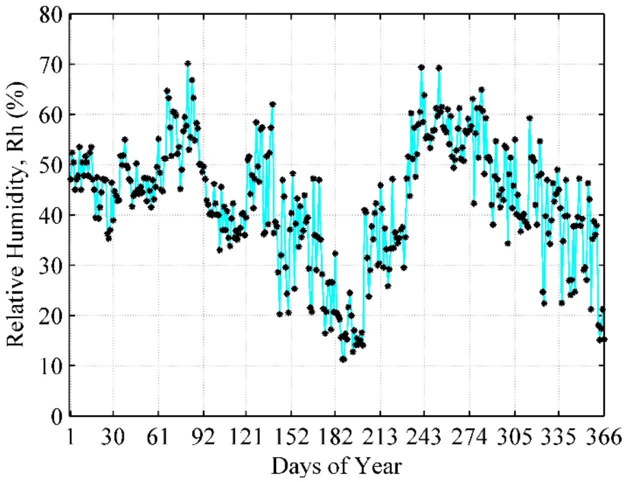

Fig. 5 Daily average relative humidity.

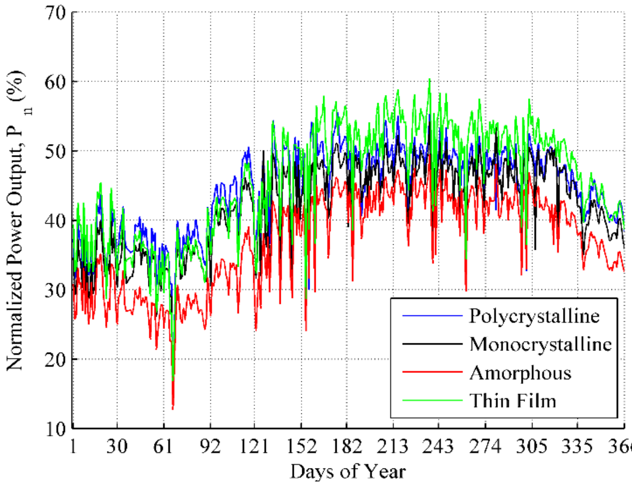

Fig. 6 Daily average normalized power.

Table 1
Yearly average normalized power output

	Photovoltaic module technologies			
	p-Si	m-Si	a-Si	Thin Film
Rated power (W)	40	40	40	50
Yearly average normalized power output (%)	43.97	41.61	36.78	45.61

3.3 Module temperature

Figure 7 represents the daily average measured module temperature (T_m) of the studied modules. The minimum and maximum daily average measured module temperature of p-Si, m-Si, a-Si and thin film were noted as 28.20°C and 57.85°C, 27.45°C and 56.82°C, 28.17°C and 58.07°C, and 27.77°C and 58.83°C respectively. While the yearly average T_m of p-Si, m-Si, a-Si and thin film were found as 43.96°C, 43.45°C, 44.29°C and 43.55°C respectively. The minimum module temperature was observed in the month of January and maximum in May and June.

In comparison of crystalline photovoltaic modules, the p-Si module gained 0.5°C more yearly average temperature than m-Si and in noncrystalline modules. a-Si attained 0.4°C more module temperature than thin film module. In overall, it was observed that p-Si, m-Si and thin film module attain 0.3°C, 0.8°C and 0.7°C less yearly average temperatures than a-Si modules respectively.

It was observed from comparison for temperature accomplishment that a-Si module achieved more temperature than other modules. It was deduced that all studied modules attain less temperature from December-January (calm months) and maximum temperature from May-June (hottest months). It was revealed that modules accomplished and released temperature slowly and gradually throughout the studied period.

3.4 Obtained module temperature coefficients

The trend of temperature coefficients (μ) versus module temperature is presented in Figure 8. The average temperature coefficients of p-Si, m-Si, a-Si and thin film were found as -0.40, -0.34, -0.29 and -0.25 percentage per degree centigrade respectively. It was observed that crystalline PV modules have maximum effect of module temperature than noncrystalline PV modules due to composition and characteristics of their material.

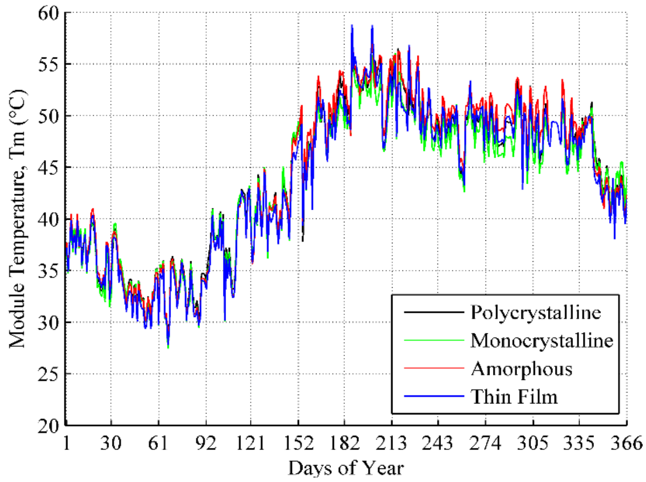

Fig. 7 Daily average module temperature.

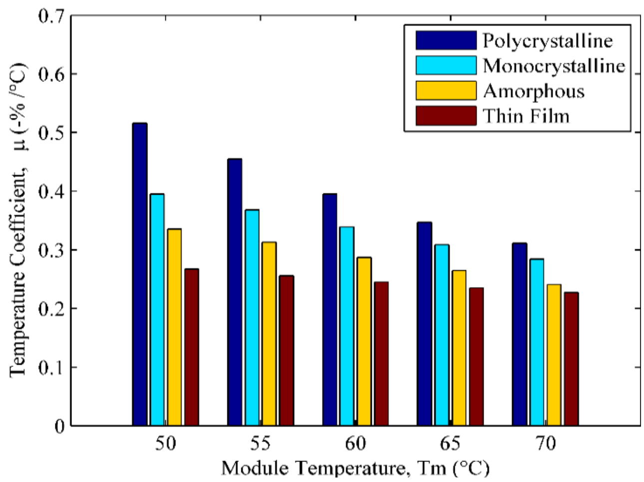

Fig. 8 Module temperature coefficients.

3.5 Effect of module temperature on the efficiency of PV modules

Figure 9 illustrates the daily average efficiency of crystalline (polycrystalline and monocrystalline) modules. The highest daily average reduction of polycrystalline module efficiency was noted as 1.91% and minimum with 0.18% when daily average module temperature was 57.85°C and 28.21°C respectively. Since, the average polycrystalline module efficiency was found 1.1% less from its rated efficiency of 14.6% when average module temperature was 43.96°C. Similarly, the maximum daily average reduction of monocrystalline module efficiency was noted as 1.78% and minimum as 0.13% when the daily average module temperature was 56.83°C and 27.45°C respectively. Since, the yearly average monocrystalline module efficiency reduction was found 1.04% from its rated efficiency 16.50% when average module temperature was 43.46°C.

The daily average efficiency of non-crystalline (amorphous and thin film) modules are illustrated in Figure 10. The maximum daily average reduction of amorphous module efficiency was noted as 0.50% and minimum as 0.04% when module the temperature was 58.07°C and 25.12°C respectively. Yearly average amorphous module efficiency reduction was found 0.30% from its rated efficiency of 5.30% when the average module temperature was 44.29°C. Besides that, the highest daily average reduction efficiency of thin film module efficiency was recorded as 0.67% and minimum as 0.15% when module temperature was 58.83°C and 27.77°C respectively. Yearly average efficiency reduction of thin film module was noted as 0.31% from its rated efficiency of 6.70% when the average module temperature was 43.55°C.

It was revealed that the minimum reduction of all examined module's efficiency was noted in December and January months due to unperturbed months. Maximum efficiency reduction was observed in May and June months. Besides that, the overall reduction trend in efficiency were recorded from April to October because these months were found hottest months. Furthermore, it was observed that the increment and decrement in efficiency of examined modules was depends on the module temperature and material properties and vice versa.

Polycrystalline (p-Si), m-Si, a-Si and thin film modules gave 92.4%, 93.7%, 94.4% and 95.4% yearly average normalized efficiencies respectively as shown in Table 2. Among all modules, thin film module demonstrated maximum yearly average normalized efficiency in actual atmospheric conditions.

Table 2
Electrical efficiencies of studied PV modules

Efficiency	Photovoltaic module technologies			
	p-Si	m-Si	a-Si	Thin Film
Rated efficiency (%)	14.6	16.5	5.3	6.7
Yearly average efficiency output (%)	13.49	15.46	5.00	6.39
Yearly average normalized efficiency (%)	92.4	93.7	94.4	95.4

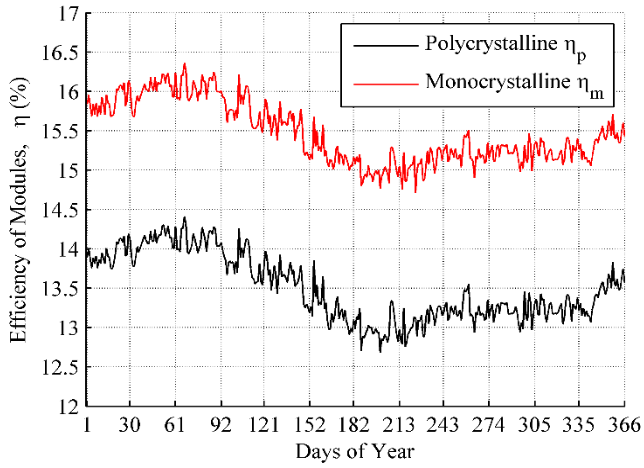

Fig. 9 Efficiency of crystalline photovoltaic modules versus time (days).

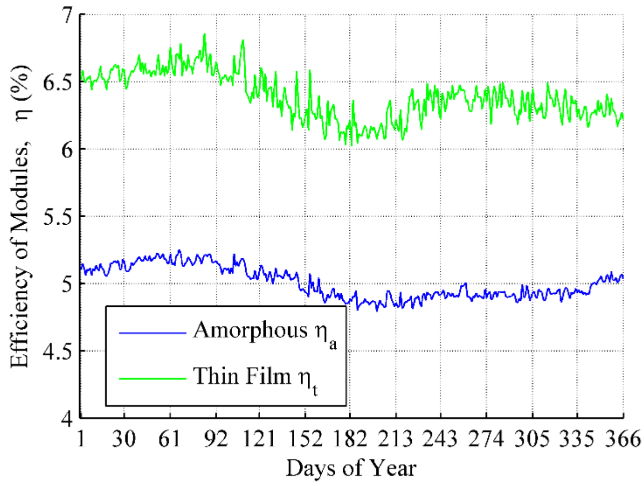

Fig. 10 Efficiency of non-crystalline photovoltaic modules versus time (days).

If there is enough space for mounting and installation of modules, then thin film module technologies could be the best option in hot climatic areas. The main cause of temperature increase of modules was higher radiations at noon, thus the power out of modules became lower due to negative impact of module temperature versus power output.

4. Conclusion

Maximum daily average values of global solar radiation were noted as 756.98 W/m², ambient temperature 41.12°C, wind velocity 6.14m/s and relative humidity 70.16% during study period.

It was found that p-Si, m-Si, a-Si and thin film modules produced 43.97%, 41.61%, 36.78% and 45.61% yearly average normalized power output. It is concluded that the performance of thin film module was relatively excellent among the examined modules on yearly average basis. The output trend of polycrystalline and monocrystalline were found close to each other.

Yearly average module temperature of p-Si, m-Si, a-Si and thin film was found 43.96°C, 43.45°C, 44.29°C and

43.55°C respectively. It was discovered that amorphous module attains 0.3°C, 0.8°C and 0.7°C more yearly average temperatures than p-Si, m-Si and thin film modules respectively. The attainment and release of module temperature may be associated with the material properties of PV module technologies.

The average temperature coefficient for polycrystalline, monocrystalline, amorphous and thin film module was calculated as -0.40 %/°C, -0.34 %/°C, -0.29 %/°C and -0.25 %/°C respectively. On the basis of yearly average normalized efficiency, p-Si, m-Si, a-Si and thin film modules showed 92.41, 93.72, 94.40 and 95.37 yearly average normalized efficiencies of their rated efficiencies.

It is concluded from the study that the temperature has more impact on the efficiency of polycrystalline, monocrystalline and amorphous than that of thin film. It was revealed that the minimum reduction of modules efficiency was noted in December and January months due to unperturbed months, whereas, the maximum efficiency reduction was observed in the months of May and June. Besides that, the overall reduction trend in efficiency was recorded from April to October because these months were found hottest. Furthermore, it was observed that the increment and decrement in efficiency of examined modules depends on their material properties.

Acknowledgments

Authors are thankful to the authorities of Quaid-e-Awam University of Engineering, Science and Technology Nawabshah, Pakistan for providing financial support and research facilities during this effort.

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