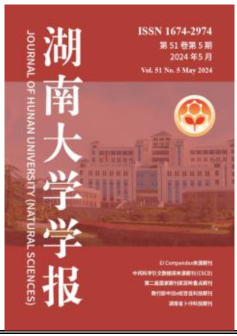

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Electrical Characteristics of Half-Cut Bifacial PERC Monocrystalline Photovoltaic Modules under Outdoor Conditions in Nawabshah

Muhammad Moosa Jakhrani[1], Abdul Sattar Saand[1], Abdul Qayoom Jakhrani[2]*, Abdul Rehman Jatoi[3], Kishan Chand Mukwana[3]

[1] Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

[2] Department of Energy Systems Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

[3] Department of Environment Engineering, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

* Corresponding author: aqbaloch@quest.edu.pk

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Abstract: Photovoltaic modules are typically rated and tested in laboratories under standard test conditions. Such conditions cannot be maintained outdoors due to the random nature of environmental conditions and operating parameters, such as the topography of the target location, slope, orientation, elevation, albedo, and available technologies. The impact of the backside of bifacial modules on electricity generation remains uncertain due to their ability to generate power from both the front and back surfaces. This study aims to experimentally analyze and predict the electrical characteristics of half-cut bifacial PERC monocrystalline photovoltaic (PV) modules under outdoor conditions in Nawabshah. In this connection, an experimental system was mounted over a departmental building for data recording and analysis. The global solar radiation (Grad) of the study site was measured using a light meter (HD-2302), and the ambient temperature (Ta), wind speed (Ws), and relative humidity (Rh) were measured using a digital anemometer PROVA AVM-05. The electrical characteristics of both the front and back sides of the modules were documented using PROVA-1101. These data were collected consistently from 09:00 to 16:00, at hourly intervals, over a period of five months spanning from February to June 2023. In addition, different existing models were used to predict the electrical characteristics of bifacial PV modules based on recorded data. During the analysis period, it was observed that the front side of the modules generated approximately 91% of the output power, while the backside accounted for 9%. The Evan–Florschuetz model equation was found to be more suitable for predicting bifacial module efficiency because it gives less error based on measured data.

Keywords: ambient temperature, half-cut bifacial photovoltaic module, humidity, statistical analysis, solar radiation, wind speed.

纳瓦布沙阿户外条件下半切双面 PERC 单晶光伏组件的电气特性

摘要：光伏组件通常在标准测试条件下在实验室中进行评级和测试。由于环境条件和操作参数的随机性，例如目标位置的地形、坡度、方向、海拔、反照率和可用技术，因此无法在室外维持此类条件。双面组件背面对发电的影响仍然不确定，因为它们能够从正面和背面发电。本研究旨在通过实验分析和预测纳瓦布沙室外条件下半切双面 PERC 单晶光伏(光伏)组件

的电气特性。为此，在部门大楼上安装了实验系统以记录和分析数据。使用测光表(高清-2302)测量研究地点的总体太阳辐射(毕业)，并使用数字风速计普罗瓦动静脉畸形-05 测量环境温度(Ta)、风速(Ws)和相对湿度(Rh)。使用普罗瓦-1101 记录模块正面和背面的电气特性。这些数据是在 2023 年 2 月至 6 月的五个月期间，以每小时为间隔，从 09:00 到 16:00 持续收集的。此外，还使用了不同的现有模型根据记录的数据预测双面光伏组件的电气特性。在分析期间，观察到组件的正面产生了约 91%的输出功率，而背面占 9%。埃文·弗洛舒茨模型方程被发现更适合预测双面组件的效率，因为它基于测量数据产生的误差更小。

关键词：环境温度、半切双面光伏组件、湿度、统计分析、太阳辐射、风速。

1. Introduction

Energy serves as the foundation for economic growth and sustainable development. It can be derived from various sources, including fossil fuels such as coal, oil, and natural gas, and alternative sources like hydro, solar, wind, biomass, and geothermal energy [1]. Nevertheless, fossil fuels are the main source of greenhouse gases and ultimately cause global warming. On the other hand, energy demand is continuously increasing due to an increase in the world’s population and industrial developments. To properly handle the energy crisis, the countries focus on increasing the share of renewable energy sources in the total energy demand. It is possible to add approximately 1220 gigawatts to the system using renewable sources by 2024 [2, 3].

In addition to other renewable energy sources, solar energy systems are more robust, environmentally friendly, green, reliable, and sustainable. Solar energy can be generated either through solar thermal or photovoltaic (PV) systems. PV systems are easier to maintain and provide direct electricity to consumers compared to thermal systems. Hence, solar PV technologies are usually preferred [4, 5]. However, their performance is directly related to the amount of solar radiation received by the solar modules and indirectly with the Ws, Ta, Rh, and mounting methods [5-8].

Pakistan is a developing and one of the most populous countries in the world. An uninterrupted source of energy is required to maintain its development and tackle energy security problems. At the moment, the country is suffering from an acute energy crisis and falls into darkness from 10 to 12 h per day [4, 5]. Pakistan generates approximately 120,785 GWh of electricity, with a shortfall of approximately 51,765 GWh in 2018 to meet the demand [9, 10]. Fortunately, Pakistan has a huge amount of available solar radiation, with an average global solar insolation of 5-7 kWh/m2/day. It is an attractive option to supply electricity to isolated locations where the transmission lines from the national grid are difficult to extend [11].

The efficiency of polycrystalline (p-Si), monocrystalline (m-Si), and amorphous (a-Si) PV modules is 12-13%, 14-15%, and 6-7%, respectively, under standard test conditions (STC) [12]. However, different aspects, such as geographical conditions, weather parameters, and operational settings, can reduce their efficiency [13-15]. Ambient temperature has a negative impact on the electrical characteristics of PV modules by 0.2% to 0.5%/ºC beyond nominal cell operating temperature [16, 17].

The PV industry is now producing Passivated Emitter and Rear Cell (PERC) modules instead of silicon-based technologies [18, 19], with a combined predicted market share of 45-60% by 2027 [19, 20]. The reported efficiency of PERC technology based on the deposited passivation layers is around 22% [21]. It has also been shown that bifacial PV modules can achieve higher system efficiency ranging from 5% to 25% compared to monofacial modules. However, the actual impact of bifacial modules is still under debate as it is influenced by geographical location, environmental conditions, operational parameters, and module configuration [21-23].

Bifacial modules are said to offer greater benefits in snowy conditions, but their performance and backside gain in hot environments and outdoor conditions are still not well understood [24, 25]. In addition, different empirical efficiency models were used to predict solar module efficiency. This is because the random nature of environmental conditions influences the electrical characteristics of modules and alters their efficiency.

The purpose of this study was to examine the electrical characteristics (both front and back) of half-cut bifacial PERC monocrystalline PV modules in the outdoor environments of Nawabshah city, which is one of the hottest places in Pakistan, and to determine the backside gain of the bifacial modules compared to the front side. In addition, this study explores the suitability of existing models for predicting module efficiency in outdoor environments.

2. Electrical Characteristics of PV Modules

The electrical characteristics of PV modules comprise the output power, current, and voltage under various conditions. Typically, the current and voltage are measured at maximum power points, short-circuit current, and open-circuit voltage.

Normally, the electrical characteristics of PV modules are rated under STC by the manufacturer. The STC are maintained in indoor environments by maintaining solar radiation at 1000 W/m^2, PV module temperature of 25°C, and air mass of 1.5 [13, 26].

2.1. PV Module Power Output and Efficiency

Electrical power is the result of the voltage and current working together. It can be measured directly using specialized instruments or calculated by determining the voltage and current output from the generator [6, 27]. The maximum power output (Pmax) can be computed using Equation (1), and the overall efficiency of the PV module (ηoa) based on the rated power can be computed using Equation (2) [28].

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

$$\eta_{oa} = \left(\frac{P_r}{A_a \times G_{stc}} \right) \tag{2}$$

where *Vmax* and *Imax* are the maximum voltage (V) and maximum current (A), respectively, and *Pr, Aa*, and *Gstc* are the rated power of the PV module, the area of the PV module, and the solar radiation, respectively, under STC.

2.2. Prediction of PV Module Efficiency

Numerous efficiency models have been proposed and validated by researchers using various databases in locations worldwide. However, these models are typically certified for specific locations and seasons. Therefore, it is essential to confirm their applicability and suitability before implementing them for optimal results. The model equations for calculating PV module efficiency can be found in Table 1. Previous studies [29, 30] focused solely on module temperature (Tc) as a variable. In [31], two variables were considered: module temperature (Tc) and solar radiation (G). Additionally, a simple model based on module temperature (Tc) was proposed in [32].

Table 1 Existing models for predicting PV module efficiency (The authors)

References	Model Equations
[29]	$\eta_{PV} = \eta_{Tref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right]$ where βref is 0.0035/°C
[31]	$\eta_{PV} = \eta_{Tref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right) + \gamma \log_{10} G_T\right]$ where βref is 0.0045/°C, and γ is 0.12
[32]	$\eta_{PV} = \eta_{Tref} - \mu\left(T_c - T_{ref}\right)$ where μ is 0.0035/°C
[33]	$\eta_{PV} = -0.05 T_{surface} + 13.75$
[30]	$\eta_{PV} = \eta_{ref}\left[1 - MPTC\left(T_{NOCT} - T_c\right)\right]$ where MPTC is 0.0035/°C

In [33], a single variable was introduced to model surface temperature, with a coefficient of -0.05, along with a constant of 13.75. Researchers employed various statistical tools, such as mean absolute error (MAE), mean square error (MSE), and standard deviation (σ), to validate and analyze the deviation between the measured and calculated power output and efficiency of PV modules. Eq. (3) is used by [7, 34] and Eq. (4) and (5) by [35].

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left(measured - calculated\right) \tag{3}$$

$$MSE = \frac{1}{N}\sqrt{\left(measured - calculated\right)^2} \tag{4}$$

$$\sigma = \sqrt{\frac{\Sigma\left(x_i - \mu\right)}{N}} \tag{5}$$

3. Material and Methods

In this study, two monocrystalline bifacial half-cut PERC photovoltaic modules with same specifications were purchased and their electrical characteristics were examined as given in Table 2. The system was mounted by facing true south at the slope of 26° with respect to horizontal over the departmental buildings at QUEST Nawabshah as shown in Fig. 1.

Table 2 Electrical characteristics of examined PV modules (The authors)

Description	Units	Values
Manufacturer	---	A-Solar
Model	---	JAM72530-545/MR
Open Circuit voltage (Voc)	V	49.60
Short circuit current (Isc)	A	13.86
Rated Voltages (Vmax)	V	41.64
Rated Current (Imax)	A	12.97
Rated Power (Pmax)	W	545
Open circuit voltage tolerance	%	+_2
Open circuit current tolerance	%	+_4
Power production tolerance	%	+_3
Testing condition	STC	STC
PV module area	m2	

Fig. 1 Experimental setup for data logging and analysis (The authors)

One module was made open to the both sides to see its combined (front and back side) electrical characteristics and other was covered from the front side and open from the back for examining its backside performance. Weather parameters, namely Grad (W/m²), Ta (°C), Ws (m/sec), and Rh (%) were measured using professional weather station HP-2000. Electrical characteristics of PV module, viz., Voc, Isc, Vmax, Imax and Pmax of each PV module were measured by using PV Analyzer PROVA-1011. The data loggers and computers were linked with PV modules for data storage and analysis. Each reading was taken with an interval of 1 hour from 09:00 to 16:00 hours at Pakistan Standard Time persistently for five months from February to June 2023.

4. Results and Discussion

The average values of *Grad*, *Ta*, *Ws*, *Rh* and power of both examined PV modules are illustrated in Fig. 2 and 3. The average values of *Voc*, *Isc*, *Vmax*, *Imax* and *Pmax* output of modules are depicted in Fig. 4-8.

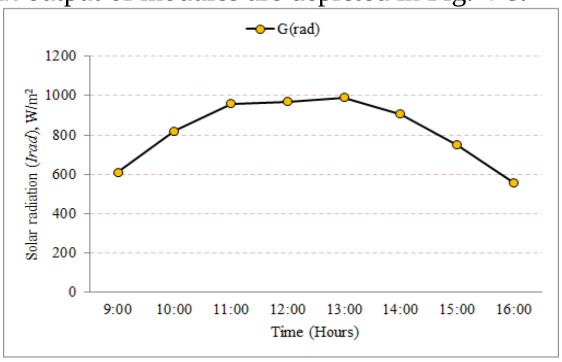

Fig. 2 Measured values of global solar radiation (Grad) (The authors)

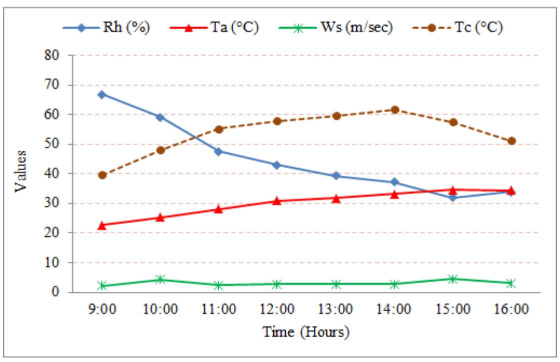

Fig. 3 Measured values of Ta, Ws, and Rh during the study period

(The authors)

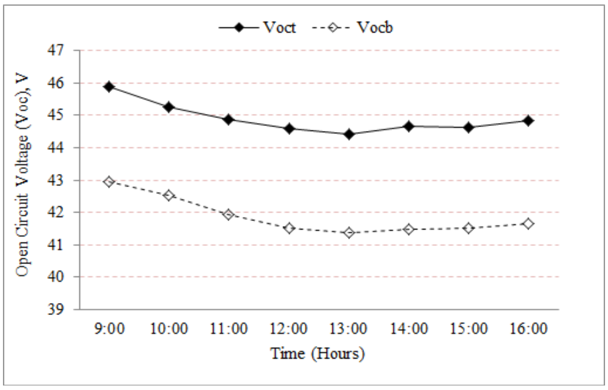

Fig. 4 Voc values of open-rack and back-side PV modules (The authors)

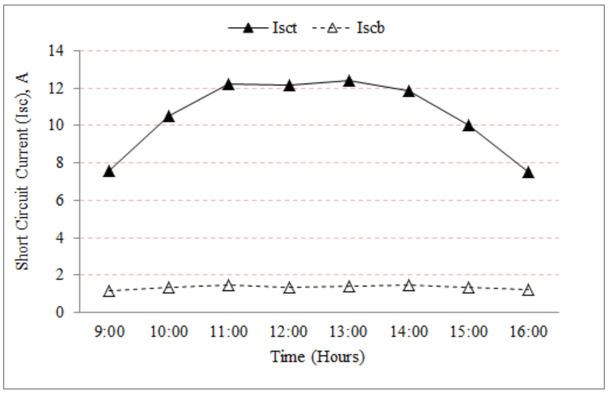

Fig. 5 Isc values of open-rack and back-side PV modules (The authors)

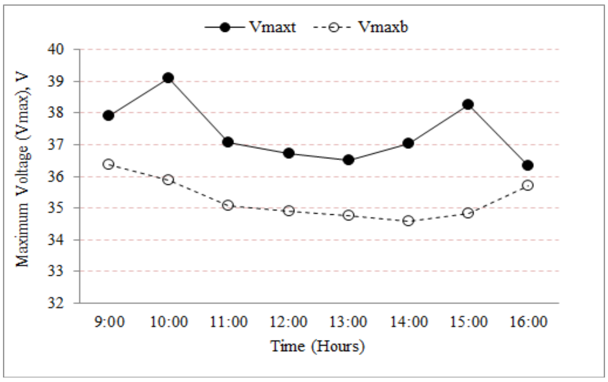

Fig. 6 Vmax values of open-rack and back-side PV modules (The authors)

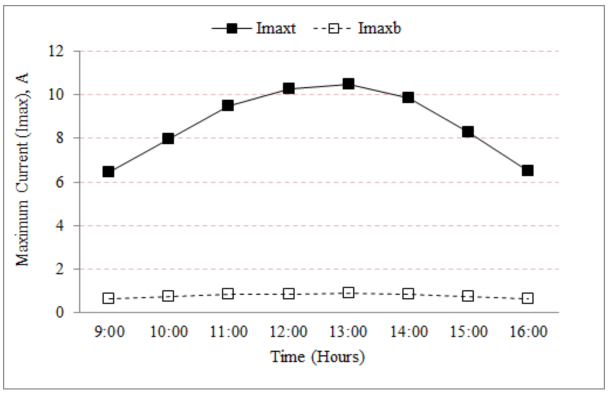

Fig. 7 Imax values of open-rack and back-side PV modules (The authors)

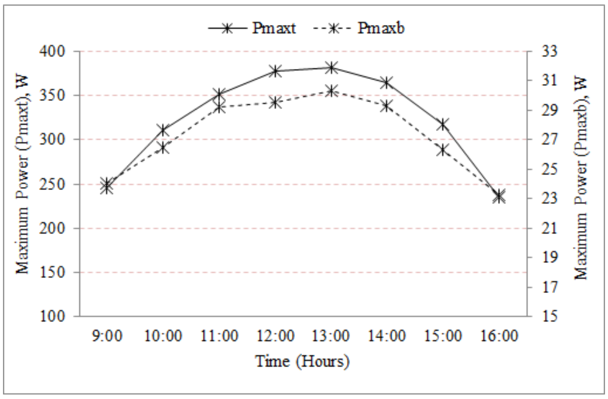

Fig. 8 Pmax values of open-rack and back-side PV modules (The authors)

4.1. Weather Parameters

Daily maximum, minimum and average of Grad were recorded as 990.0, 556.5, and 820.3 W/m^2, respectively, as shown in Fig. 2. The intensity of Grad was found increasing linearly from February to June. This was due to increasing length of the days and intensity of Grad. Daily maximum, minimum and average values of Ta, Ws and Rh are illustrated in Fig. 3. Maximum, minimum and average Ta temperature was found 34.65, 22.76 and 30.16°C respectively. Minimum to maximum Ta was noted in the months of February to June 2023 respectively. Similarly, maximum, minimum, and average values of Ws were noted as 4.50, 2.13, and 3.07 m/sec, and the Rh were 66.8, 32.0, and 45.0%, respectively. It was observed that the level of Rh was high when the Ta was low and vice-versa. It is revealed from the analysis that Rh is inversely proportional to the intensity of Grad and Ta.

4.2. Electrical Characteristics

The electrical characteristics of PV modules include Voc, Isc, Vmax, Imax, and Pmax. Fig. 4 displays the values of Voc of both PV modules. The maximum, minimum, and average Voc of open-rack PV modules was recorded as 45.9, 44.4, and 44.9 V, respectively, and the back sides of the modules gave 43.0, 41.4, and 41.9 V, respectively. Observed values of Isc of both modules are depicted in Fig. 5. Maximum, minimum, and average Isc of open-rack PV modules was noted as 12.4, 7.6, and 10.5 A, with the back sides exhibiting 1.5, 1.2, and 1.4 A, respectively. Fig. 6 depicts the maximum measured voltages of modules. Maximum, minimum, and average Vmax of open-rack PV modules was recorded as 39.1, 36.3, and 37.3 V, and the back sides of the modules gave 36.4, 34.6, and 35.2 V, respectively. Output current of both PV modules are given in Fig. 7. Maximum, minimum, and average Imax of open-rack PV modules was recorded as 10.5, 6.5, and 8.7 A, and the back sides of the modules produced 0.87, 0.65, and 0.78 A, respectively. The measured maximum power of both examined modules is shown in Fig. 8. Maximum, minimum, and average Pmax of open-rack modules was 381.92, 235.35, and 334.04 W, and the back sides of the modules produced 30.33, 23.25, and 27.31 W, respectively.

4.3. Average Power Percentage of Bifacial Modules

Fig. 9 shows the comparison of total combined average (front plus back) and only back-side percentage power output of modules. Maximum, minimum, and average total power (front plus back) was noted as 70.08, 43.18, and 59.27%, and the back sides produced only 5.56, 4.27, and 5.01% power, respectively.

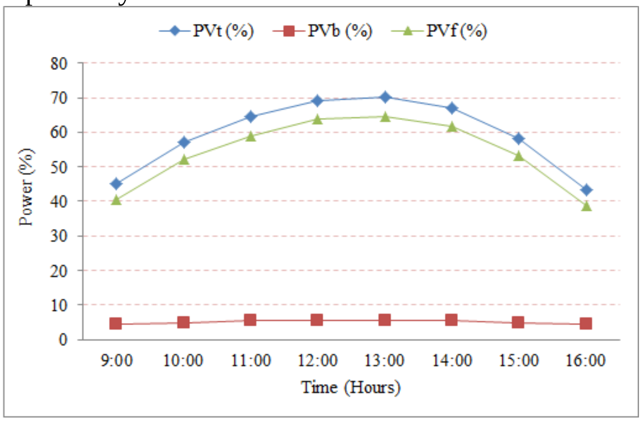

Fig. 9 Comparison of open-rack and back-side PV modules (The authors)

4.4. Average Power Output of Bifacial Modules

Fig. 10 shows the comparison of total combined average (front plus back) versus only back-side power output of examined PV modules. During the study period, the total average power output was recorded as 323.04 W, with 27.31 W coming from the back side. It is discovered that the back side of the PV module contribute only 8.45% of the total power output, with the remaining power being generated by the combined front and back sides. Luo et al. [36] reported that the average power output of backside of two bifacial modules was 8.86% and 11.30%, while Bazilian and Prasad [32] established 7.6% from a backside gain of a bifacial module. This study results shows the backside gain of 8.45%, which is comparable with the existing reported results.

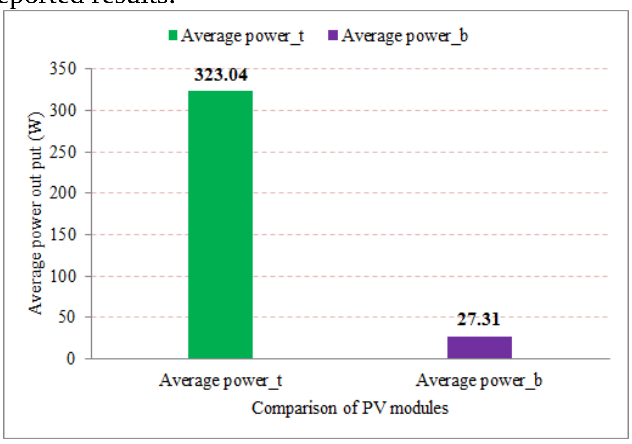

Fig. 10 Comparison of open-rack and back-side PV modules (The authors)

4.5. Efficiency of Bifacial PV Modules

Fig. 11 shows the overall efficiency of photovoltaic module, which is calculated using Eq. (2). Maximum, minimum, and average overall efficiency of bifacial PV modules was estimated as 13.89, 8.56, and 11.75%, respectively. The calculated efficiency of examined module and the results estimated by using existing model equations are presented in Fig. 12. The maximum, minimum, and average efficiency of the examined modules was noted as 18.80%, 17.27%, and 17.81%, respectively. Comparatively, Evans and Florschuetz's [29] model estimated efficiencies of 18.63%, 16.83%, and 17.47%, while Notton et al.'s [31] model estimated 25.14%, 23.57%, and 24.15%. Bazilian and Prasad's [32] model yielded efficiencies of 19.77%, 19.69%, and 19.72%, and Yamaguchi et al.'s [33] model resulted in efficiencies of 11.77%, 10.66%, and 11.05%. The results indicate that Notton et al.'s [31] model estimated the highest efficiencies, while Yamaguchi et al.'s [33] model produced the lowest values when compared to the examined modules.

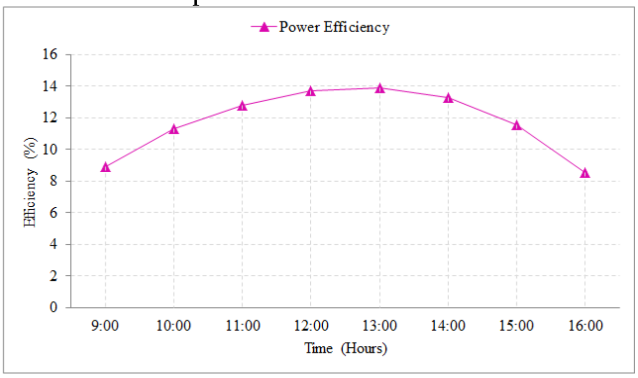

Fig. 11 Efficiency of bifacial PV modules (The authors)

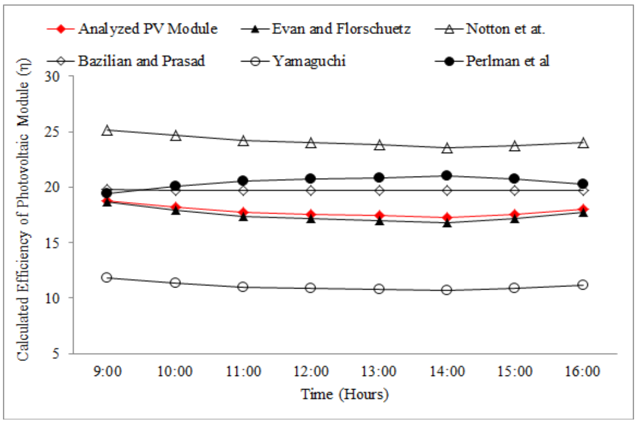

Fig. 12 Comparison of estimated study module efficiency against other models (The authors)

4.6. Statistical Analysis

The calculated MAE, MSE and standard deviation of examined module results versus other existing model equations are presented in Fig. 13-15. Evans and Florschuetz [29] and Yamaguchi et al. [33] reported positive mean absolute error values of 0.34 and 6.76, respectively. On the other hand, Notton et al.'s [31], Bazilian and Prasad's [32], and Perlman et al.'s [30] model equations yielded negative results with -6.34, -1.91, and -2.63, respectively. The model equations by Evans and Florschuetz [29] showed slightly higher values than other models. Conversely, Notton et al.'s [31], Bazilian and Prasad's [32], and Perlman et al.'s [30] model equations produced negative values when compared to the estimated values of the analyzed modules.

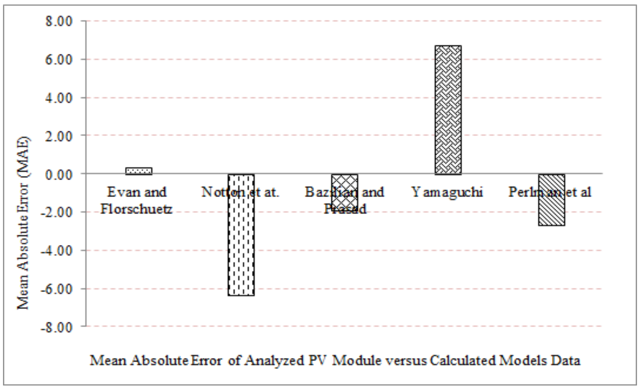

Fig. 13 Mean absolute errors (MAEs) of different models (The authors)

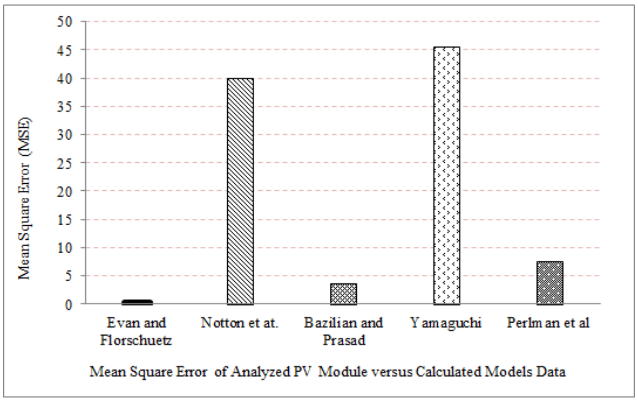

Fig. 14 Mean square errors (MSEs) of different models (The authors)

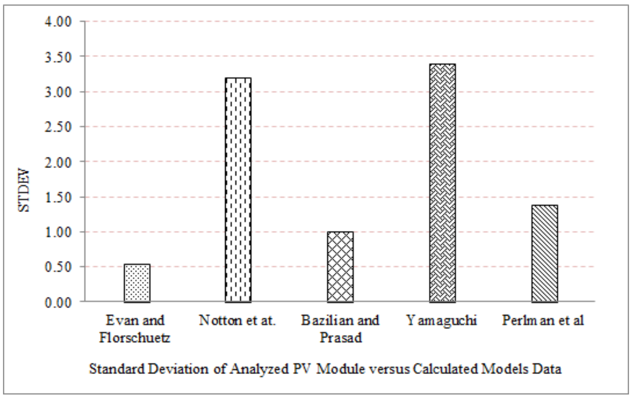

Fig. 15 Standard deviation errors (SDEs) of different models (The authors)

Moreover, Evans and Florschuetz [29] reported an MSE of 0.12, while Bazilian and Prasad [32] reported a higher value of 3.83. Perlman et al. [30] found an even higher MSE of 7.79, with Yamaguchi et al. [33] reporting a value of 45.71 and Notton et al. [31] reporting a value of 40.18. In general, the model equation proposed by Evans and Florschuetz [29] exhibited lower values of MAE, MSE, and STD than other models. On the other hand, the model developed by Yamaguchi et al. [33] showed the highest values for these metrics.

5. Conclusion

Major contribution of this study includes the determination of electrical characteristics and performance of bifacial modules in the outdoor environments. In addition, it is discovered that Evans model could predict the efficiency of bifacial modules with less error using measured data. During the study period, the average Grad, Ta, Rh, Ws, and module temperature at the site were 820.3 W/m^2, 30.2°C, 45.0%, 3.07 m/sec, and 54°C, respectively. The average maximum power output (Pmax) of PV module (front plus back side) was found to be 334.04 W and only backside gave 27.31 W. It is discovered that the contribution of backside of bifacial module is around 9% of the total power generated by bifacial PERC photovoltaic module at the outdoor conditions, which is comparable with the existing results reported by other researchers. The results of statistical analysis showed that less MAE, MSE and STD was noted from Evans and Florschuetz [29] model equation and more from Yamaguchi et al. [33] model. As a result, it is concluded that model Evans and Florschuetz [29] could be used for prediction of bifacial module efficiency at the outdoor conditions of Nawabshah city.

It is recommended that the work could be enhanced by placing different types and technologies of bifacial modules at various angles, slopes, orientations, elevations and albedo conditions for better understanding of module electrical characteristics and efficiencies.

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