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The Impact of Wind Speed and Direction on Performance Assessment of Photovoltaic Modules for Different Climatic Conditions

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ABSTRACT

The increasing climate change concern necessitated renewable and sustainable energy resources as an alternative to fossil fuels. Energy from solar photovoltaic (PV) is cheapest among all renewable sources in terms of cost and time to start a project. The performance assessment of PV projects is mainly based on solar radiation and temperature. Current performance assessments do not account for wind direction, panel geometry and panel orientation in their models so it is important to include the effect of these parameters in the performance assessment. This study aims to perform assessment of PV modules by suggesting an improved methodology incorporating environmental and geometric parameters affecting the output. Six parameters (three environmental and three geometrical) are coupled with four different heat transfer models for estimating performance parameters of PV modules under varying conditions. The performance is evaluated in terms of the module performance ratio. The results showed that wind direction and panel orientation play an important role in determining the module surface temperature, and hence affect the performance of the module. Sensitivity analysis of the models indicated that in addition to the tilt angle and wind speed, the performance of module is also dependent on the incoming wind direction. The performance of PV module predicted by accounting for these parameters is also shown to be dependent on the model used for modelling the heat transfer characteristics. These results suggest that the performance assessment of solar technologies should be done by considering climatic and geometric parameters for a more realistic assessment.

INTRODUCTION

Due to the increasing risk of global warming and adverse climate effects of fossil fuels (Wigley 1991), renewable energy sources are gaining more and more attention nowadays. Lesser emissions and cleaner production (Liang, Yu, and Wang 2019) make renewable energy a suitable alternative to fossil fuels. Among the different types of renewable energy sources solar energy (Shaikh 2017) is among the most promising ones, as sun shines everywhere in the world. Solar panels are only responsible for emissions during their manufacturing phase (Muteri et al. 2020), and throughout the operational phase the panels have negligible emissions. Several photovoltaic (PV) module technologies (monocrystalline, polycrystalline, amorphous and heterogeneous) are available for conversion of solar energy into electricity (Mesquita et al. 2019). Every module technology offers distinct features when it comes to capture efficiency and panel performance.

As different technologies of PV modules are available so a comparison should be made between then to study which technology is better. V. Perraki and P. Kounavis (Perraki and Kounavis 2016) made a comparison between crystalline and Copper Indium diSelenide (CIS) indicating that crystalline technologies are better but are also more sensitive to the environment conditions while CIS even though it has lower efficiency was less sensitive to the environment conditions which makes it more

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reliable. Similarly, the impact of temperature on the output of the panel energy is described by many researchers earlier.

The rated power and efficiency of the PV panels reported commercially are measured at Standard Test Conditions (STC), and the actual performance of panels is different than the rated parameters (Dash and Gupta 2015). Ameli et al. conducted an experimental study to investigate this effect for the environmental conditions of Malaysia (Amelia et al. 2016). They observed that with the module temperature varied with the increase in ambient temperature. For instance, at ambient temperature of 40 °C (104 °F) the module temperature was about 62 °C (143.6 °F) which, in turn, reduces the efficiency to 9 % compared to the rated value of 14 %. The efficiency of the panels is limited owing to the increase in module temperature as it captures energy from the sun rays. The variation of operating conditions of the panels cause deviation from rated power in the output. Therefore, environmental conditions like temperature, wind, humidity, dust, etc. play an important role in the output power.

The effect of wind and humidity was also observed by Rahman et al. (Rahman, Hasanuzzaman, and Rahim 2015) along with temperature. Without any cooling, the solar cell temperature increased to 56 °C (132.8 °F) at an irradiation level of 1000 W/m^2 (316.99 Btu/hr/ft^2). This resulted in a decrease in output power to 20.47 W (69.8 Btu/hr), and a decrease in electrical efficiency to 3.13%. It was observed that for every 1 °C (1.8 °F) increase in the solar cell temperature, there was a decrease in output power of approximately 0.37 W (1.26 Btu/hr) and a decrease in electrical efficiency of 0.06 %. On the other hand, an increase in relative humidity by 20 % caused a decrease in output power of about 3.16 W (10.78 Btu/hr). And the output power reduced by 7.70 W (26.27 Btu/hr) due to dust settling on the surface of the solar module. In addition to the wind speed the angle of the panel also affects the impact of the wind as the tilted panel will have different interaction with the panel compared to a flat plate. Hu et al. (Hu et al. 2022) experimentally showed that with the increase of the tilt angle the module temperature was reduced because the heat transfer coefficient was increased, from 0° to 90° the temperature of the panel decreased from 97 °C (206.7 °F) to 79 °C (174 °F) resulting in greater efficiency.

Various environmental factors are responsible for impacting the performance of PV modules. This analysis aims to investigate the impact of panel geometry and orientation, magnitude and direction of wind and incoming solar radiations on the heat transfer characteristics of the panel, by employing five different models available in literature. The calculation of heat transfer coefficient by multiple models makes it able to perform a comparative assessment of the five selected models in terms of module performance ratio. The orientation of PV panels with respect to the sun's path and prevailing wind patterns can significantly influence their efficiency and overall energy production. The angle at which the panels are inclined can affect the amount of solar radiation received, the cooling effect of wind, and the potential for dust accumulation. By examining different models and their corresponding findings, a comprehensive understanding of the relationship between panel orientation and performance can be gained. This analysis acknowledges the interconnectedness of various environmental factors and their impact on PV panel performance. By studying the effects of panel orientation on parameters like ambient temperature, irradiance, wind speed, and wind direction, valuable insights can be gained to optimize the placement and installation of PV systems. Ultimately, this research contributes to the advancement of renewable energy technologies and facilitates the development of more efficient and productive PV systems.

METHODOLOGY

The output of a PV module is proportional to the available solar irradiance and conversion efficiency, which in turn, is dependent on module temperature. In this study, the influence of wind speed, length of PV module, tilt angle of PV module, incoming wind direction, ambient temperature and irradiance, on the PV module performance was investigated by using five different heat transfer models. The rated efficiency of the PV module is defined at standard conditions (STC) of ambient temperature (25 °C, 77 °F), atmospheric pressure (1 atm, 14.69 psi), air mass ratio (1.50) and irradiance (1000 W/m^2, 316.9 Btu/hr/ft^2). The on-field conditions are different; therefore, the module temperature is different than the STC and consequently the efficiency of the module observes a linearly decreasing trend as governed by equations (Tahir et al. 2022).

$$T_s = T_{amb} + \frac{(T_{noct} - T_{STC})}{800} \times GHI \times \frac{h_{noct}}{h} \times \left(1 - \frac{\eta}{\tau\alpha}\right) \tag{1}$$

$$\eta = \eta_{STC}\big(1 - \beta(T_s - T_{STC})\big) \tag{2}$$

The performance ratio of the PV module scales the operating efficiency against the rated efficiency at STC. Therefore, it provides a means to assess whether a module performs better or worse than the rated conditions. The performance ratio is mathematically expressed as:

$$PR = \frac{\eta}{\eta_{STC}} = 1 - \beta(T_s - T_{STC}) \tag{3}$$

In literature, several factors and mathematical models are reported for determining heat transfer characteristics of PV modules (h_{NOCT}/h). The parameters considered in these models include solar irradiance, ambient temperature, wind speed & direction and PV module characteristics. Based on their usage, these models were classified into four categories: (i) models that are independent of the orientation and mainly depend on the wind speed (Shakerin 1987); (ii) models dependent only on the azimuth angle and independent of tilt angle (Elminshawy et al. 2021); (iii) models depending only on the tilt angle (Mahboub et al. 2011); and (iv) models involving both tilt and azimuth angles (S.-Y. Wu et al. 2021) (Y.-Y. Wu, Wu, and Xiao 2017).

In this study, five different heat transfer models (namely Duffie, Fuji-Imura, Wu2017, Wu2021 and Mahboub) used for performance assessment of PV module were compared. Among the selected heat transfer models Wu2021 considers the six aforementioned parameters, whereas the others simplify the modelling by considering the effects of some parameters to be negligible. The mathematical equations of heat transfer models used in this study, along with the influencing factors, are summarized in Table.1. It is to be noted that the Nusselt Number (Nu) is a non-dimensional parameter that relates the environmental conditions with the heat transfer characteristics as per equation $Nu = \frac{hL}{k}$.

Table. 1. Heat Transfer Models and Influencing Factors

Model	Mathematical Expression	Influencing Factors	Reference
Duffie	$h = 5.7 + 3.8v$	Wind speed.	(Shakerin 1987)
Fuji-Imura	$Nu = 0.14\left(GrPr^{\frac{1}{3}} - GrPr_c^{\frac{1}{3}}\right) + 0.56\left((GrPrcos(\theta))^{\frac{1}{4}}\right)$	Ambient temperature, Length, Tilt.	(Fujii and Imura 1972)
Wu2017	$Nu = (1+cos\,\theta)^a(1+sin\,\theta)^b(1+cos\,\phi)^c(1+sin\,\phi)^d(e + fRe^g)$	Wind speed, Length, Tilt, Wind Direction.	(Y.-Y. Wu, Wu, and Xiao 2017)
Wu2021	$\boldsymbol{Nu = 27.0518\,(1+cos\,\theta)^{-1.97031}(1 + sin\,\phi)^{0.1751}Re^{0.2509}\left(\frac{s}{\sigma T_a^4}\right)^{0.4535}}$	**Wind speed, Length, Tilt, Wind Direction, Ambient temperature, Irradiance.**	**(S.-Y. Wu et al. 2021)**
Mahboub	$Nu = (0.037Re^{0.8} - 871)Pr^{\frac{1}{3}} \times \frac{(1+am^b)((1+m)^{-0.5})}{1+m^c},\ m = \frac{\theta}{180-\theta}$	Wind speed, Length, Tilt.	(Mahboub et al. 2011)

From a number of PV module technologies and manufacturers available, a commonly used monocrystalline PV module of power rating 500 W (1706 Btu/hr) was used in this study. The parameters required for calculations such as Nominal Operating Cell Temperature (T_{NOCT}), Drop Coefficient (β) and Module Dimensions were extracted from manufacturer datasheet, and mentioned in table 2.

Table. 2. Technical Specifications of Selected PV Module for This Study

Parameter	Details		
Technology		Monocrystalline Silicon	
Power Rating	500 W		1706 Btu/hr
Rated Efficiency (η)		21.45%	
Drop Coefficient (β)		-0.34%	
T_{NOCT}	48 °C		(118.4 °F)
A_{pv}	2.19096 m^2		(23.571 ft^2)
Length (L)	2.148 m		(7.05 ft)

The parameters used for studying the variation in performance ratio of the PV module were ambient temperature, irradiance, incoming wind direction and speed, tilt angle, and module length. The effect of each parameter was studied independently by keeping rest of the parameters constant. The scope of each parameter was selected such that it satisfied the different climatic conditions that prevail in Pakistan as reported in literature (Tahir et al. 2022). The analysis was performed in MATLAB for following six cases:

Case 1: Ambient temperature was varied from 0 °C to 50 °C (32 °F to 122 °F).
Case 2: Global horizontal irradiance was varied from 100 W/m^2 to 1000 W/m^2 (31.69 Btu/hr/ft^2 to 316.9 Btu/hr/ft^2).
Case 3: Wind speed was varied from 1 m/s to 13 m/s (3.28 ft/s to 42.64 ft/s).
Case 4: Panel length was varied from 1 m to 3 m (3.28 ft to 9.84 ft).
Case 5: Module tilt was varied from 0° to 60°.
Case 6: Wind direction was varied from 0° to 180°.

Unless the parameter was the one being studied, the nominal values taken were as follows: ambient temperature 40 °C (104 °F); normal irradiance 800 W/m^2 (253.76 Btu/hr/ft^2); wind speed 1 m/s (3.28 ft/s); panel length 2.148 m (7.045 ft); tilt 31° and wind direction 0° from module normal.

RESULTS

The following sections deal with the results that were obtained from the simulations. The impact of each parameter was studied independently and divided into six cases, as mentioned previously in methodology. The significance of each parameter, keeping other parameters constant, is presented in the dedicated case.

Case 1: Ambient Temperature

The impact of temperature is well established in literature covering the modelling of PV modules (Kaya, Şahin, and Alma 2021). With an increase in ambient temperature, the current produced by PV cells rises while the potential difference generated is reduced. The overall effect is that the power output is reduced. This reduction is known to be linear over operational range and is accounted for in performance assessment (Skoplaki and Palyvos 2009). The implementation of this parameter is visualized in Figure 1(a). It is observed that FI and Mahboub model generate the same results as classical methods. The experimental results by Wu2021 show higher PR at lower temperatures but lesser efficiency at temperatures exceeding 45 degrees. The computational results by Wu2017 show similar trend, but overall report a lower PR. This is attributed to the underlying assumption in the computational simulation that only the front surface is responsible for cooling effect (Y.-Y. Wu, Wu, and Xiao 2017).

Case 2: Global Horizontal Irradiance

The impact of GHI is also well-documented in existing literature, and is accounted for in classical method. With an increase in irradiance, the efficiency of PV module is reduced. This is because higher insolation causes a larger amount of radiation to be absorbed as heat by the module, which causes a rise in module temperature (Koehl et al. 2011). The effect of irradiance is modelled using a quasi-steady state heat balance of the module. From Figure 1(b), it is observable that the PR predicted by Wu2021 model is slightly higher than classical method. The estimated PR by FI and Mahboub models coincide with classical method. Although the results by Wu2017 follow the same trend, the estimated PR reported by the model is considerably less than other models. This is attributed to the underlying assumption in the computational simulation that only the front surface is responsible for cooling effect (Y.-Y. Wu, Wu, and Xiao 2017).

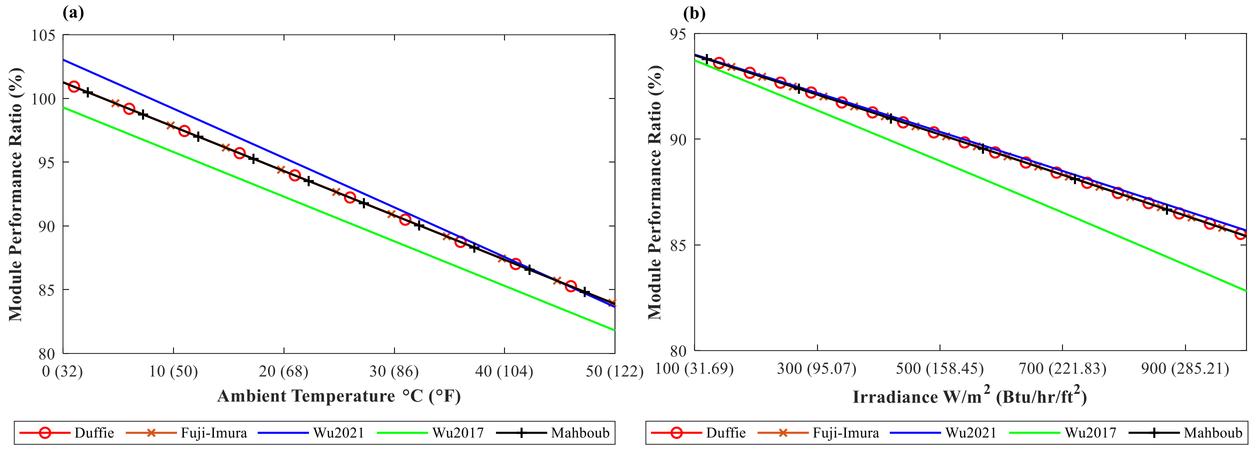

Figure 1 (a) Impact of Ambient Temperature on PR **(b)** Impact of Solar Irradiance on PR.

Case 3: Wind Speed

Wind flowing above the module surface is known to produce a cooling effect due to forced convection (Shakerin 1987). The effect of wind speed is accounted for using different techniques, which is shown in Figure 2(a). It is evident that FI model predicts slightly higher PR than classical method, which indicates that the convective heat transfer effect is slightly underestimated in classical method. The PR predicted by experimental and computational results show a similar trend, but in general predict lesser values than classical method.

The results by Mahboub are in great agreement with what is predicted using classical methods, but deviate considerably at 2.7 m/s (8.8 ft/s). This is the wind speed at which the flow regime shifts from laminar to turbulent, and hence the heat transfer characteristics change as well. While this indicates that the classical methods is specifically designed for low windy regions, the results may be too optimistic: Wu2017 and Wu2021 models are based on computational and experimental results, respectively, and report lesser PR than classical method. Moreover, it is worth noting that the deviation point of 2.7 m/s (8.8 ft/s) is characteristic to the module that is selected for this study, which has a length of 2.148 m (7.05 ft). Different modules and different installation method would indeed have different wind speed. The transition between laminar and turbulent flow regime occurs at $Re > 5 \times 10^5$, as reported in literature (Lienhard 2020).

Case 4: Module Geometry

The impact of module geometry is found to be negligible in the case of all models, despite the influence of module length on Reynold's number and flow properties. This is mostly attributed to the design assumption undertaken in a typical performance assessment i.e. the plant is operating at a quasi-steady state. Due to this assumption, the module temperature becomes a function of heat transfer ratios i.e. ratio of heat transferred at current temperature to heat transferred at a known NOCT (Kant et al. 2016). The effect of length is cancelled out as a result, as evident from Figure 2(b). Moreover, it is evident that Wu2021 estimates the highest PR, while Wu2017 estimates the lowest value.

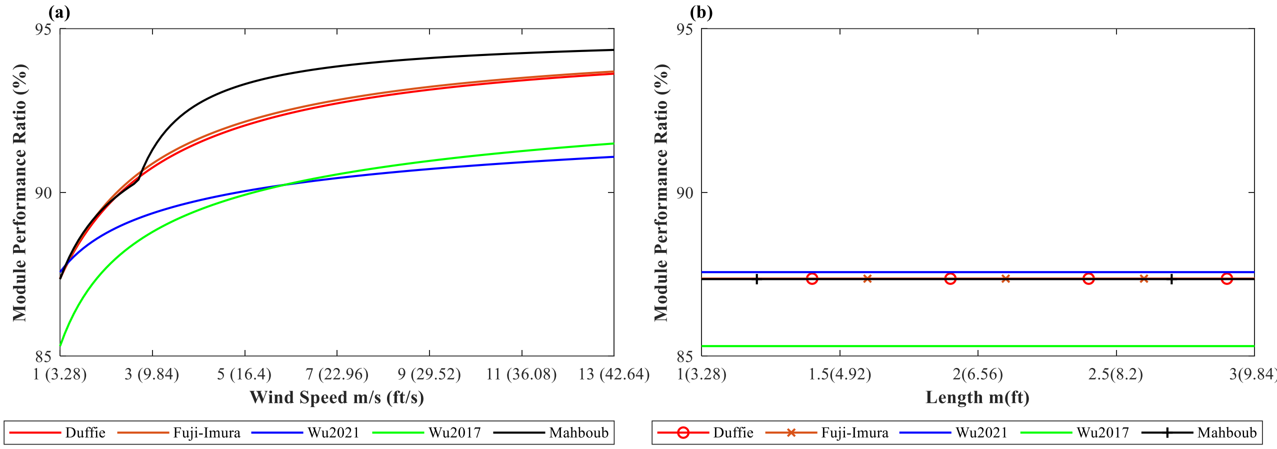

Figure 2 (a) Impact of Incoming Wind Speed on PR **(b)** Impact of Module Length on PR.

Case 5: Module Tilt

Module tilt is a parameter that is unaccounted for in the classical methods (Aste, Del Pero, and Leonforte 2014) (Ahmed et al. 2021). The effect of this parameter is employed using newer models, as shown in Figure 3(a). While tilt angle plays a key role in free convection, this effect is cancelled out due to the quasi-steady approximation as discussed earlier. As a result, the PR predicted by FI model coincides with classical method. The experimental results obtained by Wu2021 indicate a rise in PR with increase in tilt, whereas the computational results obtained by Wu2017 indicate a decrease in PR with increasing tilt. Notably, the PR predicted by Wu2021 model coincides with classical method at 30 degree tilt. The results of Wu2021 suggest that the increased height of the module due to larger tilt cause a larger surface to be in contact with fast-moving layers of incoming wind, a result also confirmed by authors (Gökmen et al. 2016). Moreover, with an increase in tilt, there is more surface area available at the back side of the module, which contributes to heat transfer via free convective currents (Panda et al. 2023). This effect is not modelled in the computer simulation by Wu2017, which assumes the back surface of the module to be perfectly isolated and, therefore, incapable of transferring heat. As a result, this model predicts a decrease in PR.

The analytical results by Mahboub combines the effect of both models, and draws a line at 30 degrees of tilt. The PR predicted by Mahboub is maximum at a tilt angle of 12.5 degrees, while it coincides with results of classical methods at 30 degrees. Beyond 30 degree tilt, this model estimates a lower PR than classical methods. This also poses an optimization problem, where the optimum tilt angle of a module depends on not only the location, but also the wind that is flowing above the module surface (Gökmen et al. 2016).

Case 6: Wind Direction

The impact of the angle between the incoming wind direction and module's normal direction is neither accounted for in classical method, nor it is accommodated in FI and Mahboub models (Gökmen et al. 2016). Wu2017 have studied the effect of wind direction using computational fluid mechanics (Y.-Y. Wu, Wu, and Xiao 2017), and Wu2021 have experimentally determined the effect (S.-Y. Wu et al. 2021). These results are shown in Figure 3(b). In case of Wu2021 results, it is observed that the PR is estimated to be maximum at an angle of 90 degrees i.e. when air is flowing from either left or right of module. This is explained by authors to be a result of both the front and back surface of the module being equally struck with incoming air, which increases the heat transfer rate. As a result, the model presents a symmetry about the module's flank position regarding the effectiveness of wind in cooling effect. This result is also reported by other authors (Elminshawy et al. 2021).

The PR predicted by Wu2017 shows a drop in efficiency until 25 degrees, where it begins to rise with increase in wind direction. The results match with non-azimuth based models at 78 degrees and with Wu2021 model at 90 degrees. The initial decrease followed by an increase is explained by authors to be a result of changing flow regimes from laminar to turbulent at localized regions. However, this decrease is also due to the fact that the back side of the module is assumed to be perfectly insulated in the computer simulation conducted by the authors, which negates the possibility of heat transfer from the back side of the module as wind changes direction. In effect, this model underestimates the PR by not accounting for the cooling effect produced by wind blowing at the back side of the module.

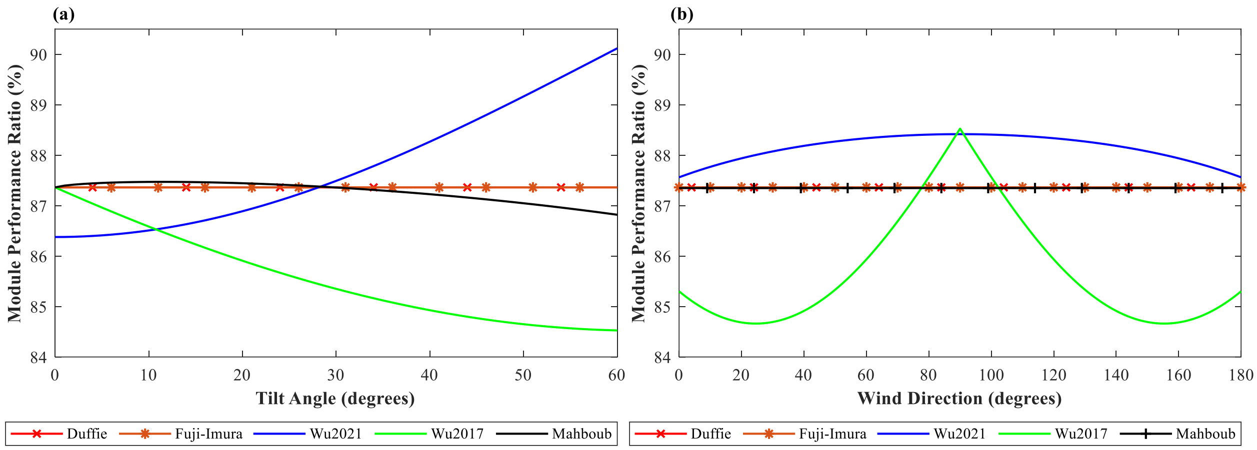

Figure 3 (a) Impact of Panel Tilt Angle on PR **(b)** Impact of Incoming Wind Direction on PR.

CONCLUSION

Performance assessment methods used today are not updated with the research that has expanded on the effect of wind direction and panel orientation. To incorporate these parameters, this study conducted a comparison of four new heat transfer models, in addition to the classical model, and assessed the effect of these parameters on the performance ratio of a monocrystalline module subject to climatic conditions prevailing in Pakistan. The following observations are made from the six cases:

Case 1: The effect of ambient temperature followed similar trend in all models, and Wu2017 estimates a lower performance ratio.

Case 2: The effect of irradiance in all models is in good agreement with classical model.

Case 3: The effect of wind speed follows the same trend in all models. While Mahboub model suggests a higher power ratio at higher wind speeds owing to turbulent flow, the experimental and CFD results disagree with the inference.

Case 4: The performance ratio is found to be independent of the panel length and, in effect, the portrait or landscape mounting.

Case 5: Performance ratio varies with the module tilt angle. The effect is negligible in case of FI, weak in case of Mahboub, and is considerable in case of Wu2021 and Wu2017.

Case 6: Performance ratio is a strong function of wind direction as per Wu2021 and Wu2017 models. Other models do not account for this parameter.

From these inferences, it is concluded that the heat transfer model suggested by Wu2021 is a suitable upgrade to the classical method: the model integrates the effect of more environmental parameters while being in excellent agreement with existing results found from classical methods. Wu2017 considerably underestimates the performance ratio due to the assumptions undertaken in the computer simulation. The results by Mahboub are in good agreement with classical methods, but overestimate the performance ratio at high wind speeds, displays weak correspondence of module tilt with performance, and does not account for wind direction. Future research includes a re-assessment of solar resource in Pakistan using modern heat transfer model (Wu2021), optimization of module tilt and azimuth with respect to environmental parameters, and module arrangement in a solar power plant for maximum cooling effect from incoming wind. These advancements in performance assessment will enable policy makers to scale and size solar power plants more realistically and more effectively.

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NOMENCLATURE

PV = Photovoltaic
T = Temperature
β = Power drop coefficient
h = Heat transfer coefficient
PR = Performance ratio
STC = Standard Testing Conditions
GHI = Global Horizontal Irradiance
η = Module efficiency
τα = Combined transmissivity and absorptivity
Re = Reynold's number
Pr = Prandtl's number
Nu = Nusselt's number
m = Tilt coefficient
θ = Tilt angle
φ = Wind direction relative to module normal
s = irradiance
FI = Fuji-Imura model
A = Module area
G = Normal irradiance
AM = Air-mass ratio

Subscripts

NOCT = Nominal Operating Cell Temperature
d = Design value
S = Surface
STC = Standard Testing Condition
amb = Ambient Temperature
ref = Reference

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