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Research Article

An Improved Empirical Model for Estimation of Temperature Effect on Performance of Photovoltaic Modules

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It is prerequisite to predict the behaviour of photovoltaic (PV) modules in a particular geographical area where the system is to be installed for their better performance and increasing lifetime. For that, models are the easiest and acceptable tools to characterise the behaviour of PV modules in any location. The purpose of this study was to develop an empirical model to predict the influence of temperature on the performance of four different PV module technologies, namely, polycrystalline, monocrystalline, amorphous, and thin film in an outdoor environment. The model has been developed by fitting of one year experimental data using the least squares method. The estimated results of the developed model were validated with real-time data (winter and summer season) and a comparison of other existing model estimates using error analysis with 95% confidence interval. The proposed model estimations confirm that the monocrystalline module performs better in winter and polycrystalline in summer as compared to amorphous and thin film in the study area. During analysis, it is revealed that developed model results are more precise and appropriate among other existing model estimations. It is concluded that the proposed model estimations could be used for the prediction of PV module temperature in similar environmental conditions as that of the study area with more accuracy and confidence. It ultimately helps to develop cost-effective and efficient PV systems.

1. Introduction

The intensities of solar radiation, ambient temperature, wind speed, relative humidity, configuration, and method of mounting are considered to be responsible for variations in the power output of photovoltaic (PV) modules [1–6]. PV module temperature is one of the key parameters which affect the performance of photovoltaic (PV) modules after solar radiations [2, 4, 7, 8]. Photovoltaic power output is proportional to the PV module operating temperature [9, 10]. Since the change of PV module temperature depends on the variation of ambient temperature, as ambient temperature increases, the module temperature increases and vice versa [4, 11]. It is because, the increase of temperature reduces the band gap of a PV module and increases the energy of the electrons in the material, which ultimately increases the recombination rate of internal carriers caused by the increasing amount of carrier concentrations [9, 12–14]. Consequently, it slightly increases the short-circuit current and considerably decreases open-circuit voltage [2, 9, 15]. Weather conditions affect the PV module temperature; therefore, its influence is necessary to be quantified. This can be done with the help of modeling, which eventually helps to design better systems for proper functioning. Several attempts have been made by different authors from different countries to exemplify the behaviour of PV modules. Some models are intuitive, and others are analytical, numerical, or empirical. Nevertheless, the majority of models are validated in indoor environments of developed countries with the exception of a few in outdoor conditions. It is a very challenging task to develop a model which represents the behaviour of various module technologies simultaneously in outdoor environments. An exact module temperature estimation model is indispensable to achieve reliable data of PV module power output [5, 11, 16–22]. The models used for the prediction of module temperature can be categorized in different ways: steady-state or dynamic, explicit or implicit, etc. [2, 9, 11]. In steady-state modeling, all parameters are assumed to be independent of time (with small time interval, i.e., an hour). However, such models are useful for specific locations and module technologies, while in the dynamic models, some parameters are considered to be varied with respect to time. Dynamic models are preferable for high-resolution input data. Explicit models predict the value of photovoltaic module temperature directly, whereas the implicit correlations involve variables that themselves depend on module temperature. In implicit models, an iteration procedure is compulsory to get the outputs [2, 5, 9, 23–30]. Nevertheless, the selection of an appropriate model is crucial for the design and sizing of photovoltaic systems. The use of an inappropriate model gives faulty predictions thus making the systems over- or undersized. The oversized system becomes costly alternative, whereas undersizing causes malfunctioning of the system. This problem can be controlled through proper sizing and designing of system components with the help of precise modeling and using of long-term reliable data [9, 20, 31-34]. Unfortunately, long-term data are not available in developing countries [31] including Pakistan [35], and the reliability of data is also questionable. Actually, photovoltaic module temperature models are submodels of power output models, as these models predict the effect of temperature on the performance of photovoltaic modules. Most of such models estimate the temperature of photovoltaic modules in indoor conditions but not in outdoor environments [36–38]. The main objective of this study was to develop a simple empirical model for the estimation of the temperature effect on four different PV module technologies, namely, polycrystalline, monocrystalline, amorphous, and thin film in an outdoor environment.

2. Existing Photovoltaic Module Temperature Models

In [39], the researchers consider only one basic climatic variable such as the ambient temperature (T_{a}) in their study. It is clear that one input variable does not reflect the whole behave of the environment. The developed model is given in equation (1) and also used by [40].

$$T_{\mathrm{m}} = 1.411 \times T_{\mathrm{a}} - 6.414. \tag{1}$$

Muzathik [38] suggested three variable models with ambient temperature T_{a} (°C), global solar radiation G_{sr} (W/m^2), and wind speed W_{v} (m/s). The model and coefficients of each variable are provided as given in Equation 2.

$$T_{\mathrm{m}} = 0.943 \times T_{\mathrm{a}} + 0.0195 \times G_{\mathrm{sr}} - 1.528 \times W_{\mathrm{v}} + 0.3529. \tag{2}$$

In addition, [2] proposed a simple and semiempirical model for the calculation of module temperature as given in equation (3). The author considered T_{a} in (°C), G_{sr} in (W/m^2), and W_{v} in (m/s). The same model is reported by [41].

$$T_{\mathrm{m}} = T_{\mathrm{a}} + \left(\frac{0.25}{5.7 + 3.8 \times W_{\mathrm{v}}}\right) \times G_{\mathrm{sr}}. \tag{3}$$

Duffie and Beckman [42] proposed a novel mathematical approach for the calculation of photovoltaic module temperature in controlled nominal operating cell temperature (NOCT) conditions: 0.8 kW/m^2 solar radiation, 20°C ambient temperature, and 1 m/s wind speed. The model depends on the input of T_{a} (°C), G_{sr} (W/m^2), W_{v} (m/s), and NOCT conditions as given in equation (4). Furthermore, the model is adopted by [9].

$$\begin{aligned} T_{\mathrm{m}} = T_{\mathrm{a}} &+ \left(\frac{9.5}{5.7 + 3.8 \times W_{\mathrm{v}}}\right)\left(\frac{G_{\mathrm{sr}}}{G_{\mathrm{sr-NOCT}}}\right) \\ &\cdot \left(T_{\mathrm{m-NOCT}} - T_{\mathrm{a-NOCT}}\right)\left[1 - \frac{\eta_m}{\tau_\alpha}\right]. \end{aligned} \tag{4}$$

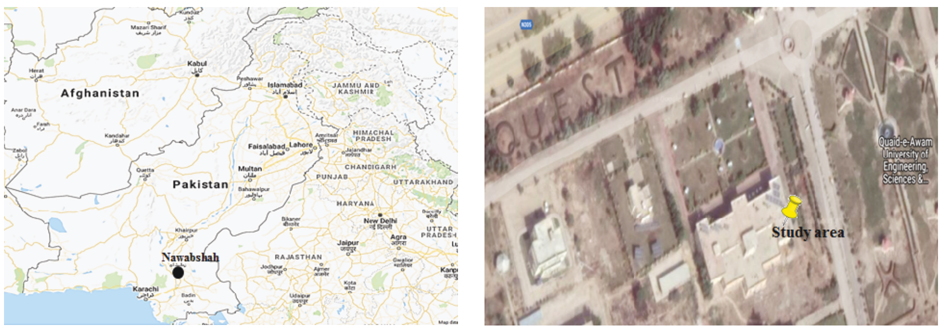
Risser and Fuentes [43] also proposed three variable models with the same variables as that of Muzathik [38] as given in equation 5. The author considered T_{a} in (°C), G_{sr} in (W/m^2), and W_{v} in (m/s). The same model is tested by [19].

$$T_{\mathrm{m}} = 1.31 \times T_{\mathrm{a}} + 0.0282 \times G_{\mathrm{sr}} - 1.65 \times W_{\mathrm{v}} + 3.81. \tag{5}$$

The authors [2, 38, 43] proposed new temperature models which were based on three basic input variables (solar radiations "G_{sr}," ambient temperature "T_{a}," and wind speed "W_{v}"). The researchers proposed linear models in their studies, but the behaviour of climatic data is parabolic with respect to time. In the morning hours, the intensities of G_{sr} and T_{a} are directly proportional, but in the evening, these are less related due to the slight decreasing trend of temperature as compared to the sharp decrease of solar radiations. The authors [9, 42] proposed a mathematical approach for the calculation of photovoltaic module temperature based on NOCT conditions. Such conditions could not be familiarized with a real outdoor condition.

Table 1: Existing PV module models.

Name of author	Empirical models
Rahman et al. [39, 40]	$T_m = 1.411 \times T_a - 6.414$
Muzathik [38]	$T_m = 0.943 \times T_a + 0.0195 \times G_{sr} - 1.528 \times W_v + 0.3529$
Skoplaki et al. [2, 41]	$T_m = T_a + (0.25/5.7 + 3.8 \times W_v) \times G_{sr}$
Duffie and Beckman [9, 42]	$T_m = T_a + (9.5/5.7 + 3.8 \times W_v)(G_{sr}/G_{sr\text{-NOCT}})(T_{m\text{-NOCT}} - T_{a\text{-NOCT}})[1 - \eta_m/\tau_\alpha]$
Risser and Fuentes [19, 43]	$T_m = 1.31 \times T_a + 0.0282 \times G_{sr} - 1.65 \times W_v + 3.81$
Almaktar et al. [40]	$T_m = 0.77 \times T_a + 0.023 \times G_{sr} - 0.137 \times W_v - 0.206 \times R_h + 26.97$



(a) Map of Pakistan

(b) Study area

Figure 1: Geographical location of the study area (Google Maps).

Table 2: Electrical characteristics of examined photovoltaic modules [14, 46].

Module parameters	Unit	Module technologies (p-Si) SUN-40P	(m-Si) SUN-40M	(a-Si) TPS-40	Thin film GS-50
V_{oc}	V	43	21.5	29	62
I_{sc}	A	1.29	2.55	2.3	1.42
V_{max}	V	35	17.5	18	43
I_{max}	A	1.14	2.29	2.2	1.17
P_{max}	W	40	40	40	50
Area of module	m^2	0.27	0.24	0.76	0.74

Almaktar et al. [40] proposed a temperature model which depends on four climatic variables, namely, solar radiations "G_{sr}," ambient temperature "T_a," wind speed "W_v," and relative humidity "R_h" as given in Equation 6.

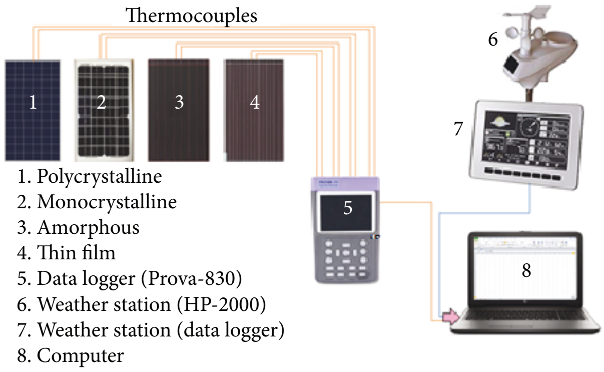
$$T_m = 0.77 \times T_a + 0.023 \times G_{sr} - 0.137 \times W_v - 0.206 \times R_h + 26.97. \tag{6}$$

It is already mentioned that the behaviour of climatic data is parabolic in nature with respect to the time of the day. Therefore, in this study, an empirical, nonlinear, multivariate, and least squares model was developed and proposed to calculate the PV module temperature in an outdoor environment. Table 1 shows the well-known PV module temperature models.

3. Materials and Methods

3.1. Study Area. The study was conducted in Nawabshah city, Shaheed Benazirabad District, Sindh, Pakistan, as shown in Figure 1. It is one of the hottest places and located at 26.14°N, 68.23°E [44] and mean 37 m above sea level [45].

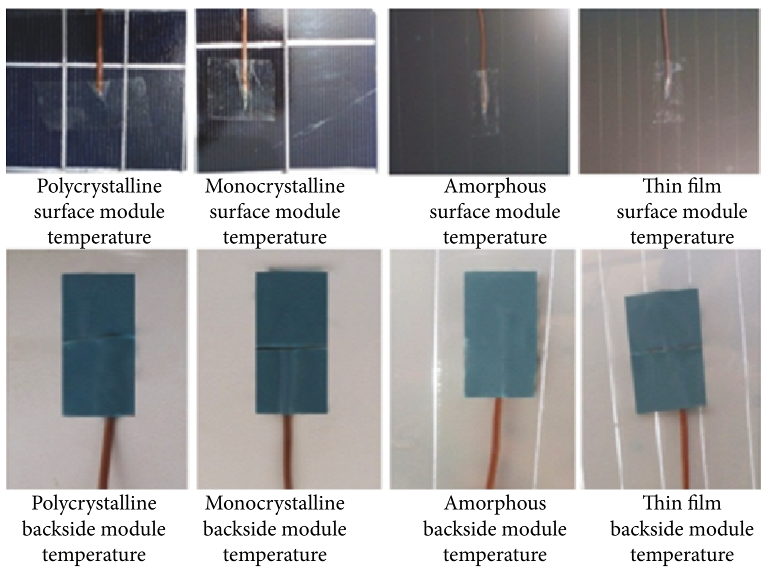
3.2. Experimental Setup. An experimental setup was installed at the Energy and Environment Engineering Department, QUEST, Nawabshah. Four generic photovoltaic modules (polycrystalline, monocrystalline, amorphous, and thin film) were used in this study, and their specifications are given in



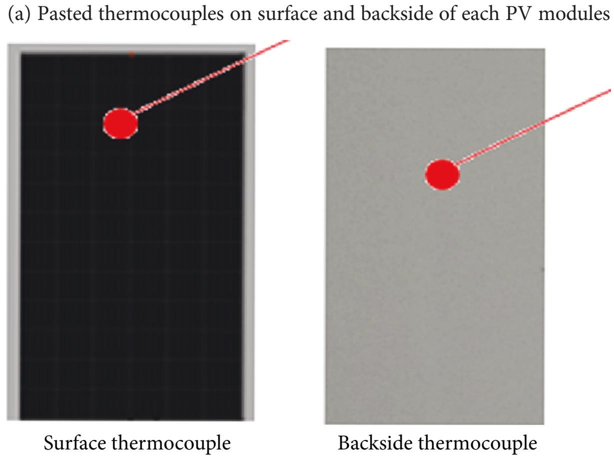
(a) Schematic flow diagram of experimental setup

(b) Experimental setup for data logging

Figure 2: Experimental setup.



(a) Pasted thermocouples on surface and backside of each PV modules



(b) Positions of thermocouple sensors (surface and backside of PV modules)

Figure 3: Pasted thermocouple sensors on the surface and backside of each photovoltaic module.

Table 2. The photovoltaic modules were fixed on an iron structure, facing true south at an inclination of 12° to the horizontal plane. Figure 2 shows the schematic diagram and experimental setup. The data of each PV module was recorded for a whole year from November, 2015, to October, 2016, for the development of a suitable model for the

Table 3: Accuracy of equipment used in this study.

Parameters	Unit	Weather station (HP-2000) Accuracy	Module temperature recorder (Prova-830) Accuracy
G_{sr}	W/m^2	±15%	—
T_a	°C	±1.0°C	—
W_v	m/s	±1 m/s (wind speed < 5) ±10% (wind speed > 5)	—
R_h	%	±5%	—
T_m	°C	—	±0.1% or 1.0°C

prediction of module temperature. The data was measured at an interval of 1 hour from 07 to 18 hours daily. Global solar radiation G_{sr} (W/m^2), ambient temperature T_a (°C), wind speed W_v (m/s), and relative humidity R_h (%) were measured with HP-2000. Photovoltaic module temperature was recorded with the help of Prova-830 (8 channel thermocouple data logger). A total of eight numbers (two on each PV module) of k-type thermocouples were pasted on the surface and backside of the photovoltaic modules as shown in Figure 3 [14, 46]. The accuracy of equipment used for data measurement is given in Table 3. The temperature sensors were pasted on the surface and backside of photovoltaic module as that of [8], and then, the average of temperature was taken as the module operating temperature [14, 46, 47].

4. Proposed Empirical Model

In this section, we develop a model for the estimation of the temperature effect on different photovoltaic (PV) module technologies, namely, polycrystalline, monocrystalline, amorphous, and thin film in the outdoor environment. In model development, one dependent variable (module temperature) and four basic independent climatic variables (global solar radiation, ambient temperature, wind speed, and relative humidity) were adopted. Furthermore, the correlation of the dependent variable with each independent variable was analyzed. The correlation of module temperature (T_m) with the global solar radiation (G_{sr}) was found to be 0.89217, ambient temperature (T_a) 0.73765, wind speed (W_v) 0.075766, and relative humidity (R_h) -0.55918. The relationship between climatic parameters and module temperature was found to be nonlinear because of the parabolic curve. Thus, it was deduced from the curve fitting that polynomial models might be suitable models, as these cover the maximum number of measured data points. Further scrutiny of models was made by fitting the data with different degrees of polynomials (1-9 degrees). It was found that the 2nd degree polynomial model covers the maximum number of data points of the measured data. Thus, an empirical second degree multivariate nonlinear model was proposed with fitting of data with the least squares method. It was assumed that photovoltaic module temperature (T_m) is the function of four variables, namely, G_{sr}, T_a, W_v, and R_h. Thus, the basic function of PV module temperature (T_m) is given in equation (7).

$$T_m = f(G_{sr}, T_a, W_v, R_h). \tag{7}$$

The general form of the model would be given in Equation 8.

$$\begin{aligned} T_m = {} & (a_1 G_{sr} + a_2 T_a + a_3 W_v + a_4 R_h + a_5) \\ & \times (b_1 G_{sr} + b_2 T_a + b_3 W_v + b_4 R_h + b_5). \end{aligned} \tag{8}$$

By expanding equation (8) with the combination of all four independent variables, equation (9) is developed, which demonstrates the output and input parameters and all involved coefficients.

$$\begin{aligned} T_m = {} & (a_1 G_{sr} b_2 T_a + a_1 G_{sr} b_3 W_v + a_1 G_{sr} b_4 R_h + a_2 T_a b_1 G_{sr} \\ & + a_2 T_a b_3 W_v + a_2 T_a b_4 R_h + a_3 W_v b_1 G_{sr} + a_3 W_v b_2 T_a \\ & + a_3 W_v b_4 R_h + a_4 R_h b_1 G_{sr} + a_4 R_h b_2 T_a + a_4 R_h b_3 W_v \\ & + a_3 {W_v}^2 b_3 + a_5 b_4 R_h + a_3 W_v b_5 + a_2 T_a b_5 + a_5 b_3 W_v \\ & + a_4 {R_h}^2 b_4 + a_1 G_{sr} b_5 + a_5 b_1 G_{sr} + a_4 R_h b_5 + a_5 b_2 T_a \\ & + a_2 {T_a}^2 b_2 + a_1 {G_{sr}}^2 b_1 + a_5 b_5). \end{aligned} \tag{9}$$

Let T_{m_meas} be the measured module temperature and T_{m_est} be the estimated module temperature. The least squares method assumes that the sum of the squares of the residuals (error) is less. Therefore, it can be estimated using Equation 10.

$$E_i = \min \sum_{i=1}^{n} \left(T_{m\_meas_i} - T_{m\_est_i} \left(G_{sr_i}, T_{a_i}, W_{v_i}, R_{h_i}; \beta \right) \right)^2. \tag{10}$$

where $i = 1, 2, \cdots, n$, as $n = 4392$ and β is the set of the coefficients of the model. The minimum value of E occurs when the gradient is zero. The model contains $m = 25$ parameters; therefore, the gradient equation is 25. Furthermore, the minimum values of E and r_i are calculated through equations (11) and (12).

$$\frac{\partial E_i}{\partial \beta_j} = 2 \sum_{i=1}^{n} r_i \frac{\partial r_i}{\partial \beta_j} = 0. \tag{11}$$

where $j = 1, 2, \cdots, m = 25$.

$$r_i = \left(T_{m\_meas_i} - T_{m\_est_i} \left(G_{sr_i}, T_{a_i}, W_{v_i}, R_{h_i}; \beta \right) \right). \tag{12}$$

Table 4: Proposed model coefficients.

Model coefficients	Photovoltaic module technologies			
	Polycrystalline	Monocrystalline	Amorphous	Thin film
α	22.5505	31.3750	33.9800	32.4500
β_1	0.03753	0.03858	0.03622	0.03340
β_2	$-5.71 \times 10 - 7$	$-1.91 \times 10 - 6$	0.00000	$-1.974 \times 10 - 6$
γ_1	0.005892	0.6672	0.1191	0.2982
γ_2	0.01179	0.0000	0.01078	0.007552
δ	-0.0002703	-0.0002805	-0.000245	-0.0001666
λ	-0.6070	-6.4460	-5.0350	-4.9540
ζ	-0.0960	-0.2100	-0.1691	-0.1935

The model equation (12) is complex and time-consuming. Thus, it requires to be simplified for easy computation and application. For that, symbolic derivatives of equation 12 were put in MAPLE software, by producing a system of equations with the coefficients β_j. Then, the obtained system of equations from MAPLE software was solved iteratively in MATLAB software. The coefficients of the developed model were approximated with an error tolerance of 0.0001. The general form of the developed model for the estimation of all four types of photovoltaic (PV) module temperatures is shown in equation (13), and model coefficients are given in Table 4.

$$T_{\mathrm{m}} = \alpha_0 + \beta_1(G_{\mathrm{sr}}) + \beta_2(G_{\mathrm{sr}})^2 + \gamma_1(T_{\mathrm{a}}) + \gamma_2(T_{\mathrm{a}})^2 + \delta(G_{\mathrm{sr}})(T_{\mathrm{a}}) + \lambda(W_{\mathrm{v}}) + \zeta(R_{\mathrm{h}}). \tag{13}$$

where α_0, β_1, β_2, γ_1, γ_2, δ, λ, and ζ are least squares coefficients of the proposed model.

5. Statistical Analysis

Statistical analysis was conducted to see the variation between models' estimated and measured results. The coefficient of determination (R^2) [48, 49], root mean square error (RMSE), and mean absolute error (MAE) [40, 48–50] were used as statistical indicators as given in equation (14), respectively. The root mean square error (RMSE) and mean absolute error (MAE) are considered in °C. The statistical analysis was done at 95% confidence level.

$$R^2 = \frac{\sum_{i=1}^{n}\left(T_{\mathrm{m\_est}_i} - \bar{T}_{\mathrm{m\_est}_i}\right)^2}{\sum_{i=1}^{n}\left(T_{\mathrm{m\_meas}_i} - \bar{T}_{\mathrm{m\_meas}_i}\right)^2},$$
$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(T_{\mathrm{m\_est}_i} - T_{\mathrm{m\_meas}_i}\right)^2}{n}}, \tag{14}$$
$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left(T_{\mathrm{m\_est}_i} - T_{\mathrm{m\_meas}_i}\right).$$

where $\bar{T}_{\mathrm{m\_est}}$ is the average estimated module temperature and $\bar{T}_{\mathrm{m\_meas}}$ is the average measured module temperature.

6. Results and Discussion

6.1. Weather Conditions. The average hourly global solar radiation (G_{sr}), maximum and minimum ambient temperature (T_{a}), wind speed (W_{v}), and relative humidity (R_{h}) of a whole year from November, 2015, to October, 2016, are shown in Figures 4–7. The yearly average total global solar radiations were found to be 6224.35 kWh/m^2/day with a maximum average of 835.25 W/m^2 at 12 hours and a minimum average of 86.02 W/m^2 at 07 hours. The values of global solar radiations are given in Figure 4. The maximum T_{a} was noted as 34.67°C at 15 hours and the minimum as 21.35°C at 07 hours with a yearly average of 30.11°C during the study period. The ambient temperature values are shown in Figure 5. Similarly, Figure 6 displays the wind speed. The maximum yearly average W_{v} was recorded as 2.60 m/s at 16 hours and the minimum as 1.30 m/s at 07 hours with a yearly average of 2.14 m/s. Likewise, the maximum yearly average R_{h} was noted as 76.90% at 07 hours and the minimum as 26.25% with a yearly average of 42.66%. The R_{h} is given in Figure 7. The yearly average values of climatic conditions like G_{sr}, T_{a}, W_{v}, and R_{h} are given in Table 5. Relative humidity was found inversely proportional to the intensity of global solar radiation and ambient temperature.

6.2. Validation of Proposed Model Results. The proposed model results were validated by comparing its estimations with measured data of winter season (for the months of December and January 2017) and summer season (for the months of May and June 2017) and with estimations of other existing models.

6.3. Proposed and Existing Model Estimations versus Measured Data of Winter Season. The comparison of the proposed model estimation versus measured and other existing model results of polycrystalline, monocrystalline, amorphous, and thin film modules are shown in Figures 8–11 for winter season, respectively. The average proposed model has estimated 0.19°C (0.61%), 0.48°C (1.61%), 0.06°C (0.19%), and 0.07°C (0.24%) low module temperatures for polycrystalline, monocrystalline, amorphous, and thin film modules, respectively, than measured ones. It was found that

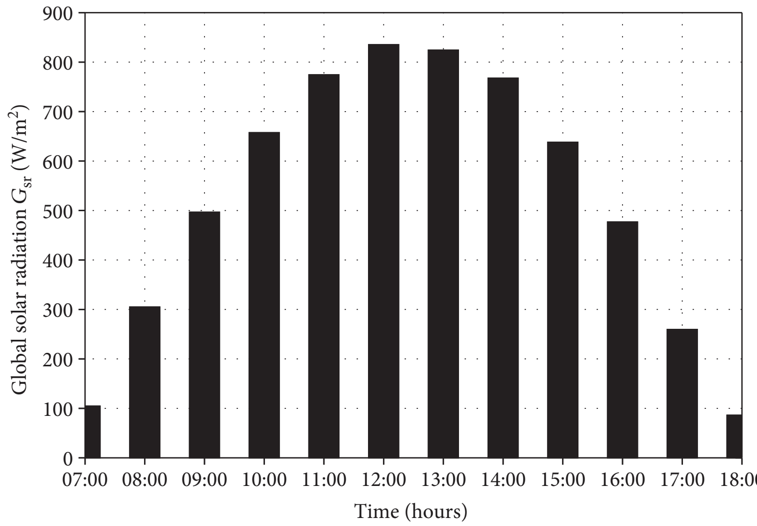


Figure 4: Yearly hourly average values of global solar radiation.

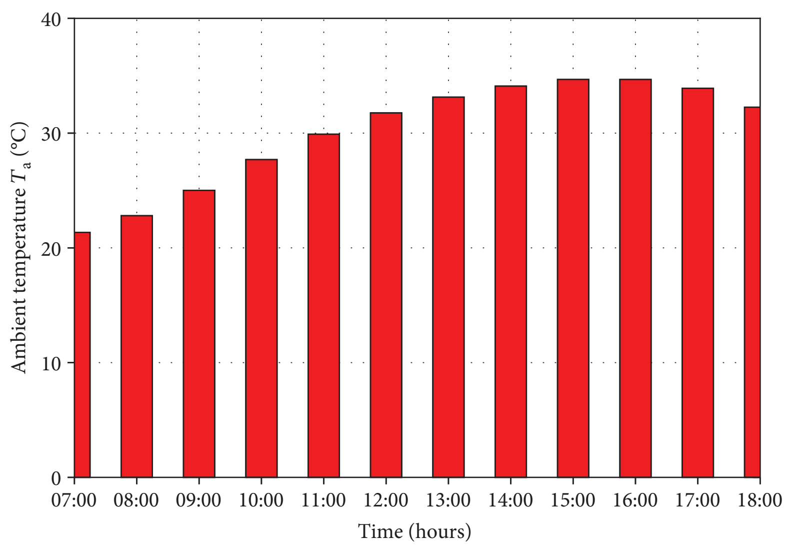


Figure 5: Yearly hourly average values of ambient temperature.

monocrystalline has a least percentage of module temperature than other module technologies. It was revealed that Rahman et al. [39], Muzathik [38], Skoplaki et al. [2] and Duffie and Beckman [42] models' predicted results are lower than those of the measured and proposed models' estimated module temperature because of the lower number of input parameters. Risser and Fuentes [43] and Almaktar et al. [40] models gave higher average module temperature of 3.40°C (10.91%) and 6.32°C (16.83%) for polycrystalline, 4.61°C (15.38%) and 7.53°C (25.09%) for monocrystalline, 3.34°C (10.68%) and 6.25°C (20.00%) for amorphous, and 4.62°C (15.43%) and 7.54°C (25.14%) for thin film modules, respectively, than the proposed model estimations.

6.4. Proposed and Existing Model Estimations versus Measured Data of Summer Season. The comparison of the proposed model estimation versus measured and other existing model results of polycrystalline, monocrystalline, amorphous, and thin film modules are shown in Figures 12–15 for summer season, respectively. The proposed model gave 0.43°C (0.84%) higher module temperature for polycrystalline and 1.31°C (2.65%), 0.90°C (1.76%), and 1.07°C (2.15%) lower module temperature for monocrystalline, amorphous, and thin film modules than the measured module temperature. It was found that monocrystalline estimates a least percentage of module temperature than amorphous and thin film modules. It was found that Rahman et al. [39], Muzathik [38], Skoplaki et al. [2], and Duffie and Beckman [42] models' predicted results are lower than those of the measured and proposed models' estimated values. Risser and Fuentes [43] and Almaktar et al. [40] models gave higher module temperatures of 15.79°C (30.42%) and 10.21°C (19.68%) for polycrystalline, 18.41°C (37.35%) and 12.83°C (26.03%) for

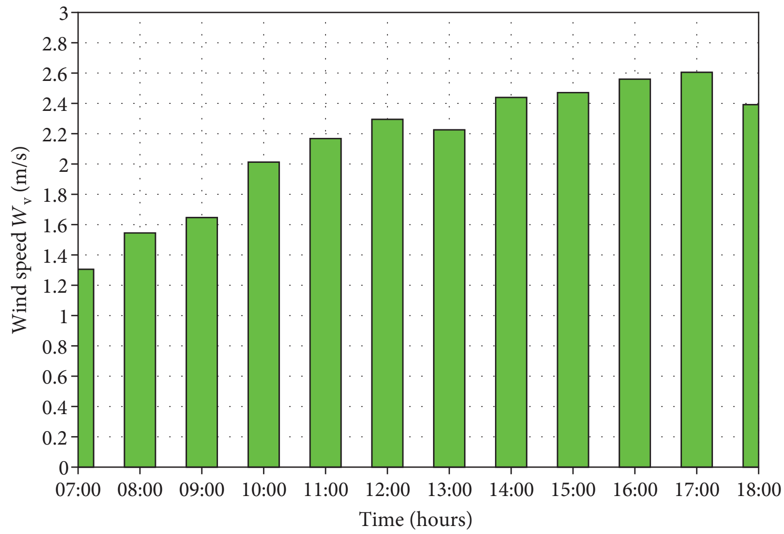


FIGURE 6: Yearly hourly average values of wind speed.

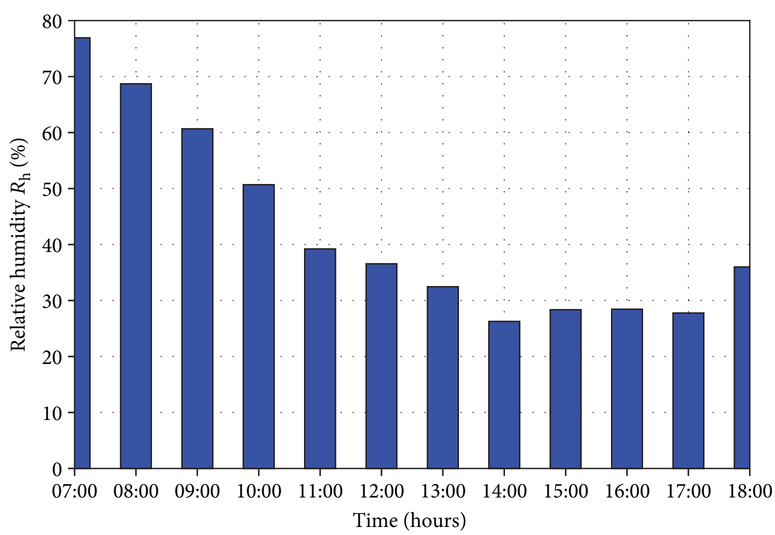


FIGURE 7: Yearly hourly average values of relative humidity.

TABLE 5: Yearly average values of climatic conditions.

	G_{sr} (W/m^2)	T_a (°C)	W_v (m/s)	R_h (%)
Maximum values	835.25	34.67	2.60	76.90
Minimum values	86.02	21.35	1.30	26.25
Average values	518.69	30.11	2.14	42.66

monocrystalline, 16.64°C (32.60%) and 11.07°C (21.68%) for amorphous, and 18.04°C (36.32%) and 12.46°C (25.09%) for thin film modules, respectively, than the proposed model's estimated values. It was found that the proposed model estimates a low temperature with 1.61% in winter and 2.65% in summer from monocrystalline than other measured modules.

7. Error Analysis

The error analysis of the proposed model estimations was checked with measured data of winter season and summer season and with estimations of other existing models. The coefficient of determination (R^2), root mean square error (RMSE) (°C), and mean absolute error (MAE) (°C) of each PV module of winter season (months of December and January) are summarized in Tables 6–8 and of the season of summer (months of May and June) in Tables 9–11, respectively.

In winter season, the maximum R^2 was given by the proposed model with 0.996, 0.998, 0.992, and 0.994 and the minimum by Rahman et al. [39] model with 0.646, 0.707, 0.650, and 0.725 for polycrystalline, monocrystalline, amorphous, and thin film modules, respectively. Similarly, the minimum

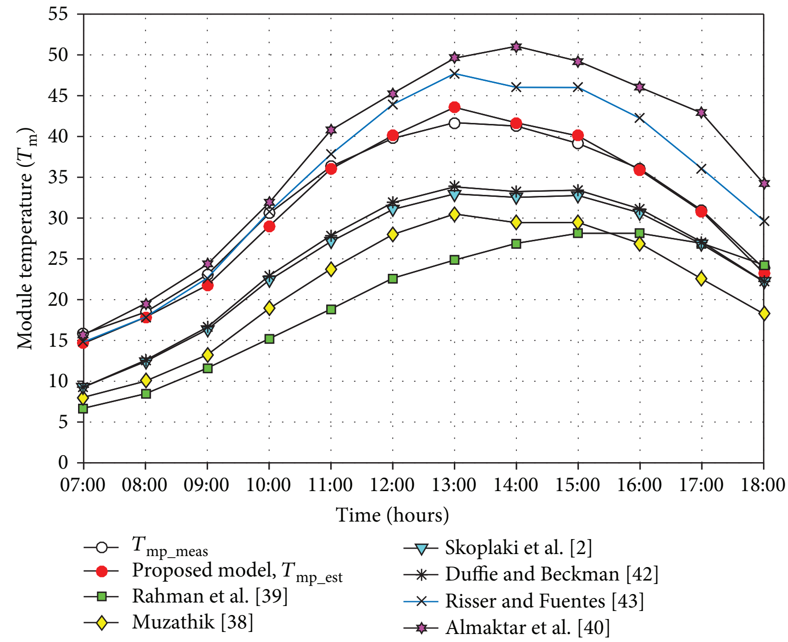


Figure 8: Proposed model estimation versus measured data and other existing model module temperature values of polycrystalline module during winter.

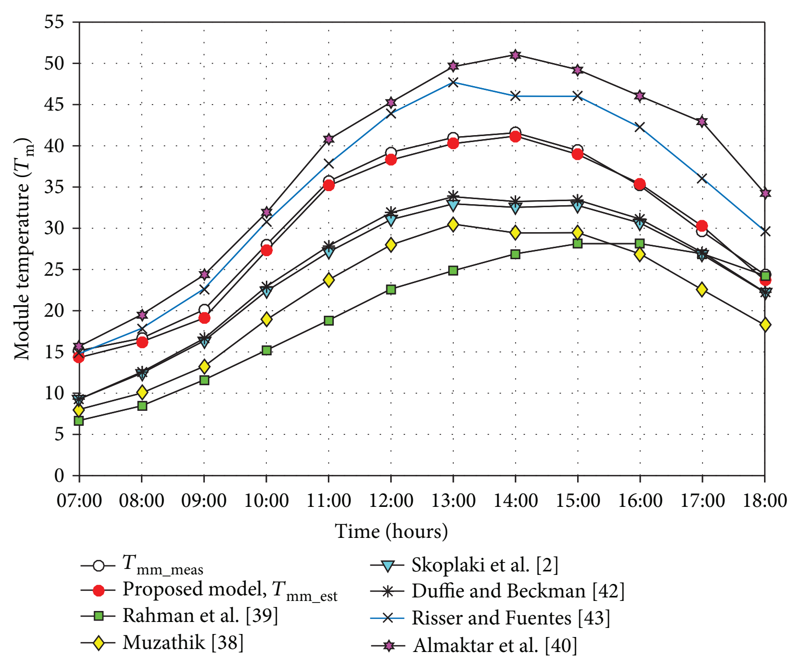


Figure 9: Proposed model estimation versus measured data and other existing model module temperature values of monocrystalline module during winter.

RMSE was noted by the proposed model with 0.955, 0.673, 0.898, and 0.763 and the maximum by Rahman et al. [39] model with 12.357, 11.009, 12.177, and 10.809 for polycrystalline, monocrystalline, amorphous, and thin film modules, respectively, than other existing models. Likewise, the minimum MAE was noted by the proposed model with 0.782, 0.636, 0.721, and 0.666 and the maximum by Rahman et al. [39] model with 11.165, 9.884, 11.069, and 9.813 for polycrystalline, monocrystalline, amorphous, and thin film modules, respectively, than other existing models.

In summer season, the maximum R^2 was given by the proposed model with 0.996, 0.995, 0.993, and 0.992 and the minimum by Rahman et al. [39] model with 0.496, 0.402, 0.477, and 0.456 for polycrystalline, monocrystalline,

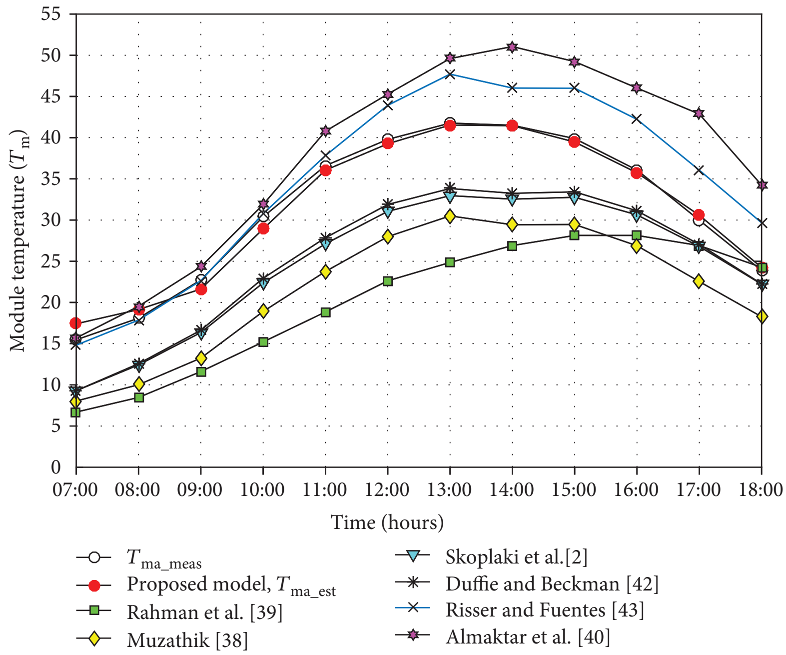


FIGURE 10: Proposed model estimation versus measured data and other existing model module temperature values of amorphous module during winter.

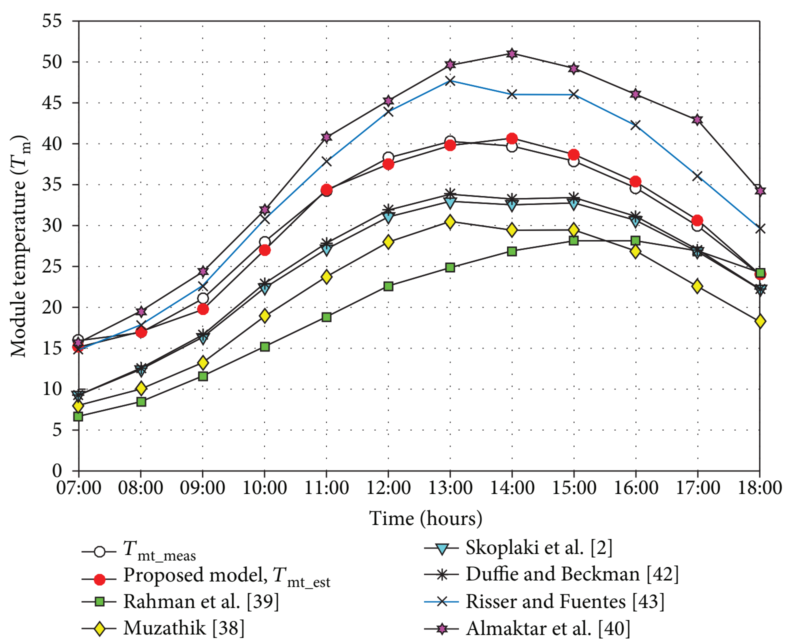


FIGURE 11: Proposed model estimation versus measured data and other existing model module temperature values of thin film module during winter.

amorphous, and thin film modules, respectively. Similarly, the minimum RMSE was noted by the proposed model with 0.996, 1.330, 1.262, and 1.502 and the maximum by Risser and Fuentes [43] model with 15.833, 18.564, 16.694, and 18.107 for polycrystalline, monocrystalline, amorphous, and thin film modules, respectively, than other existing models. Likewise, the minimum MAE was noted by the proposed model with 0.832, 1.176, 1.078, and 1.180 and the maximum by Risser and Fuentes [43] model with 15.796, 18.413, 16.649, and 18.041 for polycrystalline, monocrystalline, amorphous, and thin film modules, respectively, than other existing models.

The proposed model gave the maximum R^2 and minimum RMSE and MAE than other existing model estimations.

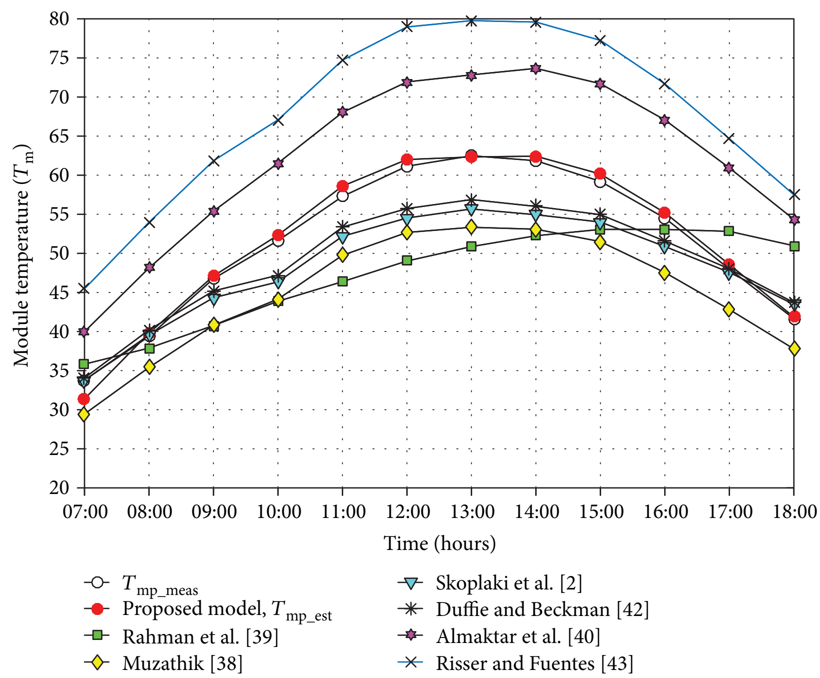


FIGURE 12: Proposed model estimation versus measured data and other existing model module temperature values of polycrystalline module during summer.

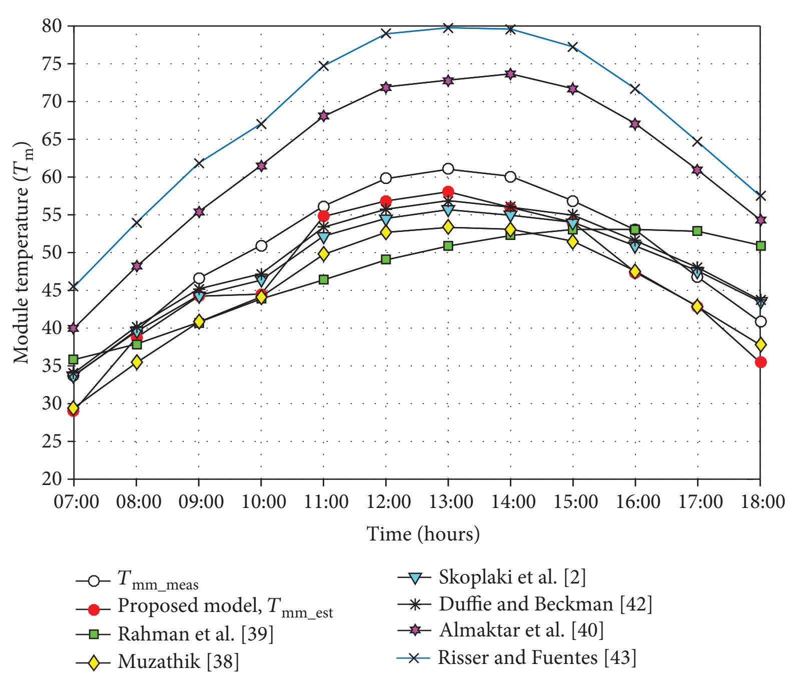


FIGURE 13: Proposed model estimation versus measured data and other existing model module temperature values of monocrystalline module during summer.

Thus, the proposed model results are more appropriate than other existing model results. It was observed that the models of one input variable show the minimum coefficient of determination and maximum root mean square error as well as the mean absolute error and vice versa for more input variable models.

8. Conclusions

Photovoltaic (PV) operating temperature plays an important role in the PV conversion process after solar radiation. It is a very challenging task to develop a model which represents the behaviour of various module technologies in outdoor

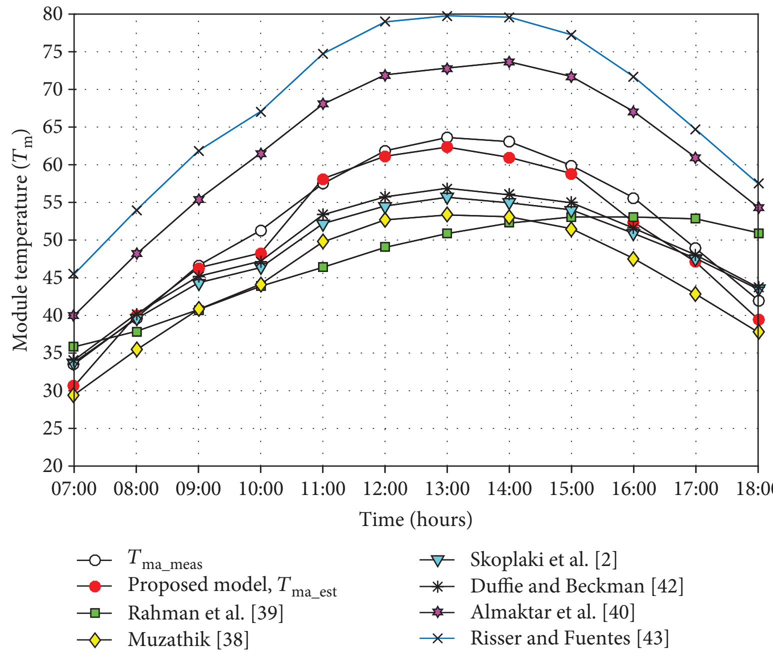


Figure 14: Proposed model estimation versus measured data and other existing model module temperature values of amorphous module during summer.

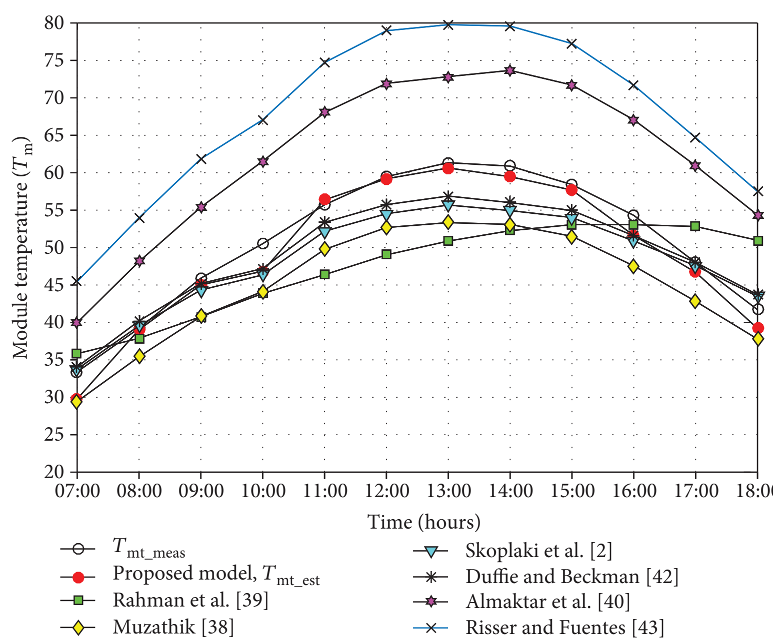


Figure 15: Proposed model estimation versus measured data and other existing model module temperature values of thin film module during summer.

environments. An empirical second degree polynomial multivariate model was developed using the least squares data fitting method to estimate the module temperature in outdoor conditions. It was validated by comparing the proposed model estimations with real-time measured data of winter and summer season and other existing model estimations through error analysis. It was revealed that the proposed model estimated the least temperature for monocrystalline module with 0.48°C (1.61%) in winter season and 1.31°C (2.66%) in summer season than other examined module technologies. Risser and Fuentes [43] and Almaktar et al. [40] models gave a higher average of module temperature with 4.62°C (15.43%) and 7.54°C (25.14%) for thin film in winter and 18.41°C (37.35%) and 12.83°C (26.03%) for monocrystalline modules in summer than the proposed model estimated values. It was found that Rahman

Table 6: Coefficient of determination (R^2) of each PV module in winter.

S. no.	Name of model	Coefficient of determination (R^2) (p-Si)	(m-Si)	(a-Si)	Thin film
(1)	Proposed model	0.996	0.998	0.992	0.994
(2)	Rahman et al. [39]	0.646	0.707	0.650	0.725
(3)	Muzathik [38]	0.970	0.982	0.968	0.986
(4)	Skoplaki et al. [2]	0.946	0.965	0.942	0.969
(5)	Duffie and Beckman [42]	0.955	0.970	0.949	0.974
(6)	Risser and Fuentes [43]	0.972	0.982	0.969	0.986
(7)	Almaktar et al. [40]	0.924	0.953	0.925	0.962

Table 7: Root mean square error (RMSE) of each PV module in winter.

S. no.	Name of model	Root mean square error (RMSE) (°C) (p-Si)	(m-Si)	(a-Si)	Thin film
(1)	Proposed model	0.955	0.673	0.898	0.763
(2)	Rahman et al. [39]	12.357	11.009	12.177	10.809
(3)	Muzathik [38]	9.935	8.678	9.854	8.560
(4)	Skoplaki et al. [2]	6.992	5.713	6.900	5.560
(5)	Duffie and Beckman [42]	6.468	5.194	6.407	5.057
(6)	Risser and Fuentes [43]	4.104	5.093	7.566	5.243
(7)	Almaktar et al. [40]	7.335	8.243	4.481	8.344

Table 8: Mean absolute error (MAE) of each PV module in winter.

S. no.	Name of model	Mean absolute error (MAE) (°C) (p-Si)	(m-Si)	(a-Si)	Thin film
(1)	Proposed model	0.782	0.636	0.721	0.666
(2)	Rahman et al. [39]	11.165	9.884	11.069	9.813
(3)	Muzathik [38]	9.636	8.426	9.701	8.413
(4)	Skoplaki et al. [2]	6.512	5.302	6.576	5.289
(5)	Duffie and Beckman [42]	6.047	4.838	6.112	4.825
(6)	Risser and Fuentes [43]	3.407	4.616	3.987	4.685
(7)	Almaktar et al. [40]	6.322	7.532	6.543	7.544

Table 9: Coefficient of determination (R^2) of each PV module in summer.

S. no.	Name of model	Coefficient of determination (R^2) (p-Si)	(m-Si)	(a-Si)	Thin film
(1)	Proposed model	0.996	0.995	0.993	0.992
(2)	Rahman et al. [39]	0.496	0.402	0.477	0.476
(3)	Muzathik [38]	0.991	0.980	0.990	0.984
(4)	Skoplaki et al. [2]	0.976	0.943	0.974	0.971
(5)	Duffie and Beckman [42]	0.983	0.955	0.983	0.979
(6)	Almaktar et al. [40]	0.982	0.946	0.973	0.974
(7)	Risser and Fuentes [43]	0.981	0.980	0.984	0.984

Table 10: Root mean square error (RMSE) of each PV module in summer.

S. no.	Name of model	Root mean square error (RMSE) (°C) (p-Si)	(m-Si)	(a-Si)	Thin film
(1)	Proposed model	0.996	1.330	1.262	1.502
(2)	Rahman et al. [39]	8.458	7.179	8.137	7.292
(3)	Muzathik [38]	7.444	4.790	6.665	5.234
(4)	Skoplaki et al. [2]	5.150	3.172	4.590	3.530
(5)	Duffie and Beckman [42]	4.363	2.655	3.853	2.952
(6)	Almaktar et al. [40]	10.321	13.114	11.209	12.596
(7)	Risser and Fuentes [43]	15.833	18.564	16.694	18.107

Table 11: Mean absolute error (MAE) of each PV module in summer.

S. no.	Name of model	Mean absolute error (MAE) (°C) (p-Si)	(m-Si)	(a-Si)	Thin film
(1)	Proposed model	0.832	1.176	1.078	1.180
(2)	Rahman et al. [39]	7.603	6.363	7.286	6.434
(3)	Muzathik [38]	7.053	4.436	6.200	4.808
(4)	Skoplaki et al. [2]	4.447	2.813	3.954	3.147
(5)	Duffie and Beckman [42]	3.799	2.239	3.334	2.646
(6)	Almaktar et al. [40]	10.218	12.835	11.071	12.463
(7)	Risser and Fuentes [43]	15.796	18.413	16.649	18.041

et al. [39] model shows the least behavior of module temperature than the measured, proposed model estimations and other existing model estimation values in both seasons. The proposed model gave around 0.998 coefficient of determination for monocrystalline and low root mean square error and mean absolute error in both seasons. It is concluded that the proposed model is more appropriate for the estimation of photovoltaic module temperature in outdoor conditions because the proposed model gave a maximum coefficient of determination and minimum root mean square error and mean absolute error in both seasons. It is recommended that the time interval of data recording may be reduced from 1 hour to minutes and PV module technologies with the same ratings may be used for a comparison purpose. The performance and effect of temperature on both free standing and building integrated systems may be checked and verified in outdoor environments.

Nomenclature

G_{sr}: Global solar radiation (W/m^2)
T_a: Ambient temperature (°C)
W_v: Wind speed (m/s)
R_h: Relative humidity (%)
T_m: Module temperature (°C)
°C: Degree centigrade
m/s: Meter per second
%: Percentage
PV: Photovoltaic
p-Si: Polycrystalline
m-Si: Monocrystalline
a-Si: Amorphous
V_{oc}: Open-circuit voltage (V)
I_{sc}: Short-circuit current (A)
V_{max}: Maximum voltage (V)
I_{max}: Maximum current (A)
P_{max}: Maximum power (W)
kW/m^2: Kilowatt per square meter
kWh/m^2/d: Kilowatt hour per square meter per day
W/m^2: Watt per square meter
mW/cm^2: Milliwatts per square centimeter
T_m: Module temperature (°C)
T_{m_meas}: Measured module temperature (°C)
T_{m_est}: Estimated module temperature (°C)
T_{mp_meas}: Polycrystalline measured module temperature (°C)
T_{mp_est}: Polycrystalline estimated module temperature (°C)
T_{mm_meas}: Monocrystalline measured module temperature (°C)
T_{mm_est}: Monocrystalline estimated module temperature (°C)
T_{ma_meas}: Amorphous measured module temperature (°C)
T_{ma_est}: Amorphous estimated module temperature (°C)
T_{mt_meas}: Thin film measured module temperature (°C)
T_{mt_est}: Thin film estimated module temperature (°C)
m: Meter
m^2: Meter square
η_m: Efficiency of module
τ_α: Transmittance of glass
k_r: Ross coefficient
R^2: Coefficient of determination
RMSE: Root mean square error (°C)
MAE: Mean absolute error (°C)

SUN: Sanak SK Union
TPS: Topray Solar, Shenzhen
NOCT: Nominal operating cell temperature
STC: Standard test conditions
QUEST: Quaid-e-Awam University of Engineering, Science and Technology

Proposed model coefficient

α_0: Alpha$_0$ (general coefficients)
β_1: Global solar radiation (G_{sr})
β_2: Global solar radiation ($G_{sr}{}^2$)
γ_1: Ambient temperature (T_a)
γ_2: Ambient temperature ($T_a{}^2$)
δ: Global solar radiation and ambient temperature ($G_{sr}{}^* T_a$)
λ: Wind speed (W_v)
ξ: Relative humidity (R_h).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors have no conflict of interest.

Authors' Contributions

The authors have worked and contributed equally to this paper. The research article is submitted with the approval of all authors.

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