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Effect of Temperature and Wind Speed on Efficiency of Five Photovoltaic Module Technologies for Different Climatic Zones

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Abstract: The objective of this study is to investigate the effect of temperature and wind speed on the performance of five photovoltaic (PV) module technologies for different climatic zones of Pakistan. The PV module technologies selected were mono-crystalline silicon (MC); poly-crystalline silicon (PC); heterogeneous intrinsic thin-film (TFH); copper–indium–allium–selenide (TFC); and thin-film amorphous silicon (TFA). The module temperature and actual efficiency were calculated using measured data for one year. The actual efficiency of MC, PC, TFH, TFC, and TFA decreases by 3.4, 3.1, 2.2, 3.7, and 2.7%, respectively, considering the effect of temperature only. The actual efficiency of MC, PC, TFH, TFC, and TFA increases by 9.7, 9.0, 6.5, 9.5, and 7.0% considering the effect of both temperature and wind speed. The TFH module is the most efficient (20.76%) and TFC is the least efficient (16.79%) among the five materials. Under the effect of temperature, the actual efficiency of TFH is the least affected while the efficiency of TFC is the most affected. The actual efficiency of MC is the most affected and that of TFH is the least affected under the combined effect of wind speed and temperature. The performance ratio of TFC is the most affected and that of TFH is the least affected under the effect of temperature and the combined effect of temperature and wind speed. The performance of PV technology, under real outdoor conditions, does not remain the same due to environmental stresses (solar irradiance, ambient temperature, and wind speed). This study plays an important role in quantifying the long-term behavior of PV modules in the field, hence identifying specific technology for the PV industry in suitable climatic conditions.

Keywords: mono-crystalline silicon; poly-crystalline silicon; heterogeneous intrinsic thin-film; copper–indium–gallium–selenide; thin-film amorphous silicon; efficiency

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1. Introduction

To avoid the worst climatic impact of fossil fuels [1,2], solar energy is attracting greater attention for electricity generation due to its clean, sustainable, and cost-effective source [3,4]; it had a worldwide capacity of 733 GW in 2020, accounting for 26% of renewable sources [5]. Asim et al. [6] evaluated the design and optimization of the pico water wheel for the rural electrification of Pakistan as well. Solar energy has promising potential for projects in Pakistan and can be used for different applications such as heating systems, thermal energy systems, air-conditioning [7], solar cooling systems, and several others. A photovoltaic (PV) module is preferred to produce electricity due to its lower maintenance costs and higher reliability, but its conversion efficiency is very low [8,9]. It only converts 15–20% of solar radiation into electricity and the rest of the radiation is converted into heat; this heat raises the module temperature, which highly impacts its performance [10].

Several PV technologies are attracting interest with the rapid growth of PV deployment [11]. These are rated under Standard Test Conditions (STC) [12] by different manufacturers, but STC does not represent PV performance under actual field conditions and is influenced by various environmental parameters such as ambient temperature and wind speed [13–16]. Due to the influence of environmental conditions, a cell's actual conversion efficiency deviates from its rated value. Environmental stresses (temperature, wind speed, humidity, and dust) are crucial parameters in PV system performance and controlling these parameters can improve the efficiency, reliability, energy production, and capacity factor of PV systems, [11,17–19] as stated by the IEA [14]. Therefore, it is necessary to maintain module temperature in order to achieve a higher output.

The influence of temperature on PV module operating characteristics has been discussed by several researchers. Radziemska [20] experimentally investigated the effect of temperature on power drop in crystalline solar cells. They observed a decrease in power with increasing cell temperature. They found that the output power and efficiency of the cell decreased by 0.65% and 0.08% with a 1K rise in temperature. Another experimental investigation was carried out to study the performance of two different PV modules under outdoor conditions in Kobe, Japan for 2 years. The results stated that the annual average of daily watt-hour efficiency and the integrated power of amorphous silicon (a-Si) was higher than that of poly-silicon (poly-Si). It was observed that a-Si performs better in summer due to its thermal recovery rate, while poly-silicon performs better in winter due to its lower module temperature. It was also indicated that a-Si might be more suitable for tropical regions [21].

Ameur et al. [14] analyzed three PV technologies named mono-crystalline (mC-Si), poly-crystalline (pC-Si), and amorphous silicon (a-Si) with different installation power capacities under different conditions of temperature and irradiance during 2014–2018. The results obtained show that the total energy output from mc-Si was greater than that from pc-Si and a-Si by 1.24% and 14.61%, respectively. They concluded that poly-crystalline silicon is the most cost-effective, while amorphous silicon is the least cost-effective technology in Ifrane, Morocco. Aly et al. [15] calculated the temperature of silicon-based commercial PV cells using a self-developed model. They analyzed the effect of physical and environmental factors on the temperature and performance of the panel. They found that cell temperature was approximately raised by 1 °C for each 1 °C rise in ambient temperature and every 30 W/m^2 rise in solar irradiance. They observed that cell temperature varied non-linearly with wind speed and it decreased by 9 °C when the wind speed changed from 0 to 1 m/s. Moreover, they concluded that the electrical performance of the panel reduces with increasing cell temperature and vice versa.

In South Africa, a study was conducted to examine the effect of both irradiance intensity and temperature on PV performance under outdoor conditions for 17 months. It was found that the output of PV decreased when the temperature increased. It was reported that the module power decreased by 7% at operating temperatures in the order of 40 °C [22]. Eke et al. [23] experimentally investigated 105 Wp multi-crystalline silicon module performance under different weather conditions in Mugla, Turkey. It was also observed that the operating temperature varied from 50.5 to 80.5 °C at 1000 W/m^2. The maximum power of the module in winter was 30% more than that in summer. It was concluded that a higher operating temperature of the module resulted in low module performance.

Asim et al. [24] evaluated a detailed study on the opportunities and challenges of renewable energy scenarios in Pakistan. However, the present study aims to comprehensively analyze the effect of environmental parameters (solar irradiance, temperature, and wind speed) on the efficiency and performance ratio of PV modules in five different climates of Pakistan. Extensive work is undertaken to evaluate and compare the performance of PV modules under different climatic conditions in nine different locations. Moreover, the efficiency of five modules, the associated performance ratio, and the capacity factor was calculated for one year under real operating conditions. The present study goes further by investigating the monthly variations in module efficiency and capacity factor. The results of this assessment can be utilized for PV installation in different regions of Pakistan and their adjacent areas in the future. The main contribution of this study is to analyze the performance of PV materials under different and variable environmental conditions, quantify the long-term behavior of PV modules, and determine specific technology for the PV industry and climate change mitigation policymakers.

2. Solar Radiation Data

The accurate performance assessment of a location is dependent on the reliability of ground-measured data. The ground-measured solar radiation data for nine locations (Bahawalpur, Hyderabad, Islamabad, Khuzdar, Karachi, Lahore, Multan, Peshawar, and Quetta) in Pakistan, where the performance of commercially available PV modules assessed in the present study, were measured by the Energy Sector Management Assistance Program (ESMAP) of the World Bank. The geographical location (latitude, longitude, and altitude) and ground-measured solar radiation data (ambient temperature, wind speed, and GHI) of the stations are mentioned in Table 1 [25]. The solar radiation systems were installed at Quaid-e-Azam Solar Park, Bahawalpur; Mehran University of Engineering and Technology (M-UET), Jamshoro/Hyderabad; the National University of Science and Technology (NUST), Islamabad; Baluchistan University of Engineering and Technology, Khuzdar; NED University of Engineering and Technology (NED-UET), Karachi; the University of Engineering and Technology (UET), Lahore; M. Nawaz Sharif University of Engineering and Technology (MNS UET), Multan; the University of Engineering and Technology (UET), Peshawar; and Baluchistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Quetta. The ground-measured solar radiation data were available for Bahawalpur, Islamabad, Lahore, and Multan from 1st November 2014 to 30th April 2017 for 30 months; for Hyderabad, Karachi, and Peshawar from 1st May 2015 to 30th April 2017 for 24 months; and for Khuzdar and Quetta from 1st October 2015 to 30th April 2017 for 19 months [26].

Table 1. Names, Abbreviations, Zone, Coordinates, Altitudes, Annual mean daily temperature, Annual mean daily GHI, Annual mean daily wind speed, and Station types for the sites [25].

Station Name	Station Code	Climate Zone	Latitude (°N)	Longitude (°E)	Altitude (m)	Temperature (°C)	GHI (W/m^2)	Wind Speed (m/s)	System Type
Lahore	LHE	B	31.6940	74.2440	224	24.819	186.57	1.916	Tier 2
Islamabad	ISB	B	33.6420	72.9840	579	24.132	195.62	1.347	Tier 1
Peshawar	PEW	B	34.0017	71.4854	340	22.266	187.15	1.270	Tier 2
Khuzdar	KZD	C	27.8178	66.6294	1220	23.782	254.66	2.397	Tier 2
Quetta	QUT	C	30.2708	66.9398	1682	19.091	250.72	2.289	Tier 2
Bahawalpur	BHL	D	29.3250	71.8190	118	24.344	217.60	2.229	Tier 1
Multan	MUL	D	30.1650	71.4980	129	26.432	204.86	1.559	Tier 2
Hyderabad	HYD	E	25.4134	68.2595	40	27.807	247.05	3.918	Tier 2
Karachi	KHI	E	24.9334	67.1116	38	26.973	218.93	2.933	Tier 2

There were two types of ground-measured solar radiation systems (Tier 1 and Tier 2), which were installed at the aforesaid nine locations (installed under ESMAP) of the World Bank). Tier 1 consisted of two types of radiation measurement instruments (Kipp & Zonen CMP21(CSP Services, Cologne, Germany) pyranometers with and without shading assembly which is used to measure DHI and GHI, respectively. The CMP21 pyranometer was calibrated using an in-lab pyranometer, whose calibration was performed against a standard pyranometer at the World Radiation Center, Davos, Switzerland. Tier 2 consisted of a CMP10 pyranometer and a twin-type Rotating Shadowband Irradiometer (RIS). The calibration of the CMP10 pyranometer was performed following the calibration of the CMP21 pyranometer. The CMP10 pyranometer was used to measure GHI and its calibration was performed using an in-lab pyranometer, which was calibrated against a standard pyranometer at the World Radiation Center, Davos, Switzerland. Twin-type RIS was used for the measurement of GHI, DHI, and DNI, and calibration was performed with a highly precise metrological station at Plataforma Solar de Almeria. The task of cleaning Tier 1 and Tier 2 was handed over to university staff and local partners of ESMAP on a daily and weekly basis, respectively. In the present study, GHI data measured using a pyranometer were used due to the daily uncertainty of ±3–4%.

The measured hourly average GHI data for the year 2016 was filtered by performing a quality check (QC 1) on the data. These checks were carried out according to the guidelines provided by the Baseline Surface Radiation Network (BSRN). These include three types of tests based on the empirical relationships of different measured quantities. These tests are physically possible limits (QC 1); the detection of any significant error in measured data (extremely rare limits) (QC 2); the detection of errors occurring for very short intervals and across quantity comparisons (QC 3); and the detection of errors which are not detected by former tests [27]. The upper and the lower limits for physically possible limits are represented in Equations (1) and (2), and extremely rare limits are shown in Equations (3) and (4) [28]. The lower limits for both tests are negative because of negative temperature values (less than zero degrees Celsius), which produce negative radiation flux due to thermal noise at night in many regions. The measured GHI data were ignored for solar zenith angles greater than 85° because the cosine error is at a maximum for lower solar elevation or a higher solar zenith angle [29].

$$\mathrm{GHI_m} < 1.5\,(S_o\ /\ S_e{}^2)\,(\cos\theta_z{}^{1.2}) + 100 \tag{1}$$

$$\mathrm{GHI_m} > -4\ \mathrm{W/m^2} \tag{2}$$

$$\mathrm{GHI_m} < 1.2\,(S_o\ /\ S_e{}^2)\,(\cos\theta_z{}^{1.2}) + 50 \tag{3}$$

$$\mathrm{GHI_m} > -2\ \mathrm{W/m^2} \tag{4}$$

In Equations (1)–(4), $\mathrm{GHI_m}$ is the measured horizontal irradiance in $\mathrm{W/m^2}$, S_o is the solar constant equal to 1367 $\mathrm{W/m^2}$, S_e is the distance between Earth and the sun in astronomical units, and θ_z is the solar zenith angle.

3. Materials and Methods

Five commercially available PV module technologies—mono-crystalline silicon (MC), poly-crystalline silicon (PC), heterogeneous intrinsic thin-film (TFH), copper–indium–gallium–selenide (TFC), and amorphous silicon (TFA) materials—were selected for the present study. The technical properties of the PV modules were taken from the manufacturer's datasheet for a specific PV module under STC for various manufacturers. The STC for PV module technologies is a reference temperature of 25 °C, an air mass (AM) of 1.5 (standard solar spectrum) [19], and global solar irradiance of 1000 $\mathrm{W/m^2}$, which has been mentioned in various pieces of research [21,22,30,31]. Based on the manufacturers' electrical specifications for each PV module, the manufacturers of each type of PV module with optimal efficiency at 300 W power were selected for pre-installation assessment of the PV modules under real operating conditions at a specific site in Pakistan, as shown in Figure 1. The methodology adopted in this study is presented in Figure 2.

The technical parameters of each photovoltaic module technology under STC obtained from the manufacturer datasheets are mentioned in Table 2, and Figure 3 shows schematic diagrams or figures for these PV technology materials. The characteristics of the PV module include the nominal operating cell temperature (T_{NOCT}) and the temperature coefficient of power or efficiency (β). The nominal operating cell temperature is the temperature of a module in a standard reference environment (SRE), which refers to an ambient air temperature of 20 °C, global solar irradiance of 800 $\mathrm{W/m^2}$ and wind speed of 1 m/s [15,32–34].

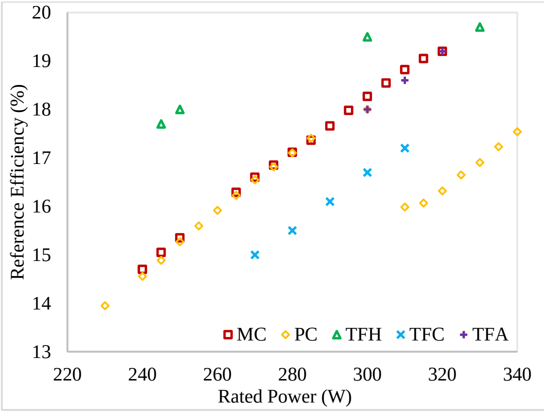

Figure 1. Reference efficiency vs. rated power.

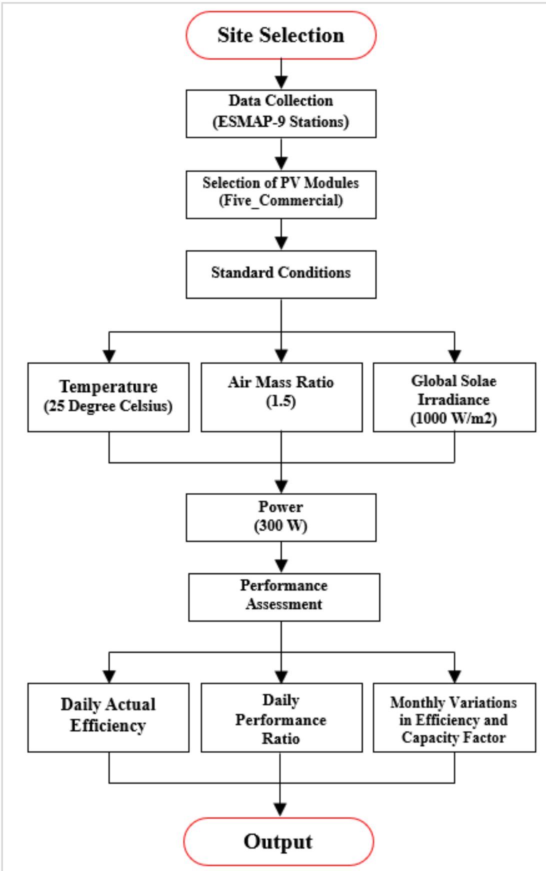

Figure 2. Flow-chart for methodology adopted in this research study.

Table 2. Specifications of different PV Modules at STC.

Module Type	MC	PC	TFH	TFC	TFA
Manufacturer	SOLUXTEC, Bitburg, Germany	REC Twinpeak, Singapore	Panasonic, Ottobrunn, Germany	Miasole, Santa Clara, CA, USA	Sunpreme, Santa Clara, CA, USA
T_{NOCT} (°C)	45	44.6	44	48	46
β_{STC} (%/°C)	0.39	0.36	0.258	0.38	0.28
η_{STC} (%)	18.5	18	19.5	16.7	18
Size (m^2)	1.620325	1.669975	1.540539	1.88268	1.675957

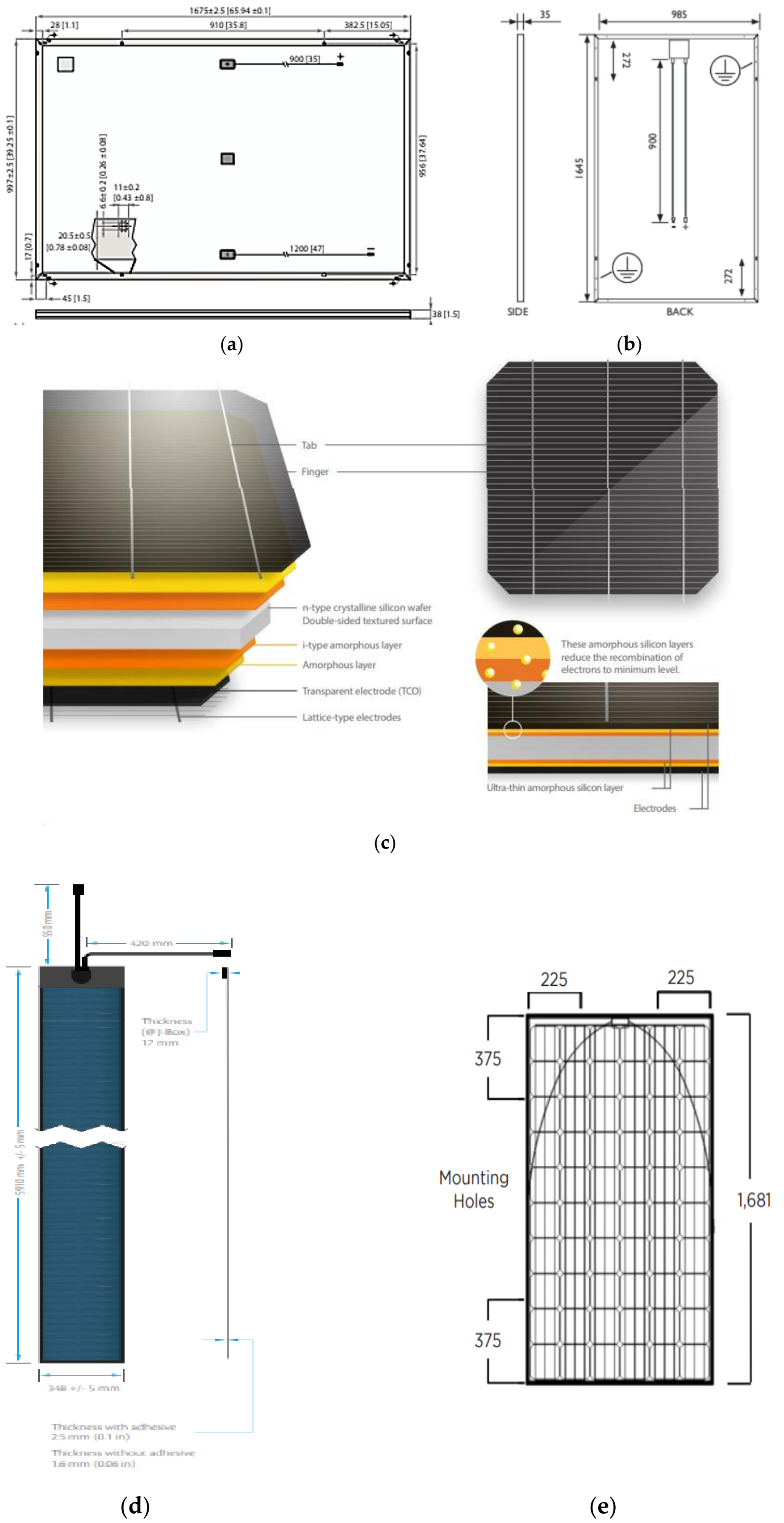

Figure 3. Schematic diagrams for PV technology materials: (**a**) poly-crystalline, (**b**) mono-crystalline, (**c**) heterogenous thin-film, (**d**) copper–indium–gallium–selenide, (**e**) thin-film amorphous silicon.

Since the performance of solar PV modules is highly dependent on meteorological conditions, the effect of ambient air temperature, solar irradiance, and wind speed was studied for the nine locations (mentioned in Table 1) to determine the conversion efficiency of five different PV modules. The meteorological conditions were the weather conditions of each location, which included the ambient air temperature, wind speed, and humidity of that specific location. These conditions affect the PV module temperature; hence, the efficiency and performance of each PV module technology vary accordingly. So, to determine the effects of climatic conditions (ambient temperature, wind speed, and solar irradiance) on PV module efficiency and performance, numerical simulations were performed in MATLAB. Horizontal clean PV modules were considered in this analysis.

The effects of ambient air temperature and global solar irradiance on the conversion efficiency of each PV module were determined based on hourly averaged data of solar irradiance. The mathematical relationship between ambient air temperature and PV module temperature is represented in Equation (3), and is discussed by several researchers [35–38]:

$$\mathrm{T_m} = \mathrm{T_a} + \frac{\mathrm{GHI}\ (T_{NOCT} - 20)}{800} \tag{5}$$

In Equation (5), $\mathrm{T_m}$ is the PV module temperature in °C, GHI is the solar irradiance in W/m^2, and $\mathrm{T_a}$ is the ambient air temperature in °C. The effect of wind speed is not considered in Equation (3), which means that the speed of wind has been taken to be 1 m/s, but wind speed has an impact on the performance of PV modules. It affects the photovoltaic module temperature, and then, PV module conversion efficiency is affected. The effect of wind speed, along with that of ambient air temperature, was found using Equation (6) for each PV module [38,39]:

$$\mathrm{T_m} = \mathrm{T_a} + \frac{\mathrm{GHI}\ (T_{NOCT} - 20)}{800} \times \frac{9.5}{5.7 + 3.8\ \mathrm{V}} \tag{6}$$

In Equation (6), V is the wind speed at height h in m/s, which can be calculated from Equation (7). The wind speed was measured at a reference height of 10 m above grade. However, according to international standards for PV module specifications, wind speed should be measured at a height of 0.7 m above the surface of the PV module. By American standards, it is specified that the wind speed should be measured at the height of the PV module. A relationship between wind speed and PV module height is given in Equation (7), which depicts the dependency of wind speed on the height [32,40,41].

$$\mathrm{V} = \mathrm{V_r} \times \left(\frac{\mathrm{h}}{\mathrm{h_r}}\right)^{1/7} \tag{7}$$

In Equation (7), $\mathrm{V_r}$ is the wind speed at the reference height, h is the PV module height in m, and $\mathrm{h_r}$ is the reference height taken as 10 m. Equation (7) has a good approximation for the wind profile in the neutral (adiabatic) atmospheric boundary layer for open land [42].

After observing the effects of weather conditions on the performance of photovoltaic technology, the PV module's conversion efficiency under actual conditions was calculated for all the technologies at the nine locations in Pakistan using Equation (8), which revealed that PV module efficiency is a function of PV module temperature and solar irradiance [43–46].

$$\eta = \eta_{\mathrm{STC}}\ [1 - \beta_{\mathrm{STC}}\ (\mathrm{T_m} - 25)] \tag{8}$$

In Equation (8), η is the PV module conversion efficiency under actual operating conditions and η_{STC} is the PV module efficiency under STC. When the conversion efficiency of each module was calculated for all the aforesaid nine locations, the energy generated (EG) by each PV module at all the locations was determined using the relationship, given as Equation (9).

$$\mathrm{EG} = \mathrm{GHI} \times \eta\ [1 - \beta_{\mathrm{STC}}\ (\mathrm{T_m} - \mathrm{T_a})] \tag{9}$$

The performances of the PV modules were compared based on the PV module's actual efficiency and energy generation, as well as performance ratio and capacity factor, in the present work. The performance ratio (PR) is the actual efficiency of the PV module related to the rated efficiency. It is an indicator of the reliability of PV technology at any location. The performance ratio for each type of PV module at different stations was calculated following Equation (10); η_{rated} is the rated efficiency of the PV module taken from the manufacturer datasheet, rated under STC in the present research work [31,47–49].

$$PR = \frac{\eta}{\eta_{rated}} \tag{10}$$

The capacity factor is the ratio of energy generated by the PV module under real operating conditions to the rated energy. Rated energy is the energy produced by the PV module when it is operated at rated power for a specific interval of time. The capacity factor (CF) was found using Equation (11), as given below [14,50,51].

$$CF = \frac{EG}{P_{rated} \times t} \tag{11}$$

In Equation (11), P_{rated} is the rated power taken from the manufacturer datasheet and t is the time assuming a non-leap year.

4. Results

The performance assessment of five PV modules at nine locations is presented in this section. For precise evaluation, the results are presented as a comparison of the different technologies at each location instead of being presented as maps (geographical variations for each specific technology). The first subsection discusses only the effect of temperature on module efficiency, whereas the second subsection discusses the effects of both temperature and wind speed. Similarly, the effect of temperature on the performance ratio is presented in Section 3, followed by the effects of both temperature and wind in Section 4. The last two subsections show monthly variations for module efficiency and capacity factor.

4.1. Effect of Temperature on the Module's Actual Efficiency

Figure 4 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Lahore at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 19.73% and 16.90% for MC, 19.11% and 16.57% for PC, 20.36% and 18.40% for TFH, 17.78% and 15.21% for TFC, and 18.86% and 16.86% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Lahore. The daily mean actual efficiencies were 18.09, 17.64, 19.23, 16.30, and 17.70% for MC, PC, TFH, TFC, and TFA, respectively, in Lahore.

Figure 5 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Islamabad at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 19.77% and 17.09% for MC, 19.15% and 16.74% for PC, 20.39% and 18.54% for TFH, 17.8% and 15.38% for TFC, and 18.88% and 16.99% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Islamabad. The daily mean actual efficiencies were 18.26, 17.79, 19.34, 16.44, and 17.82 % for MC, PC, TFH, TFC, and TFA, respectively, in Islamabad.

Figure 6 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Peshawar at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 19.84% and 16.89% for MC, 19.21% and 16.56% for PC, 20.44% and 18.40% for TFH, 17.87% and 15.20% for TFC, and 18.93% and 16.85% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Peshawar. The daily mean actual efficiencies were 18.14, 17.68, 19.26, 16.34, and 17.74 % for MC, PC, TFH, TFC, and TFA, respectively, in Peshawar.

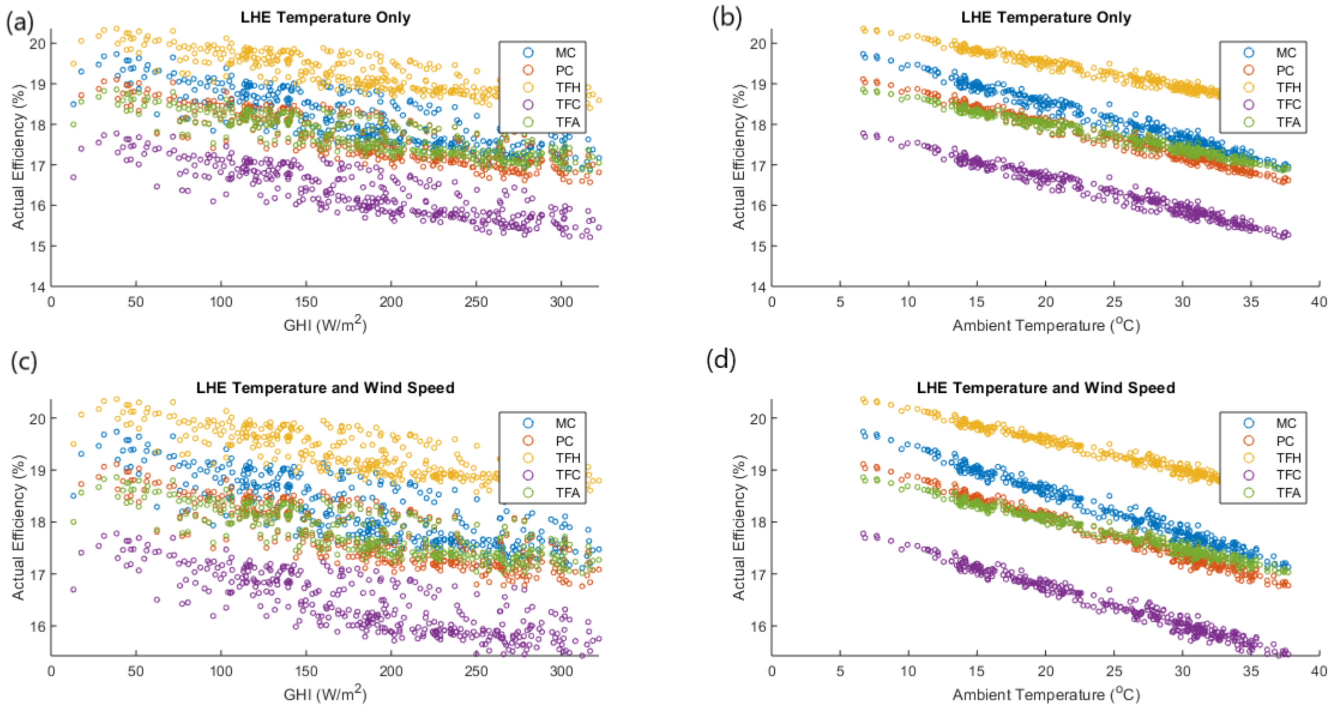

Figure 4. Daily Actual Efficiency of PV Modules in Lahore. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

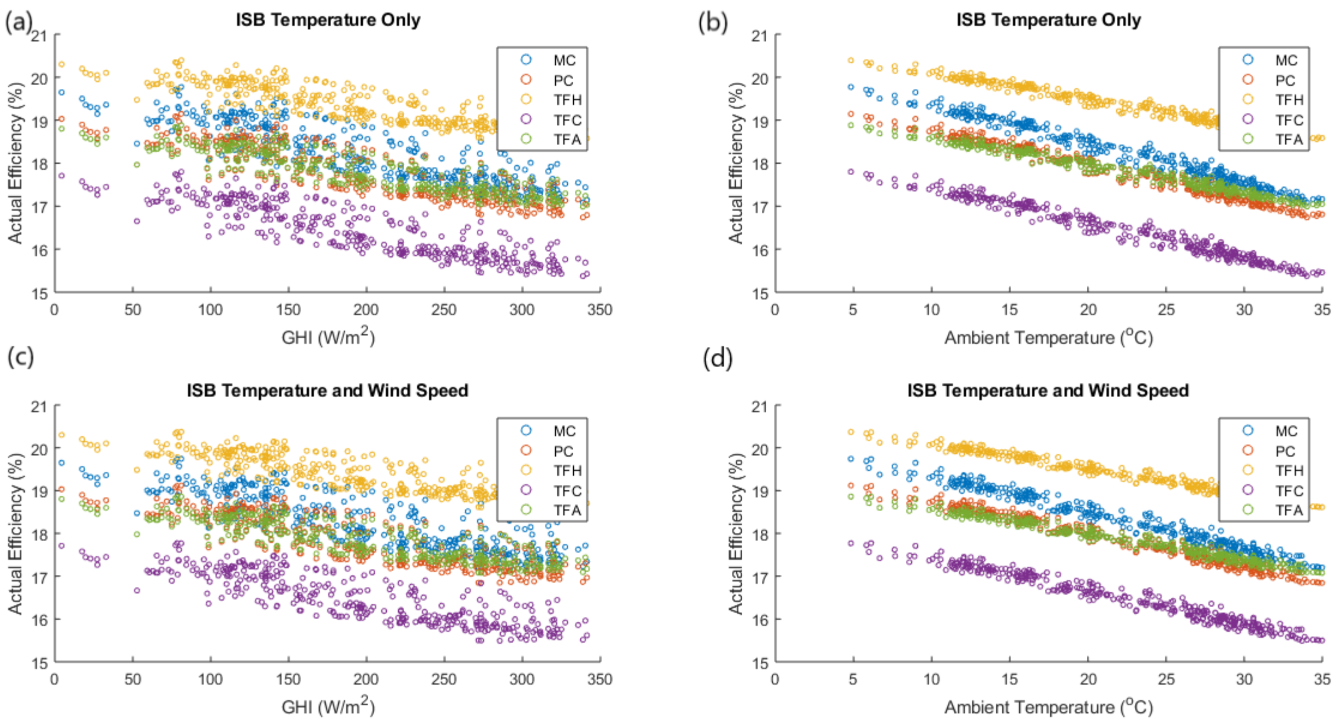

Figure 5. Daily Actual Efficiency of PV Modules in Islamabad. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

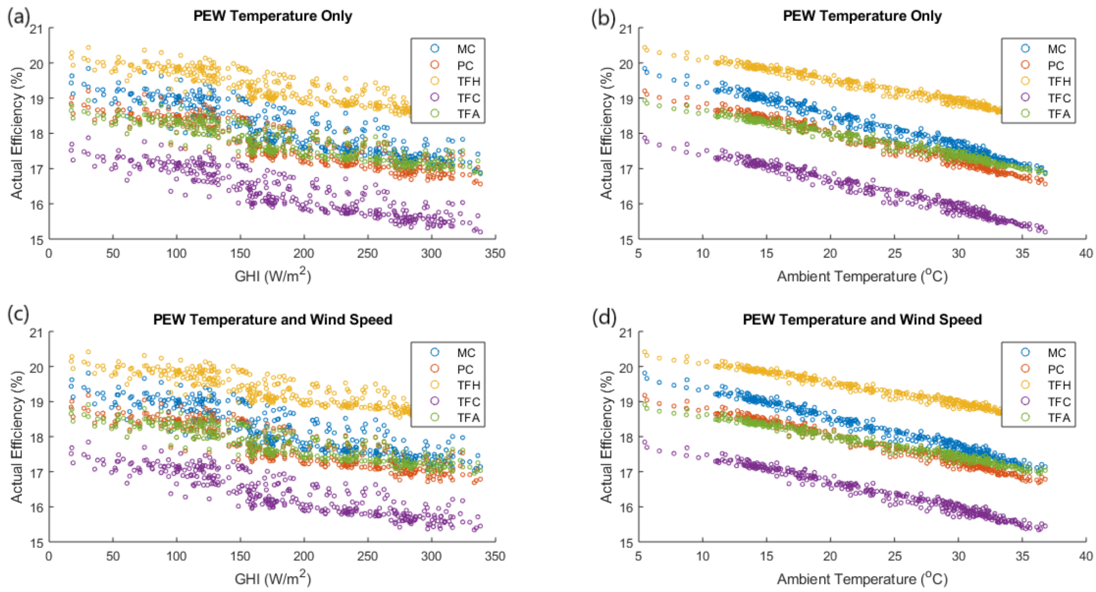

Figure 6. Daily Actual Efficiency of PV Modules in Peshawar. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 7 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Khuzdar at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 19.25% and 16.98% for MC, 18.68% and 16.64% for PC, 20.03% and 18.46% for TFH, 17.32% and 15.28% for TFC, and 18.51% and 16.91% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Khuzdar. The daily mean actual efficiencies were 18.01, 17.57, 19.18, 16.21, and 17.64 % for MC, PC, TFH, TFC, and TFA, respectively, in Khuzdar.

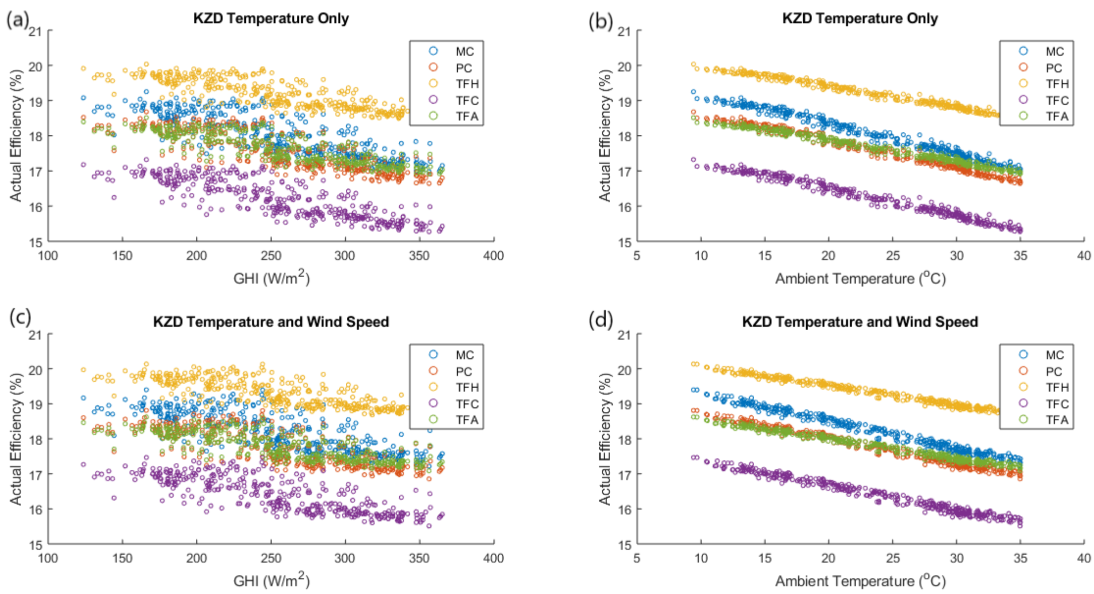

Figure 7. Daily Actual Efficiency of PV Modules in Khuzdar. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 8 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Quetta at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 19.70% and 17.23% for MC, 19.08% and 16.87% for PC, 20.35% and 18.63% for TFH, 17.71% and 15.49% for TFC, and 18.83% and 17.09% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Quetta. The daily mean actual efficiencies were 18.36, 17.88, 19.42, 16.52, and 17.89 % for MC, PC, TFH, TFC, and TFA, respectively, in Quetta.

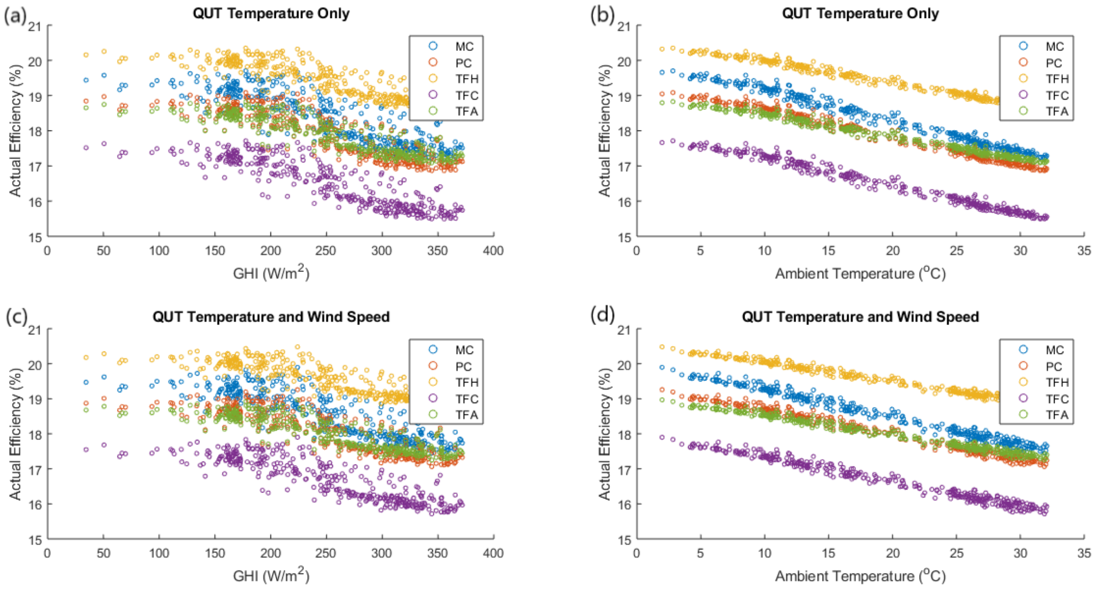

Figure 8. Daily Actual Efficiency of PV Modules in Quetta. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 9 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Bahawalpur at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 20.3% and 16.77% for MC, 19.62% and 16.46% for PC, 20.76% and 18.32% for TFH, 18.29% and 15.11% for TFC, and 19.26% and 16.77% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Bahawalpur. The daily mean actual efficiencies were 17.98, 17.54, 19.15, 16.19, and 17.62 % for MC, PC, TFH, TFC, and TFA, respectively, in Bahawalpur.

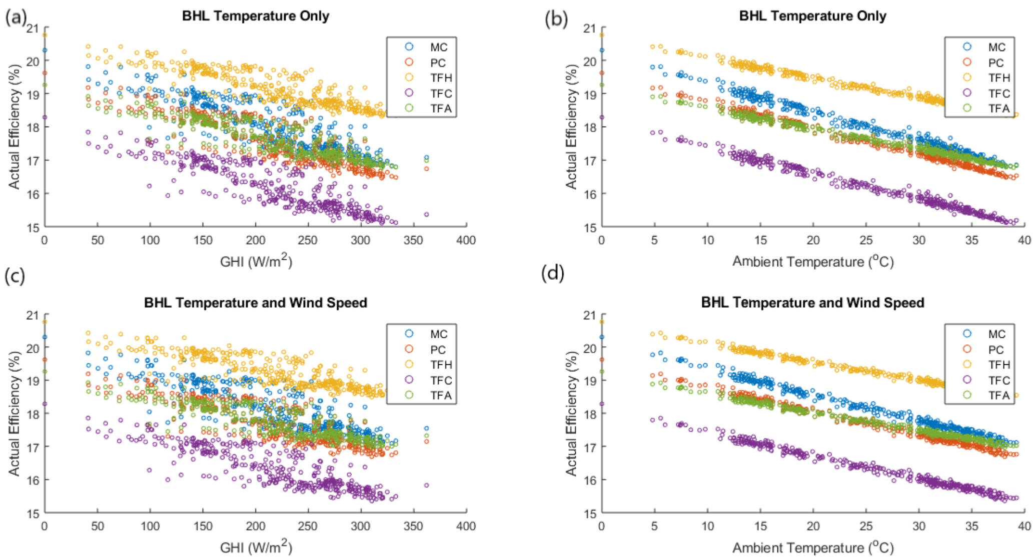

Figure 9. Daily Actual Efficiency of PV Modules in Bahawalpur. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 10 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Multan at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 19.84% and 16.78% for MC, 19.20% and 16.47% for PC, 20.44% and 18.32% for TFH, 17.87% and 15.12% for TFC, and 18.93% and 16.78% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Multan. The daily mean actual efficiencies were 17.94, 17.50, 19.12, 16.15, and 17.59 % for MC, PC, TFH, TFC, and TFA, respectively, in Multan.

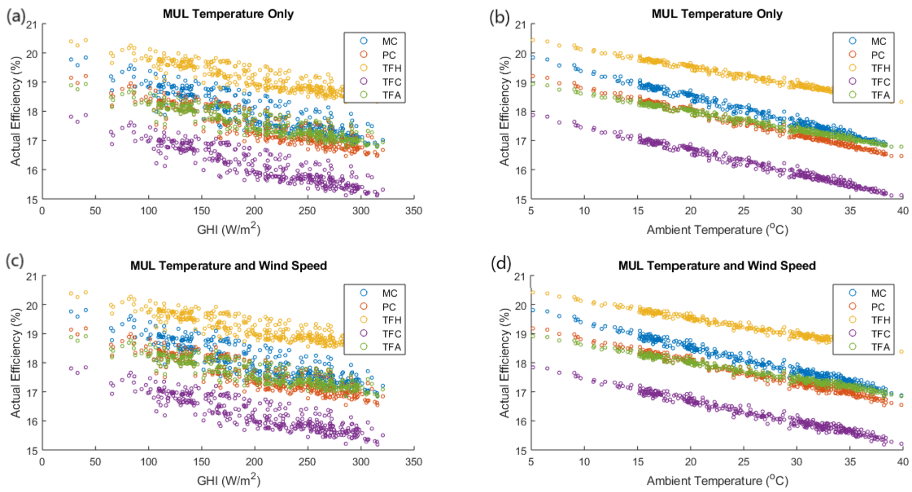

Figure 10. Daily Actual Efficiency of PV Modules in Multan. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 11 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Hyderabad at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 18.91% and 16.80% for MC, 18.37% and 16.48% for PC, 19.79% and 18.33% for TFH, 17.03% and 15.13% for TFC, and 18.28% and 16.79% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Hyderabad. The daily mean actual efficiencies were 17.74, 17.33, 18.99, 15.97, and 17.45 % for MC, PC, TFH, TFC, and TFA, respectively, in Hyderabad.

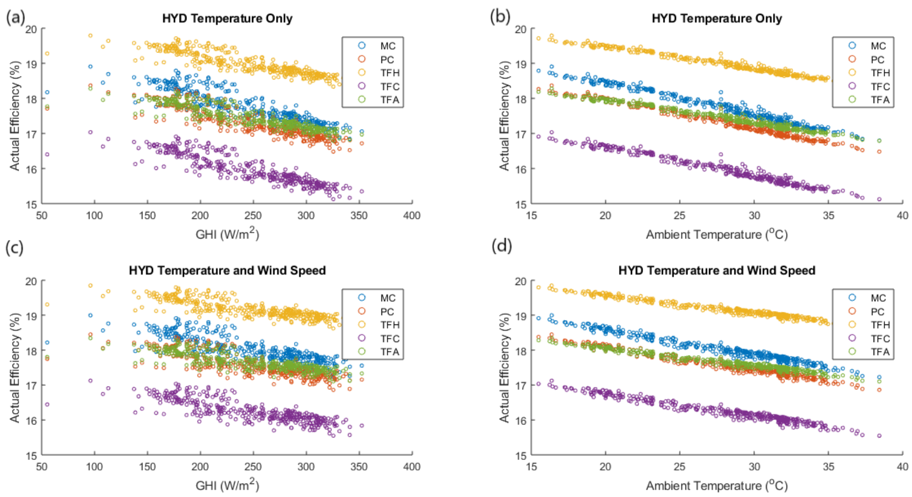

Figure 11. Daily Actual Efficiency of PV Modules in Hyderabad. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 12 shows the effect of temperature on the daily actual efficiency of the five different PV modules in Karachi at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the actual efficiencies were 18.63% and 17.24% for MC, 18.12% and 16.87% for PC, 19.59% and 18.64% for TFH, 16.79% and 15.51% for TFC, and 18.08% and 17.10% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Karachi. The daily mean actual efficiencies were 17.74, 17.33, 18.99, 15.97, and 17.45 % for MC, PC, TFH, TFC, and TFA, respectively, in Karachi.

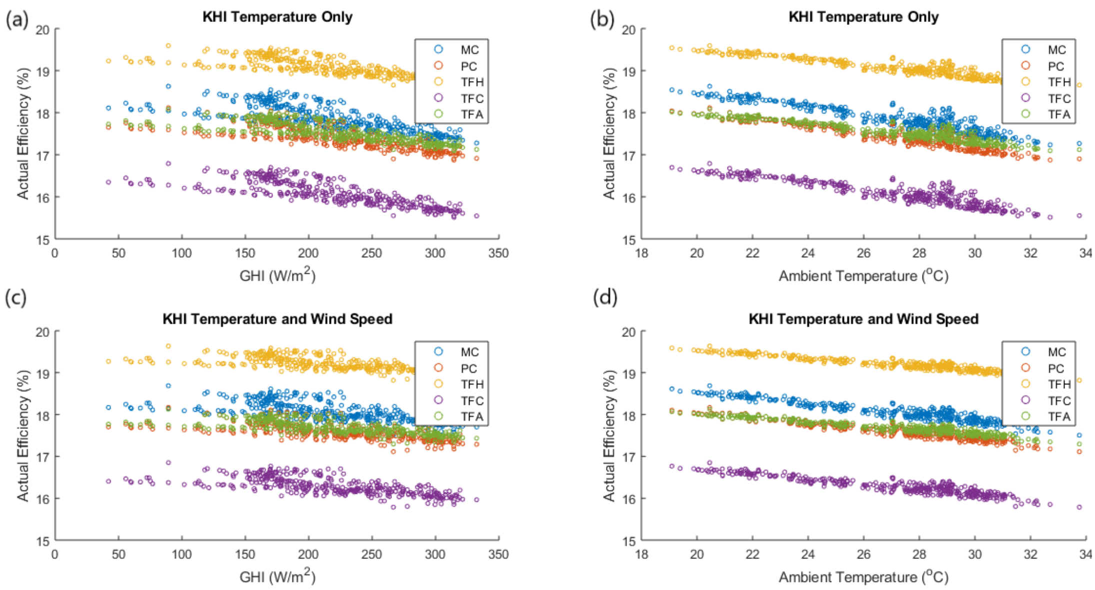

Figure 12. Daily Actual Efficiency of PV Modules in Karachi. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

4.2. Effect of Temperature and Wind Speed on Module's Actual Efficiency

Figure 4 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Lahore at different GHIs (c) and ambient temperatures (d). The maximum values of daily the actual efficiencies were 19.74% and 17.11% for MC, 19.11% and 16.76% for PC, 20.36% and 18.55% for TFH, 17.78% and 15.43% for TFC, and 18.86% and 17.02% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHI and daily ambient temperatures in Lahore. The daily mean actual efficiencies were 18.20, 17.73, 19.30, 16.40, and 17.78 % for MC, PC, TFH, TFC, and TFA, respectively, in Lahore.

Figure 5 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Islamabad at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 19.74% and 17.20% for MC, 19.12% and 16.84% for PC, 20.37% and 18.61% for TFH, 17.77% and 15.49% for TFC, and 18.86% and 17.08% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Lahore. The daily mean actual efficiencies were 18.30, 17.83, 19.37, 16.49, and 17.85 % for MC, PC, TFH, TFC, and TFA, respectively, in Islamabad.

Figure 6 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Peshawar at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 19.81% and 17.03% for MC, 19.18% and 16.69% for PC, 20.42% and 18.50% for TFH, 17.84% and 15.34% for TFC, and 18.91% and 16.96% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Peshawar. The daily mean actual efficiencies were 18.19, 17.72, 19.29, 16.38, and 17.77 % for MC, PC, TFH, TFC, and TFA, respectively, in Peshawar.

Figure 7 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Khuzdar at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 19.40% and 17.22% for MC, 18.81% and 16.86% for PC, 20.13% and 18.62% for TFH, 17.47% and 15.2815.51% for TFC, and 18.62% and 17.09% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Khuzdar. The daily mean actual efficiencies were 18.21, 17.74, 19.31, 16.40, and 17.79 % for MC, PC, TFH, TFC, and TFA, respectively, in Khuzdar.

Figure 8 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Quetta at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 19.90% and 17.45% for MC, 19.26% and 17.06% for PC, 20.48% and 18.78% for TFH, 17.90% and 15.72% for TFC, and 18.97% and 17.25% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Quetta. The daily mean actual efficiencies were 18.54, 18.05, 19.54, 16.70, and 18.02 % for MC, PC, TFH, TFC, and TFA, respectively, in Quetta.

Figure 9 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Bahawalpur at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 20.3% and 17.03% for MC, 19.62% and 16.69% for PC, 20.76% and 18.49% for TFH, 18.29% and 15.35% for TFC, and 19.26% and 16.96% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Bahawalpur. The daily mean actual efficiencies were 18.14, 17.68, 19.26, 16.35, and 17.74 % for MC, PC, TFH, TFC, and TFA, respectively, in Bahawalpur.

Figure 10 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Multan at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 19.81% and 16.86% for MC, 19.18% and 16.54% for PC, 20.42% and 18.38% for TFH, 17.84% and 15.19% for TFC, and 18.91% and 16.84% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Multan. The daily mean actual efficiencies were 18.01, 17.57, 19.17, 16.23, and 17.65 % for MC, PC, TFH, TFC, and TFA, respectively, in Multan.

Figure 11 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Hyderabad at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 19.00% and 17.23% for MC, 18.45% and 16.86% for PC, 19.85% and 18.62% for TFH, 17.12% and 15.55% for TFC, and 18.34% and 17.10% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Hyderabad. The daily mean actual efficiencies were 18.03, 17.58, 19.18, 16.25, and 17.66 % for MC, PC, TFH, TFC, and TFA, respectively, in Hyderabad.

Figure 12 shows the effect of temperature and wind speed on the daily actual efficiency of the five different PV modules in Karachi at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the actual efficiencies were 18.69% and 17.51% for MC, 18.17% and 17.11% for PC, 19.63% and 18.82% for TFH, 16.85% and 15.79% for TFC, and 18.13% and 17.30% for TFA. Among the five PV modules, the maximum daily actual efficiency was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Karachi. The daily mean actual efficiencies were 18.07, 17.62, 19.21, 16.29, and 17.69 % for MC, PC, TFH, TFC, and TFA, respectively, in Karachi.

4.3. Effect of Temperature on Performance Ratio

Figure 13 shows the effect of temperature on the daily performance ratio of the five different PV modules in Lahore at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 106.7% and 91.34% for MC, 106.2% and 92.06% for PC, 104.4% and 94.37% for TFH, 106.4% and 91.11% for TFC, and 104.8% and 93.67% for TFA. The daily mean performance ratio was 97.80, 98.00, 98.61, 97.59, and 98.36 % for MC, PC, TFH, TFC, and TFA, respectively, in Lahore. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Lahore.

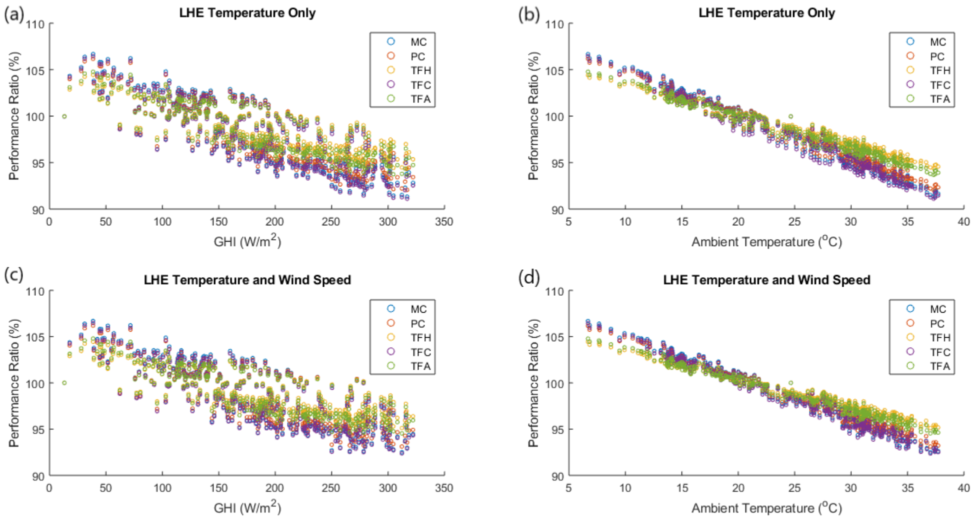

Figure 13. Daily Performance Ratio of PV Modules in Lahore. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 14 shows the effect of temperature on the daily performance ratio of the five different PV modules in Islamabad at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 106.9% and 92.35% for MC, 106.4% and 93.00% for PC, 104.6% and 95.05% for TFH, 106.6% and 92.07% for TFC, and 104.9% and 94.39% for TFA. The daily mean performance ratio was 98.68, 98.82, 99.19, 98.44, and 98.99 % for MC, PC, TFH, TFC, and TFA, respectively, in Islamabad. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Islamabad.

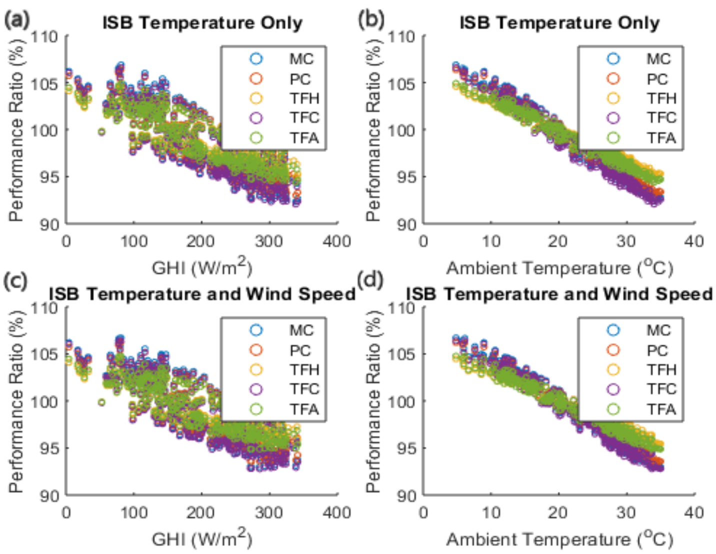

Figure 14. Daily Performance Ratio of PV Modules in Islamabad. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 15 shows the effect of temperature on the daily performance ratio of the five different PV modules in Peshawar at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 107.2% and 91.28% for MC, 106.7% and 92.01% for PC, 104.8% and 94.34% for TFH, 107% and 91.02% for TFC, and 105.2% and 93.62% for TFA. The daily mean performance ratio was 98.06, 98.24, 98.78, 97.84, and 98.54 % for MC, PC, TFH, TFC, and TFA, respectively, in Peshawar. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Peshawar.

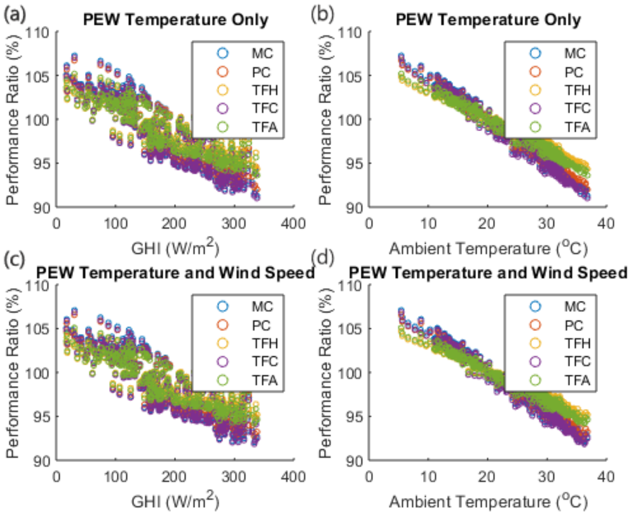

Figure 15. Daily Performance Ratio of PV Modules in Peshawar. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 16 shows the effect of temperature on the daily performance ratio of the five different PV modules in Khuzdar at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 104.1% and 91.77% for MC, 103.8% and 92.46% for PC, 102.7% and 94.67% for TFH, 103.7% and 91.47% for TFC, and 102.9% and 93.96% for TFA. The daily mean performance ratio was 97.37, 97.62, 98.34, 97.08, and 98.02% for MC, PC, TFH, TFC, and TFA, respectively, in Khuzdar. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Khuzdar.

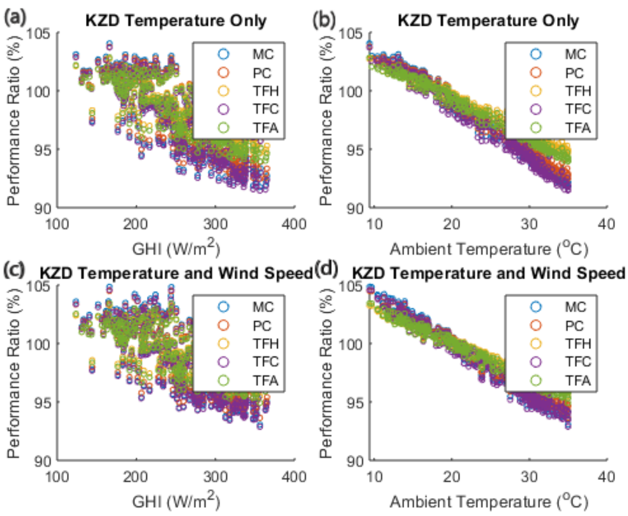

Figure 16. Daily Performance Ratio of PV Modules in Khuzdar. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 17 shows the effect of temperature on the daily performance ratio of five different PV modules in Quetta at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 106.5% and 93.11% for MC, 106% and 93.71% for PC, 104.3% and 95.56% for TFH, 106.1% and 92.78% for TFC, and 104.6% and 94.93% for TFA. The daily mean performance ratio was 99.25, 99.35, 99.58, 98.91, and 99.37 % for MC, PC, TFH, TFC, and TFA, respectively, in Quetta. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Quetta.

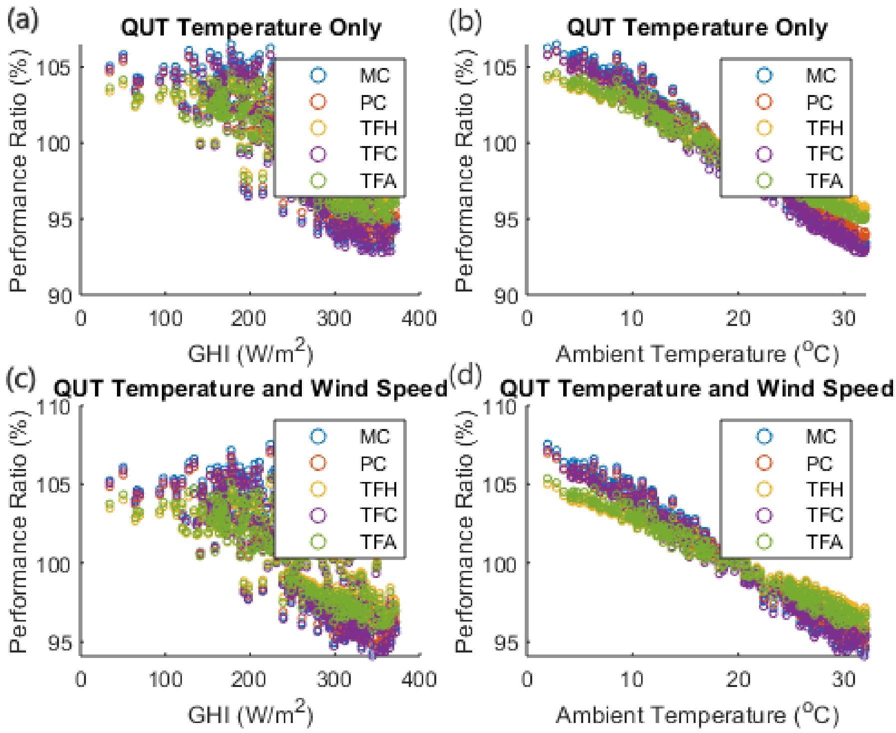

Figure 17. Daily Performance Ratio of PV Modules in Quetta. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 18 shows the effect of temperature on the daily performance ratio of the five different PV modules in Bahawalpur at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 109.7% and 90.67% for MC, 109% and 91.44% for PC, 106.5% and 93.93% for TFH, 109.5% and 90.45% for TFC, and 107% and 93.19% for TFA. The daily mean performance ratio was 97.19, 97.44, 98.21, 96.95, and 97.91 % for MC, PC, TFH, TFC, and TFA, respectively, in Bahawalpur. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Bahawalpur.

Figure 19 shows the effect of temperature on the daily performance ratio of the five different PV modules in Multan at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 107.2% and 90.73% for MC, 106.7% and 91.49% for PC, 104.8% and 93.96% for TFH, 107% and 90.52% for TFC, and 105.5% and 93.24% for TFA. The daily mean performance ratio was 96.95, 97.22, 98.05, 96.73, and 97.74 % for MC, PC, TFH, TFC, and TFA, respectively, in Multan. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Multan.

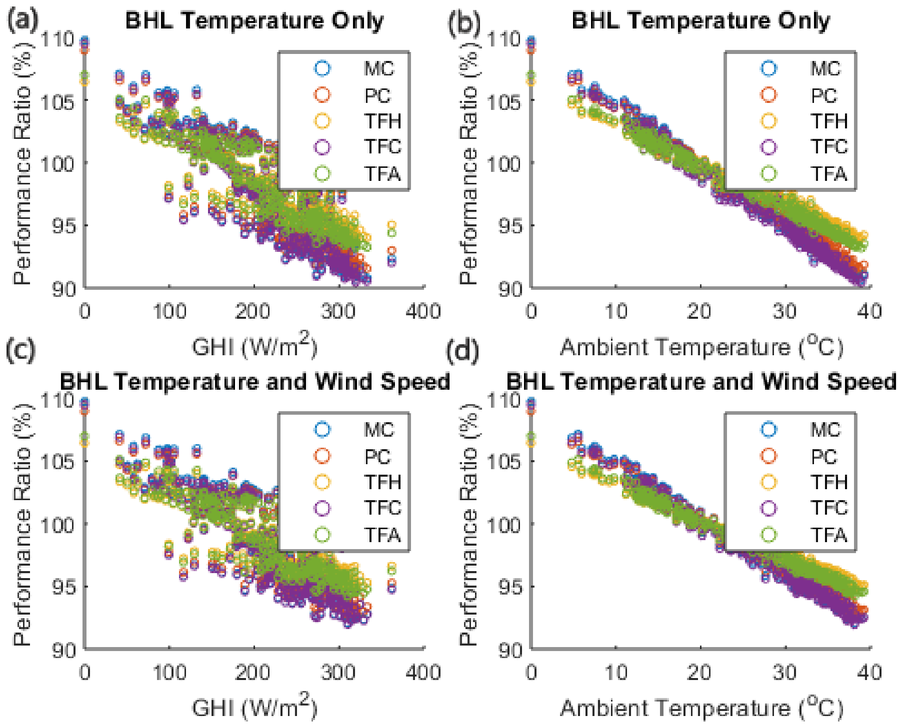

Figure 18. Daily Performance Ratio of PV Modules in Bahawalpur. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

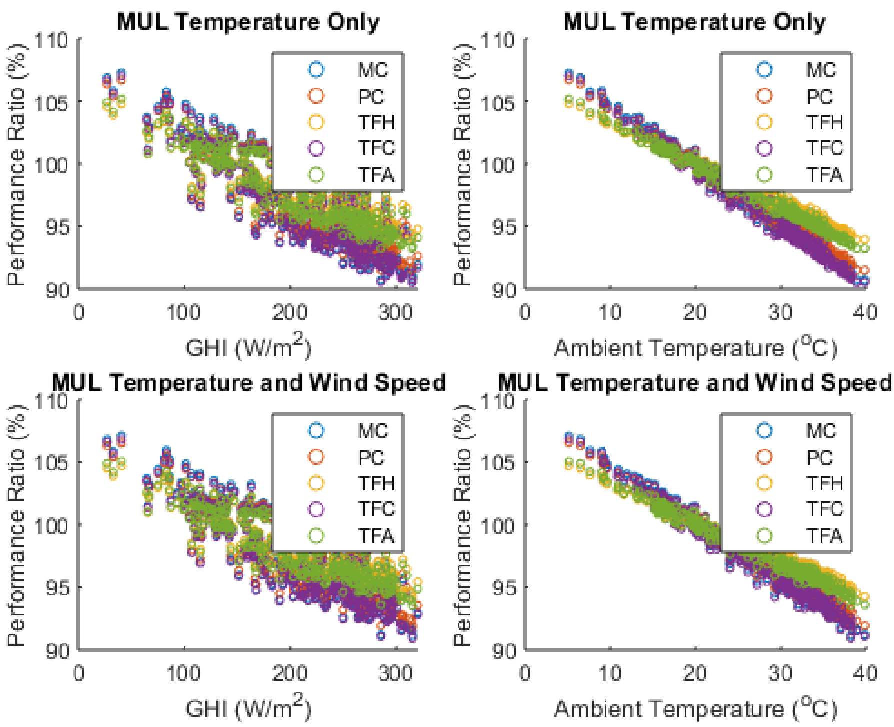

Figure 19. Daily Performance Ratio of PV Modules in Multan. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 20 shows the effect of temperature on the daily performance ratio of the five different PV modules in Hyderabad at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 102.2% and 90.8% for MC, 102% and 91.56% for PC, 101.5% and 94.02% for TFH, 102% and 90.57% for TFC, and 101.5% and 93.28% for TFA. The daily mean performance ratio was 95.90, 96.26, 97.37, 95.65, and 96.97 % for MC, PC, TFH, TFC, and TFA, respectively, in Hyderabad. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Hyderabad.

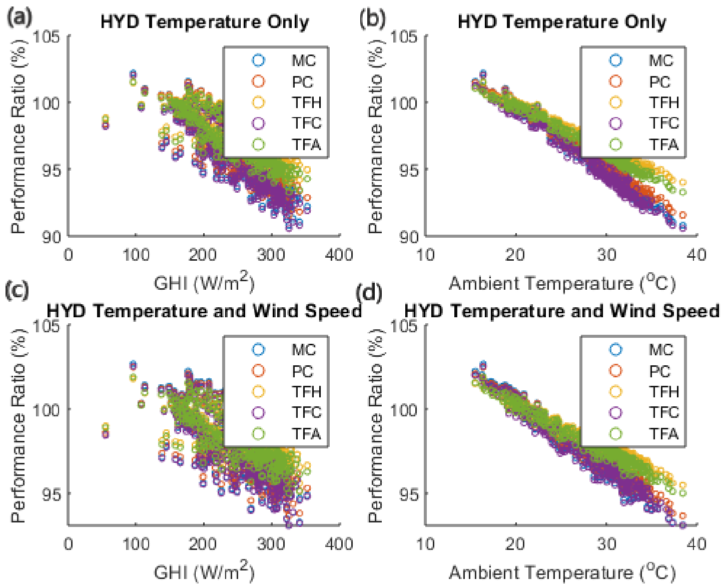

Figure 20. Daily Performance Ratio of PV Modules in Hyderabad. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

Figure 21 shows the effect of temperature on the daily performance ratio of the five different PV modules in Karachi at different GHIs (a) and ambient temperatures (b). The maximum and minimum values of the daily performance ratio were 100.7% and 93.16% for MC, 100.6% and 93.74% for PC, 100.5% and 95.58% for TFH, 100.5% and 92.89% for TFC, and 100.5% and 94.98% for TFA. The daily mean performance ratio was 96.57, 96.87, 97.8, 96.35, and 97.46 % for MC, PC, TFH, TFC, and TFA, respectively, in Karachi. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Karachi.

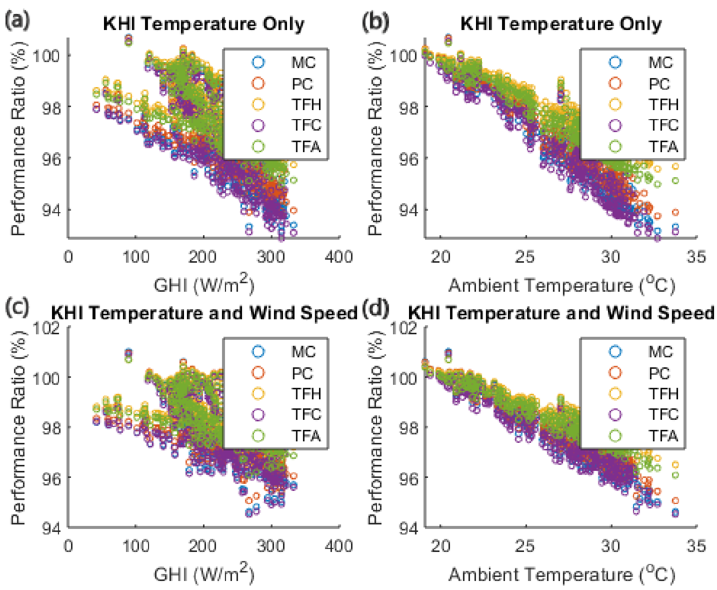

Figure 21. Daily Performance Ratio of PV Modules in Karachi. (**a**) GHI only (**b**) Amb temp only (**c**) GHI with Temp & windspeed (**d**) Amb temp & wind speed.

4.4. Effect of Temperature and Wind Speed on Performance Ratio

Figure 13 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Lahore at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 106.7% and 92.51% for MC, 106.2% and 93.12% for PC, 104.4% and 95.12% for TFH, 106.5% and 92.37% for TFC, and 104.8% and 94.54% for TFA. The daily mean performance ratio was 98.38, 98.53, 98.97, 98.22, and 98.79% for MC, PC, TFH, TFC, and TFA, respectively, in Lahore. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Lahore.

Figure 14 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Islamabad at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 106.7% and 92.99% for MC, 106.2% and 93.57% for PC, 104.5% and 95.44% for TFH, 106.4% and 92.77% for TFC, and 104.8% and 94.88% for TFA. The daily mean performance ratio was 98.94, 99.05, 99.35, 98.72, and 99.18 % for MC, PC, TFH, TFC, and TFA, respectively, in Islamabad. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Islamabad.

Figure 15 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Peshawar at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 107.1% and 92.07% for MC, 106.6% and 92.37% for PC, 104.7% and 94.85% for TFH, 106.9% and 91.86% for TFC, and 105.1% and 934.20% for TFA. The daily mean performance ratio was 98.31, 98.47, 98.93, 98.11, and 98.73% for MC, PC, TFH, TFC, and TFA, respectively, in Peshawar. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Peshawar.

Figure 16 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Khuzdar at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 104.9% and 93.06% for MC, 104.5% and 93.64% for PC, 103.2% and 95.49% for TFH, 104.6% and 92.88% for TFC, and 103.5% and 94.93% for TFA. The daily mean performance ratio was 98.42, 98.57, 99.01, 98.22, and 98.81 % for MC, PC, TFH, TFC, and TFA, respectively, in Khuzdar. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Khuzdar.

Figure 17 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Quetta at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 107.5% and 94.31% for MC, 107% and 94.79% for PC, 105% and 96.31 % for TFH, 107.2% and 94.10% for TFC, and 105.4% and 95.83% for TFA. The daily mean performance ratio was 100.2, 100.3, 100.2, 100.0, and 100.1% for MC, PC, TFH, TFC, and TFA, respectively, in Quetta. Among the five PV modules, the maximum daily mean performance ratio was observed for PC and the minimum for TFC at different daily GHIs and daily ambient temperatures in Quetta. Moreover, MC and TFH were found to have the same daily mean performance ratio in Quetta.

Figure 18 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Bahawalpur at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 109.7% and 92.06% for MC, 109% and 92.72% for PC, 106.5% and 94.82% for TFH, 109.5% and 91.94% for TFC, and 107% and 94.22% for TFA. The daily mean performance ratio was 98.06, 98.23, 98.76, 97.90, and 98.55% for MC, PC, TFH, TFC, and TFA, respectively, in Bahawalpur. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Bahawalpur.

Figure 19 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Multan at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 107.1% and 91.15% for MC, 106.6% and 91.89% for PC, 104.7% and 94.24% for TFH, 106.8% and 90.95% for TFC, and 105.1% and 93.54% for TFA. The daily mean performance ratio was 97.37, 97.6, 98.31, 97.19, and 98.05% for MC, PC, TFH, TFC, and TFA, respectively, in Multan. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Multan.

Figure 20 shows the effect of temperature and wind speed on the daily performance ratio of the five different PV modules in Hyderabad at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 102.7% and 93.12% for MC, 102.5% and 93.67% for PC, 101.8% and 95.49% for TFH, 102.5% and 93.10% for TFC, and 101.9% and 95.01% for TFA. The daily mean performance ratio was 97.43, 97.65, 98.34, 97.33, and 98.11% for MC, PC, TFH, TFC, and TFA, respectively, in Hyderabad. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Hyderabad.

Figure 21 shows the effect of temperature on the daily performance ratio of the five different PV modules in Karachi at different GHIs (c) and ambient temperatures (d). The maximum and minimum values of the daily performance ratio were 101% and 94.62% for MC, 100.9% and 95.07% for PC, 100.7% and 96.50% for TFH, 100.9% and 94.53% for TFC, and 100.5% and 96.08% for TFA. The daily mean performance ratio was 97.66, 97.86, 98.49, 97.54, and 98.28% for MC, PC, TFH, TFC, and TFA, respectively, in Karachi. Among the five PV modules, the maximum daily mean performance ratio was observed for TFH and the minimum for TFC at different daily GHIs and daily ambient temperatures in Karachi.

4.5. Monthly Variations in Module's Actual Efficiency

Monthly variations in the actual efficiency of all the modules are shown in Figures 22a–30a at all the locations when the effect of temperature was accounted for in the analysis for the year 2016. Figures 22c–30c show the monthly variations in the actual efficiency of the five mentioned PV modules throughout the whole year at all the locations when the effect of both temperature and wind speed was considered. It was observed that all the modules have a maximum (minimum) monthly average efficiency in January (June) in Lahore. The values for the monthly mean actual efficiency range between 19 and 19.3% for MC, 18.4 and 18.7% for PC, 19.8 and 20% for TFH, 17 and 17.3% for TFC, and 18.3 and 18.8% for TFA (Figure 22a).

In Islamabad, all the modules were found to have maximum (minimum) monthly average efficiency in January (June). The values for the monthly mean actual efficiency range between 19 and 19.4% for MC, 18.5 and 18.8% for PC, 19.9 and 20.1% for TFH, 17.1 and 17.5% for TFC, and 18.4 and 18.7% for TFA (Figure 23a).

In Peshawar, the maximum (minimum) monthly average efficiency of each PV module was in January (June). The values for the monthly mean actual efficiency range between 19 and 19.2% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA (Figure 24a).

The monthly maximum (minimum) average efficiency was observed in January (June) for all the PV modules in Khuzdar. The values for the monthly mean actual efficiency range between 19 and 19.2% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA (Figure 25a).

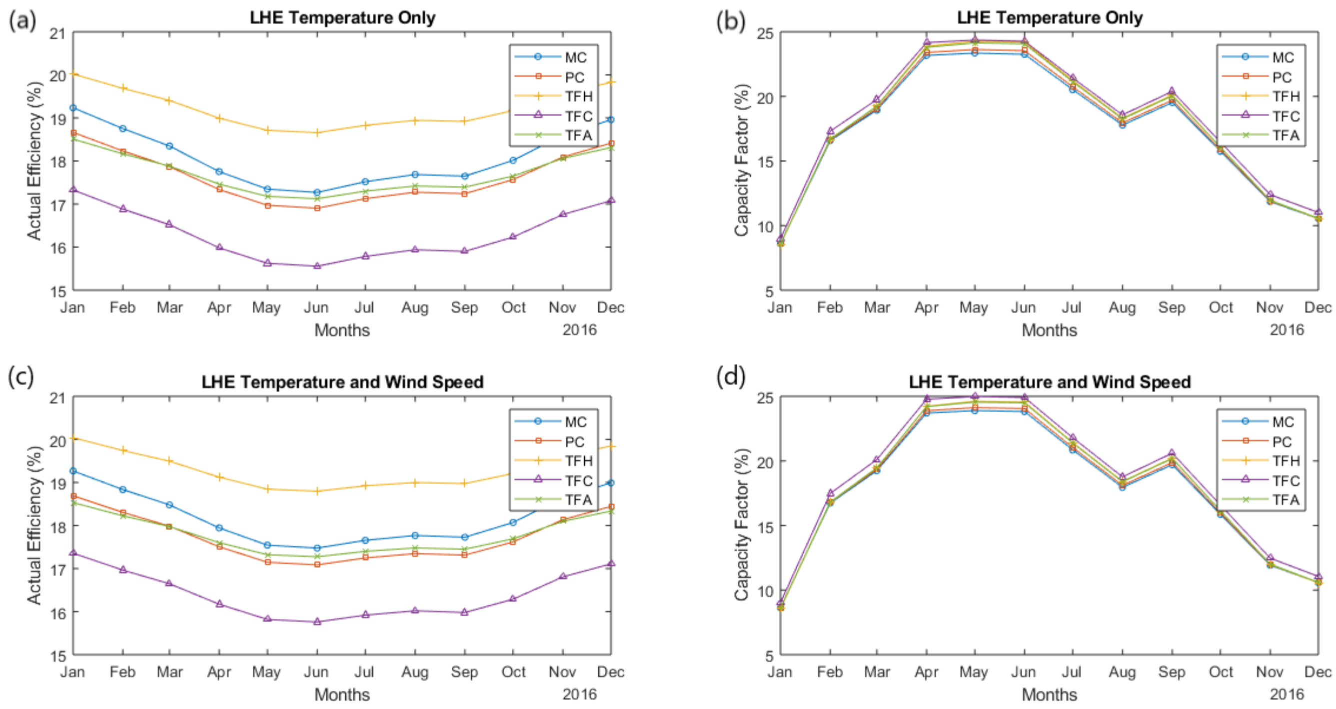

Figure 22. Monthly variations in efficiency and CF in Lahore. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

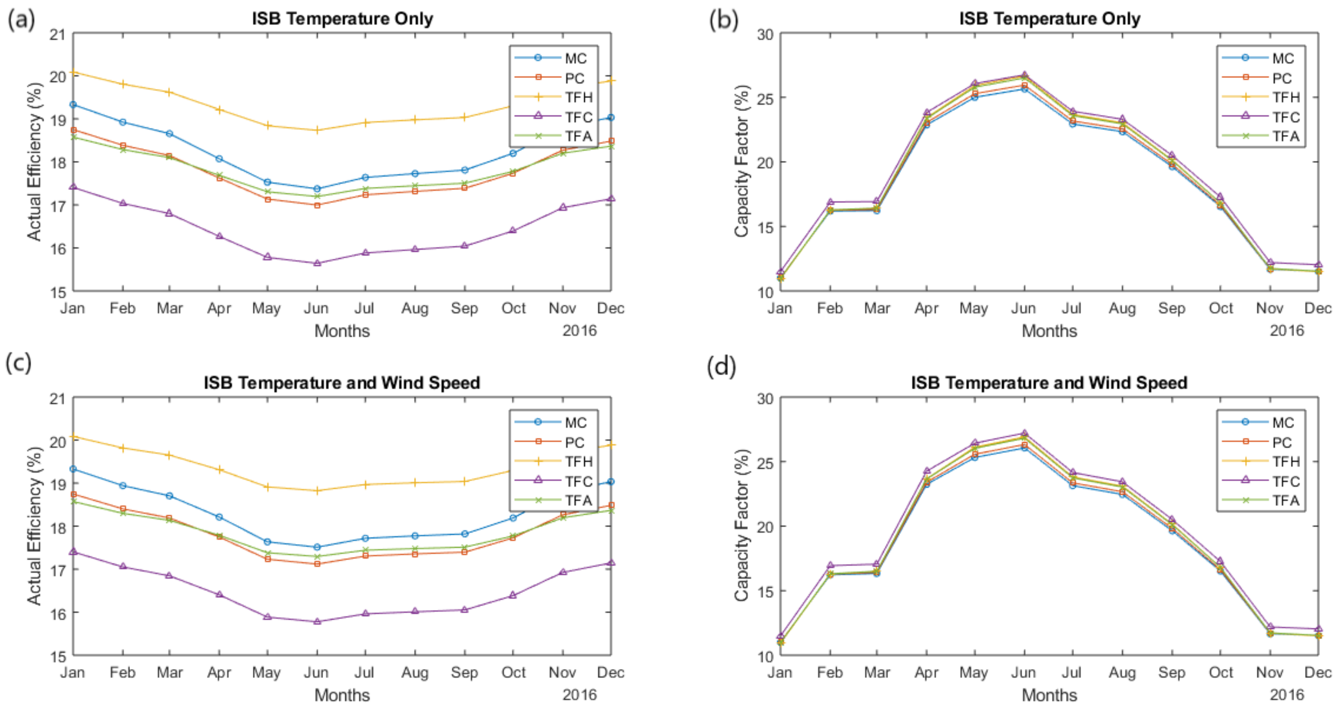

Figure 23. Monthly variations in efficiency and CF in Islamabad. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

In Quetta, the maximum (minimum) monthly average efficiency in January (June) of all the modules was examined. The values for the monthly mean actual efficiency range between 19 and 19.2% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA (Figure 26a).

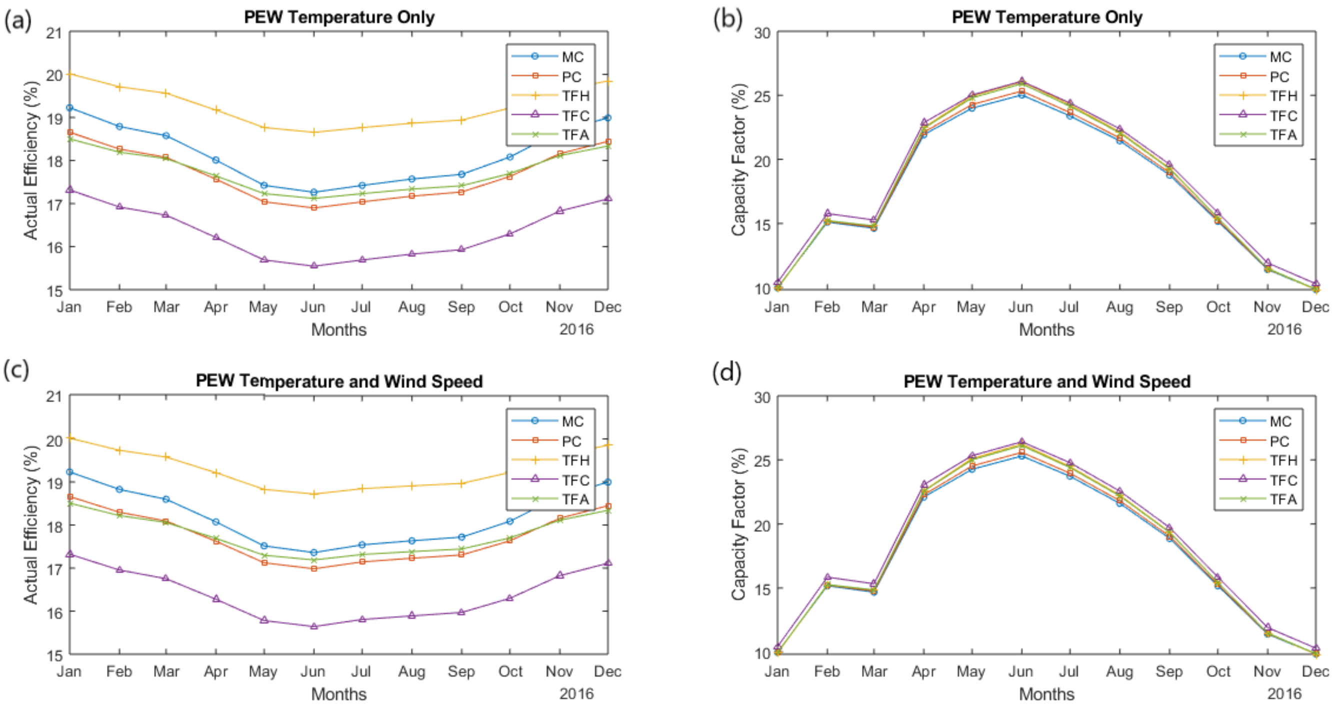

Figure 24. Monthly variations in efficiency and CF in Peshawar. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

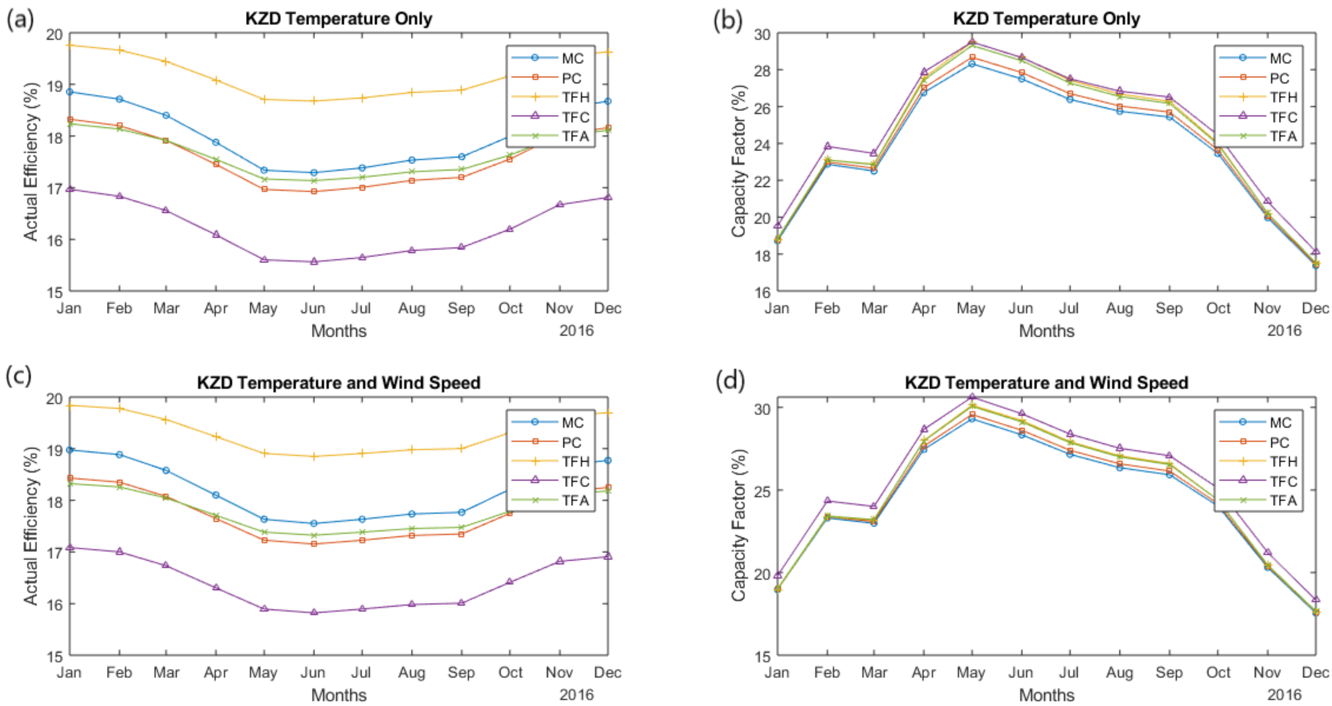

Figure 25. Monthly variations in efficiency and CF in Khuzdar. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

The maximum (minimum) monthly average efficiency of all the modules in Bahawalpur was inspected in January (June). The values for the monthly mean actual efficiency range between 17.0376% and 19.2066% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA, accounting the effect of temperature only (Figure 27a).

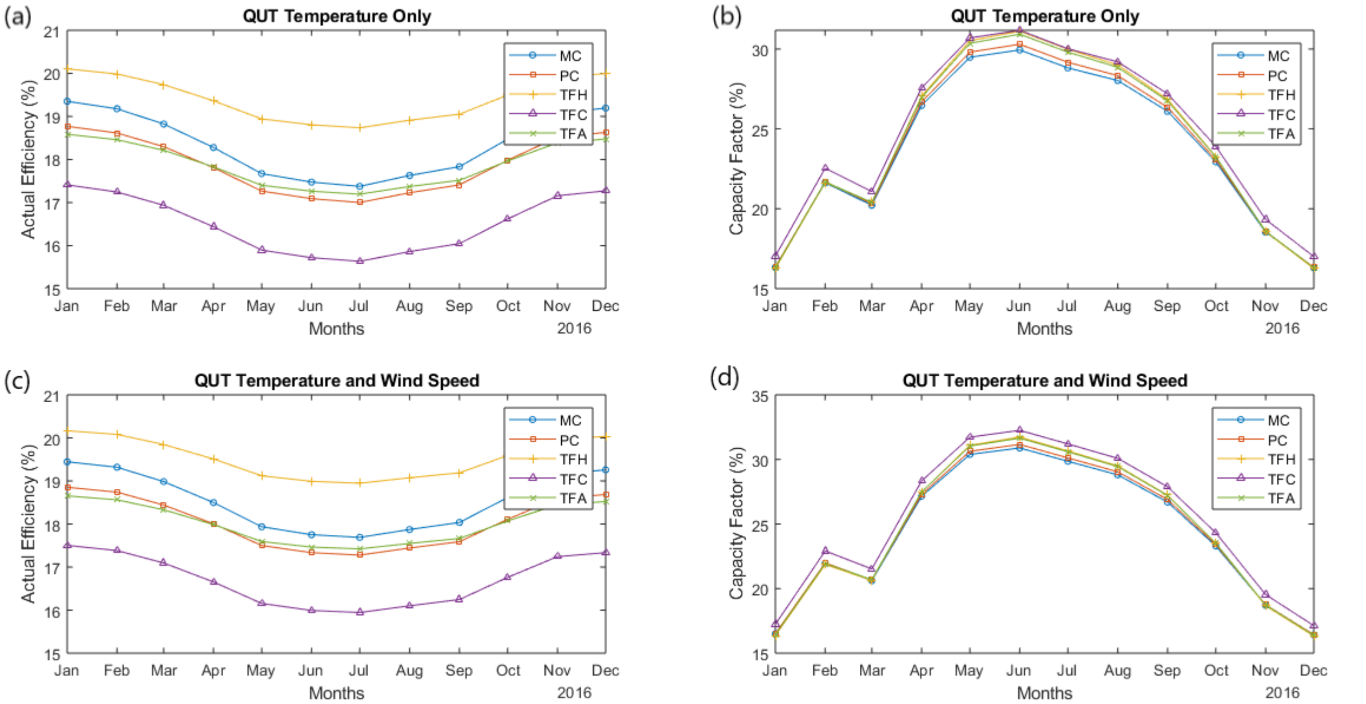

Figure 26. Monthly variations in efficiency and CF in Quetta. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

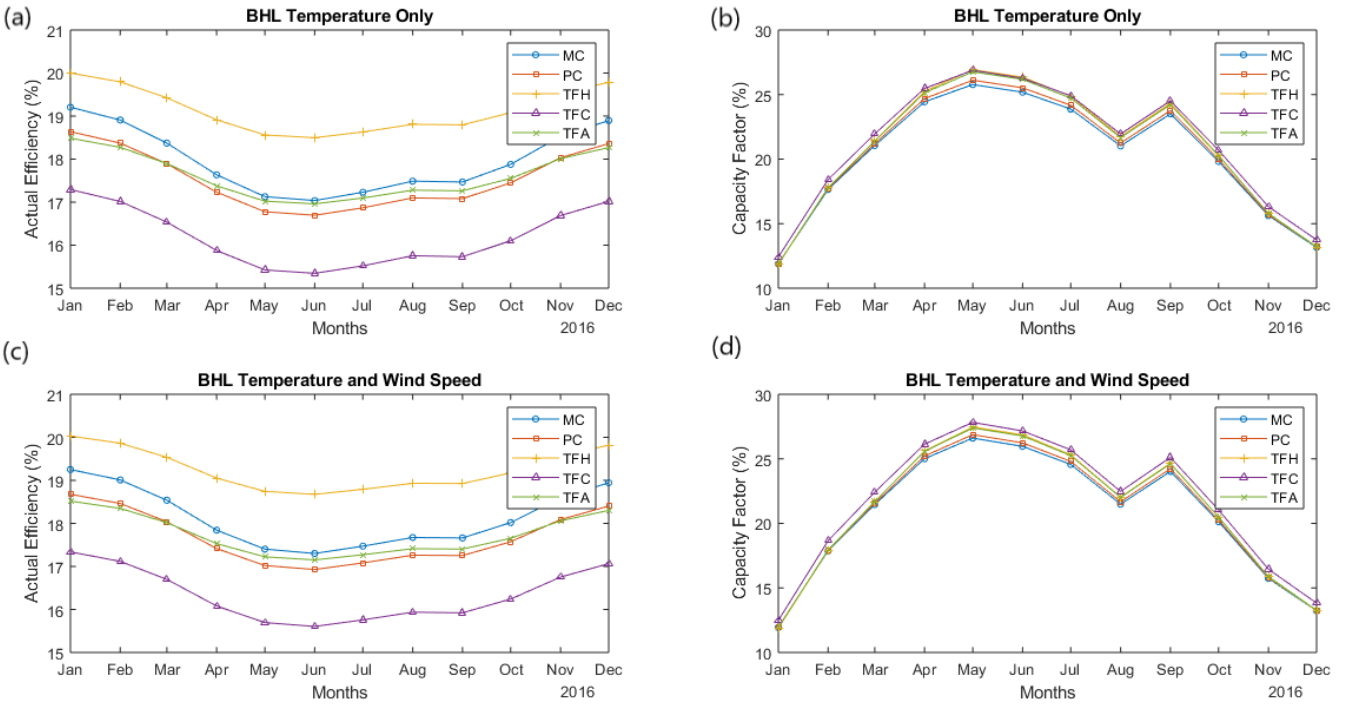

Figure 27. Monthly variations in efficiency and CF in Bahawalpur. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

In Multan, the maximum (minimum) monthly average efficiency of the aforesaid five PV modules was analyzed in January (June). The values for the monthly mean actual efficiency range between 19 and 19.2% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA (Figure 28a).

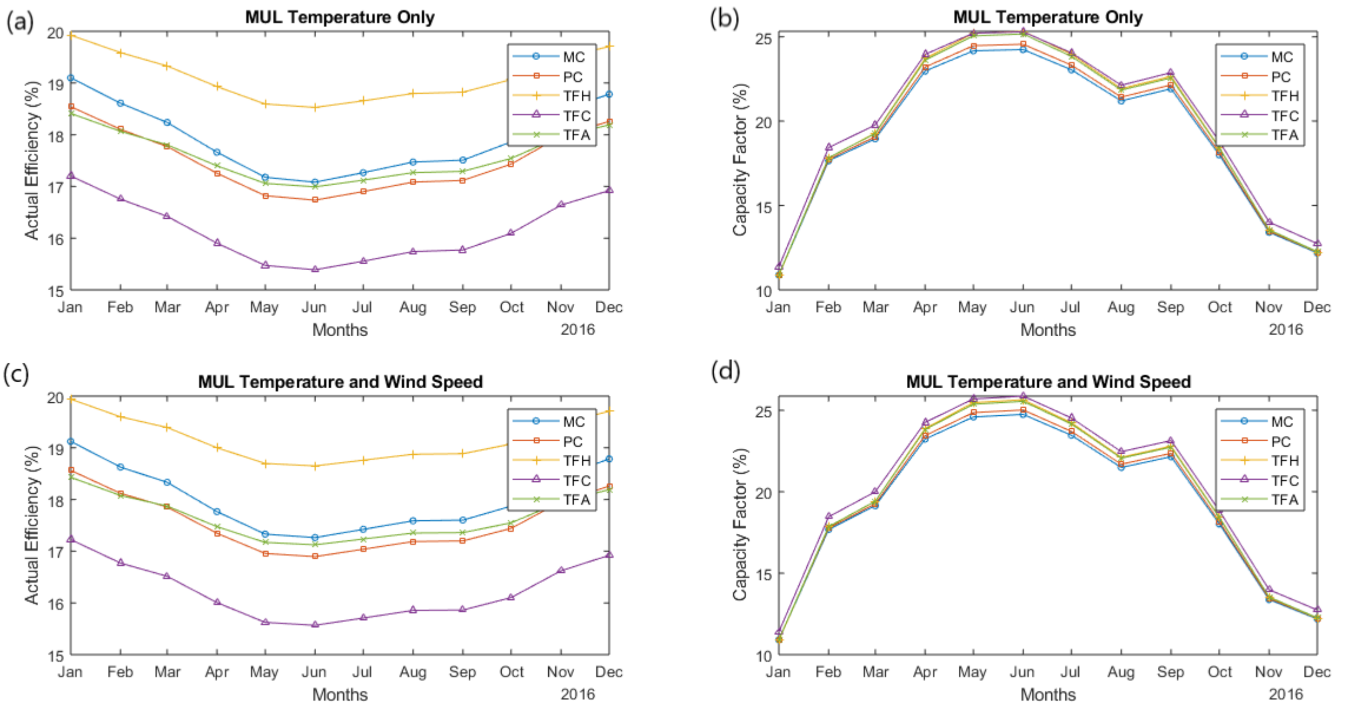

Figure 28. Monthly variations in efficiency and CF in Multan. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

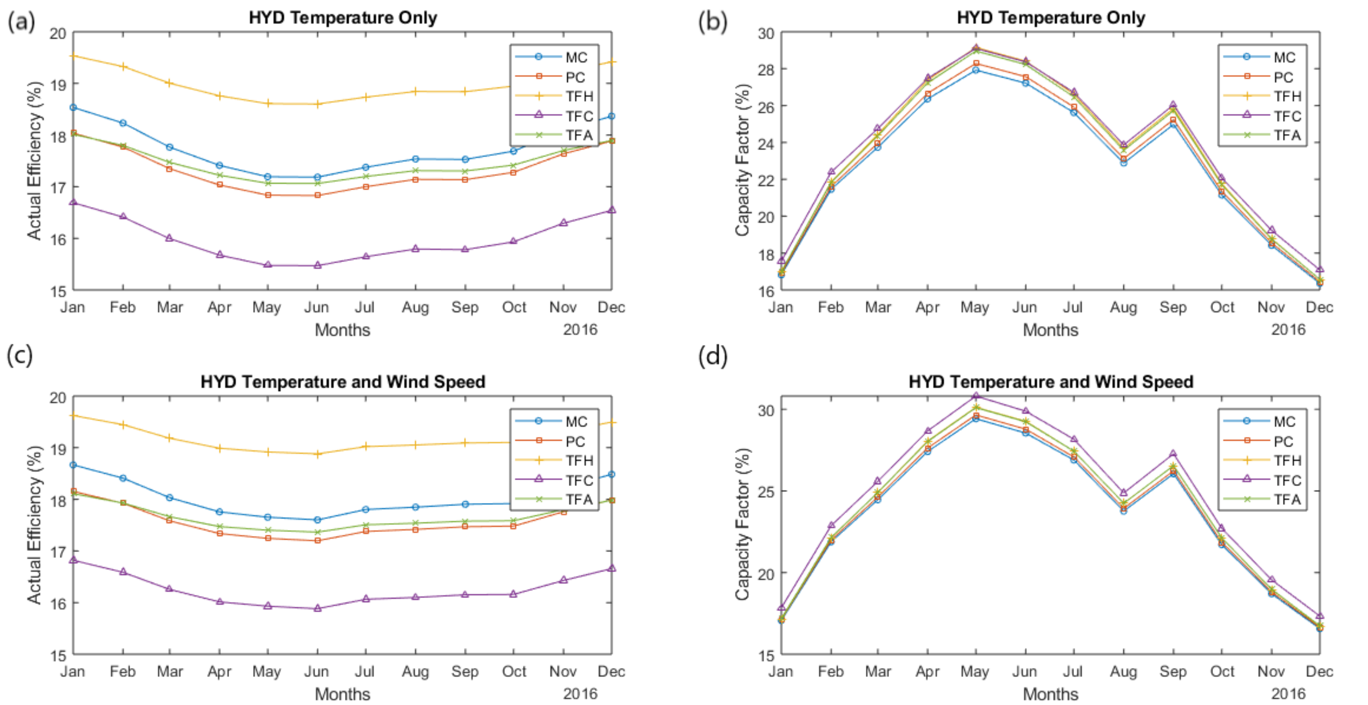

Figure 29. Monthly variations in efficiency and CF in Hyderabad. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

In Hyderabad, the maximum (minimum) monthly average efficiency of all the modules was in January (June). The values for the monthly mean actual efficiency range between 19 and 19.2% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA (Figure 29a).

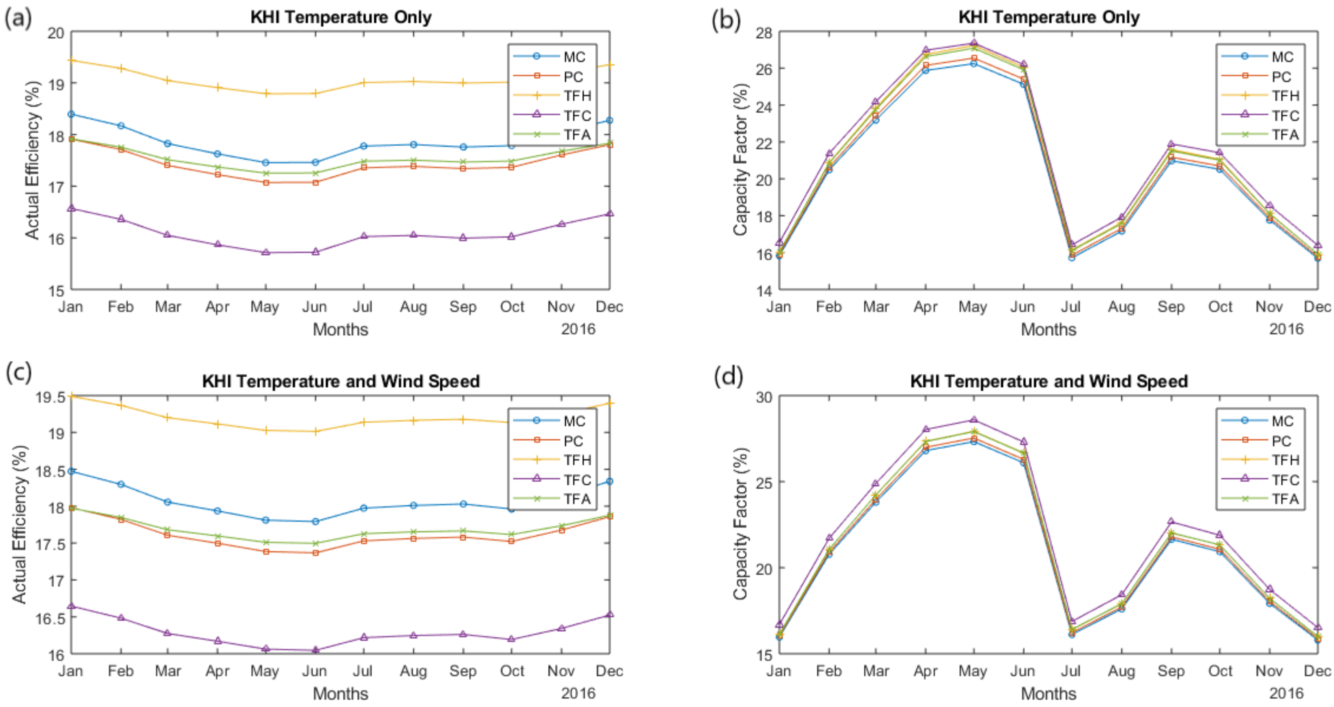

Figure 30. Monthly variations in efficiency and CF in Karachi. (**a**,**b**) Temp only (**c**,**d**) Temp & wind speed.

The maximum (minimum) monthly average efficiency of all the modules in Karachi was noticed in January (June). The values for the monthly mean actual efficiency range between 19 and 19.2% for MC, 18.4 and 18.8% for PC, 19.9 and 20% for TFH, 17.05 and 17.3% for TFC, and 18.3 and 18.5% for TFA (Figure 30a).

4.6. Monthly Variations in Capacity Factor

Figure 22c shows the monthly variations in the capacity factors of the PV modules in Lahore considering the effect of temperature only. The capacity factor was at a maximum in May for all the PV modules and at a minimum in January. The values of the capacity factor in May, June, and July were comparable for MC, PC, and TFC. The value of CF in September was noticed to be greater than that in August for all the modules. In Figure 22d, it is seen that CF increased in March–September (1–2%) for TFC when the effect of both temperature and wind speed was accounted for.

Figure 23c illustrates the monthly variations in the capacity factor of the PV modules in Islamabad considering the effect of temperature only. The capacity factor was at a maximum in June for all the PV modules and at a minimum in January. The values of the capacity factor in February and March were comparable for TFC. From Figure 23d, it is clear that CF improved in April–August (1–2%) for TFC considering the effect of both temperature and wind speed.

Figure 24c shows the monthly variations in the capacity factor of the PV modules in Peshawar when the effect of only temperature was considered. The capacity factor was at a maximum in May for all the PV modules and at a minimum in January. The values of the capacity factor in May, June, and July were comparable for all the PV modules. The value of CF in March was observed to be lower than that in February for all the modules. The value of CF increased in March–September (1–2%) for TFC when the effect of both temperature and wind speed was considered, as shown in Figure 24d.

Figure 25c shows the monthly variations in the capacity factor of the PV modules in Khuzdar considering the effect of temperature only. The capacity factor was at a maximum in May for all the PV modules and at a minimum in January. The value of CF in March was observed to be lower than that in February for all the modules. Figure 25d shows that CF increased in February–November (1–2%) for TFC when the effect of both temperature and wind speed was considered.

Figure 26c shows the monthly variations in the capacity factor of the PV modules in Quetta considering the effect of temperature only. The capacity factor was at a maximum in June for all the PV modules and at a minimum in January. The values of the capacity factor in December and January were comparable for all the PV modules. The value of CF in March was observed to be lower than that in February for all the modules. The value of CF increased in February–September (1–2%) for TFC when the effect of both temperature and wind speed was considered, as presented in Figure 26d.

Figure 27c shows the monthly variations in the capacity factor of the PV modules in Bahawalpur considering the effect of temperature only. The capacity factor was at a maximum in May for all the PV modules and at a minimum in January. It was noticed that the value of CF in September was greater than that in August for all the modules. It is observed in Figure 27d that the value of CF increased in March–October (1–2%) for TFC when the effect of both temperature and wind speed was considered.

Figure 28c shows the monthly variations in the capacity factor of the PV modules in Multan considering the effect of temperature only. The capacity factor was at a maximum in May for all the PV modules and at a minimum in January. The values of the capacity factor in May and June were comparable for all the PV modules. Figure 28d depicts that the value of CF increased in March–October (1–2%) for TFC when the effect of both temperature and wind speed was taken into account.

Figure 29c shows the monthly variations in the capacity factor of the PV modules in Hyderabad considering the effect of temperature only. The capacity factor was at a maximum in May for all the PV modules and at a minimum in December. The value of CF in September was noticed to be greater than that in August for all the modules. Figure 28d shows that the value of CF increased in March–November (1–2%) for TFC when the effect of both temperature and wind speed was taken into account.

Figure 30c shows the monthly variations in the capacity factor of the PV modules in Karachi considering the effect of temperature only. The capacity factor was at a maximum in May for all the PV modules and at a minimum in January and July. It was noticed that the value of CF in August was greater than that in July and lower than that in September for all the modules. The value of CF increased in March–November (1–2%) for TFC when the effect of both temperature and wind speed was taken into account, as noticed in Figure 30d.

5. Discussion

In Figures 4a–12a, the daily actual efficiency of the different PV modules is shown as a function of temperature and GHI at nine locations. It was observed that five different PV modules have high daily actual efficiency at low GHI and high temperature. This is because the increase in solar irradiance increases the temperature of the PV module, which increases the thermal losses and decreases the PV module's actual efficiency. While at lower solar irradiance, the temperature of the PV module decreases and minimizes the temperature losses, leading to an increase in actual efficiency. A detailed discussion on the risk-benefit assessment of solar energy for traditional as well as building-heating purposes can be found in Ref. [52].

The most efficient PV module was TFH in Quetta with a daily mean actual efficiency of 19.42%, and the least efficient was TFC in Hyderabad with a daily mean actual efficiency of 15.97% among all the PV modules, as shown in Table 3. This is because of the low daily ambient temperature and the highest altitude of Quetta among all the stations. The highest actual efficiency of TFH is due to various factors, including a lower module power temperature coefficient and the spectral effect.

Table 3. Daily Mean Actual Efficiency of Five PV Modules at Different Stations Considering Temperature Effect.

Locations, Modules	LHE	ISB	PEW	KZD	QUT	BHL	MUL	HYD	KHI
MC	18.09	18.26	18.14	18.01	18.36	17.98	17.94	17.74	17.87
PC	17.64	17.79	17.68	17.57	17.88	17.54	17.5	17.33	17.44
TFH	19.23	19.34	19.26	19.18	19.42	19.15	19.12	18.99	19.07
TFC	16.3	16.44	16.34	16.21	16.52	16.19	16.15	15.97	16.09
TFA	17.7	17.82	17.74	17.64	17.89	17.62	17.59	17.45	17.54

Figures 4a–12a depict that the daily actual efficiency of five different PV modules depends upon the ambient air temperature when the effect of temperature is taken into consideration. It was seen that the daily actual efficiency of each PV module varies inversely with the variation in ambient air temperature. The efficiency of each PV module reduced when the ambient temperature increased and the reduction in actual efficiency was found to be different for different PV modules at different locations. This different effect of ambient temperature on the efficiency of the five PV modules was observed in the range of values of its daily actual efficiency at nine locations, as mentioned earlier (Section 4.1). It was also observed that the slope of MC was steepest, while that of TFH was least inclined among the other PV modules at all the stations. This shows that the daily actual efficiency of MC is strongly dependent on ambient temperature (most sensitive to ambient temperature) and TFH has the least dependency (least sensitive to ambient temperature). This is because the temperature-induced efficiency losses of MC are more significant compared to other PV technologies. In Islamabad, Peshawar, and Hyderabad, the effect of temperature on the daily actual efficiency of TFC was greater than that of PC. For the rest of the cities, the effect of temperature on the actual efficiency of TFC and PC was similar. The daily actual efficiency of TFA was more affected by ambient temperature as compared to TFH daily actual efficiency at the nine locations.

The aforementioned PV modules were observed to have high daily actual efficiency when the intensity of solar irradiance is low and low daily actual efficiency when irradiance is high, as shown in Figures 13a–21a. The daily actual efficiency of the PV module is inversely proportional to daily solar irradiance when the effect of both temperature and wind speed are considered in the analysis. As mentioned earlier, solar irradiance raises the thermal losses in the PV modules, and as a result, the actual efficiency of the PV modules lessens and vice versa. Moreover, it was observed that adding the effect of wind speed to that of temperature enhances the value of the daily mean actual efficiency of each PV module at all the stations. This increase in the calculated daily mean actual efficiencies of MC, PC, TFH, TFC, and TFA was 0.61, 0.51, 0.36, 0.61 and 0.45% in Lahore, 0.22, 0.22, 0.16, 0.30 and 0.17% in Islamabad, 0.28, 0.23, 0.16, 0.24 and 0.17% in Peshawar, 1.11, 0.97, 0.68, 1.17 and 0.85% in Khuzdar, 0.98, 0.95, 0.62, 1.09 and 0.73% in Quetta, 0.89, 0.80, 0.57, 0.99 and 0.68% in Bahawalpur, 0.39, 0.40, 0.26, 0.50 and 0.34% in Multan, 1.63, 1.44, 1.00, 1.75 and 1.20% in Hyderabad, and 1.12, 1.03, 0.73, 1.24 and 0.86% in Karachi, respectively. Among all the PV modules, TFH is the most efficient PV module (19.54%) in Quetta and TFC is the least efficient PV module (16.23%) in Multan, as presented in Table 4. The highest daily actual efficiency of the TFH PV module in Quetta is due to its highest altitude and low daily ambient temperature among all the stations. The reason is that the wind speed reduces the temperature of the module, and thus, minimizes the temperature losses and increases the value of the daily mean actual efficiency of the PV module.

Table 4. Daily Mean Actual Efficiency of Five PV Modules at Different Stations Considering Combine Effect of Temperature and Wind Speed.

Locations, Modules	LHE	ISB	PEW	KZD	QUT	BHL	MUL	HYD	KHI
MC	18.20	18.30	18.19	18.21	18.54	18.14	18.01	18.03	18.07
PC	17.73	17.83	17.72	17.74	18.05	17.68	17.57	17.58	17.62
TFH	19.30	19.37	19.29	19.31	19.54	19.26	19.17	19.18	19.21
TFC	16.40	16.49	16.38	16.40	16.70	16.35	16.23	16.25	16.29
TFA	17.78	17.85	17.77	17.79	18.02	17.74	17.65	17.66	17.69

Figures 13–21 illustrate the daily performance ratio based on the rated efficiency of each PV module considering the temperature effect and both the temperature and efficiency effect. It was clear that the daily PR of the PV modules varies inversely with both GHI and ambient temperature due to variations in temperature-dependent daily actual efficiency. A decrease in daily PR was observed because of a reduction in the PV module's actual efficiency with high daily GHI values and ambient temperature. Moreover, the daily mean performance ratio of HIT was observed to be at a maximum (98.61% in Lahore, 99.19% in Islamabad, 98.78% in Peshawar, 98.34% in Khuzdar, 99.58% in Quetta, 98.21% in Bahawalpur, 98.05% in Multan, 97.37% in Hyderabad, and 97.80% in Karachi), while that of TFC was found to be at a minimum (97.59% in Lahore, 98.44% in Islamabad, 97.84% in Peshawar, 97.08% in Khuzdar, 98.91% in Quetta, 96.95% in Bahawalpur, 96.73% in Multan, 95.65% in Hyderabad, and 96.35% in Karachi) among all the PV modules when analyzing the temperature only. Similar trends were noticed considering the effect of both temperature and wind speed in the analysis. However, the added effect of wind speed enhanced the daily performance ratio for each PV module due to increasing daily actual efficiency as PR is the actual module efficiency related to the rated efficiency of the module. The increase in the performance ratio of all the modules is presented in Table 5, which depicts that the effect of wind speed on the performance of all the PV modules is seen most prominently in Hyderabad and least in Peshawar. The reason for this is that Hyderabad possesses the highest value of mean wind speed and Peshawar has the lowest value of mean wind speed, as mentioned earlier (Table 1).

Table 5. Percentage Increase in Daily Performance Ratio of Five PV Modules at Different Stations Considering Combine Effect of Temperature and Wind Speed.

Locations, Modules	LHE	ISB	PEW	KZD	QUT	BHL	MUL	HYD	KHI
MC	0.59	0.26	0.25	1.08	0.96	0.90	0.43	1.60	1.07
PC	0.54	0.23	0.23	0.97	0.96	0.81	0.39	1.44	1.02
TFH	0.37	0.16	0.15	0.68	0.62	0.56	0.27	1.00	0.66
TFC	0.65	0.28	0.28	1.17	1.10	0.98	0.48	1.76	1.24
TFA	0.44	0.19	0.19	0.81	0.73	0.65	0.32	1.18	0.84

6. Conclusions

In this study, the effect of temperature and wind speed was determined to predict the performance of five PV modules (MC, PC, TFH, TFC, and TFA) under real operating conditions at nine stations (Lahore, Peshawar, Quetta, Bahawalpur, Karachi, Islamabad, Khuzdar, Multan, and Hyderabad) in Pakistan for one year. The technical data of the PV modules with a capacity of 300 W, available under STC, were used from the manufacturers' datasheets.

The results showed that the performance of TFH was the best, while that of TFC was the worst, at all the stations among the aforesaid PV technologies.

The monthly analysis showed that the efficiency of the PV modules was at a maximum in winter due to lowered T_m.

The actual efficiency of MC, PC, TFH, TFC, and TFA had a maximum decrease at Karachi of all the stations and was decreased by 3.4, 3.1, 2.2, 3.7, and 2.7%, respectively, considering the effect of temperature only. Meanwhile, it had a maximum increase at Bahawalpur of all the stations and was increased by 9.7, 9.0, 6.5, 9.5, and 7.0% considering the effect of both temperature and wind speed.

The MC module was most affected by V, while TFH was least affected. The performance ratio of the TFC module was most affected and that of TFH was least affected by wind speed and temperature.

It can be concluded that the TFH module performed efficiently in five different climatic conditions in Pakistan under the effect of temperature and wind speed. This study is a way forward for researchers to conduct comprehensive research using different real outdoor constraints.

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Abbreviations

Name	Description
PV	Photovoltaic
DHI	Diffuse Horizontal Irradiance
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
MC	Mono-crystalline silicon
PC	Poly-crystalline silicon
ESMAP	Energy Sector Management Assistance Program
TFH	Heterogeneous intrinsic thin-film
TFC	Copper–indium–gallium–selenide
TFA	Thin-film amorphous silicon
STC	Standard Test Conditions

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