Article

Comparative Analysis of Power Output, Fill Factor, and Efficiency at Fixed and Variable Tilt Angles for Polycrystalline and Monocrystalline Photovoltaic Panels—The Case of Sukkur IBA University

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Abstract: Photovoltaic technology mainly uses beam, diffused, and reflected solar radiation to produce power. To increase the photovoltaic power output, the surface of the solar panel must be at the optimal tilt angle. In this paper, a numerical study is carried out to investigate the optimal tilt angle for a 1 MW PV system installed at Sukkur IBA University (latitude = 27.7268° N, longitude = 68.8191° E). Moreover, power output, efficiency, and fill factor are calculated for polycrystalline and monocrystalline solar panels. Results obtained at different tilt angles are used to compare the solar gain from photovoltaic modules installed at the university. In conclusion, an optimal tilt angle is decided for both polycrystalline and monocrystalline solar panels used at Sukkur IBA University. It was found that the optimal tilt angle for the installed 1 MW systems is 29.5 degrees.

Keywords: tilt angle; irradiance; efficiency; MATLAB/Simulink; PV solar system; comparison of mono- and polycrystalline modules

1. Introduction

Renewable and non-renewable energy sources are predominantly used for power generation. Non-renewable sources have been slashed and reduced because of emissions of poisonous gases and market restrictions. Renewable sources are becoming prevalent due to the fact that they are environmentally approachable and mitigate the use of fossil fuels [1,2]. Solar energy is available in abundance, and can be used to reduce the cost of power generation [3]. Due to its geographical location, Pakistan receives intense solar irradiance throughout the year. Thus, the country has paid great attention to generating electrical power and easing the shortfall of electricity, and emissions of materials that degrade the atmosphere can be reduced. However, the output rating of solar panels illustrates the size and cost of such systems. The value of the key parameter, efficiency, should lie between 13 and 25% [4].

To abate the size and cost of solar panels, one of the foremost methods is to receive maximum solar radiation on the module. It is well known that the amount of solar radiation received mainly depends on the angle of incidence. There are various methods to fulfill the task of increase the panels’ efficiency in this way, and one of the more popular methods is tracking the sun [5]. Solar-tracking systems are classified as single-axis and dual-axis tracking systems that depend upon adjustment of the degree of freedom [6]. Practical results between fixed and solar-tracking systems have been compared, with results showing that...
single-axis systems cause a 20–25% improvement in efficiency [7–9], whereas in the case of dual-axis systems the improvement ranges from 35 to 40% [7–10]. Solar-tracking systems have a slightly higher cost than stationary systems.

There is also a very important way to extract the maximum power—the maximum power point tracking method. This technique is applied in charge controllers and inverters using converters such as buck converters, boost converters, and buck-boost converters. Different techniques are used for MPPT, including constant voltage, P&O, and incremental conductance. Veer et al., in 2021 [11], worked on the MPPT technique with a buck-boost converter using the P&O algorithm in a photovoltaic system. Another researcher also worked on MPPT using a modified P&O algorithm for a photovoltaic system, with experimental validation [12]. This MPPT technique has also some drawbacks with regard to its implementation on the hardware.

The performance of power output is affected by various parameters, such as time, location with respect to geography, solar panel inclination angle, shading, and orientation of the panel [13–16]. Tilt angle is related to efficiency, so it is one of the key areas in the research field to increase efficiency and overcome the area of the collector. Numerous experiments have been conducted to test efficiency by using various observations, suitable descriptions, designs, and the interactions between various factors and site-related specifications for installation purposes [17,18].

To the best of our knowledge, no single framework exists that covers all of the key performance parameters of the solar PV systems. In this paper, a numerical study is carried out to find the optimal tilt angle for each month for monocrystalline and polycrystalline PV modules of a 1 MW PV system installed at Sukkur Biodiversity. In addition, for optimal tilt angles, various parameters—including irradiance, fill factor, maximum power, and efficiency—are investigated for both types of PV module.

This paper is organized as follows: Section 2 presents the background study of the solar PV systems at Sukkur IBA University, with the PV modules’ specifications. Section 3 highlights the methodology of the research, with flowcharts and mathematical modelling, for finding the optimal tilt angle and calculating different performance parameters. Sections 4 and 5 examine the results under different conditions, and give a conclusion and remarks on the future extension of this work, which could include the validation of these simulated results with experimental results.

2. Background Study

Solar energy is a ubiquitous source to utilize, and is resilient to change in climate extremes. Pakistan has an enormous solar capacity of 2900 GW [19]; each year, 1900–2200 kWh/m² of solar irradiation makes it among the most feasible regions in the globe in terms of the availability of solar energy [20,21]. Figures 1 and 2 show maps of the photovoltaic solar power potential and solar uninterrupted standard irradiance of Pakistan, respectively. This represents that the country has higher potential and good values of irradiance to overcome the energy crisis and economic burden from fossil fuels. Pakistan is trying to increase the share of Renewable energy sources like Photovoltaic systems technologies across the region [22–28].

To this end, Sukkur IBA University has installed a PV system with a capacity of 1 MW. The specifications of this system cover the supply of a photovoltaic solar system that is operated in conjunction with a DC-generating set (i.e., the associated solar invertors) to provide the necessary AC power supply to Sukkur IBA University. All of the roofs of the buildings and parking areas have been used to mount the PV modules to make the university green and environmentally friendly, as shown in Figure 3.
Figure 1. Solar PV power potential map [22].

Figure 2. Solar DNI map of Pakistan [22].
This PV plant, with both monocrystalline and polycrystalline modules, is the only plant in the Sukkur region with a capacity of 1 MW. The photovoltaic modules are composed of silicon solar cells. The crystalline silicon-based photovoltaic cells are categorized as mono- and polycrystalline [29], and the specific values of the essential parameters of the polycrystalline and monocrystalline PV panels used at Sukkur IBA University are listed in Table 1.

Table 1. Specifications of the polycrystalline and monocrystalline PV modules.

| Parameters                        | Polycrystalline PV Module | Values |
|-----------------------------------|---------------------------|--------|
| Rated power P<sub>m</sub>         |                           | 260 W  |
| Voltage at maximum power V<sub>mp</sub> |                           | 31.4 V |
| Current at maximum power I<sub>mp</sub> |                           | 8.37 A |
| Open-circuit voltage V<sub>oc</sub> |                           | 38.4 V |
| Short-circuit current I<sub>sc</sub> |                           | 8.94 A |

| Parameters                        | Monocrystalline PV Module | Values |
|-----------------------------------|---------------------------|--------|
| Rated power P<sub>m</sub>         |                           | 280 W  |
| Voltage at maximum power V<sub>mp</sub> |                           | 31.8 V |
| Current at maximum power I<sub>mp</sub> |                           | 8.93 A |
| Open-circuit voltage V<sub>oc</sub> |                           | 39.0 V |
| Short-circuit current I<sub>sc</sub> |                           | 9.45 A |

The efficiency of the monocrystalline PV modules is much greater than that of the polycrystalline PV modules [30]. The performance of the solar cells is defined by standard test conditions. These test conditions are solar spectrum irradiance known as air mass of 1.5, irradiance of 1000 W/m², and a fixed cell temperature of 25 °C [31]. This article mainly focuses on the performance parameters of the solar modules, including irradiance, maximum power, fill factor, and efficiency. The workflow used to determine all of the performance parameters is illustrated in Section 3.
3. Methodology

In this paper, the case of Sukkur IBA University, Sukkur, Sindh, Pakistan is considered, where a grid-tied solar photovoltaic system of around 1 MW is installed. These modules are located on roof-mounted racks and in overhead locations such as parking lots or other paved areas. MATLAB/Simulink software was used to carry out the simulations and numerical methods at the existing fixed angles. Furthermore, after analyzing the results at existing angles, the numerical analysis was repeated at variable angles to determine the optimal tilt angle. A polycrystalline module of 260 W was fixed at a 5° tilt angle, and a monocrystalline module of 280 W was tilted at 15°.

There are different parameters for analyzing the performance of solar PV modules. We analyzed the irradiance, maximum power, fill factor, and efficiency. For simplicity, a flowchart of our research is given in Figure 4, which clearly shows how the data of the PV module are utilized for numerical analysis using MATLAB/Simulink software in order to find the performance parameters at the existing tilt angle. Then, the next step was to find the optimal tilt angle, maximum power, fill factor, and efficiency at both angles. Finally, a comparison of the parameters of the monocrystalline and polycrystalline modules was carried out.

![Flowchart of this work.](image-url)
Subsequently, the consistent values $G_{sc}$, $\varphi$, $\rho_g$, and $H$ were utilized, and $n$ was adjusted to 1, indicating the first day of the year, when the structure is inclined from $0^\circ$ to $90^\circ$ only for the specified day, and the optimal tilting angle is obtained with the highest solar irradiance. At this point, $n$ was increased by 1, and on the specified day of each month, different parameters have been tested and measured to check the optimal tilt angle for 365 days. For appropriate analysis, the tilt angle varied from $0^\circ$ to $90^\circ$, with a $1^\circ$ step size.

In order to evaluate irradiance, we used a process to accurately measure first $\delta$, $\omega_s$, and $\omega_{ss}$, and then $H_0$, $K_T$, $H_d$, $H_b$, $R_d$, $R_b$, and $H_T$. These parameters were calculated using the equations given below. The total solar radiation on the tilted surface can be calculated using the equation given in [32,33]:

$$H_T = H_b \times R_b + H_d \times R_d + H \times \rho_b \times \left(1 - \frac{\cos \beta}{2}\right)$$  \hspace{1cm} (1)

where $R_b$ and $R_d$ in represent the tilt coefficients that help us to evaluate the beam solar radiation and the diffused solar radiation on the tilted surface, respectively. The coefficients can be determined as described in [32–35], using Equations (2) and (4):

$$R_b = \frac{\left(\cos(\varnothing - \beta) \times \cos(\delta) \times \sin(\omega_{ss})\right) + \left(\omega_{ss} \left(\frac{\pi}{180}\right) \sin(\varnothing - \beta) \sin(\delta)\right)}{\left(\cos(\varnothing) \times \cos(\delta) \times \sin(\omega_s)\right) + \left(\omega_s \left(\frac{\pi}{180}\right) \sin(\varnothing) \sin(\delta)\right)} \hspace{1cm} (2)$$

where $\rho_b$ is the ground reflectance or albedo (reflectance of ground = 0.2), $\beta$ is the optimal tilt angle (the angle at which the PV panel receives the maximum amount of solar radiation), $\varnothing$ is the latitude of Sukkur IBA University ($27.7268^\circ$ N, $68.8191^\circ$ E), and $\delta$ is the declination angle of the Earth, and can be calculated as follows:

$$\delta = 23.45 \sin\left[\frac{360(n + 284)}{365}\right] \hspace{1cm} (3)$$

where $\omega_s$ is the sunset hour angle and $\omega_{ss}$ is the sunrise hour angle of the inclined plane.

$$R_d = \frac{H_b \times R_b + \left(1 - \frac{H_b}{H}\right) \times \left(1 + \frac{\cos \beta}{2}\right) \times \left[1 + \sqrt{\frac{H_b}{H} \times \sin\left(\frac{\beta}{2}\right)^3}\right]}{H_b} \hspace{1cm} (4)$$

where $H_b$ is the beam direct radiation’s incident angle, $H$ is the global solar radiation at the horizontal surface, and $H$ is the monthly average daily extraterrestrial radiation (kwh/m$^2$/day). The statistics associated with global solar radiation on a flat surface are taken from the NASA database.

By means of Equations (1)–(4), the irradiance can be conveniently measured at various apparently inclined angles. In Figure 3, the first two panels display the approach for determining the optimal tilt angle on the map.

3.1. Maximum Power Output

The maximum power output can be calculated using the following equation [36,37]:

$$P_{max} = FF \times V_{oc} \times I_{sc} \hspace{1cm} (5)$$

where FF denotes the fill factor, $V_{oc}$ denotes the open-circuit voltage, and $I_{sc}$ is the short-circuit current. The values of $V_{oc}$ and $I_{sc}$ are taken from the specifications of the PV modules.

3.2. Fill Factor (FF)

The fill factor is the ratio of the actual maximum power to the product of open-circuit voltage ($V_{oc}$) and short-circuit current ($I_{sc}$). It can be calculated using the following equation [26]:

$$FF = \frac{(V_{mp} \times I_{mp})}{(V_{oc} \times I_{sc})} \hspace{1cm} (6)$$
where $V_{mp}$ is the maximum power voltage, $I_{mp}$ is the maximum power current, $V_{oc}$ is the open-circuit voltage, and $I_{sc}$ is the short-circuit current. All of these values are taken from the specifications of the PV modules.

3.3. Efficiency ($\eta$)

The efficiency can be calculated using the following equation [38]:

$$\eta = \frac{FF \cdot I_{sc} \cdot V_{oc}}{P_{light}}$$

(7)

4. Results and Discussion

By employing mathematical modelling as described in Section 3, the irradiance level for a polycrystalline solar panel was calculated at a 5° tilt angle, and for a monocrystalline panel it was calculated at a 15° tilt angle. Irradiance was also calculated at 29.5° and variable tilt angles for both types of panel on the 21st day of every month of 2019. We also analyzed the declination angle, irradiance level, power output, fill factor, and efficiency of the solar panels at different angles to compare the numerical and experimental results.

4.1. Polycrystalline Module Tilted at 5 Degrees

To find the irradiance level at a 5° tilt angle, the maximum irradiance on a horizontal surface ($H$) in Wh/m²/day and W/m²/day was taken from the NASA database and used in Equation (1). Then, the irradiance level obtained after 5° tilt was employed for a model of a solar module developed in MATLAB/Simulink using the parameters given in Table 1, so as to obtain the power output, fill factor, and efficiency of the PV module.

The maximum efficiency was obtained from the months of September to March, and was between 27 and 29%, while the fill factor was between 0.74 and 0.76 in these months. The power output, fill factor, and efficiency of the PV module were not constant, and changed every month. The variations in these parameters by month are shown in Table 2.

The variations in the power output, fill factor, and efficiency of the solar PV module fixed at a tilt angle of 5° are depicted in Figure 5. It can be observed that the power output from the panels fluctuates throughout the year.

| Month    | H-W  | Tilt Angle | Irradiance Level After Tilt | Declination Angle of the Earth | $I_{sc}$ | $V_{oc}$ | $V_{mp}$ | $I_{mp}$ |
|----------|------|------------|-----------------------------|---------------------------------|---------|---------|---------|---------|
| January  | 913.415 | 5 | 1024 | −20.14 | 9.15 | 38.35 | 31.37 | 8.56 |
| February | 921.951 | 5 | 996.5 | −11.23 | 8.91 | 38.31 | 31.4 | 8.33 |
| March    | 1069.51 | 5 | 1117 | −0.403 | 9.98 | 38.55 | 31.3 | 9.33 |
| April    | 1148.78 | 5 | 1160 | 11.58 | 10.37 | 38.553 | 31.23 | 9.7 |
| May      | 1293.9 | 5 | 1277.9 | 20.14 | 11.42 | 38.72 | 31.13 | 10.66 |
| June     | 1367.07 | 5 | 1340 | 23.45 | 11.97 | 38.81 | 31.05 | 11.18 |
| July     | 1392.68 | 5 | 1375.7 | 20.44 | 12.29 | 38.85 | 31 | 11.48 |
| August   | 1250 | 5 | 1265 | 11.75 | 11.3 | 38.63 | 31.12 | 10.56 |
| September| 1267.07 | 5 | 1321.6 | −0.2 | 11.81 | 38.73 | 31.06 | 11.03 |
| October  | 1076.83 | 5 | 1166.2 | −11.75 | 10.42 | 38.53 | 31.25 | 9.74 |
| November | 1097.56 | 5 | 1232 | −20.44 | 11.01 | 38.6 | 31.16 | 10.29 |
| December | 852.439 | 5 | 971 | −23.45 | 8.68 | 38.28 | 31.47 | 8.11 |
4.2. Polycrystalline Module Tilted at Variable Angles

Table 3 shows the simulated results of solar irradiance and optimal tilt angles on the 21st day of every month of 2019. The optimal tilt angle of every month for Sukkur IBA University was calculated. Firstly, the total solar radiation for tilt angles between 0° and 90° with an interval of 1° was calculated, and the angle with maximum radiation was determined to find the optimal tilt angle. Then, the irradiance levels obtained at the optimal tilt angles were given to the solar module—a model developed in MATLAB/Simulink using the parameters given in Table 1—to determine the power output, fill factor, and efficiency of the PV module, which are shown in Table 3.

Table 3. Monthly specific daily global irradiance (H), optimal tilt angle (deg), declination angle of the Earth, irradiance level after tilt, $I_{sc}$, $V_{oc}$, $I_{mp}$, and $V_{mp}$.

| Month     | H-W  | Optimal Tilt Angle | Irradiance Level After Tilt | Declination Angle of the Earth | $I_{sc}$ | $V_{oc}$ | $V_{mp}$ | $I_{mp}$ |
|-----------|------|--------------------|-----------------------------|-------------------------------|----------|----------|----------|----------|
| January   | 913.41 | 57.73              | 1630                        | −20.14                        | 14.56    | 39.02    | 30.683   | 13.57    |
| February  | 921.95 | 47                 | 1310                        | −11.23                        | 11.70    | 38.76    | 31.090   | 10.93    |
| March     | 1069.5 | 30.95              | 1229                        | −0.403                        | 10.98    | 38.60    | 31.176   | 10.26    |
| April     | 1148.7 | 10.16              | 1164                        | 11.58                         | 10.40    | 38.5     | 31.262   | 9.724    |
| May       | 1293.9 | 0                  | 1294                        | 20.14                         | 11.56    | 38.68    | 31.090   | 10.81    |
| June      | 1367.0 | 0                  | 1367                        | 23.45                         | 12.21    | 38.74    | 31.026   | 11.40    |
| July      | 1392.6 | 0                  | 1392.7                      | 20.44                         | 12.44    | 38.81    | 31.002   | 11.61    |
| August    | 1250   | 9.834              | 1265.8                      | 11.75                         | 11.31    | 38.63    | 31.121   | 10.57    |
| September | 1267.0 | 30.62              | 1452                        | −0.2                          | 12.97    | 38.92    | 30.889   | 12.11    |
| October   | 1076.8 | 47.74              | 1549                        | −11.75                        | 13.84    | 38.94    | 30.764   | 12.99    |
| November  | 1097.5 | 58.06              | 1977                        | −20.44                        | 17.65    | 39.39    | 30.174   | 16.42    |
| December  | 852.43 | 61.197             | 1677.6                      | −23.45                        | 14.9     | 39.04    | 30.602   | 13.97    |
Table 3 shows the variation in tilt angle throughout the year. Solar panels with small-input global solar irradiance on the horizontal surface between 7000 and 9000 Wh/m²/day received maximum irradiance of between 1200 w/m²/day and 1977 W/m²/day at tilt angles of 30° or above in the months from September to March. The value of irradiance decreased from April to August at angles of 0 to 11°, and the average value of irradiance was 1442.342 W/m²/day. This value of irradiance is greater than the value at a 5° tilt angle. The maximum efficiency of the PV panels was determined, and it was usually between 29 and 50% from September to March, while the fill factor was between 0.74 and 0.75 in these months. The power output, fill factor, and efficiency of the PV modules are not constant every month throughout the year, but vary, as shown in Figure 6. Figure 6 shows the power output, fill factor, and efficiency of solar PV modules at different tilt angles. From Figure 6, it can be observed that the power output from PV panels fluctuates throughout the year. Therefore, maximum power can be obtained from the solar modules using different tilt angles for each month.

![Figure 6. Power, efficiency, and FF at variable optimal tilt angles, by month.](image)

4.3. Polycrystalline Module Tilted at 29.5 Degrees

To find the radiance levels at a 29.5° tilt angle, maximum irradiance on a horizontal surface (H) in Wh/m²/day and W/m²/day was taken from the NASA database and used in Equation (1). Then, the irradiance levels obtained at 29.5° tilt were given to the solar module—a model developed in MATLAB/Simulink using the parameters given in Table 1—to determine the power output, fill factor, and efficiency of the PV module.

Table 4 shows the parameters for a solar PV module fixed at a tilt angle of 29.5°, which is the suggested angle for Sukkur IBA University. For a tilt angle of 29.5°, solar panels with small-input global solar irradiance on the horizontal surface between 1000 and 1367 W/m²/day received maximum irradiance of between 1229 w/m²/day and 1749 w/m²/day, which is greater than the irradiance received on solar panels at a tilt angle of 5°. In other words, the solar panels received maximum irradiance every month of the year at an angle of 29.5°, and maximum efficiency was obtained from the solar panels as compared with the tilt angle of 5°. The maximum efficiency obtained from the PV panels was usually between 21 and 43%, and the fill factor was between 0.74 and 0.76. The power output, fill factor, and efficiency of the PV modules were not constant throughout the year, but varied on a monthly basis, as shown in Figure 6.
Table 4. Monthly specific daily global irradiance (H), optimal tilt angle (deg), declination angle of the Earth, irradiance level after tilt, $I_{sc}$, $V_{oc}$, $I_{mp}$, and $V_{mp}$.

| Month      | H-W   | Tilt Angle | Irradiance Level after Tilt | Declination Angle of the Earth | $I_{sc}$ | $V_{oc}$ | $V_{mp}$ | $I_{mp}$ |
|------------|-------|------------|-------------------------------|--------------------------------|---------|--------|--------|--------|
| January    | 913.41| 29.5       | 1447.27                       | −20.14                         | 12.93   | 38.93  | 30.9   | 12.07  |
| February   | 921.95| 29.5       | 1253.4                        | −11.23                         | 11.2    | 38.66  | 31.15  | 10.46  |
| March      | 1069.5| 29.5       | 1229                          | −0.403                         | 10.98   | 38.6   | 31.17  | 10.26  |
| April      | 1148.7| 29.5       | 1108                          | 11.58                          | 9.9     | 38.46  | 31.28  | 9.27   |
| May        | 1293.9| 29.5       | 1102.8                        | 20.14                          | 9.86    | 38.47  | 31.29  | 9.22   |
| June       | 1367.0| 29.5       | 1109.5                        | 23.45                          | 9.92    | 38.45  | 31.27  | 9.28   |
| July       | 1392.6| 29.5       | 1182                          | 20.44                          | 10.56   | 38.61  | 31.2   | 9.88   |
| August     | 1250  | 29.5       | 1202.5                        | 11.75                          | 10.75   | 38.55  | 31.2   | 10.04  |
| September  | 1267.0| 29.5       | 1451.6                        | −0.2                           | 12.97   | 38.92  | 30.89  | 12.11  |
| October    | 1076.8| 29.5       | 1476.6                        | −11.75                         | 13.19   | 38.85  | 30.86  | 12.31  |
| November   | 1097.5| 29.5       | 1749.5                        | −20.44                         | 15.62   | 39.16  | 30.5   | 14.56  |
| December   | 852.43| 29.5       | 1440.2                        | −23.45                         | 12.87   | 38.81  | 30.92  | 12.01  |

Figure 7 shows the power output, fill factor, and efficiency of the PV module fixed at a tilt angle of 29.5°, and reveals that maximum power can be obtained from the solar modules at a 29.5° rather than 5° tilt angle.

4.4. Monocrystalline Module Tilted at 15 Degrees

To find the irradiance level at a 15° tilt angle, maximum irradiance on a horizontal surface (H) in Wh/m²/day and W/m²/day was taken from the NASA database and used in Equation (1). Then, the irradiance level obtained at 15° tilt was given to the solar module developed in MATLAB/Simulink using the parameters given in Table 1, to determine the various parameters of the Monocrystalline PV module as represented in Table 5.

The efficiency obtained from the PV panel was at its maximum for the months of September to March, and remained between 30 and 39 %, while the fill factor was between 0.74 and 0.76 in these months. The variations in the power output, fill factor, and efficiency of the panel at a tilt angle of 15° are shown in Figure 8. It can be observed that the power output from PV panels fluctuates throughout the year, and maximum power can be obtained from solar modules in the months of September to January.
Table 5. Monthly specific daily global irradiance (H), optimal tilt angle (deg), declination angle of the Earth, irradiance level after tilt, $I_{sc}$, $V_{oc}$, $I_{mp}$, and $V_{mp}$.

| Month      | H-W     | Tilt Angle | Irradiance Level After Tilt | Declination Angle of the Earth | $I_{sc}$ | $V_{oc}$ | $V_{mp}$ | $I_{mp}$ |
|------------|---------|------------|----------------------------|--------------------------------|---------|--------|--------|--------|
| January    | 913.415 | 15         | 1222                       | −20.14                         | 11.55   | 39.25  | 31.54  | 10.8903 |
| February   | 921.951 | 15         | 1125                       | −11.23                         | 10.63   | 39.14  | 31.65  | 10.0379 |
| March      | 1069.51 | 15         | 1186                       | −0.403                         | 11.21   | 39.22  | 31.56  | 10.5814 |
| April      | 1148.78 | 15         | 1161                       | 11.58                          | 10.97   | 39.16  | 31.59  | 10.3612 |
| May        | 1293.9  | 15         | 1227.6                     | 20.14                          | 11.6    | 39.23  | 31.52  | 10.9442 |
| June       | 1367.07 | 15         | 1265.5                     | 23.45                          | 11.96   | 39.26  | 31.46  | 11.282  |
| July       | 1392.68 | 15         | 1319                       | 20.44                          | 12.47   | 39.38  | 31.39  | 11.7522 |
| August     | 1250    | 15         | 1261.5                     | 11.75                          | 11.92   | 39.27  | 31.47  | 11.245  |
| September  | 1267.07 | 15         | 1403                       | −0.2                           | 13.26   | 39.42  | 31.28  | 12.4879 |
| October    | 1076.83 | 15         | 1320                       | −11.75                         | 12.47   | 39.37  | 31.39  | 11.7604 |
| November   | 1097.56 | 15         | 1474                       | −20.44                         | 13.93   | 39.52  | 31.16  | 13.1181 |
| December   | 852.439 | 15         | 1187.5                     | −23.45                         | 11.22   | 39.22  | 31.55  | 10.5975 |

Figure 8. Power, efficiency, and FF at a 15° fixed tilt angle, by month.

4.5. Monocrystalline Module Tilted at Variable Angles

To find the irradiance levels at variable tilt angles, maximum irradiance on a horizontal surface (H) in Wh/m²/day and W/m²/day was obtained from the NASA database and used in Equation (1). Table 3 depicts the simulated results obtained for solar irradiance and optimal tilt angles on the 21st day of each month of 2019. Here, the optimal tilt angle for every month was determined for the PV system installed at the university. Using the software, the total solar radiation for tilt angles between 0° and 90° with an interval of 1° was calculated, and the angle with maximum radiation was determined to find the optimal tilt angle. Moreover, the irradiance levels obtained at optimal tilt angles were given to the solar module—a model developed in MATLAB/Simulink using the parameters given in Table 1—to determine the $I_{sc}$, $V_{oc}$, $V_{mp}$ and $I_{mp}$ of the PV module, which are given in Table 6.

Figure 9A,B depict the variation in the tilt angle, fill factor, and efficiency of the PV system throughout the year. It can be seen that the maximum irradiance was obtained from September to March for angles greater than 300°. The irradiance decreased from April to August for angles of 0 to 110°. The average value of irradiance was 1442.342 W/m²/day, and this is greater than the value at a 15° optimal tilt angle.
Table 6. Monthly specific daily global irradiance (H), optimal tilt angle (deg), declination angle of the Earth, irradiance level after tilt, $I_{sc}$, $V_{oc}$, $I_{mp}$, and $V_{mp}$.

| Month    | H-W     | Optimal Tilt Angle | Declination Angle of the Earth | Irradiance Level after Tilt | $I_{sc}$ | $V_{oc}$ | $V_{mp}$ | $I_{mp}$ |
|----------|---------|--------------------|--------------------------------|-----------------------------|----------|---------|---------|---------|
| January  | 913.41  | 57.73              | −20.14                         | 1630                        | 15.4     | 39.7    | 30.94   | 14.477  |
| February | 921.95  | 47                 | −11.23                         | 1310                        | 12.38    | 39.26   | 31.42   | 11.666  |
| March    | 1069.5  | 30.95              | −0.403                         | 1229                        | 11.62    | 39.23   | 31.52   | 10.956  |
| April    | 1148.8  | 10.16              | 11.58                          | 1164                        | 11       | 39.15   | 31.58   | 10.39   |
| May      | 1293.9  | 0                  | 20.14                          | 1294                        | 12.23    | 39.31   | 31.42   | 11.533  |
| June     | 1367.1  | 0                  | 23.45                          | 1367                        | 12.92    | 39.38   | 31.34   | 12.168  |
| July     | 1392.7  | 0                  | 20.44                          | 1392.7                      | 12.57    | 39.35   | 31.36   | 11.852  |
| August   | 1250    | 9.834              | 11.75                          | 1265.8                      | 11.96    | 39.26   | 31.46   | 11.283  |
| September| 1267.1  | 30.62              | −0.2                           | 1452                        | 13.72    | 39.43   | 31.18   | 12.93   |
| October  | 1076.8  | 47.74              | −11.75                         | 1549                        | 14.64    | 39.61   | 31.04   | 13.779  |
| November | 1097.6  | 58.06              | −20.44                         | 1977                        | 18.68    | 39.94   | 30.35   | 17.511  |
| December | 852.44  | 61.197             | −23.45                         | 1677.6                      | 15.85    | 39.73   | 30.85   | 14.9    |

Figure 9. (A) Influence of variable tilt angles on PV power output. (B) Influence of variable tilt angles on efficiency and fill factor.
4.6. Monocrystalline Module Tilted at 29.5 Degrees

To find the irradiance level at a 29.5° tilt angle, maximum irradiance on a horizontal surface (H) in Wh/m²/day and W/m²/day was taken from the NASA database and used in Equation (1). Then, the irradiance level obtained at 29.5° tilt was given to the solar module developed in MATLAB/Simulink using the parameters given in Table 1, to determine the declination angle of the Earth, irradiance level after tilt, Isc, Voc, Imp, and Vmp as mentioned in Table 7.

Table 7. Monthly specific daily global irradiance (H), optimal tilt angle (deg), declination angle of the Earth, irradiance level after tilt, Isc, Voc, Imp, and Vmp.

| Month    | H-W  | Tilt Angle | Irradiance Level after Tilt | Declination Angle of the Earth | Isc  | Voc  | Imp  | Vmp  |
|----------|------|------------|-----------------------------|--------------------------------|------|------|------|------|
| January  | 913.41 | 29.5       | 1447.27                     | −20.14                         | 11.6 | 39.23| 31.52| 10.9429 |
| February | 921.95 | 29.5       | 1253.4                      | −11.23                         | 11.85| 39.26| 31.49| 11.1702 |
| March    | 1069.51| 29.5       | 1229                         | −0.403                         | 11.62| 39.23| 31.52| 10.9559 |
| April    | 1148.78| 29.5       | 1108                         | 11.58                          | 10.47| 39.06| 31.65| 9.89384 |
| May      | 1293.9 | 29.5       | 1102.8                      | 21.14                          | 10.42| 39.08| 31.67| 9.8437 |
| June     | 1367.07| 29.5       | 1109.5                      | 23.45                          | 10.49| 39.05| 31.65| 9.90679 |
| July     | 1392.68| 29.5       | 1182                         | 20.44                          | 11.17| 39.23| 31.57| 10.5445 |
| August   | 1250   | 29.5       | 1202.5                      | 11.75                          | 11.36| 39.17| 31.55| 10.7236 |
| September| 1267.07| 29.5       | 1451.6                      | 0.2                            | 13.71| 39.43| 31.19| 12.9176 |
| October  | 1076.83| 29.5       | 1476.6                      | −11.75                         | 13.95| 39.51| 31.16| 13.1393 |
| November | 1097.56| 29.5       | 1749.5                      | −20.44                         | 16.53| 39.69| 30.73| 15.5301 |
| December | 852.439| 29.5       | 1440.2                      | −23.45                         | 13.61| 39.46| 31.22| 12.8171 |

The efficiency obtained from the PV panel was at its maximum, ranging from 31 to 46%, from September to March. In addition, the obtained fill factor ranged from 0.74 to 0.75. The power output, fill factor, and efficiency of the PV module did not remain constant, but varied each month throughout the year, as shown in Figure 10.

Figure 10 depicts variations in power, efficiency, and FF at an optimal fixed tilt angle of 29.50° for each month, revealing that the panel received irradiance ranging from...
1250 $\text{W/m}^2/\text{day}$ to 1451 $\text{W/m}^2/\text{day}$. These values are greater as compared to the irradiance falling on a panel at a 150° tilt angle. This value was received for the months of September to March. Hence, the 1 MW PV system installed at Sukkur IBA University received maximum irradiance at the angle of 29.50°.

5. Conclusions

The utilization of solar systems has become common due to their major advantages. The key requirement of their use is to attain maximum efficiency from solar collectors. Maximum efficiency can be achieved by installing solar trackers, but unfortunately, these have a high cost. Another feasible solution is to work on the optimal tilt angle to obtain maximum power. The optimal tilt angle is dependent on the declination angle of the Earth and the latitude of the geographical location. Experimental analysis shows that maximum irradiance can be obtained by adjusting the PV surface at a certain angle at regular intervals, with variations in the Sun’s path.

In this paper, a comparative analysis was carried out on different tilt angles to investigate the irradiance using MATLAB/Simulink. The installed system at Sukkur IBA University employs a 15° tilt angle. To determine the optimal tilt angle, the photovoltaic module was varied from 0 to 900 degrees, and for simplification, the data for the 21st day of each month for the year 2019 were selected. The optimal tilt angle for each month was determined on the basis of the maximum irradiance values taken from calculations at different tilt angles. The results were taken at both fixed and variable tilt angles, and it was found that the maximum irradiance can be achieved at 29.5 degrees, as compared to the 15 degrees used at Sukkur IBA University.

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Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| $H_T$        | Total solar radiation received on a tilted surface |
| $H_b$        | Solar beam radiation on a horizontal surface |
| $R_b$        | Tilt coefficient to calculate direct solar direct radiation |
| $H_d$        | Solar diffused radiation on a horizontal surface |
| $R_d$        | Tilt coefficient to calculate solar diffused radiation |
| $H$          | Global solar radiation on a horizontal surface |
| $\rho_g$     | Ground reflectivity coefficient |
| $\beta$      | Tilt angle of the surface |
| $\omega_{ss}$| Sunrise hour angle on a tilted surface |
| $\omega_s$   | Sunrise hour angle on a horizontal surface |
| $\Omega$     | Latitude of the location |
| $\delta$     | Declination angle of the Earth |
| $n$          | Counted number of days |
| $K_T$        | Clearness index |
| $H_o$        | Monthly average daily extraterrestrial radiation |
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