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Research Article

Determining Optimum Tilt Angle for 1 MW Photovoltaic System at Sukkur, Pakistan

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Solar energy is directly converted into electrical energy by using photovoltaic (PV) panels. The efficiency of PV panel varies with its orientation and tilt angle with the horizontal plane. In this paper, we investigate the optimum tilt angle of solar panels installed at Sukkur IBA University. The optimum angle for tilted surfaces varying from 0° to 90° in steps of 1° was calculated for the values of which the daily total solar radiation was maximum for a specific period. It was found that the optimum tilt angle changed between 0° and 61.1° throughout the year in Sukkur IBA University, Sindh Pakistan (latitude = 27.7268° N, longitude = 68.8191° E). For calculating irradiance, optimal fixed (15 and 29.5 degrees) and variable tilt angles are used for every month of year 2019. The irradiance calculated at 15 degrees tilt angle is compared with the fixed angle of 29.5 and variable angles. It was found that optimal tilt angle for the region of Sukkur located in northern Pakistan is to be 29.5 degrees.

1. Introduction

There are two main resources of power, namely, conventional and nonconventional. Nonconventional resources have become popular due to various advantages such as being nonpollutant, fuel free, and nonexhausted [1]. From renewable or nonconventional resources power from solar energy keeps vital role in power sector due to several pros like reliable, economic, environment friendly, and wide availability [2]. Power from solar can be generated from PV modules and thermal process; however, in Pakistan, more focus is on PV modules. It is imperative to check the performance of solar modules which sturdily depends on the solar radiation, tilt angle, and uncontrolled factors such as atmospheric conditions, latitude, season, capacity factor, orientation, and time-of-day [3–9].

A key requirement to achieve maximum power from solar is to avoid the shading effects on solar modules and usage of solar tracking systems. Solar tracking system is the best solution for tracking sunrays to approach the tilt angle continuously, but these trackers are expensive and are not always applicable [10, 11]. Another option is to set the panel with a fixed optimum tilt angle (the angle can be changed in each month or each season manually or have a one tilt angle for the whole year).

Selection of tilt angle has become a hot area research to improve system efficiency. Numerous studies have been carried out to check the performance of PV systems by using different observations, proper diagrams, design, and relationships between different parameters and characteristics related to choosing proper installation site [12–14].

Optimum tilt angle for solar PV system is different due to geographical locations and seasonal variations. The geographical factors include declination angle and data related to solar resources which are important to decide the optimal tilt angle for solar PV system [15].

For determining the optimal tilt angle of solar PV module, it is important to calculate declination angle of the sun and estimation of solar radiation on the tilted surface [16]. Conversely, solar radiation attenuates after entering the atmosphere of the earth due to absorption, scattering by small particles and reflection of objects [17].

Moreover, researchers have also suggested different theoretical models for calculating the optimum tilt angles of several solar collectors and consider a collector with given structural parameters that the latitude of installation site, climate conditions, tilt, and azimuth angles are related to collectible radiations in a year [18, 19].

Sukkur region, located in northern Pakistan, has great solar radiation potential since the number of sunshine is large. Its rural areas face acute power cut off usually 14 to 16 hours per day. So the farmers are resorting to PV systems to cultivate small areas by using drip irrigation method and for other purposes. But due to unavailability of proper data, PV systems are installed in random orientations so they do not get optimal power. Therefore, by employing the analytical and numerical methods, we have found out the optimal angle for PV systems for the given region. This research work will provide local community a way to achieve maximum power output which is bound to give numerous economic benefits.

2. Theory and Work Flow

In this paper, we have calculated and compared irradiance on fixed and variable optimal tilt angle by using MATLAB/Simulink. The fixed angles are 15 degrees and 29.5 degrees. A 15-degree tilt angle is currently used at Sukkur IBA University for PV solar system.

Initially, constant values G_{SC}, φ, ρ_g, and H have been used, and n is set to one which means first day of the year after that surface is tilted from 0 to 90 degrees for given day and obtain the optimum tilt angle at maximum irradiance. Next, n is increased by one and continue to find the optimum tilt angle at given day results and is continued till the value of 365.

Tilt angle is varying from 0 to 90 degrees with one degree step size for accurate results. For finding irradiances, we have gone through the steps to first calculate the δ, ω_s, and ω_{ss}, then Ho, K_T, H_d, H_b, R_d, R_b, and H_T. These factors can be premeditated by the equations given below.

The equation used to calculate the total solar radiation on the tilted surface is given as [20, 21]:

$$H_T = H_b * R_b + H_d * R_d + H * \rho_g * \left(\frac{1 - cos\beta}{2}\right). \quad (1)$$

R_b and R_d in equation (1) are the tilt coefficients to calculate the beam solar radiation and the diffused solar radiation on the tilted surface, respectively. The coefficient can be determined by [20–23] as given in equations (2) and (6):

$$R_b = \frac{(\cos(\varnothing-\beta) * \cos(\delta) * \sin(\omega_{ss})) + (\omega_{ss}(\pi/180)\sin(\varnothing-\beta)\sin(\delta))}{(\cos(\varnothing) * \cos(\delta) * \sin(\omega_s)) + (\omega_s(\pi/180)\sin(\varnothing)\sin(\delta))}, \quad (2)$$

where $P_g$is the ground reflectance/albedo (reflectance of ground = 0.2), β is the optimum tilt angle and it is the angle on which PV panel received maximum amount of solar radiations, Ø is the latitude of Sukkur IBA University (27.7268° N, 68.8191° E), and$\delta$is the declination angle of the earth and can be calculated by:

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

where$\omega_s$is the sunset hour angle, which is equal to:

$$\omega_s = \cos^{-1}[-\tan\delta\ \tan\varphi]. \quad (4)$$

$\omega_{ss}$is the sunrise hour angle of inclined plane and can be calculated as:

$$\omega_{ss} = \min\left[\cos^{-1}(-\tan\delta\tan\varnothing), \cos^{-1}(-\tan(\varnothing-\beta)\tan\varnothing)\right]. \quad (5)$$

Now, the tilt coefficient diffuse solar radiation on the tilted surface can be calculated as:

$$R_d = \frac{H_b}{H_\circ} * R_b + \left(1 - \frac{H_b}{H_\circ}\right) * \left(1 + \frac{\cos\beta}{2}\right) * \left[1 + \sqrt{\frac{H_b}{H}} * \sin\left(\frac{\beta}{2}\right)^3\right], \quad (6)$$

where$H_b$is the beam direct radiation incident angle equals to:

$$H_b = H - H_d. \quad (7)$$

Here,$H$is the global solar radiations at horizontal surface.

The data related to global solar radiations on horizontal surface is taken from NASA database.

H_d is the solar diffused radiations at horizontal surface which is applicable for any location within latitude 40° N and 40° S and calculated by [24, 25]:

$$H_d = 1.00 - 1.13K_T, \quad (8)$$

where$K_T$is the clearness index.

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the earth. And it can be calculated from equation (9):

$$K_T = \frac{H}{H_o}. \quad (9)$$

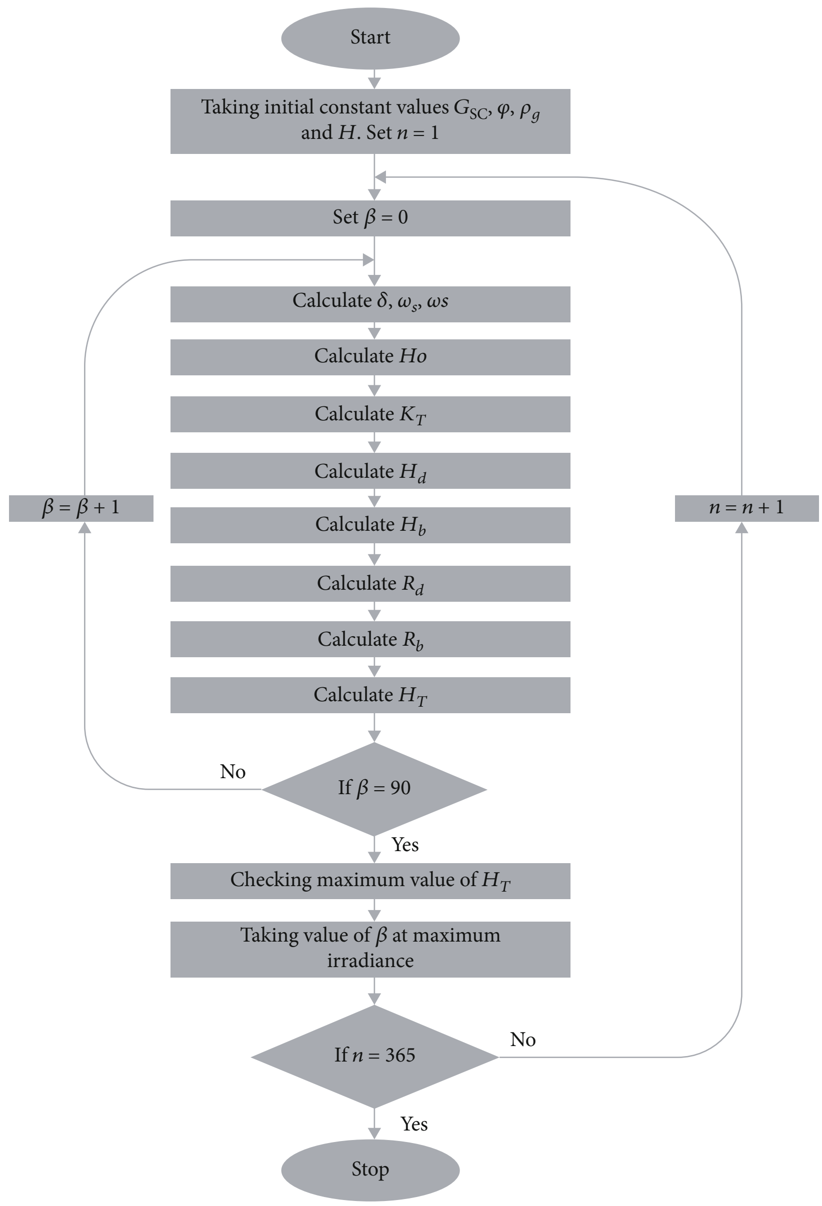

Figure 1: Flowchart for finding optimal tilt angle.

H and H_o in equation (9) are global solar radiations on horizontal surface and monthly average daily extraterrestrial radiation (kwh/m^2/day) and can be calculated by:

$$H_o = \frac{24}{\pi} G_{sc}\left(1 + 0.33\ \cos\frac{360\,n}{365}\right) \cdot \left(\cos\varnothing\cos\delta\ \sin\omega_s + \frac{\pi\omega_s}{180}\ \sin\varphi\ \sin\delta\right). \quad (10)$$

G_{sc} in equation (10) is the solar constant referred as 1353 W/m^2 [24]. Other parameters are taken as constant values.

Using equations from (1) to (10), we can now easily calculate the irradiance at different supposed tilted angles. The procedure for finding optimum tilt angle is shown in flow chart in Figure 1.

3. Results and Discussion

Through mathematical modeling as discussed in Section 3, irradiance level on solar panel is calculated at 15° tilt angle, 29.5 degree, and variable tilt angles on every 21st of the every month of 2019. A 15-degree angle is used at Sukkur IBA University. We are going to check the declination angle and irradiance at different angles to compare the results.

3.1. Surface Tilted at 15 Degrees. The input data for finding maximum irradiance on solar panel are global solar radiations on horizontal surface (H) in Wh/m^2/day and W/m^2/day carried from NASA database as shown in Table 1.

Table 1: Monthly specific daily global irradiance (H), year days, days of the month, tilt angle (deg), irradiance level after tilt, and declination angle of the earth.

H-Wh/m^2/day	H-W/m^2/day	Year day	Month day	Tilt angle (deg)	Irradiance level after tilt	Declination angle of earth
7490	913	21	21 Jan	15	1222	-20.14
7560	921	52	21 Feb	15	1125	-11.23
8770	1069	80	21 Mar	15	1186	-0.403
9420	1148	111	21 Apr	15	1161	11.58
10610	1293	141	21 May	15	1227.6	20.14
11210	1367	172	21 Jun	15	1265.5	23.45
11420	1392	202	21 Jul	15	1319	20.44
10250	1250	233	21 Aug	15	1261.5	11.75
10390	1267	264	21 Sep	15	1403	-0.2
8830	1076	294	21 Oct	15	1320	-11.75
9000	1097	325	21 Nov	15	1474	-20.44
6990	852	355	21 Dec	15	1187.5	-23.45

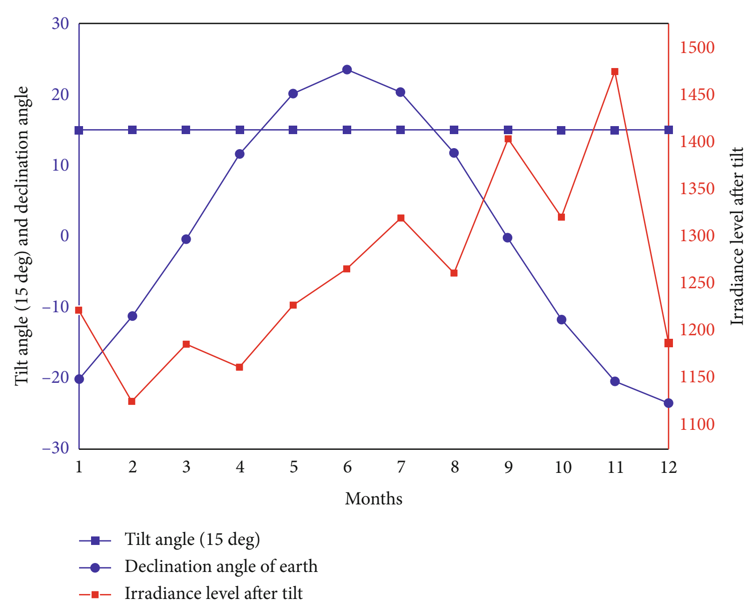

Figure 2: Specific monthly irradiance on fixed tilt angle (15 deg) and declination angle vs. months.

After putting this input data in equations, we have calculated declination angle and irradiance at fixed optimal tilt angle using MATLAB/Simulink model. The value of irradiance is maximum 1474 W/m^2/day in November and minimum 1125 W/m^2/day in February. The average value of irradiance throughout the year will be 1262.675 W/m^2/day. The irradiance is not constant in every month throughout the year, but it is varying as shown in Figure 2.

The graph shows that solar PV module is fixed at tilt angle of 15° where it has received irradiance between 1300 w/m^2/day and 1474 w/m^2/day in 4 months, between 1200 w/m^2/day and 1300 w/m^2/day for 3 months, and 1100 w/m^2/day and 1200 w/m^2/day for 5 months in year 2019. 15° tilt angle is optimal for months (Oct–Feb) referring to Table 1. For input irradiance in these months, the output of tiled surface is high, but in Sukkur region, the maximum irradiance received in months from Apr to Sep. So 15° tilt angle is not optimal for Sukkur region. As shown in Figure 2, the irradiance level is varied because of change in declination angle.

3.2. Surface Tilted at Variable Angles. The input data is used to find the irradiance and declination angle at different variable angles. The results achieved from calculations are shown in Table 2.

Table 2 shows the simulated results of solar irradiance and optimal tilt angles of every 21st of the every month of 2019. Monthly optimal tilt angle of solar photovoltaic of Sukkur IBA University was calculated. In the program, the total solar radiation for tilt angles between 0° and 90° with an interval of 1° is calculated, and the angle with maximum radiations is determined to find optimum tilt angle. The data in Table 2 is plotted in Figure 3, which shows the variable tilt angles of solar panel over the year.

Table 2: Monthly specific daily global irradiance (H), year days, days of the month, tilt angle (deg), irradiance level after tilt, and declination angle of the earth.

H-Wh/m^2/day	H-W/m^2/day	Year day	Month day	Optimum tilt angle (deg)	Irradiance level after tilt	Declination angle of earth
7490	913	21	21 Jan	57.73	1630	-20.14
7560	921	52	21 Feb	47	1310	-11.23
8770	1069	80	21 Mar	30.95	1229	-0.403
9420	1148	111	21 Apr	10.16	1164	11.58
10610	1293	141	21 May	0	1294	20.14
11210	1367	172	21 Jun	0	1367	23.45
11420	1392	202	21 Jul	0	1392.7	20.44
10250	1250	233	21 Aug	9.834	1265.8	11.75
10390	1267	264	21 Sep	30.62	1452	-0.2
8830	1076	294	21 Oct	47.74	1549	-11.75
9000	1097	325	21 Nov	58.06	1977	-20.44
6990	852	355	21 Dec	61.19	1677.6	-23.45

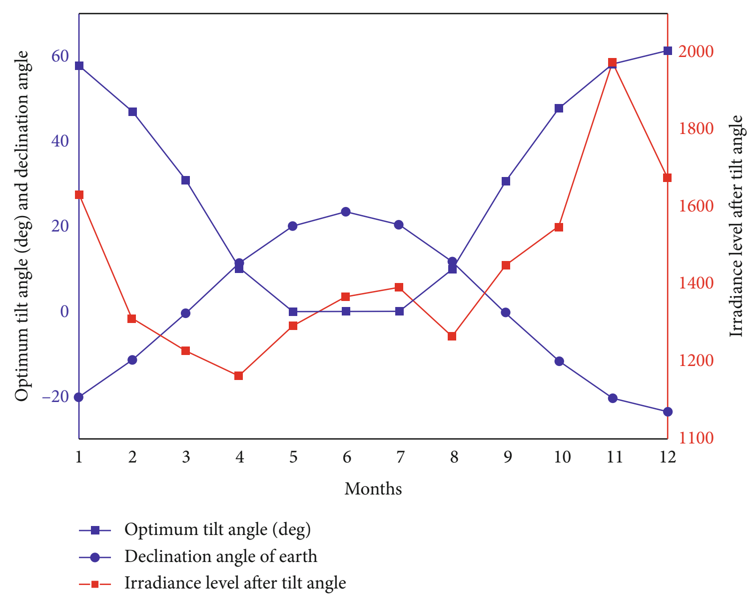

Figure 3: Specific monthly irradiance on variable optimal tilt angle and declination angle versus months.

Table 3: Monthly specific daily global irradiance (H), year days, days of the month, tilt angle (deg), irradiance level after tilt, and declination angle of the earth.

H-Wh/m^2/day	H-W/m^2/day	Year day	Month day	Tilt angle (deg)	Irradiance level after tilt	Declination angle of earth
7490	913	21	21 Jan	29.5	1447.27	-20.14
7560	921	52	21 Feb	29.5	1253.4	-11.23
8770	1069	80	21 Mar	29.5	1229	-0.403
9420	1148	111	21 Apr	29.5	1108	11.58
10610	1293	141	21 May	29.5	1102.8	20.14
11210	1367	172	21 Jun	29.5	1109.5	23.45
11420	1392	202	21 Jul	29.5	1182	20.44
10250	1250	233	21 Aug	29.5	1202.5	11.75
10390	1267	264	21 Sep	29.5	1451.6	-0.2
8830	1076	294	21 Oct	29.5	1476.6	-11.75
9000	1097	325	21 Nov	29.5	1749.5	-20.44
6990	852	355	21 Dec	29.5	1440.2	-23.45

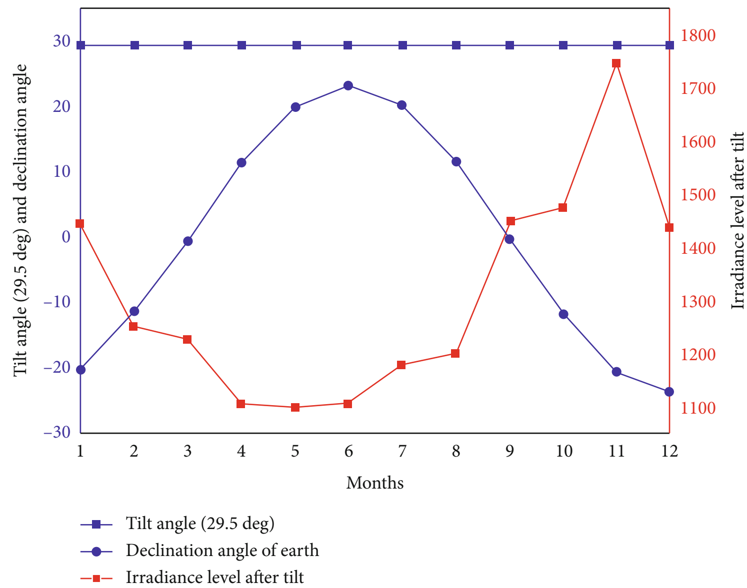

Figure 4: Specific monthly irradiance on optimal fixed tilt angle (29.5 deg) and declination angle versus months.

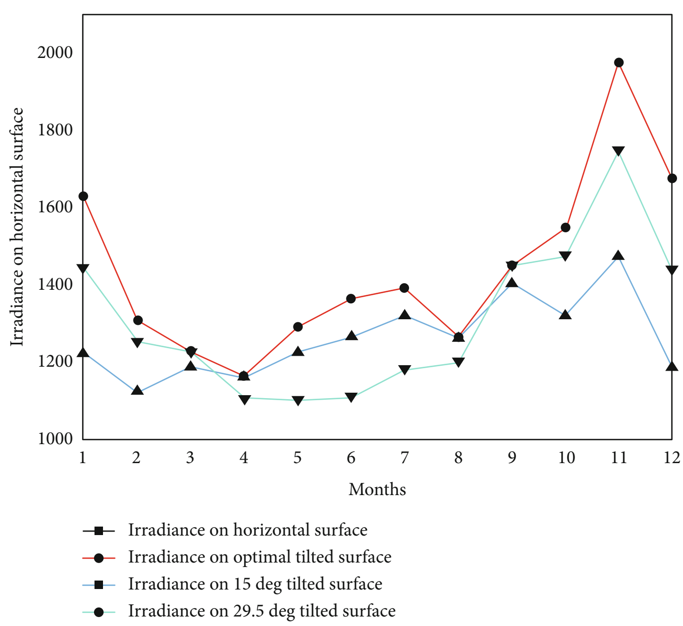

Figure 5: Comparison of irradiance on different tilt angles.

Solar panel with small input global solar irradiance on horizontal surface between 7000 and 9000 Wh/m^2/day received maximum amount of irradiance between 1200 w/m^2/day and 1977 W/m^2/day on tilt angle of 30° or above in the month from September to March. It is actually getting maximum irradiance for seven months at an angle 30° or above. The value of irradiance is found to decrease from April to August at an angle of 0 to 11 degrees, and the average value of irradiance is 1442.342 W/m^2/day. This value of irradiance is greater than the value at 15 degrees optimal tilt angle.

3.3. Surface Tilted at 29.5 Degrees. We have taken a fixed optimal tilt angle of 29.5 degrees to check the irradiance. The value is actually taken as the average value of all variable angles to see the irradiance level. The results of irradiance and declination angle are shown in Table 3.

From Table 3, it is shown that the maximum value of irradiance is 1749.5 in the month of November. The minimum value is 1102.08 in the month of May. The average value of irradiance throughout the year is 1312.698 W/m^2/day. The data of Table 3 is plotted in Figure 4.

Figure 4 shows that solar PV module is fixed at tilt angle of 29.5° that is the suggested angle to Sukkur IBA University, at 29.5° tilt angle solar panel with small input global solar irradiance on horizontal surface between 7000 and 9000 Wh/m^2/day received maximum amount of irradiance between 1250 w/m^2/day and 1451 w/m^2/day which are greater than irradiance received on solar panel at 15° tilt angle. This value is receiving from September to March. Means solar panel received 7 months out of 12 months maximum irradiance at an angle 29.5°.

3.4. Comparison of Irradiance on Different Tilt Angles. After receiving irradiance at fixed and variable angles, we have get our results. The results at all conditions are compared as shown in Figure 5. At 15 degrees tilted angle, the irradiance is approximately same as in the first four months, then slightly increases for three months and finally reaches at maximum value in the month of November. If we compare irradiance level of 29.5 degrees with 15 degrees, then in first four months, the irradiance value is greater, and then, from 5th to 8th month, it is decreased. However, average value of irradiance will be greater than 15 degrees value. On variable tilted angle case, we have received maximum value of 1977 w/m^2/day in the month of November. Although this value is greater than 15 degree and 29.5 degree values, yet it is impossible to practically use variable optimal tilt angle.

After comparison from all results, we are suggesting to use optimal tilt angle of 29.5 degrees to get the maximum irradiance value.

4. Conclusion

In this paper, an analytical and numerical analysis has been carried out on different tilt angles to check the irradiance by using MATLAB/Simulink. A 15-degree tilt angle is used at Sukkur IBA University for solar system of 1 MW. For finding optimum tilt angle, the PV module is tilted from 0 to 90 degrees, where the value of H is obtained from NASA database, and for simplification, the data is taken at 21st of every month of year 2019. The optimal tilt angle of each month is decided on the maximum value of irradiance taken from calculations at different tilt angles.

The results are taken at both fixed and variable tilt angles which shows that maximum irradiance can be achieved at 29.5 degrees as compared to 15 degrees used at Sukkur IBA University.

The method employed in this paper can also be used for installing the PV systems in other locations so as to obtain maximum power from system.

Nomenclature

H_T: Total solar radiations received on tilted surface
H_b: Solar beam radiations on horizontal surface
R_b: Tilt coefficient to calculate direct solar direct radiations
H_d: Solar diffused radiations on horizontal surface
R_d: Tilt coefficient to calculate solar diffused radiations
H: Global solar radiations on horizontal surface
ρ_g: Ground reflectivity coefficient
β: Tilt angle of surface
ω_{ss}: Sunrise hour angle on tilted surface
ω_s: Sunrise hour angle on horizontal surface
$\varnothing$: Latitude of the place
δ: Declination angle of the earth
n: Counted number of days
K_T: Clearness index
H_o: Monthly average daily extraterrestrial radiation.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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