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Optimal Tilt Angle and Spacing for Rooftop Solar PV System in Hot Humid Climate-A Case Study

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Abstract:
Solar energy received by a PV surface depends on the incidence angle of the sun rays on it. The solar angle changes with time of the day, day of the year and installed location of the PV arrays. The PV modules of the array must be placed perpendicular to the sun so as to receive maximum irradiance. In absence of such placement, the PV system may exhibits mediocre performance. So, it is therefore required to install the PV modules at an optimum tilt. The performance of PV array is also susceptible to shadow problems as well. In this paper, the installation aspects of PV systems such as positioning of PV arrays with respect to tilt angle and separation criteria of their rows to mitigate the horizontal shadow effect is presented. Whenever, the PV arrays are installed, it is to be fixed at an appropriate tilt angle so as to receive maximum irradiance. The separation of the rows of arrays was done so as to make it shadow free. The optimum tilt angle and spacing was found out and validated by a prototype site installation for a 11.2 kWp solar photovoltaic system at SOA, Bhubaneswar, India and the monthly, seasonally and annually optimum tilts, solar flux gain and energy yield are found out for this location. The maximum solar flux gain of 32.97% is found in the month of December having GSR of 4.72 kWh/m^2/day at an optimum tilt of 40^0 and minimum solar flux gain is in the month of July, August and September. The shading is also increased in summer (May, June, July, and August) by the tilt adjustment which causes cooling.

Keywords:*Tilt angle; solar irradiance; spacing; power generation*.

I. INTRODUCTION

The increasing energy demand in domestic and industrial sector is forcing the conventional generations to exceed their generation capacities that lead to huge rise in pollutants in the environment. The world's energy demand from conventional sources such as coal can be reduced by solar energy that can be the perfect solution to reduce pollutants causing greenhouse effect in the environment. Solar energy that is available abundantly in earth surface can be the perfect solution to meet the energy crisis of the whole world. In India, more than 90% of the regions receive an average solar insolation of 3.0-6.5 kWh/m^2/day i.e. 10.8-23.4 MJ/m^2/day during summer [1]. However, during the month of May, some parts of northern India receive a solar insolation up to 7.5 kWh/m^2/day i.e. 27 MJ/m^2/day [2]. The potential of the solar irradiance has been used for various purposes such as solar thermal, solar cooker, solar water heating, solar photovoltaic (PV), day lighting, heating of buildings and crop drying. In past, many researches have been done in order to extract maximum irradiance from sun for utilization. The most prominent source for the use of solar irradiance is solar photovoltaic (PV) in which the irradiance of sun is converted into electricity by the principle of photoelectric effect. The power generation from PV systems depends on the amount of solar irradiance incident on its surface i.e. more the irradiance received by the PV surface; more will be the power generation. The performance of the PV system gets highly influenced by its orientation, location, climatology, latitude, tilt angle, geographical region, azimuth angle and proper positioning [3]. The power generation from the PV system also gets affected due to various shading

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conditions and can be mitigated using various topologies [4]. Tilt angle (β) is one of the major constituent of PV system that decides the amount of solar irradiance received by the PV surface. The performance of PV system can be enhanced by employing solar tacking equipment that tracks the trajectory of sun's motion in order to receive maximum solar irradiance on the surface [5, 6]. Solar tracking equipment requires either servo motors or manual adjustment of the angle of PV surface according to sun's position. However, these are not economical as the tilt angle of PV surface varies every hour, season and month. It has been investigated that the inclined tracking system almost requires 350% more area (6.94 ha) whereas two axis tracking system requires 550% more area (4.81 ha) as compared to a PV plant having static PV modules that requires an area of 1.08 ha [7]. Also, automatic solar trackers have servo motors that require energy for its operation that is in the range of 6-12 % of the total energy produced [8]. The motors also require periodic maintenance and replacement that adds cost to the system. Also, the tracker consists of complicated moving parts that increase the capital cost of system and adds to cost of final energy produced from PV system [9]. Various methods have been suggested by researchers to optimize the orientation of flat surfaces at optimum tilt inclination (β_{opt}) [3]. The performance of PV system with sun tracking system has been studied experimentally in the literature [10]. It has been found that there is a slight average gain in power generated by PV system with sun tracker as compared to PV system without sun tracker. In another literature, it has been found that, the weekly adjustment of horizontal axis and continuous adjustment of vertical axis for tracking system even produced a slightly more energy as compared to existing PV system at fix tilt angle [6]. For maximizing the performance of PV system, the tilt angle can be adjusted every hour, month, season, bi-annually and annually [8]. In general, the surface orientation of PV systems of northern hemisphere is kept at due south i.e. $\gamma=0^o$and southern hemisphere are kept at due north titled at certain angle in order to receive maximum solar irradiance throughout the year where 'γ' is the surface azimuth angle. It has been investigated that the value of optimum tilt angle (β_{opt}) depends upon the latitude (ϕ) and azimuth (β) [9-10].. It has been found that by adjusting the azimuth angle of 10-20^o and keeping the tilt angle of the system equal to the latitude of the location, maximum solar irradiance can be tracked [3]. But, these techniques are not reliable as the values could differ from the actual values. The optimum tilt angles estimation for India using Liu & Jordan model has been proposed in literature [8,10]. It has been found that the optimum yearly tilt angle is approximately equals to the latitude of the location. It has been suggested by the authors that, the optimum tilt angle during summer should be (ϕ-16^o) and (ϕ+19^o) during winter. The comparison between measured solar irradiance data and different anisotropic and isotopic models for solar irradiance estimation on inclined surface for city Bhopal, India (23^{o}17'N, 77^{o}36'E) has been done in the literature [12]. The authors concluded that for best solar irradiance estimation on inclined plane with least statistical errors, Badescu model is most appropriate. The statistical analysis and comparison of diffused solar irradiance on tilted surface using various models for the city Lucknow, India (26.75^{o}N, 80.50^{o}E) has been performed in literature [13, 14]. The authors concluded that for best estimation of solar irradiance, Klucher's model is most appropriate. It has been studied in various literatures that the most widely used approach for estimating solar irradiance of a location is Liu & Jordan isotropic model. The estimation of solar radiation and optimal tilt angles for south facing surfaces in humid subtropical climatic region of India has been done in literature [12]. In India, most of the PV arrays are oriented in the flat roof of the building and place in such a way that they can receive maximum insolation to generate maximum energy throughout the year. Mutual shading between PV modules or arrays can result in decreased power output but this effect is less taken into account and hardly has very less number of approaches to solve this effect [16].

The effect of mutual shading is mostly estimated than calculated and is treated as one of the important parameter for power loss up to 15% over the year in PV system [13-16].The effect of mutual shading strongly depends on the layout of the PV modules or arrays and the system such as series/ parallel connection, placement of bypass diodes, etc. In this paper, the optimal tilt angle for various months and seasons has been calculated for Bhubaneswar, India using mathematical approach in MATLAB programming. The annual tilt angle for the city has been found out so that the PV modules or arrays installed in the city can receive maximum solar irradiance throughout year to generate maximum power. The optimum spacing between two PV modules or arrays has been proposed so as to reduce the effect of mutual shading. The above mentioned approaches have been validated by a prototype rooftop installation of PV system.

Nomenclature

γ	Surface Azimuth Angle (in degree)	β_{opt}	Optimum Tilt Angle (in degree)
β	Tilt Angle (in degree)	ϕ	Latitude of the location (in degree)
δ	Declination Angle (in degree)	ω	Angular displacement of the Sun
θ	Solar angle of incidence	I_T	Tilt Factor
I_b	Component of Beam Radiation	I_d	Component of Diffused Radiation
I_{pg}	Component of Ground Diffused Radiation	R_b	Geometric factor
l	Length of PV module	h	Height of PV module
S	Spacing between PV modules	P_M	Maximum Power
V_{OC}	Open Circuit Voltage	I_{SC}	Short Circuit Current
V_M	Maximum Voltage	I_M	Maximum Current
S	Spacing between PV modules or array	F_{ST}	

1.1. Location under Study

Bhubaneswar is a well-known and fastest growing smart city of India having 20.2961^O N latitude and 85.8245^O N longitude and is geographical well-situated for solar energy potential. Bhubaneswar receives an average global solar radiation (GSR) of 5-5.5 kWh/m^2/day as . The city receives a good amount of solar insolation with highest during the month of April (6.2 kWh/m^2/day) and lowest during the month of August (3.8 kWh/m^2/day).

Table 1- Monthly variation of GSR and declination angle (δ) of Bhubaneswar

Sl No.	Month	Representative Days Number	GSR of respective days	Declination angle (δ) (in degree)
1	January	17 (17th)	3.7	-20.9170
2	February	47 (16th)	4.17	-12.9546
3	March	75 (16th)	4.84	-2.4177
4	April	105 (15th)	4.93	9.4149
5	May	135 (15th)	4.28	18.7919
6	June	162 (11th)	3.43	23.0859
7	July	198 (17th)	2.94	21.1837
8	August	229 (17th)	3.81	13.1224
9	September	258 (15th)	3.43	2.2169
10	October	288 (15th)	3.73	-9.5944
11	November	318 (14th)	3.66	-18.9120
12	December	344 (10th)	3.43	-23.0496

Table 1 represents the monthly variation of GSR and calculated declination angle (δ) on horizontal plane of Bhubaneswar.

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II. FORMULATIONS

In this section, a model is presented in which the PV modules are kept facing towards south and the ratio of beam radiation flux falling on a tilted surface to that on a horizontal surface is defined as the tilt angle of beam radiation.

The solar angle of incidence on surface can be calculated by using the equation given below [14].

$$\cos\theta = \cos\delta\cos\omega(\cos\gamma\sin\beta\sin\phi + \cos\phi\cos\beta) + \sin\delta(\sin\phi\cos\beta - \cos\gamma\cos\phi\sin\beta) + \sin\gamma\sin\beta\cos\beta\sin\omega \quad (1)$$

Or

$$\theta = \cos^{-1}(\cos\delta\cos\omega(\cos\gamma\sin\beta\sin\phi + \cos\phi\cos\beta) + \sin\delta(\sin\phi\cos\beta - \cos\gamma\cos\phi\sin\beta) + \sin\gamma\sin\beta\cos\beta\sin\omega) \quad (2)$$

Where 'θ' is the solar angle of incidence; 'δ' is the declination angle; 'ω' is the angular displacement of sun; 'γ' is the surface azimuth angle; 'ϕ' is the latitude of the location; and 'β' is the tilt angle.

The solar irradiance available on horizontal surface can be converted into the irradiance on a surface inclined at an angle 'β' using a factor known as tilt factor can be multiplied into the irradiance on a horizontal surface to get the irradiance on the inclined surface.

Simple formulae for Solar Radiation for a tilted surface is as follows

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (3)$$

Where I_b, I_d and $I_{\rho g}$ are as the component beam radiation, diffused radiation and ground diffused radiation, I_T is the total radiation and R_b is the geometric factor.

$\left(\frac{1+\cos\beta}{2}\right)$ is the look angle of the collector to the sky radiation / intercept factor of the sky dome with collector.

$\left(\frac{1-\cos\beta}{2}\right)$ is the look angle of the collector for symmetrically ground reflected solar radiation.

The last two terms in the above expression (3) are neglected, as the diffuse component of solar radiation is too small as compared to Solar Global Radiation during on an average 300 days of the year. The geometric factor /tilt factor (R_b) is given by

$$R_b = \frac{\cos\theta_{at\,\beta}}{\cos\theta_{at\,\beta=0}} \quad (4)$$

For finding out the radiation on a tilt plane, the GSR is multiply with the geometric factor.

For, $\cos\theta$ at β =0:2.5:50, ϕ=20.2961° (Latitude of Bhubaneswar), ϒ=0, β=0, ω=0. Global solar radiation (GSR) is the sum of direct, diffuses, and reflected solar radiation. Direct solar radiation passes directly through the atmosphere to the earth's surface, diffuse solar radiation is scattered in atmosphere, and reflected solar radiation reaches a surface and is reflected to adjacent surfaces. So the tilt factor for the GSR may approximated by the beam radiation tilt factor. Hence the geometric separation of panels is shown in Figure 2.

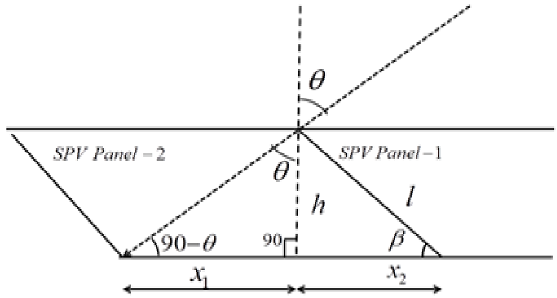

Figure 2. Geometrical separation of panels

The desired separation between the rows of the panel has been shown in Figure 2 and can be expressed as

$$S = x_1 + x_2$$

$$S = l\cos\beta + l\sin\beta\tan\theta \quad (5)$$

Where 'θ' is the angle of incidence;'h' is height of panel;'l'is length of panel; and 'S' is the shadow/spacing.

III. Solar Flux Gain Annually, on Monthly Tilted Plane and Seasonally Tilted Plane

Mean of Global Solar Radiation (MGSR) is given by,

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$$\text{MGSR}(F) = \sum_{i=1}^{n} X_i$$

Where X_i refers to the Global Solar Radiation (GSR) of months (January to December) / Seasons (summer, winter, Equinox) at the optimum tilt angle and fixed tilt angle.

Solar Flux Gain (SFG) in Percentage is given by,

$$SFG = \frac{(F_{OT} - F_{FT})}{F_{FT}} \times 100 \quad (7)$$

Where F_{OT} & F_{FT} stands for optimum tilt angle and fixed tilt

IV. SYSTEM SETUP(6)

The tilt angle for different months, seasons and annual has been calculated for the city Bhubaneswar. The results are validated using a hardware installation of 11.2 kWp Solar PV system at the roof of the E-Block, ITER, Siksha 'O' Anusandhan Deemed to be University, Bhubaneswar. The spacing between the PV arrays to avoid mutual shading has been calculated for the installed PV system. The setup of the roof top based 11.2 kWp PV system has been shown in Figure 3.

Figure 3. Setup of roof top based 11.2 kW PV system at SOA

The system has been kept fixed at a tilt angle and the spacing has been done from the calculated values of the mathematical model given in Section 2. The system consists of twenty series connected PV modules to form a string and two such strings are connected in parallel to produce power of 11.2 kWp. The specification of the PV modules connected in the system has been given in Table 2.

Table 2: Specification of pv module at stc (1000w/m^2 and 25^{o}c)

Parameters	**Rating**
Rated Peak Power (P_{max})	280 W
Open Circuit Voltage (V_{OC})	43 V
Short Circuit Current (I_{SC})	8.68 A
Voltage at MPP (V_{MP})	35 V
Current at MPP (I_{MP})	8 A
Number of series connected PV modules	20
Number of parallel connected strings	2

Table 3 Dimensions of pv modules and array

Parameter	**Dimension**
Length of the PV module	99 cm
Height of the PV module	196 cm
Length of the PV string	2000 cm
Height of the PV string	196 cm

The total area of the installed PV system is given by with fixed tilt angle of 22.5^0 is 101 square metre.

V. RESULTS AND DISCUSSIONS

5.1. Optimum Tilt angle

The tilt angles at which the PV modules/strings must be oriented to receive maximum solar irradiance throughout the year are function of solar angle and geometrical parameters of the PV modules/string that depends on the time of day, month of year and location. In this paper, the tilt

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angles are computed as a function of months, season and annual mean which corresponds to

- Monthly adjustment of tilt angle;
- Fixed tilt angle (annually).

5.1.1. Monthly adjustment of tilt angle

The simulated graph between tilt angle (β) and GSR on tilted plane for all the month of a year. It has been found that when β is kept at optimum tilt angle and the GSR on tilted plane is calculated from figure 4. (a) to figure (l).

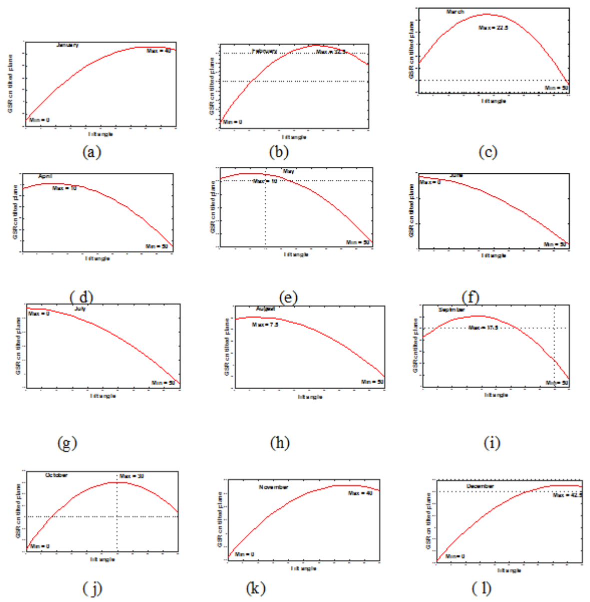

Figure 4. Effect of variation of tilt angle on mean GSR for different months of a year. (a) January (b) February (c) March (d) April (e) May (f) June (g) July (h) August (i) September (j) October (k) November and (l) December.

Table 4. Percentage of Annual Solar Flux Gain at Horizontal Plane and Optimum Tilted Plane.

Sl. No	**Month**	**GSR on Horizontal Plane**	**Monthly Optimum Tilt angle**	**GSR on Optimum Tilted Angle**	**Solar Flux Gain in %**
1.	January	3.7	40^{o}	4.92	32.97
2.	February	4.17	32.5^{o}	4.98	19.42
3.	March	4.84	22.5^{o}	5.25	8.47
4.	April	4.93	10^{o}	5.01	1.62
5.	May	4.28	10^{o}	4.51	5.37
6.	June	3.43	0^{o}	3.43	0
7.	July	2.94	0^{o}	2.94	0
8.	August	3.81	7.5^{o}	3.81	0
9.	September	3.43	17.7^{o}	3.61	5.24
10.	October	3.73	30^{o}	4.30	15.28
11.	November	3.66	42.5^{o}	4.72	28.96
12	December	3.43	40^{o}	4.72	37.60

Table 5. Percentage of Annual Solar Flux Gain at horizontal plane and Fixed Tilted plane.

Sl. No	**Month**	**GSR on Horizontal Plane**	**GSR on Fixed Tilted Angle(22.5^{0})**	**Solar Flux Gain in %**
1.	January	3.7	4.65	25.67
2.	February	4.17	4.89	17.26
3.	March	4.84	5.24	8.26
4.	April	4.93	4.91	-0.40
5.	May	4.28	4.41	3.03
6.	June	3.43	3.10	-9.62
7.	July	2.94	2.7	-8.16
8.	August	3.81	3.70	-2.88
9.	September	3.43	3.6	4.95
10.	October	3.73	4.26	14.20
11.	November	3.66	4.52	23.49
12	December	3.43	4.40	28.27

Table 6. Percentage of Annual Solar Flux Gain at Fixed Plane and Optimum Tilted Plane.

SL NO	**Month**	**GSR on Fixed Tilted Angle(22.5^{0})**	**GSR on Optimum Tilted Angle**	**Solar Flux Gain in %**
1	January	4.65	4.92	5.80
2	February	4.89	4.98	1.84

3	March	5.24	5.25	0.19
4	April	4.91	5.01	2.03
5	May	4.41	4.51	2.27
6	June	3.10	3.43	10.64
7	July	2.7	2.94	8.89
8	August	3.70	3.81	2.97
9	September	3.6	3.61	0.28
10	October	4.26	4.30	0.94
11	November	4.52	4.72	4.42
12	December	4.40	4.72	7.27

5.1.2 Fixed tilt angle (annually)

The simulated graph between tilt angle (β) and GSR on a fixed tilted plane for all month of a year. It has been found that when β is kept fix, the tilt angle and the GSR on tilted plane is calculated.

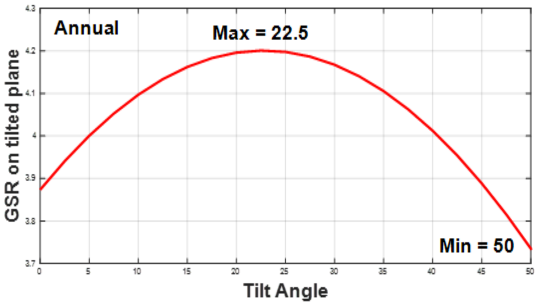

Figure 5. Annual fixed optimum tilt on mean GSR

From the simulated calculations using the formulations given , it has been found that, for Bhubaneswar, the optimum fixed tilt angle at which PV surface receives maximum GSR i.e. 4.20 kWh/m^2/day is 22.5^o [47].

5.2. Optimum Spacing for PV modules/strings

In this section, the optimal spacing that should be to maintain between the PV modules/strings in order to avoid mutual shadowing has been found out. The spacing for 11.2 kWp on-grid systems has been calculated that has been installed at a fixed tilt angle. The spacing also represents the length of shadow of PV modules at a particular time period. The maximum shadow length of the PV modules for different months has been calculated and the spacing has been done with respect to the maximum shadow length. Table 7 represents the maximum shadow length of the PV modules of 11.2 kWp systems in every month.

5.3 Shadow Formation Seasonal Adjustment of Array

The percentage of shadow found in monthly, seasonally and annually adjustment of arrays is given by

$$S = \left(\frac{S_i - S_j}{S_j} \right) \times 100 \qquad (8)$$

Where S is the percent of shading, S_i shading due to the optimum tilt angle and S_j is the Shading due to the fixed tilt angle of SPV arrays.

Table 7: Maximum Shadow Length of PV Modules/String of 11.2 kWp System

Sl. No	Month	Shadow Length/ Spacing (in cm) at optimum tilt (S_i)	Shadow Length/ Spacing (in cm) at fixed tilt (S_j)	Shading (%)
1	January	260.5	246.77	5.56
2	February	234.35	230.26	1.77
3	March	212.48	212.48	0
4	April	199.56	195.50	2.07
5	May	193.92	183.05	5.94
6	June	196	177.42	10.47
7	July	196	179.92	8.94
8	August	197.54	190.52	3.68
9	September	206.17	205.57	0.29
10	October	226.08	224.20	0.84
11	November	252.92	242.27	4.39
12	December	269.49	251.87	6.99

It has been found that at 22.5^{o} fixed tilt angle throughout the year, the PV system encountered maximum shadow length (269.45 cm) during December. So, the optimal spacing between the PV strings must be of at least 269.45 cm

Table 8 Electrical energy yield in all months of the year

SL NO	Month	Energy Yield in kWh
1	January	1339.28
2	February	1376.09
3	March	1614.53
4	April	1462.86
5	May	1491.99
6	June	1141.41
7	July	1044.62
8	August	1202.04
9	September	1143.65
10	October	1336.38
11	November	1290.03
12	December	891.58

Table 8. Represents, the power generated by the 11.2 kWp PV system in representative day of every month of year recorded using Wattmon and Delta Solivia Monitor 2.0 software.

The 11.2 kWp on-grid systems studied in this paper is oriented at a fixed tilt angle of 22.5^{o} according to the computational results and has been calculated using equation 4. The 22.5^{o} is optimal tilt angle of the installed location i.e. Bhubaneswar. The voltage generated by the 11.2 kWp systems has been recorded every hour using a device named Wattmon. The system setup has recorded all power generated by the PV system by Wattmon using software named as Delta Solivia Monitor 2.0 from January to December.

VI. CONCLUSION

The inclination of the PV system can be adjusted in order to improve the GSR received by the surface and also enhancing the power generation. As Sun's position changes, so the optimum tilt angle of every month differs. In this paper, an estimation of monthly and annual optimum tilt angles for Bhubaneswar (capital smart city of Odisha, India) has been performed. The spacing between the PV modules/strings has been estimated in order to avoid the condition of mutual shading and spacing conditioning. The optimum tilt angle and spacing has been used for installation of an 11.2 kWp on-grid PV system. The following conclusions have been drawn:

1. If the Solar Photovoltaic Panels are adjusted to monthly optimum tilt angle, the GSR increased and Solar Flux Gain increased by 13 percent annually comparing with horizontally placing and fixed tilt (22.5^{0}).
2. If the solar photovoltaic panels placed horizontally then the solar flux gain will be 4% annually.
3. The annual optimum tilt angle (β_{opt}) for Bhubaneswar is 22.5^{o}, which is nearly equal to the latitude (20.29^{0}) of the location and the solar flux gain is around 9 percent annually.
4. The spacing to be maintained between the PV modules/strings strongly depends on the shadow length that changes with time of the day and length of the PV modules used in the system. The spacing between PV modules/strings should be more than the maximum shadow length. The spacing for the 11.2 kWp system installed in Bhubaneswar is 251.8 cm because it fixed .But if it is adjusted monthly the shading increased in months like May, June, July, August which will work as space conditioning in summer season i.e. it will keep the building cool and power generation increased. The area requires for the fixed tilt and optimum tilt is 101 square metre and 108 square metre respectively. So the more area required for installing in optimum tilt is 7 square metre.
5. The energy yield for whole year is given by 15335 kWh because it is placed in fixed tilt angle but this generation can increase by adjusting the tilt angle of Solar PV system.

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So, it is recommended to adjust the tilt angle in monthly basis so that the PV surface can receive maximum GSR to produce more electrical energy and also cooling effect for summer (May, June, July, August).The shading is increased by 5-6% in May, 10-11 % in June, 8-9 % in July and 3-4 % in August, so the building will work as space conditioning in summer season and also enhancing the efficiency of the system.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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