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Optimizing the Angle of Tilt for Solar Panels for Bangalore (India)

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Abstract

Solar energy is a very important source of renewable energy. The geographical location of India makes solar energy a very promising form of renewable energy. Most of the solar panels are fixed at an angle equal to the latitude of the place. India being in the Northern hemisphere and hence for maximum radiation, the panels are tilted towards south. In this article, the effect of the tilt angle of the panels on the increase in yield of solar radiation is highlighted.

By changing the tilt angle every month, the yield is shown to have increased by 6.7 % and by changing it twice a year, increase of 6% is observed. Another option of changing the tilt angle three times in specified months in a year will result 6.5% increase in the yield. Hence the tilt angle can be varied to obtain an increase in yield. It was observed from the study that for the years 2015, 2016 and 2017 there is an increase in the percentage of yield of solar radiation. Since the trend of the graph shows that the magnitude of peak radiation occurs at the mentioned tilt angles and this pattern is applicable for the forthcoming years, namely for the years 2018, 2019, 2020 and so on.

Keywords: Efficiency, Inclined Surface, India, Optimal Tilt, Solar energy, Solar Panel.

1. INTRODUCTION

The energy from Sun which is an important source of renewable energy. The geographical location of India makes the solar energy very promising form of renewable energy. Government of India aims to generate 100 GW by 2022. As of 31-March-2019, much of India's installed capacity reached 28.18 GW. One of the largest solar parks is located at Pavagada, Tumakuru District, in Karnataka, India. [1], with 2050 MW capacity. Kamuthi solar power plant [2], is the biggest plant with 650MW capacity followed by power plant at Shakthisthal, Karnataka [3]. The total solar energy harnessed by the solar panels is primarily dependent on the absorption of the radiation by the panel, and incidence of more solar radiation will yield more power. Considering this, the tilt of a solar panel is important for harvesting solar energy. For Bangalore, the tilt angle is 13^0, and it also the latitude of the place. Optimizing the tilt angle to obtain maximum solar radiation is the focus of the current study. The best approach to get maximum solar yield is by using an active Sun tracker, which is not very cost effective and efficient (as it requires additional equipment and power). Changing the tilt of the solar panels monthly or seasonally by some means is an effective way of getting more yield as proven from literature. Liu and Jordan [4] have mentioned in their work about the methods of measurement of solar radiation and its analysis.

From literature, Markam et.al [5] it was found that optimizing the tilt will yield higher power output. The yield increased by 5.03% if optimized monthly and 4.54% if optimized seasonally. Also, studies by T. Khatib [6] and [7] have shown that optimal for a single year is the same as the site's latitude and the tilt angle for solar panels is 2.83° during summer and 57.48° for the winter months. Ghosh [8], Ashok Kumar [9] and A. Lanjewar [10] mention the increase in solar radiation due to the effect of optimal tilt on varying seasons.Safdarian [11], in his work mentions the method of determining optimal tilt angle in Iran.

The Figure A1 [Appendix A] depicts the locations in India and outside as references for the current study in estimating the optimal tilts. The data used in the present work was obtained from BMS College of Engineering. Bengaluru. Data for four years, (from January-2015 till November-2018) were collected, grouped and the desired results were obtained [Appendix B]. However, the data for 2018 could not be used as it had a lot of missing parameters. The radiation data for 2015, 2016 and 2017 were used to determine the optimal tilt angle of the solar panel for Bangalore. The tilt angles obtained for each year (month wise and season wise) are calculated using the empirical formulae given below.

2. **MATHEMATICAL FORMULAE**

The equation for global radiation can be expressed as,

$$G_o = B_o + D_o + R_o \qquad (1)$$

Where G_o, B_o, D_o and R_o are the global radiation, beam radiation, diffused radiation, and reflected radiation on the tilted surface. Global radiation is the total amount of all the radiation that falls hits the ground (Horizontal Surface). This includes both Diffused and Direct radiation. Direct or Beam radiation is the radiation from the Sun which directly hits the surface without getting diffused. Diffused radiation is the solar radiation which reaches the ground after being scattered from reflected particles and other suspended matters from the atmosphere. Finally, the radiation which has been reflected by atmospheric and non-atmospheric particles is called as Reflected radiation.

Equation (1) can be expressed as,

$$G_o = (G-D)\,R_B + D\,R_D + G\,\rho\,R_R \qquad (2)$$

Where ρ is reflectivity for ground which in the present work is taken as 0.3 and G is the measured global horizontal irradiance. While D is diffused solar radiation, which is been theoretically estimated with the help of the following equations.

$$D = 0.165\,G \qquad (\text{for } K_t \geq 0.8) \qquad (3)$$

$$D = G\,(0.95 - 0.16(K_t) + 4.3(K_t)^2 - 16.4(K_t)^3 + 12.3(K_t)^4) \qquad (\text{for } 0.22 \leq K_t \leq 0.8) \qquad (4)$$

In Equation (2), R_B is defined as the ratio between average daily beam radiation for a month on a tilted surface and on the horizontal surface for the Northern hemisphere and is estimated as

$$R_B = \frac{(\cos(\phi-\beta)*\cos(\delta)*\sin(\omega)) + (\omega\sin(\phi-\beta)*\sin(\delta))}{(\cos(\phi)*\cos(\delta)*\sin(\omega)) + (\omega\sin(\phi)*\sin(\delta))} \qquad (5)$$

Here,

ω: Sunshine hour angle,

δ: declination angle

The equation for declination angle is given by,

$$\delta = 23.45 * \sin\left(\frac{360*[N+284]}{365}\right) \qquad (6)$$

In Equation (6) N is the day number of the particular year. N will be 1 for January 1st and 31 for January 31st.

For the ease of calculation, the average monthly solar radiation was calculated by taking every month's mid value as the day number (N), and ω is given by

$$\omega = \cos^{-1}(-\tan(\phi)\tan(\delta)) \qquad (7)$$

ϕ: is latitude of Bangalore which is 13^0

From equation (2), R_D is defined as the ratio between monthly diffused radiation of the tilted surface and the horizontal surface. If the distribution of sky diffuse - radiation is isotropic, then the equation is,

$$R_D = \frac{1+\cos(\beta)}{2} \qquad (8)$$

$R_{R:}$ is the amount of reflected solar energy on the surface.

$$R_R = \frac{1-\cos(\beta)}{2} \quad . \quad . \quad . \quad . \quad . \quad .. \quad . \qquad (9)$$

Where, β is the tilt angle of the solar panel

Combining the Equations (5), (8) and (9) the resulting equation can be written as,

$$G_0 = (G\text{-}D)\,\frac{(\cos(\phi-\beta)*\cos(\delta)*\sin(\omega)) + (\omega\sin(\phi-\beta)*\sin(\delta))}{(\cos(\phi)*\cos(\delta)*\sin(\omega)) + (\omega\sin(\phi)*\sin(\delta))} + D\,\frac{1+\cos(\beta)}{2} + G\,\rho\,\frac{1-\cos(\beta)}{2} \qquad (10)$$

A sample calculation for the estimation of G_O is given in Appendix C.

3. PROCEDURE FOR ESTIMATING OPTIMAL TILT ANGLE:

In equation (10) all quantities for every hour of every day of each month for a given year are available. The latitude of Bangalore is 13°. The panel will be tilted at 13° which is the latitude of Bengaluru. The results of the calculated G_O are shown in Table 1. In the present work, the value of β (tilt angle) is varied from 0 to 90° for every month and the angle which gives highest value of solar power generated is established and it is termed as "Optimal Tilt" for that month. Tables 1, 2 and 3 give details of tilt angle and radiation for 2015, 2016 and 2017.

Table 1: Tilt angle (β) and the corresponding Radiation (G_0) for Year 2015

Tilt angle β	G_0 (W/m^2)											
	Jan	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
0	309.0	374.0	392.0	369.0	338.0	300.0	282.0	278.0	303.0	330.0	204.0	271.0
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
11	349.78.	407.05.	405.21.	361.64.	316.46.	277.61.	.265.10	269.49.	306.95.	353.14.	.218.78	313.26.
12	353.0	409.49	405.84	360.46	314.04	275.2	263.23	268.38	306.88	354.75	219.87	316.66
13	356.13	411.83	406.38	359.19	311.55	272.73	261.3	267.21	306.74	356.27	220.93	319.97
18	370.49	422.02	407.61	351.64	298.01	259.51	250.88	260.57	304.99	362.62	255.55	335.32
30	395.50	435.97	400.78.	325.4	258.71	222.40	220.92	239.40	293.64	368.90	232.07	363.29
35	401.79	437.30	393.91	311.29	239.82	204.99	206.62	228.55	286.02	367.74	232.83	371.03
38	404.36	436.81	388.67	301.99	227.86	194.07	197.59	221.53	280.67	365.99	232.72	374.53
39	405.02	436.44	386.74	298.76	223.77	190.37	194.52	219.11	278.76	365.22	232.60	375.5
45	406.81	431.96	373.31	278.04	198.34	167.44.	175.39	203.75	266.01	358.81	230.86	379.28
48	406.33	428.30	365.42	266.88	185.09	155.60	165.45	195.59	258.83	354.45	229.36	379.84
89	312.5	292.8	194.56	79.41	0	0	20.04	65.02	120.16	226.78	171.42	301.88
90	308.4	287.82	189.32	74.47	0	0	16.62	61.7	116.16	222.38	169.26	298.17

Table 2: Tilt angle (β) and the corresponding Radiation (G_0) for year 2016

Tilt angle β	G_0 (W/m^2)											
	Jan	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
0	286.0	343.00	376.00	399.00	354.00	264.00	249.00	248.00	258.00	341.00	304.00	271.0
.	.	.	.	.	.	.	.	.	.	.	.	.
10	320.68	370.70	387.33	391.64	334.40	249.98	238.77	242.80	260.46	363.73	338.19	307.48
11	323.74	372.99	387.97	390.40	332.01	248.31	237.51	242.03	260.42	365.54	341.18	310.74
12	326.72	375.2	388.51	389.07	329.54	246.59	236.20	241.22	260.33	367.26	344.08	313.92
13	329.63 329.63	377.31	388.96	387.64	327.0	244.82	234.85	240.37	260.18	368.89	346.91	317.02
18	342.91	386.52	389.85	379.20	313.17	235.31	227.49	235.45	258.68	375.72	359.74	331.36
30	366.07	399.00	382.59	350.18	273.06	208.19	205.89	219.47	249.86	382.84	381.40	357.27
35	371.89	400.09	375.73	334.68	253.77	195.33	195.44	211.20	244.09	381.89	386.45	364.32
38	374.26	399.57	370.55	324.49	241.56	187.23	188.80	205.81	240.05	380.21	388.33	367.45
39	374.87	399.20	368.65	320.95	237.39	184.47	186.53	203.95	238.61	379.47	388.77	368.31
43	376.35	396.77	360.20	306.10	220.26	173.17	177.19	196.19	232.41	375.59	389.53	370.81
45	376.53	394.97	355.48	298.28	211.43	167.36	172.37	192.13	229.05	373.1	389.33	371.5
48	376.08	391.55	347.78	286.09	197.90	158.49	164.98	185.82	223.68	368.71	388.30	371.82
89	289.24	266.85	182.95	82.53	0	30.03	54.56	83.65	121.17	237.64	292.04	294.88
90	285.44	262.28	177.93	77.18	0	27.03	51.91	81.03	118.23	233.09	288.00	291.28

Table 3: Tilt angle (β) and the corresponding Radiation (G_0) for year 2017

Tilt angle β	G_0 (W/m^2)											
	Jan	**Feb**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
0	314.0	386.00	398.00	396.00	356.00	290.00	269.00	251.00	249.00	254.00	304.00	230.00
.	.	.	.	.	.	.	.	.	.	.	.	.
9	348.64	414.49	409.23	389.84	338.62	273.72	257.52	246.36	251.07	266.57	335.13	255.18
11	355.44	419.75	410.67	387.47	333.89	269.44	254.40	244.83	251.00	268.74	341.18	260.16
12	358.72	422.24	411.24	386.14	331.41	267.22	252.77	243.99	250.90	269.73	344.09	262.55
13	361.90	424.62	411.72	384.73	328.85	264.94	251.09	243.11	250.74	270.67	346.91	264.89
18	376.49	434.98	412.16	376.35	314.95	252.74	241.95	238.05	249.24	274.49	359.74	275.64
19	379.14	436.74	412.55	374.41	311.95	250.14	239.98	236.91	248.80	275.07	362.05	277.59
28	398.66	447.76	407.22	353.16	281.97	224.56	220.31	224.75	242.69	277.61	378.72	292.91
30	401.92	449.02	404.98	347.55	274.61	218.38	215.49	221.61	240.83	277.50	381.41	294.71
35	408.31	450.25	397.71	332.16	255.21	202.23	202.79	213.11	235.37	276.18	386.46	299.70
38	410.92	449.67	392.23	322.05	242.93	192.09	194.75	207.58	231.58	274.66	388.35	301.83
39	411.59	449.26	390.22	318.54	238.74	188.64	192.01	205.66	230.23	274.03	388.78	302.40
43	413.21	446.51	381.28	303.80	221.51	174.54	180.74	197.69	224.41	270.93	389.54	303.93
45	413.41	444.49	376.28	296.05	212.64	167.33	174.93	193.52	221.26	269.03	389.34	304.26
46	413.35	443.31	373.65	292.07	208.14	163.68	171.99	191.39	219.63	267.99	389.10	304.31
89	317.58	300.31	193.66	81.91	0	0	34.92	82.24	120.86	175.17	292.06	240.20
90	313.41	295.17	188.34	76.61	0	0	31.80	79.55	118.14	172.11	288.02	237.32

4. RESULTS AND DISCUSSIONS:

In the following sections, the results given in Table 4 and Figures 1-3 are discussed further on two counts.

i) Monthly optimal tilt angle for each year, the corresponding solar power available and the average values of increase in yield for that year with respect to the position of solar panel at 13° latitude.

ii) a similar analogy is brought out if the solar panel is tilted only twice during a year (which is highly likely for large solar parks) and the corresponding yield and the percentage of increase in the yield for the same year with respect to the position of solar panel at 13° latitude are studied.

Optimal tilt angles on monthly basis

From the given data, the optimal tilt angles have been calculated for every month using equation (10) for 2015, 2016 and 2017. The values are tabulated and represented graphically.

The optimized angle of tilt is given for all the months is tabulated in Table 4. The overall increase of yield after optimization is tabulated in Table 8 (it is very clear that there is increase in the yield if the tilt is optimized monthly with respect to normal tilt angle where β is 13^0). The individual percentage increase in yield for the years 2015.2016 and 2017 is shown in Tables 5, 6 and 7.

Table 4: Optimum Tilt Angles for every month for the years 2015, 2016 and 2017

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2015	45	35	18	0	0	0	0	0	11	30	38	48
2016	45	35	18	0	0	0	0	0	10	30	43	48
2017	45	35	18	0	0	0	0	0	9	28	43	46

Table 5: Percentage increase in yield when tilted monthly for the year 2015

Month	Radiation (W/m^2) at 13^0	Max Radiation (W/m^2) at optimal tilt angle
Jan	356.13	406.81
Feb	411.83	437.30
Mar	406.38	407.61
Apr	359.19	369.00
May	311.55	338.00
Jun	272.73	300.00
Jul	261.30	282.00
Aug	267.21	278.00
Sep	306.74	306.95
Oct	356.27	368.90
Nov	220.93	232.84
Dec	319.97	379.84
Total	**3849.26**	**4107.13**
% increase		**6.69**

Table 6: Percentage increase in yield when tilted monthly for the year 2016

Month	Radiation (W/m^2) at 13 ^{0}	Max Radiation (W/m^2) at optimal tilt angle
Jan	329.63	376.53
Feb	377.31	400.09
Mar	388.96	389.85
Apr	387.64	399.00
May	327.00	354.00
Jun	244.82	264.00
Jul	234.85	249.00
Aug	240.37	248.00
Sep	260.18	260.46
Oct	368.89	382.84
Nov	346.91	389.53
Dec	317.02	371.82
Total	**3823.56**	**4085.12**
% increase		**6.84**

Table 7: Percentage increase in yield when tilted monthly for the year 2017

Month	Radiation (W/m^2) at 13 ^{0}	Max Radiation (W/m^2) at optimal tilt angle
Jan	361.90	413.41
Feb	424.62	450.25
Mar	411.72	412.66
Apr	384.73	396.00
May	328.85	356.00
Jun	264.94	290.00
Jul	251.09	269.00
Aug	243.11	251.00
Sep	250.74	251.09
Oct	270.67	277.61
Nov	346.91	389.54
Dec	264.89	304.31
Total	**3803.28**	**4060.87**
% increase		**6.77**

Table 8: Percentage increase in yield obtained by tilting monthly as compared to 13 ^{0}tilt

Year	2015	2016	2017
% Increase	6.69	6.84	6.77

In all the Figures 1, 2 and 3 the yield corresponding to 13^{0} tilt is indicated as a vertical line in the graph for every month for the years 2015, 2016 and 2017.

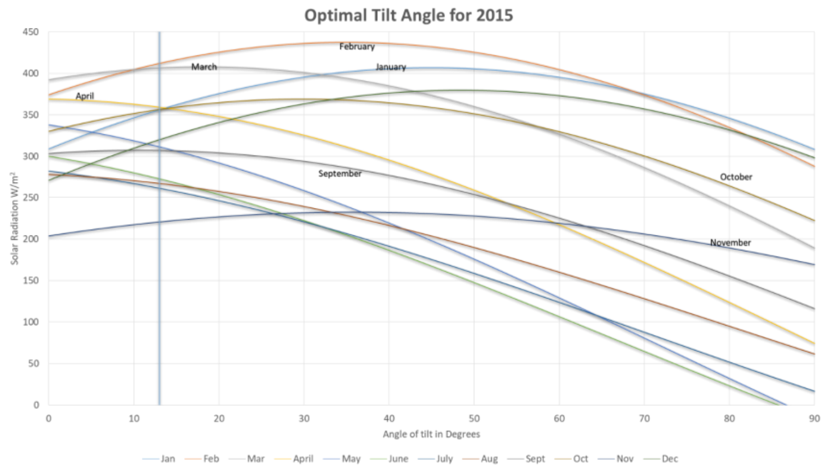

Figure 1: Optimum tilt angles for 2015

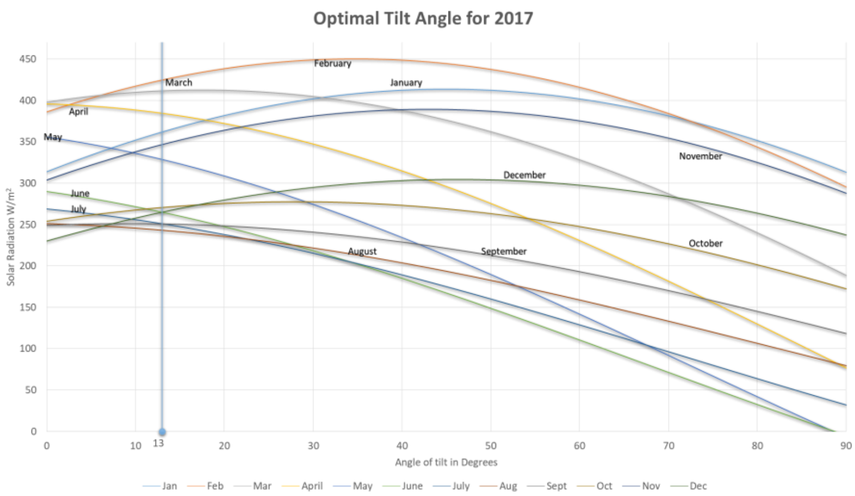

Figure 2: Optimum tilt angles for 2016

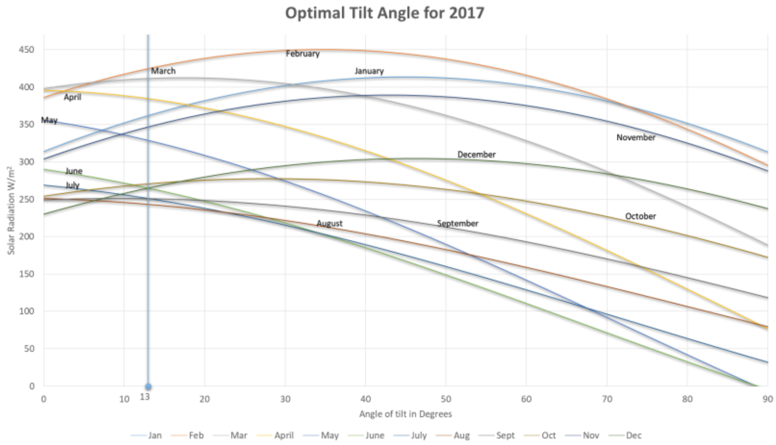

Figure 3: Optimum tilt angles for 2017

The Maximum yield for every month is shown in the Figures 4, 5 and 6 respectively.

a) Yield when the panel is kept at 13° throughout the year

b) Yield when the panels are oriented at their optimal angle

c) Yield when the panels are tilted twice a year at 0^0 and 39^0.

As it can be observed from Figure. 4, the variation for the latter two conditions (b) and (c) are not very much different. Condition c) can be a practical solution for large solar parks.

A similar procedure is adopted for years 2016 and 2017 and the corresponding yield for all the three conditions are shown in Figures 5 and 6.

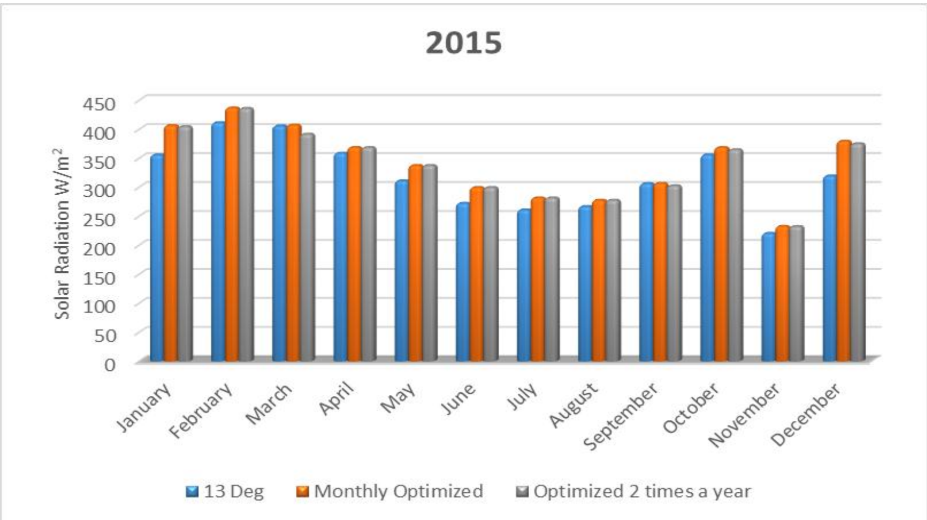

Figure 4: Yield obtained for monthly for conditions a), b) and C) as stated above for the year 2015

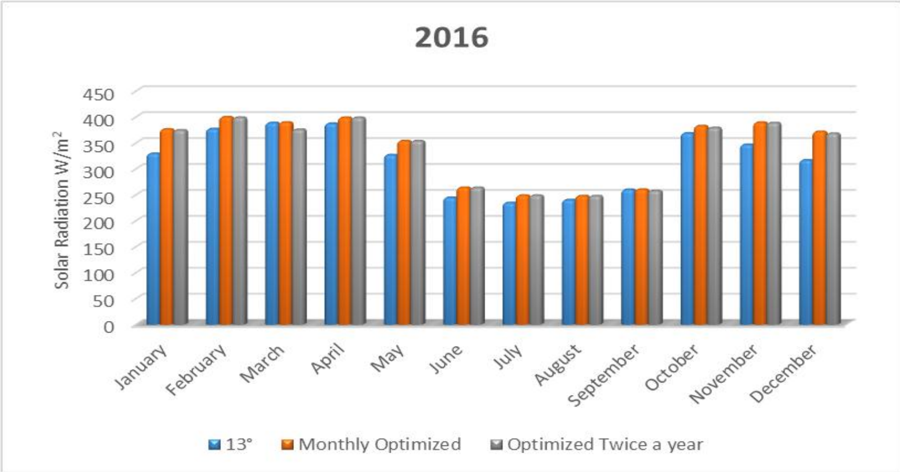

Figure 5: Yield obtained for monthly for conditions a), b) and C) as stated above for the year 2016

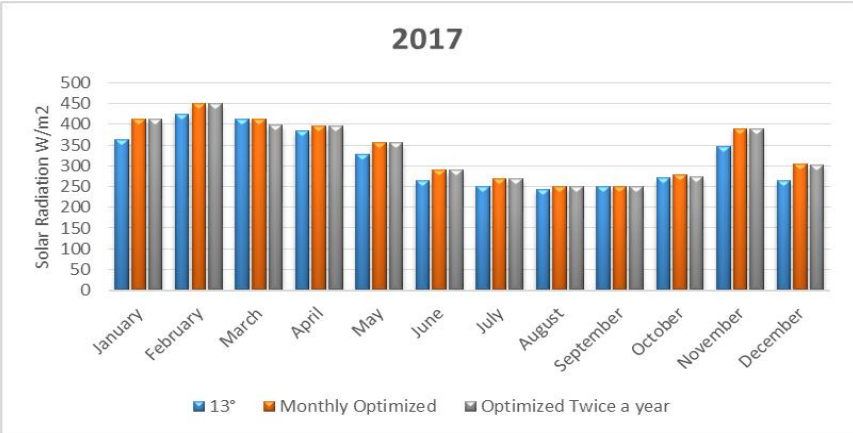

Figure 6: Yield obtained for monthly for conditions a), b) and C) as stated above for the year 2017

From Table 4 it can be inferred that during the months April to August the maximum yield is found when the panel is kept flat (0^0). If the panel is kept at local Latitude angle which is 13^0, the yield is much less. Also considering a tilt of 39^0, which is much higher than the latitude of Bangalore (13^0) will give good yield. Keeping the panels at optimal inclinations will increase the yield. This is depicted in Table 8 which shows that by changing the tilt every month the increase of the collected solar energy in the years 2015, 2016 and 2017 are 6.69 %, 6.84 % and 6.77 % respectively. Changing the tilt of the solar panel every month is not very practical, therefore changing the tilt angles at least 2 or 3 times a year is more appropriate. As it can be observed from Table 4, the tilt during March to September is kept at 0^0 and October to February at 39^0. There has been an increase of 5.91 to 6.14 % for all the 3 years if the panels are tilted to the optimal angle 2 times a year. The individual percentage increase in yield for the years 2015, 2016 and 2017 when tilted twice is shown in

Table 9, 10 and 11. Table 12 shows the increase in the yield for the years 2015, 2016 and 2017.

Table 9: Increase in percentage yield when tilted twice for the year 2015

Month	Radiation (W/m^2) at 13^0	Max Radiation (W/m^2) at optimal tilt angle	Radiation for tilt 0 and 39 deg(W/m^2)
Jan	356.13	406.81	405.02 (39^0)
Feb	411.83	437.30	436.44 (39^0)
Mar	406.38	407.61	392.00 (0^0)
Apr	359.19	369.00	369.00 (0^0)
May	311.55	338.00	338.00 (0^0)
Jun	272.73	300.00	300.00 (0^0)
Jul	261.30	282.00	282.00 (0^0)
Aug	267.21	278.00	278.00 (0^0)
Sep	306.74	306.95	303.00 (0^0)
Oct	356.27	368.90	365.22 (39^0)
Nov	220.93	232.84	232.60 (39^0)
Dec	319.97	379.84	375.50 (39^0)
Total	**3849.26**	**4107.25**	**4076.78**
% increase			**5.91**

Table 10. Increase in percentage yield when tilted twice for the year2016

Month	Radiation (W/m^2)	Max Radiation (W/m^2)	Radiation for tilt of 0 and 39 deg (W/m^2)
Jan	329.63	376.53	374.87 (39^0)
Feb	377.31	400.09	399.20 (39^0)
Mar	388.96	389.85	376.00 (0 ^{0})
Apr	387.64	399.00	399.00 (0 ^{0})
May	327.00	354.00	354.00 (0 ^{0})
Jun	244.82	264.00	264.00 (0 ^{0})
Jul	234.85	249.00	249.00 (0 ^{0})
Aug	240.37	248.00	248.00 (0 ^{0})
Sep	260.18	260.46	258.00(0 ^{0})
Oct	368.89	382.84	379.47 (39^0)
Nov	346.91	389.53	388.77 (39^0)
Dec	317.02	371.82	368.31(39^0)
Total	**3823.56**	**4085.12**	**4058.62**
% increase			**6.14**

Table 11: Increase in percentage yield when tilted twice for the year2017

Month	Radiation(W/m^2) at 13 deg	Max Radiation(W/m^2)	Radiation for tilt of 0 and 39 deg (W/m^2)
Jan	361.90	413.41	411.59(39^0)
Feb	424.62	450.25	449.26(39^0)
Mar	411.72	412.66	398.00(0^0)
Apr	384.73	396.00	396.00(0^0)
May	328.85	356.00	356.00(0^0)
Jun	264.94	290.00	290.00(0^0)
Jul	251.09	269.00	269.00(0^0)
Aug	243.11	251.00	251.00(0^0)
Sep	250.74	251.07	249.00(0^0)
Oct	270.67	277.61	274.03(39^0)
Nov	346.91	389.54	388.78(39^0)
Dec	264.89	304.31	302.40(39^0)
Total	**3803.28**	**4060.85**	**4035.06**
% increase			**6.09**

Table12: Percentage increase in Yield for two tilts during a year

Year	2015	2016	2017
% Increase	5.91	6.14	6.09

5. Optimizing the solar panel tilt by tilting thrice a year

From Table 4 it is observed that changing the tilt angle of the panel can be done three times in a year also to produce a good yield. The panel needs to be aligned at 0^0 during the months April, May, June, July and August. During the months of March and September the panel should be aligned at 13^0. In the months of January, February, October, November and December the panel needs to be tilted at 39^0. With this kind of combination, the increase in percentage of yield for 2015, 2016 and 2017 were found to be 6.38% and 6.54% and 6.5% respectively. The individual percentage increase in yield for the years 2015, 2016 and 2017 is shown in Table 13, 14 and 15. The consolidated values for these three years is depicted in Table 16.

Table 13: Increase in percentage yield when tilted thrice for the year2015

Month	Radiation (W/m^2) at 13^0	Max Radiation (W/m^2)	Radiation for tilt angles of 0, 13 and 39 deg (W/m^2)
Jan	356.13	406.81	405.02(39^0)
Feb	411.83	437.30	436.44(39^0)
Mar	406.38	407.61	406.38(13^0)
Apr	359.19	369.00	369.00 (0^0)
May	311.55	338.00	338.00(0^0)
Jun	272.73	300.00	300.00(0^0)
Jul	261.30	282.00	282.00(0^0)
Aug	267.21	278.00	278.00(0^0)
Sep	306.74	306.95	306.74(13^0)
Oct	356.27	368.90	365.22(39^0)
Nov	220.93	232.84	232.60(39^0)
Dec	319.17	379.84	375.50(39^0)
Total	**3849.26**	**4107.25**	**4094.90**
% increase			**6.38**

Table 14: Increase in percentage yield when tilted thrice for the year 2016

Month	Radiation (W/m^2) at 13^0	Max Radiation (W/m^2)	Radiation for tilt of 0, 13 and 39 deg (W/m^2)
Jan	329.63	376.53	374.87(39^0)
Feb	377.31	400.09	399.20(39^0)
Mar	388.96	389.85	388.96(13^0)
Apr	387.64	399.00	399.00 (0^0)
May	327.00	354.00	354.00 (0^0)
Jun	244.82	264.00	264.00(0^0)
Jul	234.85	249.00	249.00(0^0)
Aug	240.37	248.00	248.00(0^0)
Sep	260.18	260.46	260.18(13^0)
Oct	368.89	382.84	379.47(39^0)
Nov	346.91	389.53	388.77(39^0)
Dec	317.02	371.82	368.31(39^0)
Total	**3823.56**	**4085.12**	**4073.76**
% increase			**6.54**

Table15: Increase in percentage yield when tilted thrice for the year2017

Month	Radiation (W/m^2)	Max Radiation (W/m^2)	Radiation for tilt of 0, 13 & 39 deg (W/m^2)
Jan	361.90	413.41	411.59(39^0)
Feb	424.62	450.25	449.26(39^0)
Mar	411.72	412.66	411.72(13^0)
Apr	384.73	396.00	396.00(0^0)
May	328.85	356.00	356.00(0^0)
Jun	264.94	290.00	290.00(0^0)
Jul	251.09	269.00	269.00(0^0)
Aug	243.11	251.00	251.00(0^0)
Sep	250.74	251.07	250.74(13^0)
Oct	270.67	277.61	274.03(39^0)
Nov	346.91	389.54	388.78(39^0)
Dec	264.89	304.31	302.40(39^0)
Total	**3803.28**	**4060.85**	**4050.52**
% increase			**6.50**

Table 16: % increase in Yield for tilt three times in a year (0, 13 and 39 degrees)

Year	2015	2016	2017
% Increase in yield	6.38	6.54	6.50

Comparing the results obtained when the panel is tilted every month with the values obtained when the panel is tilted twice a year, we observe that tilting twice a year is a better option as tilting monthly is cumbersome and the increase in yield is also better when tilted twice. Another better option is to tilt the panel three times a year to the tilt angles mentioned in the above study to obtain a good percentage increase in yield.

4. CONCLUSIONS

In this study, an optimization of tilt angle of the solar panel based on Liu and Jordan model was carried out. This model was based on theoretical evaluation from the measured data from a pyranometer during 2015, 2016 and 2017. The present study shows that the percentage yield can be increased by setting the tilt angle of the panel to a particular angle called the optimal tilt angle. It was observed that the percentage of radiation yield is 6.69 % in 2015 followed by 6.84% in 2016 and 6.77% in 2017 respectively when the tilt angle is changed every month. However, changing the tilt angle every month is not a very convenient as a practical measure, hence the tilt angle was assumed to be changed twice in a year (by keeping the panel at 0 degrees and 39 degrees for specified months). The increase in yield when tilted twice a year was 5.91 % in 2015 ,6.14 % in 2016 and 6.09 % in 2017.Further studies revealed that tilting the panel three times in a year during specified months will result in an increase in radiation yield of 6.38% in 2015 ,6.54 % in 2016 and 6.50% in 2017.

NOMENCLATURE:

G_o	Global Radiation on tilted Surface (W/m^2)
G	Global Radiation (W/m^2)
B_o	Beam Radiation on tilted Surface (W/m^2)
B	Beam Radiation (W/m^2)
D_o	Diffused Radiation on tilted Surface (W/m^2)
D	Diffused Radiation (W/m^2)
R_o	Reflected Radiation on tilted Surface (W/m^2)
R	Reflected Radiation (W/m^2)
ρ	Reflectivity index for ground
Φ	Latitude of Bangalore
β	Angle of tilt (°)
δ	Angle of declination (°)
ω	Sunshine hour angle (°)
N	Day number of the year

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APPENDIX A: Sample locations in India and neighbouring countries

Figure A1 depicts the locations in India and its neighbouring countries referred in the current work

APPENDIX B: Unfiltered data of radiation for the years 2015-2018

Measurements of solar radiation were done using a pyranometer at the BMS College of Engineering, Bengaluru. This instrument measures the radiation incident on horizontal plane. The instrument may be tilted at any angle. The spectral range covers wavelengths from 0.4µm to 1.2µm. This instrument also measures the temperature data in degree Celsius (°C). The data is obtained and stored in excel sheet in the following format; [DD-MM-YYYY HH: min] [At °C] [Solar Radiation W/m^2] for every hour of the day from the 1st January, 2015 to 15th November, 2018. A sample of the measured data for January 2015 is shown in Table B1. The filtered data without the "Power Off" values is shown in Table B2, which is further used to generate global radiation.

Table B1: Sample Raw solar radiation data

Date DD-MM-YY H-M	Temperature in (^{0}C)	Measured Radiation in (W/m^2)
01-01-2015 08:00	*Power off*	*Power off*
01-01-2015 09:00	*Power off*	*Power off*
01-01-2015 10:00	*Power off*	*Power off*
01-01-2015 11:00	*Power off*	*Power off*
01-01-2015 12:00	*Power off*	*Power off*
01-01-2015 13:00	27.6	552
01-01-2015 14:00	27.8	433
01-01-2015 15:00	28.2	367
01-01-2015 16:00	27.6	147
01-01-2015 17:00	26.9	41
01-01-2015 18:00	26.0	7
01-01-2015 19:00	25.4	7
01-01-2015 20:00	25.1	7

Table B2: Data after filtering

Date DD-MM-YY H-M	Temperature in (^{0}C)	Measured Radiation in (W/m2)
01-01-2015 13:00	27.6	552
01-01-2015 14:00	27.8	433
01-01-2015 15:00	28.2	367
01-01-2015 16:00	27.6	147
02-01-2015 06:00	22.6	7
02-01-2015 07:00	22.8	58
02-01-2015 08:00	24.1	123
02-01-2015 09:00	24.9	247
02-01-2015 10:00	25.2	254
02-01-2015 11:00	26	339
02-01-2015 12:00	26.8	421

In the solar radiation data, there are certain errors appearing as “power off’. The software will remove these errors and filtered data is available. This type of data is available for all the months and years and this is processed.

Appendix C: ***Sample Calculation to estimate Go***

The Equations (1-10) have been implemented to obtain the global radiation, G_O on a tilted surface (from 0^0 to 90^0 with an increase of 1^0).

$$\delta = 23.45 \sin(360\frac{[284+N]}{365})$$

N = 16 (the mid date of the month)

$\omega = \cos^{-1}(-\tan(\phi)\tan(\delta))$

$\Phi = 13^0$ (Latitude value of Bangalore)

$\delta = -21.10^0$ and $\omega = 84.89^0$

$R_B = \frac{\cos(\phi-\beta)\cos(\delta)\sin(\omega)+\omega\sin(\phi-\beta)\sin(\delta)}{\cos(\phi)\cos(\delta)\sin(\omega)+\omega\sin(\phi)\sin(\delta)}$, ($\beta$ is the tilt angle)

$R_D = \frac{1+\cos(\beta)}{2}$,

$R_R = \frac{1-\cos(\beta)}{2}$,

The values of δ, ω, β and ϕ are substituted in above equations.

$R_B = 1.030168$

$R_D = 0.987185$

$R_R = 0.012815$

The value of G_0 is obtained by the equation

$G_O = (G-D) R_B + DR_D + G \rho R_R$

$G_0 = 309$ W/m^2, is the measured global average radiation for January

$D = 50.99$ W/m^2, from Equation.3 with ($\rho = 0.3$, Reflectivity index for ground)

$G_O = 356.1$ W/m^2

This value includes the radiation due to diffusion, beam and reflection R_B, R_D and R_R and hence is greater than the measured value.

The above steps are followed, and the measured data is modified for every month.