Journal of Investigations on Engineering & Technology
Volume 3, Issue 2, 37-47, 2020

Assessing Performance of Manually Controlled Solar Tracking System in Climate Condition of Kano, Nigeria

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(Alınış / Received: 13.09.2020, Kabul / Accepted: 27.11.2020, Online Yayınlanma / Published Online: 31.12.2020)

Keywords
Altitude Angle
Azimuth Angle
Solarimeter
Solar Irradiance
Solar Tracker

Abstract: A solar tracking system is a mechanism used to move and position a solar photovoltaic in such a way that it is positioned and oriented perpendicular to the sun beam for maximum amount of solar irradiance and maximum power outputs. However, fixed solar panel is more preferred than tracking module because it is cost effective. In this paper, the amount of solar irradiance of the tracking module is compared with fixed solar module by experimentally in Kano, Nigeria for the three months (May, June, July, 2019). It was observed that the highest average amount solar irradiance extracted by tracking collector was 10923.67 W/m2 and average solar irradiance harnessed by stationary collector (without tracking) was 9151.33 W/m2. The average percentage change of solar irradiance with tracking was 16.22 % over solar irradiance without tracking (stationary). In conclusion, the dual-axis tracking module is extracting more amount of solar irradiance than fixed module.

1. Introduction

Nowadays, renewable energy research is trending in the world of the researchers due to its reliability, sustainability and it is naturally free. Solar energy is an abundant and free from pollutant source of energy, but most of the developing countries are wasting much megawatt produced by the Sun due to lack of technology of harnessing this energy.

Photovoltaic (PV) system is solar energy technology that utilized solar energy by society. The solar photovoltaic (PV) system consists of cells connected into modules which convert solar radiation intensity harnessed by the modules into electricity. The output of this conversion depends on some parameters such as the amount of solar radiation intensity harnessed by the modules, the quality of the manufacturing materials solar PV cell, its temperature, and so on [1] [2].

The solar PV modules are usually arranged with series and/or parallel connections and oriented with the sunlight direction where the solar modules are fixed to position the sun trajectory with considering the country latitude angle [3]. But sun is moving along its path throughout the day, and for solar modules to extract maximum amount of solar radiation intensity, the solar beam must reach the solar modules perpendicularly. For the solar modules to attain solar beams at 90^o, the mechanism that track the sun trajectory perpendicularly throughout the hours of the day, this mechanism is called solar tracking system.

The solar tracking system are classified into two based on mechanism of freedom of movement as single (one) and dual (two) axes solar tracking system. The single axis solar tracker is a tracker that track the solar beams in one direction, whereas, dual axes tracker is tracking the solar beams in two directions and its more efficient than single axis tracker. The power output by the dual axis tracker is between 20% to 30% more than that of single axis tracker and it is depending on the seasonal climate and geographical location [4, 5].

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Fixed solar PV modules can harness maximum amount of solar radiation intensity when the modules are tilted on the optimal tilt angle of the location [6-8]. The performance of the solar tracking system depends on the optimum tracking mechanism of the system [9-12]. And solar PV with fixed modules has a lower operating cost and requires less maintenance effort.

Many authors have been studied solar tracking systems. Rustemli et al. [13] performed an experimental comparison between fixed module and sun-tracking module for the geographical condition of Van, Turkey. Another comparison indicated that the solar tracking system generated about 20% to 25% more power output by fixed solar modules, this study was done by Zhang et al. in 2015 [14]. Tirmikci and Yavuz performed similar work in 2015, where by their result was found that the dual axis tracker was 40% more efficient than fixed panels where single trackers have 20% [15]. Several other comparisons were provided in [3, 16-18].

2. Solar Tracking Angles

Flat plate collectors absorb beam radiation diffuse radiation and solar radiation reflected from the ground. In order to calculate the maximum absorbed radiation for tracking flat plate collectors, there is need to relate the amount of solar irradiance harnessed by the collector to the total solar irradiance on the horizontal surface. For a fully tracking flat plate collector, the slope of the collector must be equal to the complement of the sun's Altitude angle.

2.1 Declination angle (δ)

The declination angle (δ) is the angular position of the sun when it is on the local meridian with respect to the plane of the equator [19]. It is given by Duffie and Beckman [20].

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

Where: n is day of the year counted from 1st January of the year.

2.2 Solar Altitude Angle (α)

Solar altitude angle can be defined as the angle between the horizontal and line to the sun, and solar altitude angle is the complement of the zenith angle [19]. The value of the solar altitude angles depends on the time of day, the time of year and the latitude on Earth [20].

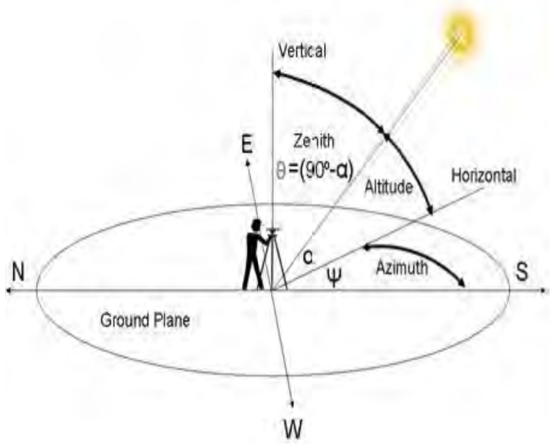

Figure 1. Solar Angles [20]

The sine of solar altitude angle (α) is equal to the cosine of zenith angle (θ) which is related as given by [21]:

$$\sin\alpha = \cos\theta = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega \quad (2)$$

2.3 Hour Angle (ω)

The hour angle refers to the angular displacement of the Sun when the Earth is rotation along it is axis at 15° per hour due east or west of the local meridian; morning negative, afternoon positive as shown in Figure 1 [19].

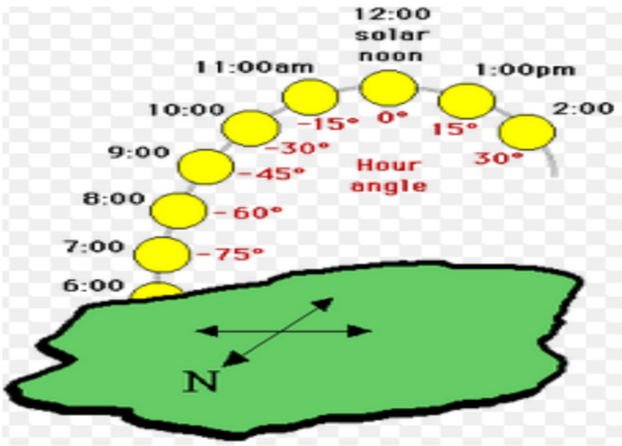

Figure 2. Hour Angle [22]

2.4 Solar Azimuth Angle (ψ)

Solar azimuth angle is the angle between south of the projection of the beam radiation to the horizontal plane [19]. Solar azimuth can be computed using the expression given by Duffie and Beckman below [19]:

$$\psi = sign(\omega)\left|\cos^{-1}\left(\frac{\cos\theta \sin\emptyset - \sin\delta}{\sin\theta \cos\emptyset}\right)\right| \quad (3)$$

Where: ψ is the solar azimuth angle; α is solar altitude angle; ϕ is latitude angle; δ is the declination angle; ω is the hour angle and θ is the zenith angle.

2.5 Tilt angle

Tilt angle can be defined as the angle between solar collector and the horizontal. It is taken as positive for the surface sloping towards south and negative sloping towards north [20].

3. Materials and Method

The experiment was conducted at Bayero University, Kano using the dual-axis (Azimuth and Altitude) solar tracking system constructed with manual operation which controlled by worm and worm wheel gear and rack and pinion gear for azimuth tracking and altitude tracking respectively. The system was developed at department of mechanical engineering, faculty of engineering of Bayero University, Kano.

In order to test the performance of azimuth-altitude solar tracking system, the system must be set on the particular azimuth and altitude angles for the testing site on different interval of the time for the day.

3.1 Altitude and Azimuth Angles of the Site

The altitude and azimuth angles of the site (Bayero University, Kano) were determined for three (3) selected days of three (3) consecutives months (May, June and July) and then used for measuring the solar irradiance.

On Friday 17th May, 2019

n=137 days from January 2019, Latitude of Kano State ϕ=12.2°N.

Then from "Eq. 1", the declination angle:

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

$$\delta = 23.45 \sin\left[\frac{360(137+284)}{365}\right] = 19.26^o$$

At 8:00a.m, the hour angle is given by [19]:

$$\omega = (ST - 12) \times 15^o$$

Where: ST is Local Solar Time=8:00a.m

$$\omega = (8 - 12) \times 15^o$$

$$\omega = -60^o$$

From "Eq. 2", the altitude angle:

$$\sin\alpha = \cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

$$\sin\alpha = \sin 12.2 \sin 19.26 + \cos 12.2 \cos 19.26 \cos(-60) = 0.6324$$

$$\therefore \alpha = 39.2^o$$

The Zenith Angle is given by [19]:

$$\theta = \cos^{-1}(\sin\alpha)$$

$$\theta = \cos^{-1}(0.6324) = 50.77^o$$

From "Eq. 3", the Azimuth Angle:

$$\psi = sign(\omega)\left|\cos^{-1}\left(\frac{\cos\theta\sin\emptyset - \sin\delta}{\sin\theta\cos\emptyset}\right)\right|$$

$$\psi = -\left|\cos^{-1}\left(\frac{\cos 50.77 \sin 12.2 - \sin 19.26}{\sin 50.77 \cos 12.2}\right)\right| = -105^o$$

Values for the subsequent hours were computed and presented in table A1 of the appendix A.

On Saturday 18th May, 2019

n=138 days from January 2019, Latitude of Kano State ϕ=12.2°N.

Then from "Eq. 1", the declination angle:

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

$$\delta = 23.45 \sin\left[\frac{360(138+284)}{365}\right] = 19.49^o$$

At 8:00a.m, the hour angle is given by [19]:

$$\omega = (ST - 12) \times 15^o$$

Where: ST is Local Solar Time=8:00a.m

$$\omega = (8 - 12) \times 15^o = -60^o$$

From "Eq. 2", the altitude angle:

$$\sin\alpha = \cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

$$\sin\alpha = \sin 12.2 \sin 19.49 + \cos 12.2 \cos 19.49 \cos(-60) = 0.5312$$

$$\therefore \alpha = 32.1^o$$

The Zenith Angle is given by [19]:

$$\theta = \cos^{-1}(\sin\alpha)$$

$\theta = \cos^{-1}(0.5312) = 57.91^o$

From "Eq. 3", the Azimuth Angle:

$$\psi = sign(\omega)\left|\cos^{-1}\left(\frac{\cos\theta\sin\emptyset - \sin\delta}{\sin\theta\cos\emptyset}\right)\right|$$

$$\psi = -\left|\cos^{-1}\left(\frac{\cos 57.91\sin 12.2 - \sin 19.49}{\sin 57.91\cos 12.2}\right)\right| = -105.5^o$$

Values for the subsequent hours were computed and presented in table A1 of the appendix A.

On Sunday 19th May, 2019

n=139 days from January 2019, Latitude of Kano State ϕ=12.2°N.

Then from "Eq. 1", the declination angle:

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

$$\delta = 23.45\sin\left[\frac{360(139+284)}{365}\right] = 19.71^o$$

At 8:00a.m, the hour angle is given by [19]:

$$\omega = (ST-12)\times 15^o$$

Where: ST is Local Solar Time=8:00a.m

$$\omega = (8-12)\times 15^o = -60^o$$

From "Eq. 2", the altitude angle:

$$\sin\alpha = \cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

$$\sin\alpha = \sin 12.2\sin 19.71 + \cos 12.2\cos 19.71\cos(-60) = 0.4932$$

$$\therefore \alpha = 29.55^o$$

The Zenith Angle is given by [19]:

$$\theta = \cos^{-1}(\sin\alpha)$$

$$\theta = \cos^{-1}(0.4932) = 60.45^o$$

From "Eq. 3", the Azimuth Angle:

$$\psi = sign(\omega)\left|\cos^{-1}\left(\frac{\cos\theta\sin\emptyset - \sin\delta}{\sin\theta\cos\emptyset}\right)\right|$$

$$\psi = -\left|\cos^{-1}\left(\frac{\cos 60.45\sin 12.2 - \sin 19.71}{\sin 60.45\cos 12.2}\right)\right| = -105.9^o$$

Values for the subsequent hours were computed and presented in table A1 of the appendix A. And the values for the months of June and July were computed and presented in table A2 and A3 of the appendix 'A' respectively.

3.2 Experimental Procedure

Two flat plate solar collectors were used to test the tracking accuracy of the system. The first solar collector was mounted on the system and the stationary solar collector was tilted and oriented to the latitude angle (12.2°) of Kano state Nigeria and facing south at the testing location as shown in Fig. 2 [23].

After mounting of the system, the following steps were adopted in order to measure the solar irradiance of both tracking and stationary collector:

a) In the morning, the handle 'B' was rotated such that the system faced earthward direction.
b) Two solarimeters were placed on both tracking and stationary collectors.
c) On Friday by 8:00a.m, the handle 'A' was rotated and set at 39.2° (altitude angle of the site).
d) The solar irradiances of both tracking and stationary collectors were measured.
e) Step 'c' was repeated hourly based on the solar altitude and azimuth angles presented in table A1 of appendix A and the solar irradiances were measured hourly.
f) The above steps were repeated on Saturday and Sunday and the solar irradiances of the system were measured in the month of May, 2019.
g) The above procedures were repeated on three selected days of the months of June and July, and the solar irradiances of the system were measured for all the months.

Figure 3. Experimental Set-up showing tracking collector and stationary collector

4. Results and Discussion

4.1 Results

The results of the experiments for both tracking solar collector and stationary solar collector for each day were recorded and presented in tabular form (Appendix B) and Figures 3, 4 and 5 presents the comparison of average solar insolation of the three-month test with tracking and without tracking (stationary).

4.2 Discussion of the Results

After testing the dual solar tracker for three months, the amount of solar irradiance for both tracking solar collector and stationary solar collector were observed to have the maximum amount of solar irradiance falling on the two collectors was at noon (12:00pm) for the months of May and June 2019 with the exception of July, 2019. There were also significant differences between the amounts of solar irradiance falling on the tracking system compared to that by stationary collector. The total average amount of solar irradiance falling on the tracking and stationary collectors for the month of May, 2019 were 10923.7W/m^2 and 9151.33 W/m^2 with percentage change of 16.2% as shown in Table B2. Similarly, for the month of June, the total average amount of solar irradiance falling on the tracking and stationary collectors were 6416.33 W/m^2 and 6187.67 W/m^2 with percentage change 3.56% (Table B4). The total amount of solar irradiance falling on the tracking and stationary collectors were 7437.33 W/m^2 and 7244.33 W/m^2 with percentage change of 2.595% for the month of July, 2019 refer to Table B6.

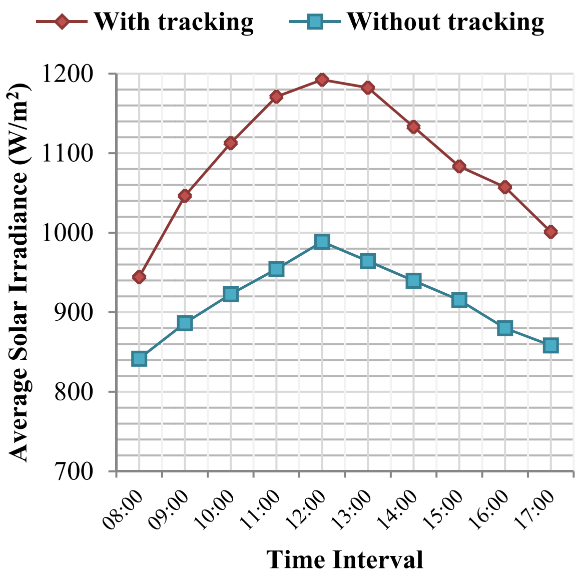

Figure 4. Average Solar Irradiance (W/m^2) at the Test Site for the Month of May, 2019

Finally, it was found that every day there was difference in amount of solar irradiance on tracking collector and stationary collector. Also, the amount of solar irradiance increases with increase in time from morning to noon whereas it is decreases from noon to evening for the month of May and June refer to Figures 4 and 5 respectively. In Figure 6, the curve is polynomial curve this is because in month of July there were rainfalls between 10:36 am to 12:17 pm of the first testing day (Thursday, 25th July, 2019) and also the days were cloudy. But there are constraints that affect the result such as the unavailable data (Kano) of the site that will be used to compare the result with in the literatures and also shading of the tree in the site.

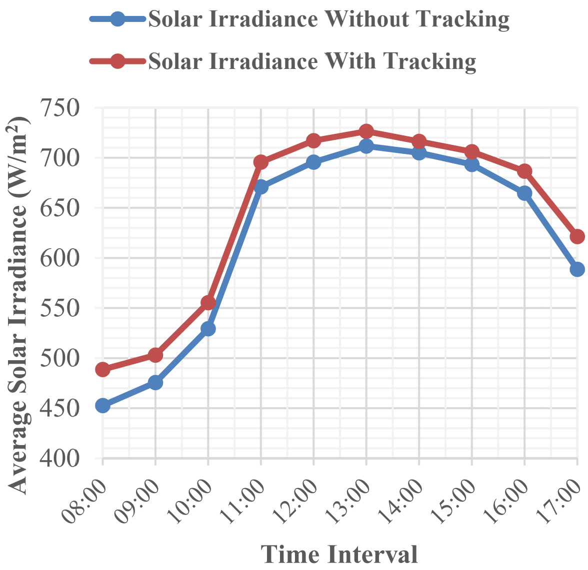

Figure 5. Average Solar Irradiance (W/m^2) at the Test Site for the Month of June, 2019

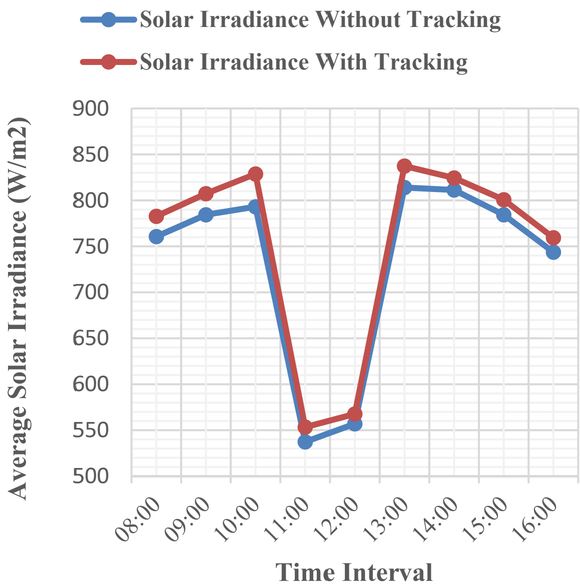

Figure 6. Average Solar Irradiance (W/m^2) at the Test Site for the Month of July, 2019

5. Conclusions and Recommendation

5.1 Conclusions

The performance of dual-axis tracking and stationary solar module was evaluated, and the following conclusions were drawn:

i. The tracking module is extracting more amount of solar irradiance than fixed module.
ii. At noontime, both modules were producing higher amount of solar irradiance.
iii. Rainfall and Cloud affected the performance of both modules.

5.2 Recommendation

To track the sun trajectory in the solar tracking system developed, operator has to be coming out and change the solar altitude and solar azimuth angles so as to optimize the maximum solar irradiance of the day accordingly. Therefore, it was recommended to develop this type of tracking system with automatic controls.

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APPENDICES

Appendix A: The Calculated Solar Altitude and Azimuth Angles of the Experimental Days

Table A1: The Calculated Solar Altitude and Azimuth Angles for the Month of May, 2019

	Fri. 17th May, 2019		Sat. 18th May, 2019		Sun. 19th June, 2019	
Time	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)
8:00	39	-105	32	-106	30	-106
9:00	55	-106	46	-106	43	-106
10:00	59	-111	60	-108	56	-103
11:00	66	-116	74	-119	74	-119
12:00	73	-121	83	177	83	177
13:00	66	-116	74	119	74	119
14:00	59	110	60	108	60	108
15:00	55	106	46	106	46	106
16:00	39	105	32	106	32	106
17:00	24	106	18	107	18	107

Table A2: The Calculated Solar Altitude and Azimuth Angles for the Month of June 2019

	Mon. 10th June, 2019		Wed. 12nd June, 2019		Tue. 11st June, 2019	
Time	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)
8:00	50	43	46	50	43	56
9:00	3	205	6	169	8	152
10:00	13	116	15	113	16	111
11:00	43	51	40	58	38	63
12:00	-11	128	-6	163	-3	213
13:00	43	51	40	58	38	63
14:00	13	116	15	113	16	111
15:00	3	205	6	169	8	152
16:00	50	43	46	50	43	56
17:00	-8	142	-4	185	-1	272

Table A3: The Calculated Solar Altitude and Azimuth Angles for the Month of July, 2019

	Thu. 25th July, 2019		Fri. 26th July, 2019		Sat 27th July, 2019	
Time	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)	Altitude Angle α (Degree)	Azimuth Angle ψ (Degree)
8:00	-63	54	4	71	-72	86
9:00	7	143	10	102	23	125
10:00	-8	131	-7	124	3	131
11:00	-50	41	-58	63	-51	81
12:00	26	55	33	149	55	98
13:00	-50	41	-58	63	-51	81
14:00	-8	131	-7	124	3	131
15:00	7	143	10	102	23	125
16:00	-63	54	4	71	-72	86
17:00	23	66	29	172	48	-11

Appendix B: Experimental Results of Solar Irradiance for the Three Month of the Test

Table B1: Solar Irradiance Measured on Friday 17th, Saturday 18th, Sunday 19th May, 2019

	Friday 17th May, 2019		Saturday 18th May, 2019		Sunday 18th May, 2019	
Time	Solar Irradiance with Tracking	Solar Irradiance without Tracking	Solar Irradiance with Tracking	Solar Irradiance without Tracking	Solar Irradiance with Tracking	Solar Irradiance without Tracking
08:00	825	703	1014	840	994	982
09:00	993	736	1076	904	1070	1019
10:00	1057	769	1143	957	1138	1042
11:00	1168	814	1175	981	1170	1068
12:00	1187	858	1198	1009	1192	1099
13:00	1180	820	1187	998	1180	1075
14:00	1076	795	1164	972	1159	1052
15:00	1059	770	1099	947	1092	1029
16:00	1053	743	1062	896	1057	1001
17:00	999	730	1006	859	998	986
Total	10597	7738	11124	9363	11050	10353

Table B2: Average Solar Irradiance for Three Days Test of May, 2019

Time	Solar Irradiance With Tracking	Solar Irradiance Without Tracking	Percentage Change
8:00	944.3333	841.6667	10.87187
9:00	1046.333	886.3333	15.29149
10:00	1112.667	922.6667	17.07609
11:00	1171	954.3333	18.5027
12:00	1192.333	988.6667	17.08135
13:00	1182.333	964.3333	18.43812
14:00	1133	939.6667	17.06384
15:00	1083.333	915.3333	15.50769
16:00	1057.333	880	16.77175
17:00	1001	858.3333	14.25241
Total	10923.67	9151.333	16.22471

Table B3: Solar Irradiance Measured on Monday 10th, Tuesday 11st, Wednesday 12nd June, 2019

	Mon. 10th June, 2019		Tue. 11st June, 2019		Wed. 12nd June, 2019	
Time	Solar Irradiance Without Tracking	Solar Irradiance With Tracking	Solar Irradiance Without Tracking	Solar Irradiance With Tracking	Solar Irradiance Without Tracking	Solar Irradiance With Tracking
08:00	762	802	596	664	-	-
09:00	806	820	621	689	-	-
10:00	941	963	647	703	-	-
11:00	994	1007	672	727	347	353
12:00	1020	1034	708	748	359	369
13:00	1035	1048	729	754	371	377
14:00	1016	1029	725	739	374	381
15:00	1008	1017	710	731	362	370
16:00	974	989	663	706	357	365
17:00	792	823	632	690	342	351
Total	9348	9532	6703	7151	2512	2566

Table B4: Average Solar Irradiance for Three Days Test of June, 2019

Time	Solar Irradiance Without Tracking	Solar Irradiance With Tracking	Percentage Change
08:00	452.667	488.667	7.36698
09:00	475.667	503	5.43406
10:00	529.333	555.333	4.68187
11:00	671	695.667	3.54576
12:00	695.667	717	2.97536
13:00	711.667	726.333	2.01927
14:00	705	716.333	1.58213
15:00	693.333	706	1.79415
16:00	664.667	686.667	3.20388
17:00	588.667	621.333	5.25751
Total	6187.67	6416.33	3.56382

Table B5: Solar Irradiance Measured on Thursday 25th, Friday 26th, Saturday 27th July, 2019

	Thur. 25th July, 2019		Fri. 26st July, 2019		Sat. 27th July, 2019	
Time	Solar Irradiance without Tracking	Solar Irradiance with Tracking	Solar Irradiance Without Tracking	Solar Irradiance With Tracking	Solar Irradiance Without Tracking	Solar Irradiance With Tracking
08:00	794	824	790	806	698	718
09:00	829	849	817	837	707	736
10:00	823	875	832	852	724	759
11:00	0	0	853	886	759	774
12:00	0	0	890	905	781	798
13:00	722	737	917	956	803	819
14:00	718	731	922	938	794	804
15:00	689	703	904	916	760	783
16:00	631	648	879	893	721	737
17:00	578	595	699	718	699	715
Total	5784	5962	8503	8707	7446	7643

Table B6: Average Solar Irradiance for Three Days Test of July, 2019

Time	Solar Irradiance without Tracking	Solar Irradiance with Tracking	Percentage Change
08:00	760.667	782.667	2.8109
09:00	784.333	807.333	2.84889
10:00	793	828.667	4.3041
11:00	537.333	553.333	2.89157
12:00	557	567.667	1.87904
13:00	814	837.333	2.78662
14:00	811.333	824.333	1.57703
15:00	784.333	800.667	2.03997
16:00	743.667	759.333	2.06321
17:00	658.667	676	2.5641
Total	7244.33	7437.33	2.59502