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Determination of the Optimal Tilt and Azimuth Angle for a Solar Tracking System considering Different Climatic Conditions

Big-Alabo Ameze [a,*] and Imaga Johnson Chigozirim[a]

[a] Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Port Harcourt, Port Harcourt, Nigeria

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Abstract

One of the major challenges faced in photovoltaic technology is the ability to harvest as much energy as possible from the sun. The peculiarity in geographic location and the sun's movement has made it difficult to get maximum irradiation from the sun. The aim of this study is to improve the efficiency of photovoltaic power generated by optimizing the altitude and azimuth of a square meter PV module and also, develop an algorithm that helps the panel to track the position of the sun for optimum power generation. University of Port Harcourt, Nigeria was used as the location chosen for this study. The results obtained present the Optimal Angles and Maximum Irradiation for 2015 to 2019. For example the optimal tilt angle for a year 2019 was 6^o with a maximum irradiance of 1.62×10^3 Wh/m^2. The azimuth angle varied from 316^o to 334^o. The contribution of this study, is that the calculated optimal tilt angle considered all the three components of the irradiance: diffuse, direct and albedo irradiance. The obtained optimal tilt and azimuth angles were then used to design both fixed and dual axis maximum power point tracking system. Thereafter, comparative analyses for both systems were conducted considering four significant climatic days: (1) The Winter Solstice (2) Summer Solstice (3) Vernal and (4) Autumnal Equinoxes:

Keywords: Maximum power point tracking; Optimal Tilt angle; Azimuth Angle; photovoltaic systems; Maximum Irradiation

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1. Introduction

Installation of solar panels in such a way that it can harvest as much energy as possible from the sun is one of the major challenges faced in photovoltaic technology as deviation in the optimal tilt angle also affects the total irradiance generated from the sun. Also, the cost of the materials such as solar panels and batteries is still an expensive investment considering the percentage efficiency of these panels as they harvest little from the sun. The variation in weather from location to location and time to time, makes the amount of sunlight uncertain for solar

*Corresponding Author Email Address:amezeodia@yahoo.com

panels. Studies [1, 2] have shown that the direct solar irradiance have significant influence on PV output. Furthermore, both theoretical [3] and experimental studies [4, 5] have been conducted to determine the optimum panels' tilt angle. Moreover, reviews have been conducted on the Tilt and azimuth angles in solar energy applications [6].

This study presents the assessment of the optimal tilt angle and azimuth angle of the location of study for the PV modules. In addition to this, an algorithm is developed for a mechanical tracking system using the ascertained optimal tilt angle and azimuth angle. Meteorological data for a period of 26 years (1994 – 2020) was collected from Solargiss.r.o (Solar resource data © 2020 Solargis). Matlab/Simulink software was used for analysis in order to determine the optimal operation of PV module to harvest greater energy from the sun more efficiently.

2. Review of Related Searches

Solar tracking systems are used to increase the amount of electric power generated from solar panels. Tracking devices are of two types – dual axis and single axis. The tracking mechanism of the ***single axis*** tracker involves the movement of the panel in only one axis. This is either horizontal when it is observed that the sun is much at noon or the vertical axis which is mainly used in period of average sun intensity and long summer. A Single-Axis Solar Tracking System and Monitoring Software have been reviewed [7, 8] and also conducted [9 –12] with the aim of increasing energy generation of the photovoltaic (PV) panels.

Dual axis is designed to track the sun both at axis (horizontal and vertical). This mechanism enables it to follow the sun at whichever angle it faces. The efficiency is improved significantly when using this mechanism as the panel faces directly to the sun at the optimum point. This makes it better than the single axis tracking system. Tracking mathematic expressions of the sun-earth geometric relationships and a predicted solar radiation model has been used for the performance analysis of a single-axis tracking system [11].

The tracking system helps to reduce the angle of incidence of the sun on the panels. The more the angle, the lesser the power generated. For the purpose of this study, the PV system is modelled to track the sun in dua3,2l axis in order to achieve higher efficiency result. The results are compared with that of a fixed optimal tilted Photovoltaic solar panel.

3. Methodology

3.1. Description of study area

The study area, University of Port Harcourt, Rivers State is located in South-South Nigeria. It is situated 16 meters above sea level. The study area has two major seasons namely the wet and dry seasons, with the rainy season from April to November while the dry season is from December to February. University of Port Harcourt is located 4.906900 latitude and 6.917000 longitude. Its warmest period is from February to April. Nigeria is exposed to the sun's rays throughout the year with long hours during the days.

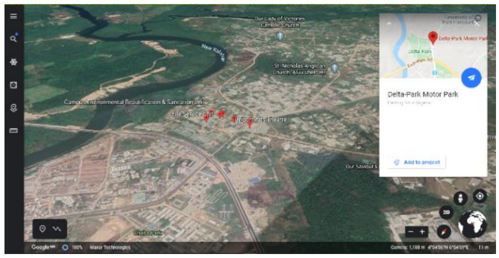

Figure 3.1. Satellite photo of Delta Motor park, University of Port Harcourt

According to researchers [13], the increase in irradiation when using mechanical tracking systems has been tripled during winter and increased by half during clear days as compared to when the PV panels are static. The value of this gain is much during the summer than it is in the winter due to the fact that at summer, there are more clear days than in the winter where harvest of the sun is generally low due to the nature of the weather.

3.2. Irradiances of Study Area

Long term average yearly value of GHI in University of Port Harcourt calculated by Solargis from time series representing 26 calendar years i.e. from 1994 to 2020 shows the average Global Horizontal Irradiance (GHI) to be 1631 kilo-watt hour per square meters.

Figures 3.1 - 3.3 below show the monthly and yearly sum of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and Diffused Horizontal Irradiance (DHI) of the study area respectively. Background color of cells in the 'Year' column represent the following: grey color – yearly column is within the standard deviation band – a normal year, red and blue color is kept to indicate exceptional years where there is deviation from the normal values. Red means higher than normal while blue means lower than normal.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
1994	147	142	155	145	140	120	100	128	131	131	143	160	1642	1994
1995	141	140	144	146	143	132	117	122	135	138	142	137	1637	1995
1996	145	143	136	147	149	126	127	116	125	140	149	141	1644	1996
1997	134	144	135	145	140	113	120	119	142	144	117	145	1598	1997
1998	150	144	144	152	159	137	123	137	123	140	126	144	1678	1998
1999	143	127	155	136	149	125	129	139	126	130	126	133	1618	1999
2000	143	145	141	141	145	121	118	124	123	133	138	162	1634	2000
2001	159	125	146	148	143	128	126	116	135	136	137	158	1657	2001
2002	137	133	136	138	147	126	121	116	138	131	144	158	1625	2002
2003	151	134	132	156	140	120	129	133	129	145	136	149	1655	2003
2004	135	135	129	133	138	125	116	132	142	143	135	149	1612	2004
2005	141	134	139	151	143	116	103	126	125	142	156	150	1625	2005
2006	138	129	133	153	142	142	114	123	117	143	144	149	1628	2006
2007	146	130	147	138	159	124	130	131	128	141	139	149	1660	2007
2008	149	125	143	143	146	124	132	129	124	143	152	146	1657	2008
2009	133	131	136	144	155	133	119	102	128	139	141	163	1624	2009
2010	151	143	126	150	139	117	129	117	124	139	134	161	1630	2010
2011	148	124	152	145	133	108	107	119	126	128	143	151	1583	2011
2012	132	119	145	148	151	120	118	136	134	136	135	153	1628	2012
2013	150	127	141	148	146	115	115	135	123	135	130	153	1619	2013
2014	150	133	135	151	153	118	119	133	131	142	139	153	1656	2014
2015	139	131	127	149	147	112	111	120	124	135	145	161	1601	2015
2016	150	140	129	144	150	132	113	123	126	144	143	141	1635	2016
2017	134	136	135	151	139	124	123	112	132	135	144	141	1606	2017
2018	150	120	131	133	146	139	121	135	136	138	131	160	1637	2018
2019	138	128	141	147	146	120	114	138	123	135	137	157	1624	2019
2020	150	--	--	--	--	--	--	--	--	--	--	--	--	2020
LTA	143	133	139	145	146	124	119	126	129	138	139	151	1631	

Figure 3.1. Global Horizontal Irradiance for University of Port Harcourt from January 1994 to January 2020

3.2.1 Diffused Horizontal Irradiance

Monthly and yearly summary of the diffused horizontal irradiance(DHI) of the study area within the period stated below.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
1994	100	94	101	93	87	79	77	87	82	82	89	98	1069	1994
1995	99	96	99	89	86	82	81	84	81	82	94	96	1067	1995
1996	101	97	95	89	84	84	84	85	80	87	99	101	1085	1996
1997	97	97	96	88	80	80	83	85	81	83	77	98	1044	1997
1998	101	96	104	89	89	77	79	88	77	89	87	93	1069	1998
1999	97	91	99	89	79	81	82	85	76	80	83	94	1038	1999
2000	99	99	102	93	90	82	83	88	80	82	89	92	1082	2000
2001	102	84	99	90	85	79	86	87	85	85	89	92	1064	2001
2002	94	91	99	94	89	77	82	84	85	84	88	95	1061	2002
2003	96	94	100	90	86	76	81	91	81	84	85	93	1057	2003
2004	96	96	94	85	90	81	80	92	84	85	85	95	1063	2004
2005	98	92	96	95	82	78	78	89	82	85	87	94	1056	2005
2006	100	90	93	94	85	80	82	88	80	86	86	99	1061	2006
2007	99	90	101	83	79	79	83	88	77	86	84	94	1045	2007
2008	99	90	97	86	85	81	86	82	82	84	88	92	1052	2008
2009	94	88	100	86	87	80	83	79	83	81	84	96	1040	2009
2010	101	91	89	93	86	78	84	82	80	82	81	93	1040	2010
2011	101	87	99	97	85	78	80	89	84	80	85	96	1060	2011
2012	94	87	103	91	87	77	82	90	81	83	82	95	1053	2012
2013	98	91	94	88	86	78	87	95	82	83	82	94	1059	2013
2014	101	94	93	88	87	75	88	89	84	85	83	96	1065	2014
2015	97	88	94	91	87	82	83	90	84	83	83	96	1057	2015
2016	99	97	93	86	86	82	80	89	84	83	86	92	1059	2016
2017	96	94	96	93	82	77	84	85	82	84	88	94	1055	2017
2018	100	86	92	84	89	83	80	89	77	81	81	96	1037	2018
2019	98	88	95	91	84	80	81	85	80	79	83	94	1039	2019
2020	99	--	--	--	--	--	--	--	--	--	--	--	--	2020
LTA	98	92	97	90	85	80	82	87	81	83	86	95	1057	

Figure 3.2. Diffused Solar Irradiance for University of Port Harcourt from January 1994 to January 2020

3.2.2 Direct Normal Irradiance

Monthly and yearly summary of the direct normal irradiance (DNI) of the study area within the period stated below.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
1994	62	60	66	65	71	57	32	55	67	68	72	85	760	1994
1995	56	57	56	72	77	68	49	50	71	74	64	56	750	1995
1996	60	58	50	73	89	56	55	41	56	71	65	55	729	1996
1997	49	59	47	76	83	46	48	44	80	84	58	65	738	1997
1998	65	61	48	80	91	80	60	66	61	69	52	71	806	1998
1999	61	45	68	57	95	63	63	71	63	66	59	51	762	1999
2000	58	58	47	61	73	53	46	45	55	68	68	99	731	2000
2001	77	51	56	73	77	69	56	36	64	69	65	94	787	2001
2002	56	54	44	54	77	68	56	40	70	64	77	88	749	2002
2003	75	52	39	84	72	61	63	55	64	83	69	77	794	2003
2004	52	50	42	63	64	58	49	50	77	77	71	75	728	2004
2005	57	54	53	70	81	53	34	51	59	78	95	77	763	2005
2006	52	50	50	75	80	82	45	49	52	79	78	69	761	2006
2007	62	50	55	72	107	67	64	56	70	78	76	75	831	2007
2008	66	43	59	72	83	59	63	61	59	83	88	75	810	2008
2009	52	55	44	74	90	73	50	33	64	84	79	95	794	2009
2010	66	66	46	72	71	53	60	47	63	78	75	96	793	2010
2011	62	47	66	59	65	41	38	44	59	68	80	76	705	2011
2012	50	40	51	71	85	59	49	62	74	75	75	81	771	2012
2013	69	45	59	77	81	50	40	54	60	74	68	81	759	2013
2014	67	49	52	80	89	60	44	60	65	82	81	80	807	2014
2015	57	55	41	71	80	43	41	48	59	76	89	89	750	2015
2016	68	54	44	76	85	70	46	45	61	83	78	67	777	2016
2017	51	53	47	74	76	64	54	36	66	71	75	64	731	2017
2018	66	43	48	63	76	75	57	62	79	78	69	88	803	2018
2019	53	50	57	73	84	57	45	70	57	75	72	87	780	2019
2020	68	--	--	--	--	--	--	--	--	--	--	--	--	2020
LTA	60	52	51	71	81	61	50	51	64	75	73	78	768	

Figure 3.3. Direct Normal Irradiance for University of Port Harcourt from January 1994 to January 2020

3.3 Determination of the Optimal Tilt Angle

In order to get the best from our solar panels, there is need to position them as accurate as possible to the direction where the sun irradiation is maximized. In finding the optimal tilt angle, the module azimuth(Am) and tilt angle (Θ_m) throughout the year irradiation is studied to investigate the orientation that yields the highest energy. Module azimuth is the angle from the North measuring Eastward to the sun on the observer horizontal plane. It varies from 0^o (North) to 360^o (the starting point). Tilt angle (Θ_m): This is the angular elevation of the position of the sun from the horizontal disk

3.3.1. Calculation of the AOI, SVF, Direct, Diffused & Albedo Irradiances

Some studies [14, 15] have used the latitude of the location as tilt angle. However, using the latitude of the study area as the tilt angle only enhances the direct component of the irradiance. Hence maximum efficiency will not be achieved. In this study all three components: direct, diffuse and albedo irradiances are considered as follows:

AOI – Angle of Incidence which is the angle the rays of sun make with the normal of the PV module.

a_m = altitude/elevation angle of the module.

A_m = Azimuth of the module

$AOI = \cos^{-1}[\cos a_m \cos a_s \cos(A_m - A_s) + \sin a_m \sin a_s]$

$SVF = (1 - \cos(tilt\ angle))/2$

Irradiance - $G_{DIRECT} = DNI \cos(AOI)$

Diffused Irradiance - $G_{diffused} = SVF \times DHI$

Albedo Irradiance - $G_{Albedo} = GHI \times a(alpha) \times (1 - SVF)$

Where alpha is the albedo coefficient which is a measure of the nature of the ground or reflecting environment.

3.3.2. Tracking The Sun

The optimal global radiation received by the tracked panel is obtained through properly driving the PV panel to rotate around the rotation axis. The predicted radiation model mentioned above for calculating solar radiation incident upon the tracking surface was developed and simulated using MATLAB. It tracks the daily radiation during sun hours

The required input data for the calculation are presented in Table 3.1:

n – this is the number of the day. This varies from 1 to 365 which accounts for the number of days in a year.

L – latitude of the location

Lo - longitude of the location

Lo std – longitude of the capital as reference.

s – tilt angle. This is obtained from the previous MATLAB model for calculating tilt angles.

ro_g – Albedo coefficient. This is a value of the ground reflection and depends on the surrounding environment.

Table 3.1: Input Values for the Tracking Panel

n	**L**	**Lo**	Lo std	**s**	**ro_g**
1 - 365	4.9069	6.917	7.3986	4 or 6	0.2

4. Results and Discussion

There are two phases of this result – Optimal angles and Mechanical tracking. The first result contains the total irradiances obtained for year 2015 through 2019. There were variations in the realised total irradiances for each as shown in Table 4.1. This is as a result of the different optimal angles for the years. The second result revealed the effect of the mechanical tracking system as compared with the fixed panels.

4.1. Optimal Tilt angles

A contour plot of the azimuth angle on the horizontal and the tilt angle on the vertical provides us with information about the energy distribution as the angle varies. The tilt and azimuth angle that correspond with the area that there is maximum energy is the optimal angles that the PV module should be positioned. The sun irradiance increases from the region of deep blue colour to the region of deep red colour.

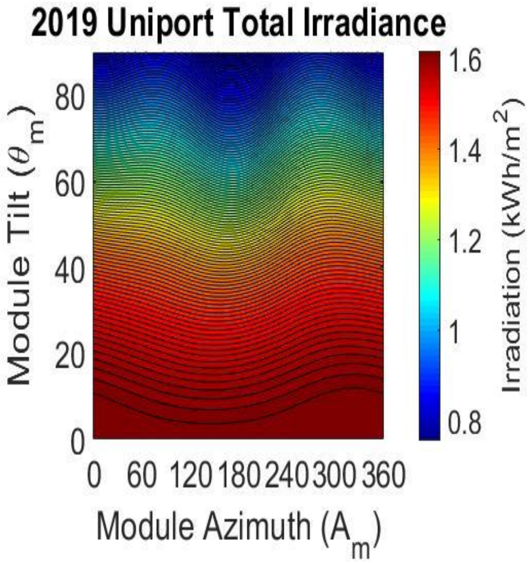

Figure 4.1: 2019 Total Irradiance

Figure 4.1 shows a contour graph of total irradiance (diffuse irradiance, direct irradiance and albedo irradiance) distribution on a square meter fixed solar panel for the year 2019. Similarly, plots were obtained for the other previous years represented in Table 4.1 below. It shows different yearly irradiation obtained when varying the panel tilt angle from 0^o to 90^o while the Azimuth angle is varied from 0^o at the North to 360^o. The colour bar representation shows the intensity of the irradiation as these angles were varied. The dark blue represents minimum irradiation while the dark red shows when the irradiation was at maximum. The angles that correspond with the highest irradiation are the optimal tilt and azimuth angles for the years analysed.

Table 4.1: Optimal Angles and Maximum Irradiation for 2015 - 2019

	2015	2016	2017	2018	2019
Max_Irradiation (10^3 Wh/m^2)	1.6024	1.6357	1.6053	1.6376	1.6245
Optimal Tilt Angle	6	4	4	4	4
Optimal Azimuth Angle	334	320	320	316	324

From Table 4.1 above, the maximum irradiation slightly varied for each year. This irradiation is as a result of the diffused, direct and albedo irradiance with the diffused irradiance having the maximum contribution.

Separate analysis of the three irradiances for 2019 shows that the direct irradiance contributed a maximum of 587 Wh/m^2, albedo irradiance has a maximum value of 162 Wh/m^2 and the diffused irradiance with a value of 1.039kWh/m^2. This accounted for the total irradiance of 1.6245 kWh/m^2 recorded for the year. See Table 4.2 below.

Table 4.2: Irradiation Distribution for 2019 Analysis

Direct Irradiance	Diffused Irradiance	Albedo Irradiance
587	1039	162

The same distribution pattern was observed for other years, analysed and the diffused irradiances recorded the highest values.

4.2 Mechanical Tracking Systems Versus Fixed Panel

Mechanical Tracking System has the ability to continually adjust the position of the module as the sun position changes to maximize the incident irradiance. This system can be divided into single or dual axis. The single axis has one rotational axis while the dual axis has two rotational axes as the name implies. The tracking system is made of an electric motor which is controlled by a computer system. This computer system has an algorithm that makes the panel to follow the sun. The algorithm is made of the coordinate of the location, the day and the time to compute the position of the sun. The dual axes with two degree of freedom are: The axis that is parallel to the ground and changes only the tilt angle and the axis that is perpendicular to the ground and changes the azimuth of the panel.

This study considers four significant solar days: (1) The Winter Solstice (2) Summer Solstice (3) Vernal and (4) Autumnal Equinoxes:

The Winter Solstice – The peculiarity of this day is that it has the shortest daylight and the longest night. This makes it to have the fewest sunshine hour in the year. This is usually December 21st or 22nd for locations in Northern Hemisphere and June 20th or 21st for location in the Southern Hemisphere. Plots are generated for optimal tilt angles of 4° and 6° (see figure 4.2)

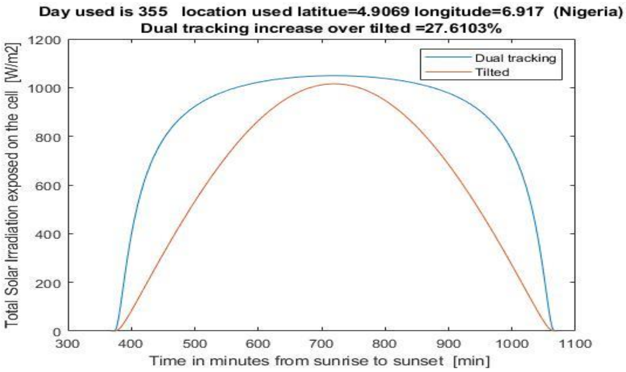

Fig 4.2: Plot of Daylight hour for Dec 21st for Optimal Tilt angle of 4°

Summer Solstice – This day is known to have the longest sunshine hour as the sun travels the longest path through the sky. In the Northern Hemisphere, it is June 20th or 21st while it is December 21st or 22nd in the Southern Hemisphere. Plots are generated for optimal tilt angles of 4° and 6° (see figure 4.3)

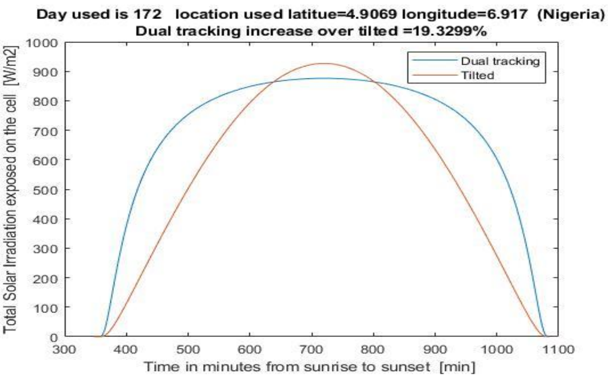

Fig. 4.3: Plot of Daylight hour for June 21st for (a) Optimal Tilt angle of 4°

Vernal and Autumnal Equinoxes takes place when the sun is directly above the equator. It records equal day and night. It occurs in March 20th or 21st and September 22nd or 23rd. Plots are generated the 80th Day and 264th day since both days are expected to have the sun directly above the equator (see figure 4.4)

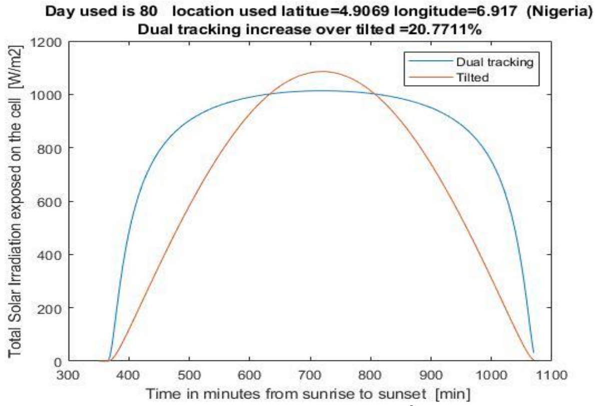

Fig 4.4: Plot of Daylight hour in the 80th Day

Similar plots can be gotten for the other days of the year by simply changing the value of “n” in the MATLAB programme.

When all the days in the year were modelled and the result compared, it was observed that a significant improvement in the irradiation was recovered by the mechanical tracking system than that of the fixed panels. Also from these plots (Figures 4.2 - 4.4), it can be seen that more solar radiation is absorbed during the summer months than in the winter months [16].

5. Conclusion

The determination of the tilt angle of a photovoltaic system plays a significant role in its performance. The panel can either be fixed at an optimal tilt angle or continuously adjusted using a solar tracking system [17]. This study presents the design of the optimal tilt angle and azimuth angle of the PV modules, using the University of Port Harcourt, Nigeria as the location of study. An algorithm is developed for a mechanical tracking system using the ascertained optimal tilt angle and azimuth angle. The uniqueness of this study is that the calculated optimal tilt angle considered all the three components of the irradiance: diffuse, direct and albedo irradiance. The obtained optimal tilt and azimuth angles are then used to design both fixed and dual axis maximum power point tracking system. Comparative analyses for both systems were conducted considering four significant climatic days: (1) The Winter Solstice (2) Summer Solstice (3) Vernal and (4) Autumnal Equinoxes:

When all the days in the year were modelled and the result compared, it was observed that a significant improvement in the irradiation was recovered by the mechanical tracking system than that of the fixed panels. Also it was seen that more solar radiation is absorbed during the summer months than in the winter months.

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