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Research article

Estimation of Solar Panel Orientation with Different Tilt Angles at Haramaya University

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Abstract

This study evaluated the performance of the solar panels at different North – South tilt angles and East – West Orientation angles during spring of 2013. The three solar panels of 4 Watts capacity each were placed on manual tracker to facilitate changing tilt and orientation angles independently. The experiment was done for one week in each month, and each first day was devoted to measure voltages for different tilt angles by changing the angles from 0° to 45° in steps of 3°, zero indicating horizontal position. During the remaining six days of the week of every month, the middle solar panel was fixed at tilt angle that yielded maximum power while the orientations of both east-facing and west panels were changed from 0° to 90° in steps of 5°angle with respect to middle solar panel, zero indicating same plane position with respect to middle solar panel. A digital multi-meter was used to record the circuit voltage of the solar panels with 10Ω resistor serving as a load. Data collection was done every 15 minutes, from 8:00 am till 5:00 pm. The study revealed that the maximum power output was obtained at the tilt angle of 3° in March and May, and 0° in April and the seasonal average tilt was found to be 3°. Maximum solar power outputs were obtained when solar panels facing east and west were oriented between 0° and 5°. This suggests that tilt angle of 3° and 0° to 5° is considered as suitable orientation angle for optimum seasonal power production at this geographical location.

Key words: Solar Panel, Tilt Angle, East/West Orientation Angle, Solar Power

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1. Introduction

A photovoltaic (PV) system should be installed to maximize the solar contribution to a particular load. Optimum PV inclination and orientation depends on local climate, load consumption temporal profile and latitude (Jayanta *et al.*, 2006). Generally, a surface with tilt angle equal to the latitude of a location receives maximum insolation. However, some locations experience a weather pattern where winter is typically cloudier than summer or the average morning and afternoon insolation is not symmetric. The maximum available energy may then be received by a surface whose azimuth angle is either east or west of due south (in the Northern hemisphere). The optimum tilt angle is thus site dependent and calculation of this angle requires solar radiation data for that particular site for the whole year. Normally, during summer, the incident insolation is maximized for a surface with an inclination 10–15^o less than and during winter, 10–15^{o}more than the latitude (Duffie and Beckman, 1991).

Ethiopia is rapidly increasing its energy consumption and is short on energy supplies. Ethiopia is one of the Horn of African countries located between 33^o and 48^o East longitudes and between 3^o and 15^o North latitude. It has a diverse climatic condition due to the contrasting altitude, which ranges from the highest point of 4650 meters above sea level at Ras Dashen Mountain to 420 meters below sea level at Dallol Depression. Fortunately, Ethiopia is located in that part of the world where sun shines for maximum number of hours (Sharew, 2007). It is, therefore, a matter of interest to assess the significance of solar energy and its utilization in different fields of applications.

The amount of solar energy incident on a solar panel in various time scales is a complex function of many factors including the local radiation latitude, longitude, location of the earth with respect to the sun at different time of year, the orientation and tilt of the exposed solar panel surface and the ground reflection properties. The performance of a solar panel is highly influenced by its East – West orientation and its North – south angle of tilt. This is due to the fact that both the orientation and tilt angle change the solar radiation reaching the surface of the panel. This study tried to estimate the orientations of solar panel with different tilt angles in the spring season to maximize the amount of solar power. Specifically;

- To find out north-south tilt angle that results in maximum daily solar panel power in spring season of the year.
- To find out east-west orientations that result in maximum PV solar power output for the location in spring season of the year.
- To determine the east-west and north-south orientation that result in maximum daily solar panel power output during the season.
- To determine the east-west orientations that result in nearly equal power output during the season.

3. Methodology

3.1. Description of the Study Area

The study was conducted at Haramaya University, which is located at 515 km east of Addis Ababa, Ethiopia, at an average altitude of 1950 meter above sea level with latitude of 9^{o}25'22"N and longitude of 42^{o}2'6"E. The place has a mean maximum temperature of 28.5^{0}C and mean minimum temperature of 12.6^{o}C. It is situated in the semi-arid tropical belt of eastern Ethiopia and is characterized by a sub-humid type of climate with an average annual rainfall of about 790 mm.

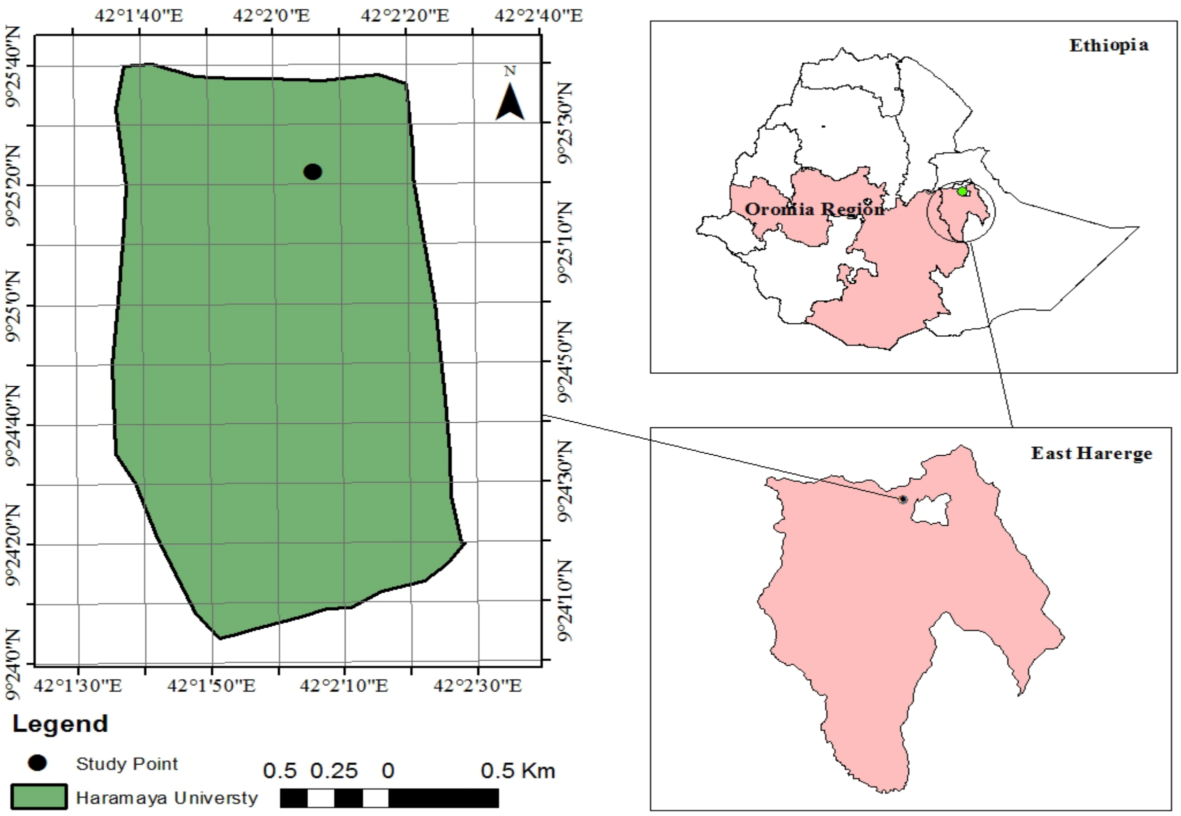


Figure 1. Map of the study area

During days when the data were collected the values of the Julian Day number, declination, hour, and solar altitude angle and day length are summarized in Table 1. Atmospheric conditions in terms of pollution and cloud movement have a bearing on a given day but they were not determined during this research work.

Table 1. Declination angle on each day measurements were taken

Month	Day	Julian Day No	Declination	Day length
March	16/03/2013	75	-2.49645	11.99471
	17/03/2013	76	-2.09400	11.97988
	18/03/2013	77	-1.69094	11.88085
	19/03/2013	78	-1.28737	12.05799
	20/03/2013	79	-0.88342	12.02450
	21/03/2013	80	-0.47922	12.01394
	22/03/2013	81	-0.07486	12.00722
April	14/04/2013	104	8.99084	12.01309
	15/04/2013	105	9.36312	12.00702
	16/04/2013	106	9.73262	12.00128
	17/04/2013	107	10.09925	11.99400
	18/04/2013	108	10.46288	11.98044
	19/04/2013	109	10.82342	11.91914
	20/04/2013	110	11.18075	12.08679
May	14/05/2013	134	18.53716	12.01097
	15/05/2013	135	18.78300	12.00709
	16/05/2013	136	19.02329	12.00343

	17/05/2013	137	19.25794	11.99954
	18/05/2013	138	19.48690	11.99489
	19/05/2013	139	19.71008	11.98851
	20/05/2013	140	19.92743	11.97794

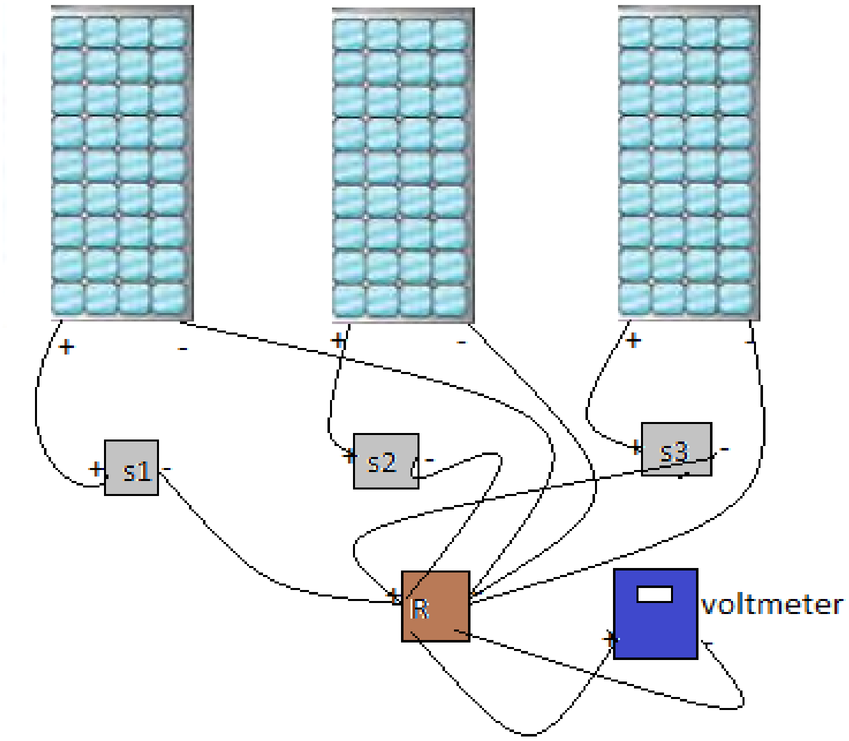
From Table 1 declination angle of the sun with respect to earth during the date of tilt angle measured is -2.49645^o in March, 8.99084^o in April, and 18.53716^o in May. This shows the sun was in the southern hemisphere in March, over head in April and nearly inclined towards North from the area where data was collected in May. Thus, the tilt angle of solar panel decreased from March to May. The tilt of the earth's axis of rotation causes one hemisphere to be illuminated more than the other. This result in differences in the length of day compared to the length of night. On the day when the day is longest in the northern hemisphere it is shortest in the southern hemisphere and vice versa.

3.2. Experimental Setup

Figure 9 shows a photographic illustration of the experimental setup. Three identical solar panels of monocrystal silicon type solar cells (Europe Panneau Solaire solar module), identified as SR01216253 (middle), SR01216488 (east facing) and SR01216758 (west facing) each with dimensions of 294x184x23mm were used. Individual module had the following specifications. Maximum power 4W, open circuit voltage (V_{oc}) = 22V, short circuit current (I_{sc}) =0.52A, voltage at maximum power (V_{pmax}) =17.8V, current at maximum power (I_{pmax}) =0.23A and conditions STC for the normal solar radiation intake intensity of 1000 W/m^2, 1.5Aat temperature T= 25°C. Each Module was used in the experiment and installed on the same altitude (place), as shown figure 9. The three modules were installed on a revolving pedestal, with the rotational axis, which enables changing of the position of the solar module from North to South and East to West. The gap between the two panels was 0.046m and the bottom row of panels (rack) was raised 0.55m above the ground.

(a)

The three solar panels were connected to 10Ω resistors together and three switches were used to close/open the circuit and to take voltage measurement of each module independently. Digital Multi-meter was used to read voltage. The base which carries the three panels was put on a table, and the table was made horizontal by water level. The true North- South and East-West direction were arranged by GPS of iP-hone device.The solar panel were orientated parallel to this direction resulting in an orientation angle of 0°. Magnetic declination, the angle difference between magnetic south and true solar south were taken into account when determining proper solar array orientation.



* s1, s2 and s3 are switches and R is resistor
(b)

Figure 2. (a) Experimental setup and (b) Circuit connection;

3.3. Experimental Work

The experiment was done for one week in each month, and each first day was used to determine tilt angle that gives best PV power output. A position of solar modules was changed around the axis in relation to horizontal plane from 0° to 45°, zero indicating horizontal position (horizon). During the remaining six days of the week, the middle solar panel (SR01216253) was fixed at this tilt angle while the other two panels (SR01216488 and SR01216758) were oriented to the true East and true West, respectively. Since solar modules of east and west facing were installed on a revolving pedestal, with the rotational axis, the position of the solar modules could be changed from 0° to 90° angle with respect to middle solar panel, zero indicating same plane position.

3.4. Calibration of Solar Panels

The three solar panels were calibrated using standard light sensors LX-1010B Digital Lux Meter with its general specifications:-Ranges: 1-50,000Lux, Calibrated to standard incandescent lamp at color temperature 2856K, Dimension: 106×57×26mm (photo detector), 230×72×30mm (meter body), 150cm (photo detector lead). For a meaningful and accurate measurement of efficiency the irradiance is measured with a solar panel whose power is calibrated with respect to a standard device. Natural sunlight intensity measured by LX-1010B Lux meter and intensity from solar panel is plotted as follows;

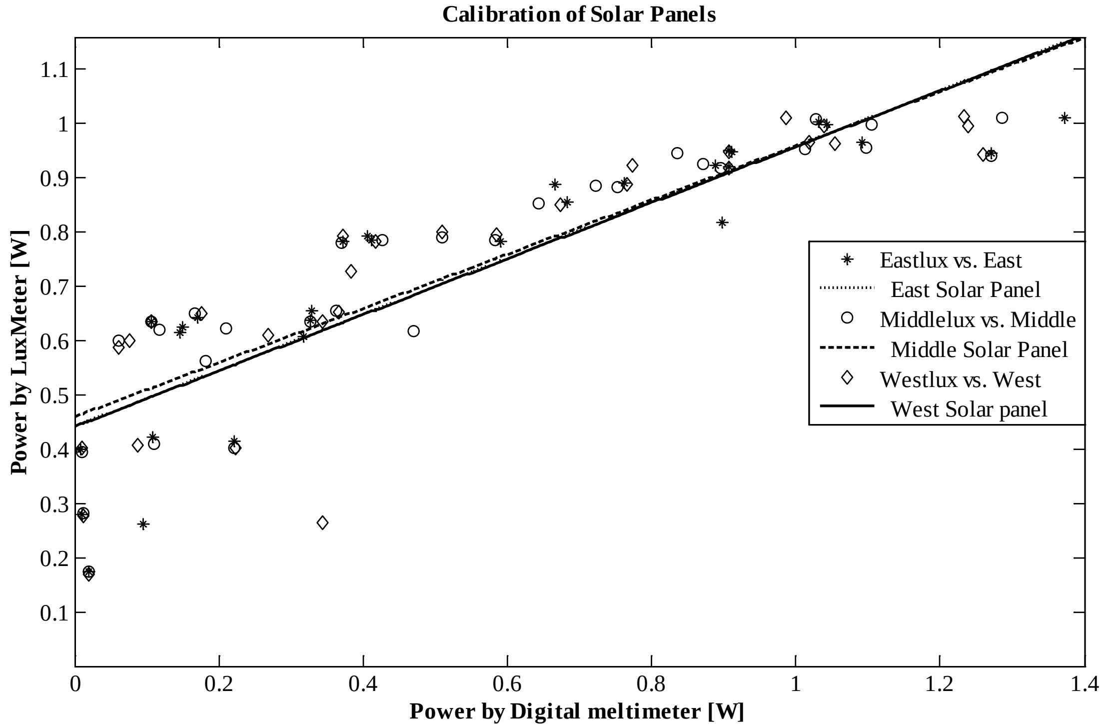


Figure 3. Calibration curve (Power by Luxmeter versus power by Multimeter)

Calibration of the Solar panels with LX-1010B showed positive linear correlation with R^2= 0.7779, 0.7918 and 0.7496 for East, Middle and West solar panels, respectively. This indicates agreement between powers estimated by lux-meter and voltage measured by multi-meter.

3.5. Data Collection

Data collection was done every 15 minutes, from 8:00 am till 5:00 pm. The tilt angles were varied between 0^o-45^o with intervals of 3^o (zero indicating horizontal position). During the first day of each week measurement made power outputs of the solar panel. This measurement was done on the first day of each of the three week. The tests were made in three replications.

During the remaining six days of each week, the east-west orientation tests were conducted. For this test, three panels were used. The middle panel (SR01216253) was fixed at north-south tilt angle that has resulted in maximum power output during the tilt angle measurement. The East facing panel (SR01216488) was attached to the fixed panel with a hinge and allowed to rotate from 0^o-90^o only in the east direction. Hence, this panel always faced east direction. Similarly, the West facing panel (SR01216758) was allowed to rotate from 0^o-90^o. Both panels (East and West facing) was allowed to rotate from 0^o-90^o. Both panels were rotated intervals of 5^o, zero indicating same plane position with respect to middle solar panel. Power (voltage) outputs from the three panels were recorded with their respective times and angles. Measurements were conducted every 15 minutes. The same procedure was repeated for the remaining two weeks of the two months.

3.6. Data Analysis

Power output of each angle was determined first by plotting power against time of the day for each tilt and orientation angles from which the figure that yielded maximum power output was selected. Data computation was done by MS-EXCEL and MATLAB. The power was computed using Equation (32).

$$P = VI = \frac{V^2}{R} \qquad (32)$$

Where V is the voltage measured and R is the resistance (fixed at 10Ω). The results of tilt angle and East - West orientation angle were analyzed separately based on the power outputs of the three panels.

4. Results and Discussions

4.1. North – South Tilt Angle

Result (voltage) obtained from experiment are shown in Appendix I and graphs of power versus time of a specific day for sample tilt angles are shown in figure 11. Only 6 of the 16 tilt angles are shown in order to reduce congestion. Visually 0^o and 3^o tilt angles show maximum power compared to the other angles. The power in each tilt angle is average value of each week of the corresponding month. The marked or bold graph in each figure is the tilt angle for which maximum power was obtained. The figure shows that the maximum powers were recorded at 3^o during March and May and at 0^o in April. It is often practicable to orient the solar collector at an optimum tilt angle, and to correct the tilt from time to time. In the northern hemisphere, the solar panel is south facing and the optimum tilt angle depends only on the latitude. No definite value is given by researchers for the optimum tilt angle (Amita and Yogesh, 2013).

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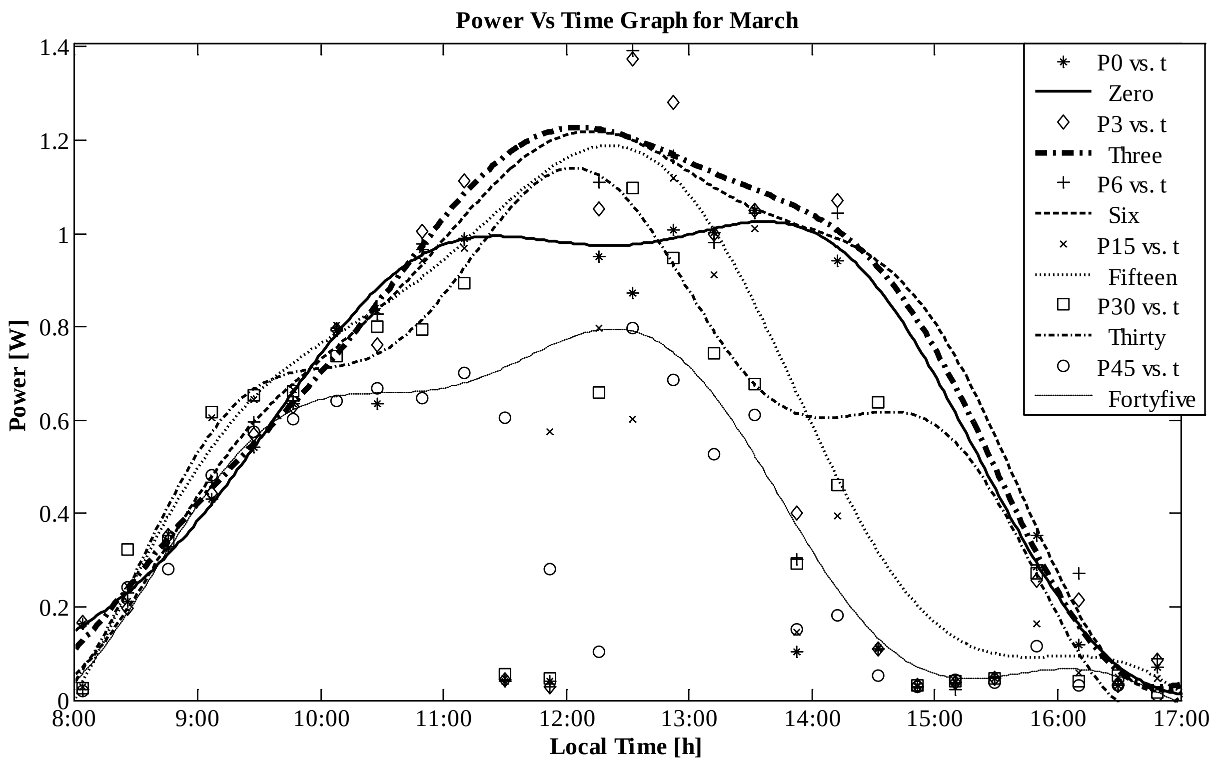

Figure 4. Power versus Time Graph of different Tilt Angles on 16/03/2013. P0, P3, P6, P15, P30 and P45 in the legend represent tilt angles of 0, 3, 6, 15, 30 and 45 degrees, respectively. The lines are all fitted lines.

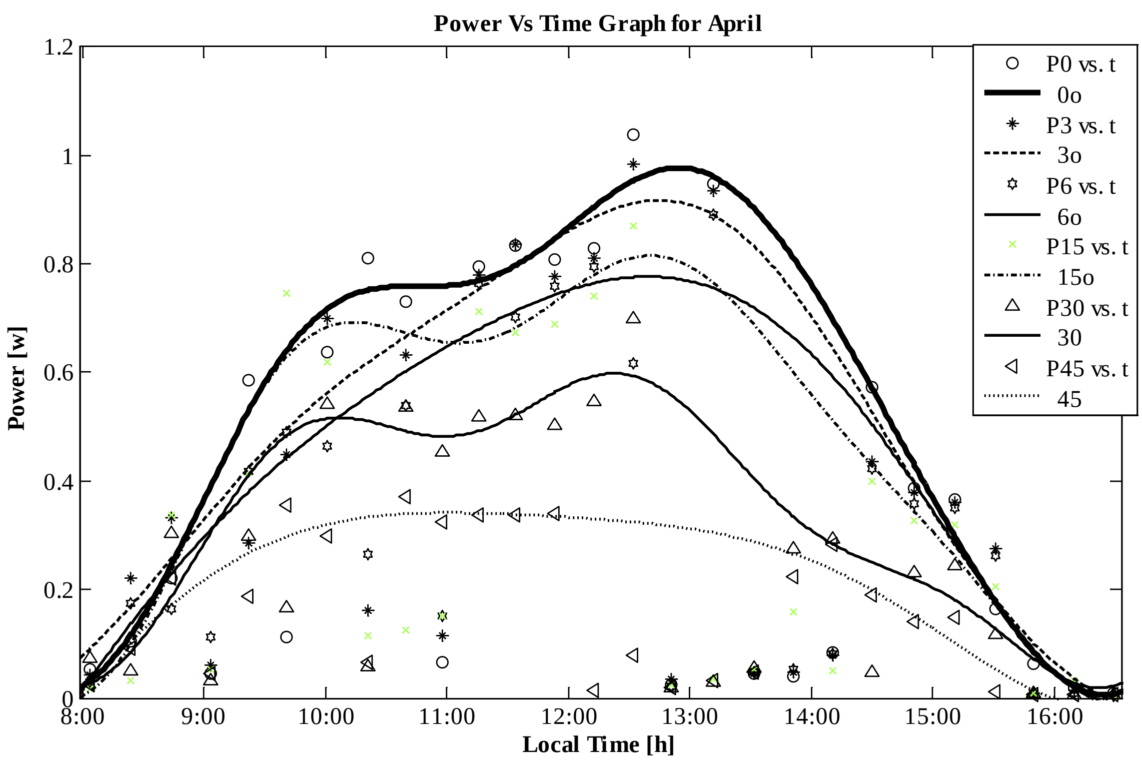

Figure 5. Power versus Time Graph of different Tilt Angles shown on 14/04/2013. P0, P3, P6, P15, P30 and P45 in the legend represent tilt angles of 0, 3, 6, 15, 30 and 45 degrees, respectively. The lines are all fitted lines.

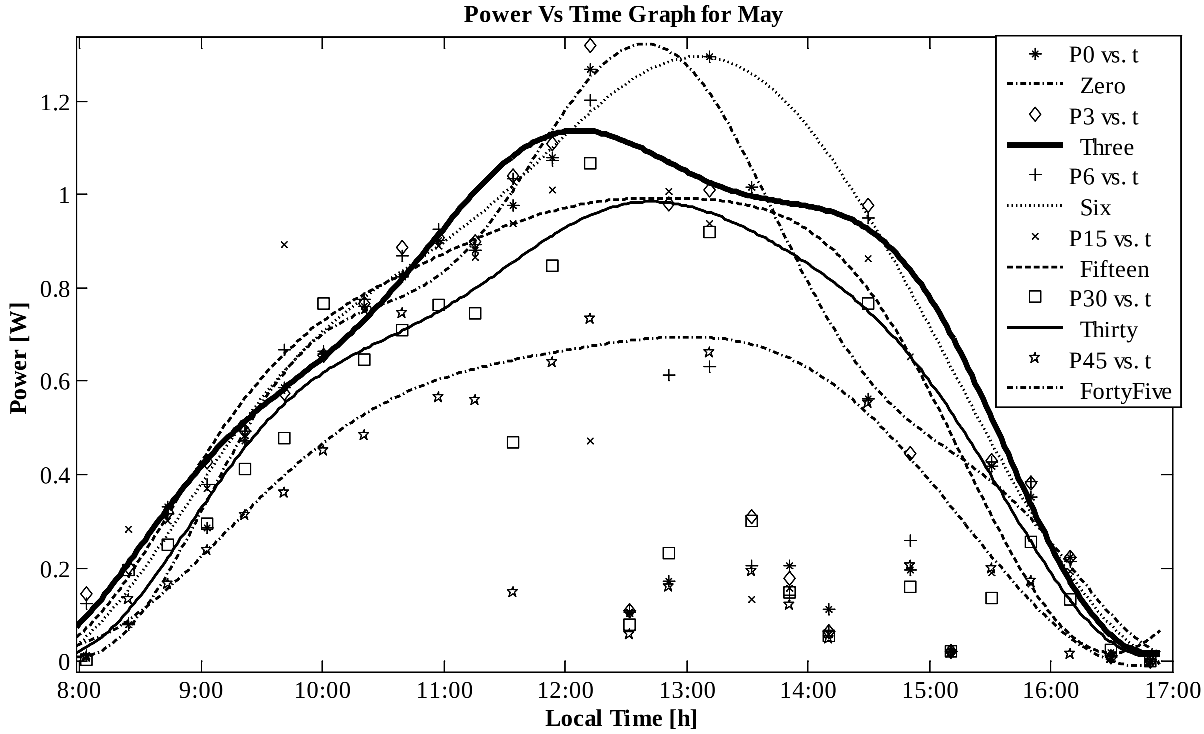

Figure 6. Power versus Time Graph of different Tilt Angles shown on 14/05/2013. P0, P3, P6, P15, P30 and P45 in the legend represent tilt angles of 0, 3, 6, 15, 30 and 45 degrees, respectively. The lines are all fitted lines.

In order to make objective comparison between the different tilt angles, area under each curve was calculated and the results are summarized in Table 2.

Table 2. Area under the curve for Power versus Time of each tilt angle

Tilt Angle	March	April	May	Season average
0^o	6.04279	**4.8836**	5.87493	5.60044
3^o	**6.59546**	4.53177	**6.59996**	**5.90906**
6^o	6.58848	4.02515	6.5314	5.72292
9^o	6.43165	4.39043	6.24169	5.68792
12^o	5.82009	4.21153	5.92736	5.31966
15^o	5.31801	4.22848	5.65403	5.06684
18^o	6.03987	3.47881	5.42387	4.98085
21^o	5.28005	3.4445	5.95702	4.89385
24^o	5.29157	3.45322	5.20627	4.65035
27^o	5.59848	3.52828	5.12429	4.75035
30^o	5.53335	3.16095	5.26575	4.65335
33^o	5.04858	2.94018	4.74409	4.24428
36^o	4.3593	2.73799	4.57308	3.89012
39^o	4.24617	2.27625	4.31662	3.61301
42^o	4.05656	2.13912	4.06631	3.42066
45^o	3.68364	1.92117	3.77932	3.12804

As seen in the table, maximum area was observed at 3^o in March, 0^o in April and again 3^o in May. Seasonal average shows 3^o as the best tilt angle for the location. The results obtained from the experiment indicated that no constant optimal tilt angle was observed over the three months. This is because of the daily and monthly variability in tilt angle, however small. Table 2 shows that the maximum power was recorded during March and

May. The lowest recorded performance for all the angles considered occurred during April. This is due to the cloudy nature of the month.

As example, the next figure shows that the results obtained from the first day which was in 16/03/2013 of 3^o tilt angle. The figure indicated that measured solar power versus time graph of solar panels with their cumulative sum area, which was obtained using MATLAB. In similar fashion, the cumulative sum area of each North – South tilt angle and East – West orientation angle is found.

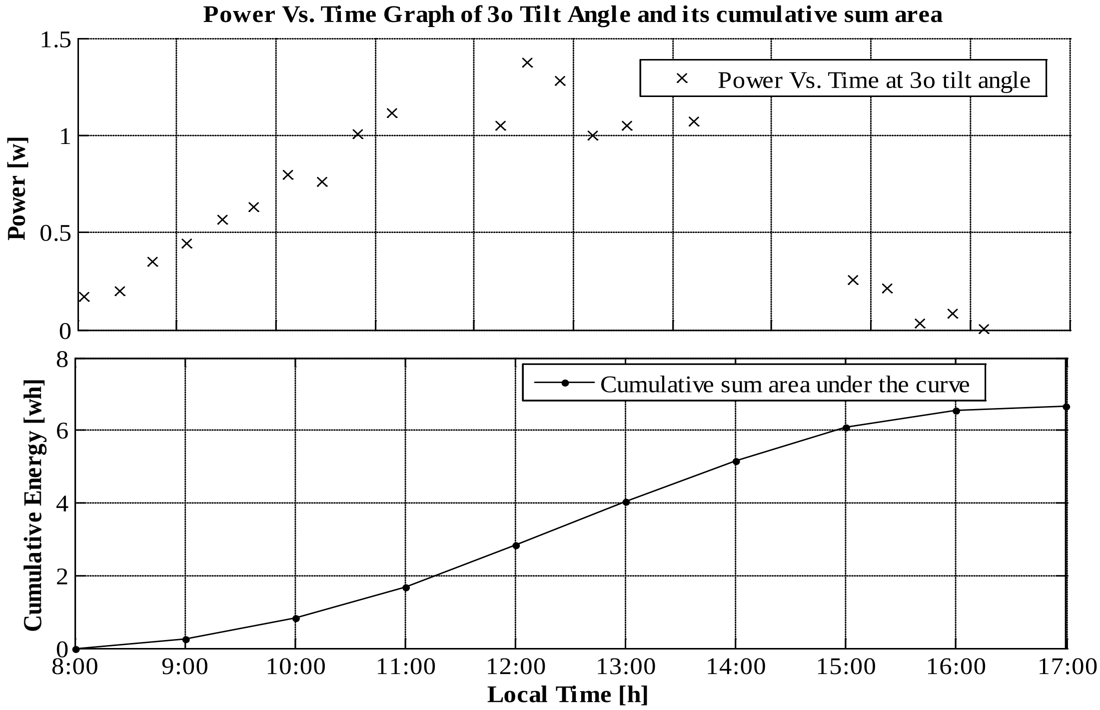

Figure 7: Power versus time graph of 3^o tilt angle and its cumulative sum (16/03/2013)

The Solar panel with 3^o tilt angle is therefore more perpendicular to the sun's light than the one with horizontal installation angle (0^o) and thus received more solar power in spring season. From this, the seasonal optimum tilt angle (3^o) at the location is small, or nearly horizontal. This, in general, is in agreement with the results of many other researchers (e.g. Jamil and Tiwari, 2009). It is generally known that in the northern hemisphere, the solar panel is south facing and the optimum tilt depends upon the latitude and the day of the year. In winter months, the optimum tilt is greater, whilst in summer months the optimum tilt is less. But in autumn and spring season the optimum tilt angle is nearly equal to the latitude of the area (Jamil and Tiwari, 2009). Compared to the latitude of the experimental area of about 9^o, the experiment revealed a lower tilt angle of only 3^o for the season.

If the solar panel surface were tilted 3^o towards south to collect maximum power in spring season, the seasonal total power would be increased by 5.51% from the solar panel's maximum total power for a panel installed horizontally (0^o tilt angle) (Table 2). Since changing the tilt angle to its daily and monthly optimum values throughout the year does not seem to be practical, a better alternative is changing the tilt angle once every season (Murat *et al*., 2004). Table 2 reveals that this location received higher amount of solar radiation in the months of

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March and May compared to April. The reduction in power in the month of April could be due to more cloud cover during the experimental days of the month.

Murat *et al*. (2004) reported that the output of the PV arrays could be increased by 20–25% at almost no investment if they could be installed at a slope equal to the mean monthly slope for the site of application and the slope adjusted once a month. Yakup and Malik (2001) recommended that the solar collectors should be mounted at the monthly average tilt angle and the slope adjusted every month. Their study indicated that such installation would allow an increase in the efficiency of the collector more than 4.4% over that of a similar collector fixed at the annual tilt angle.

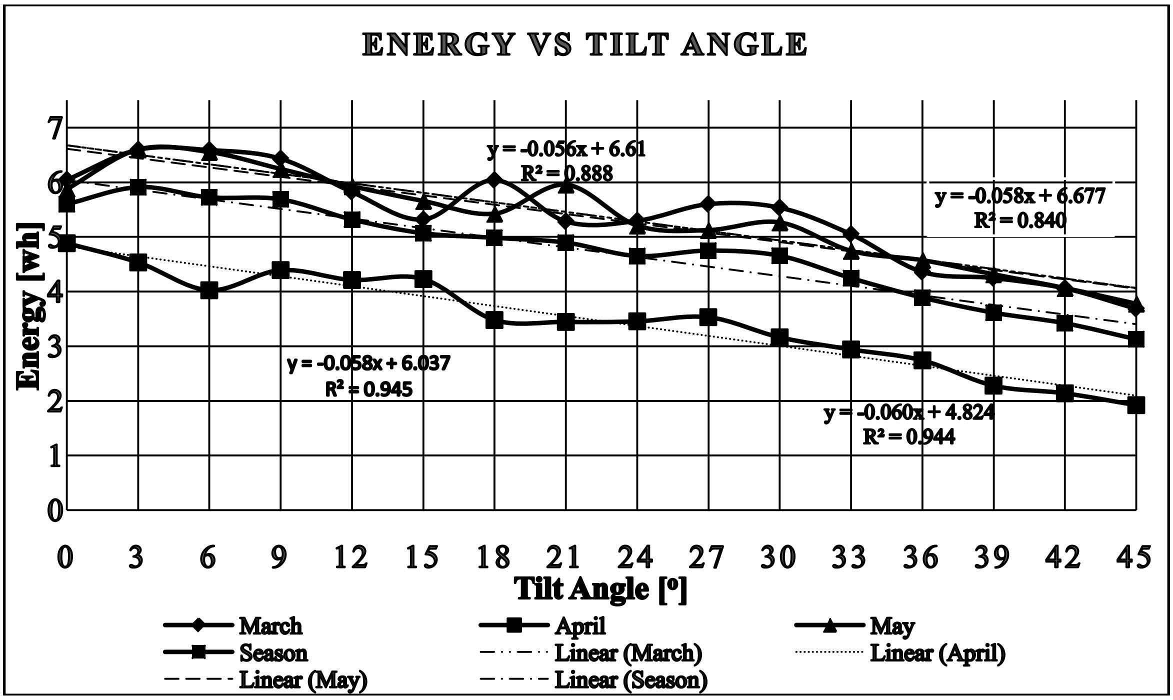


Figure 8. Energy [wh] versus tilt angle[^{o}] of the season

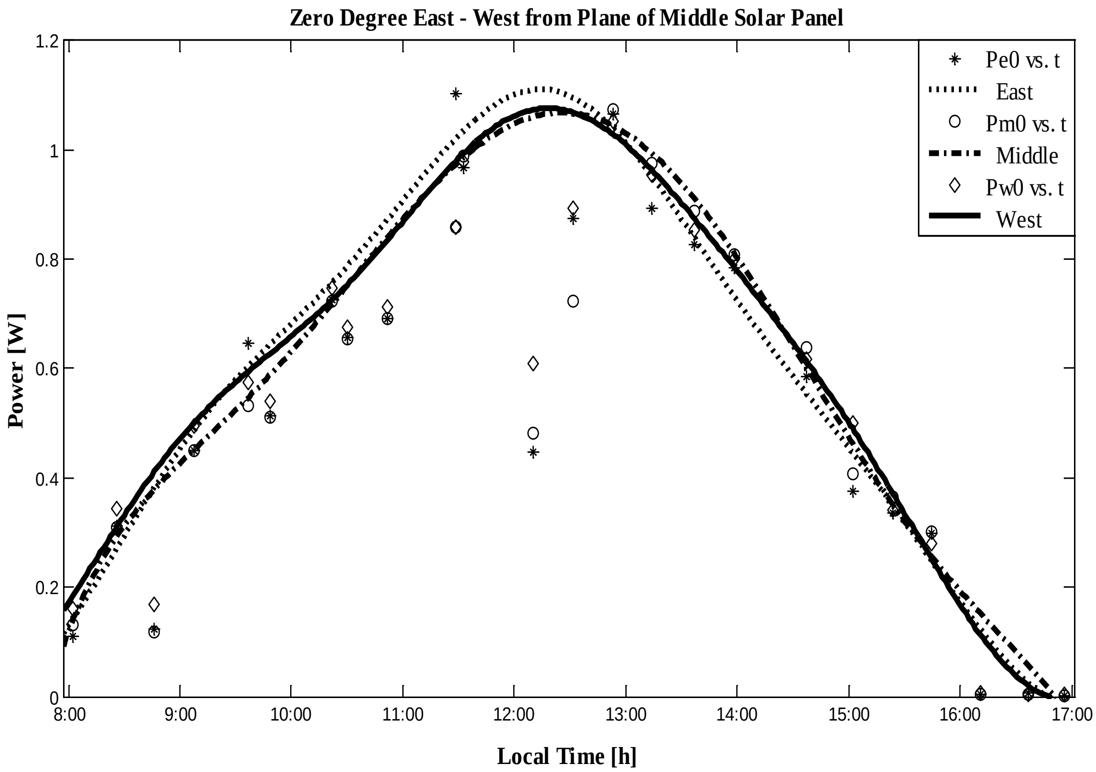
Table 3. Coefficients of Linear trends of Energy versus tilt angle shown in figure 15.

	a	b	R^2
March	-0.0581	6.6763	0.8407
April	-0.0607	4.8241	0.9447
May	-0.0568	6.61	0.8887
Season	**-0.0585**	**6.087127**	**0.9451**

Thus, an analysis was performed to correlate the dependence of total energy received versus tilt angle shown in figure 15. The corresponding regression constants obtained at 95% confidence intervals are given in Table 3. The result shows that optimum energy of a solar panel could be easily obtained as a function of tilt angle by means of the coefficients of a linear regression ($y = ax + b$). The negative slope for each day of the month shows that energy decreased while tilt angle increased. In the figure, the curve increased between 0^o to 3^o and decreased thereafter. When solar panel is set at the monthly optimum tilt angle (Table 2), there is increasing power of 9.15 %, 12.34% in March and May, respectively as compared to 0^o tilt angle. Similarly there is an increase of 5.51% of PV power when PV is set at seasonal tilt angle. This indicates that the efficiency of solar collection at the optimum tilt angle is increased compared to the horizontal position (0^o tilt angle). It can be pointed out that the optimum tilts angle increases towards the beginning and end of season.

4.2. East–West Orientation of Solar Panels

With one solar panel orientated towards East the other towards West at various inclination angles (0^o – 90^o) powers generated are shown in Figure 16. The figures shown are samples. The figures show solar power increases gradually from early morning until noon. Subsequently, it decreases gradually until late afternoon. The highest production during a sunny day is observed at noon. Perez and Coleman (1993) recommended an angle that puts the panel perpendicular to the sun rays at noon but the best angle at noon does not account for best angle in capturing solar energy at other times of the day.



(a)

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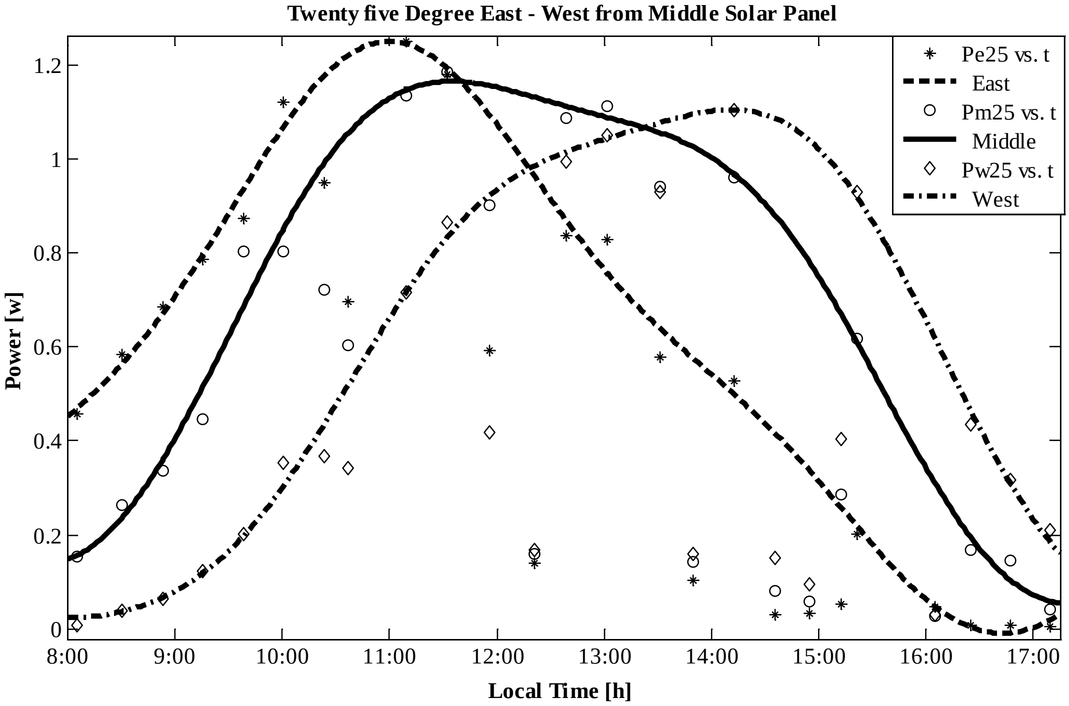

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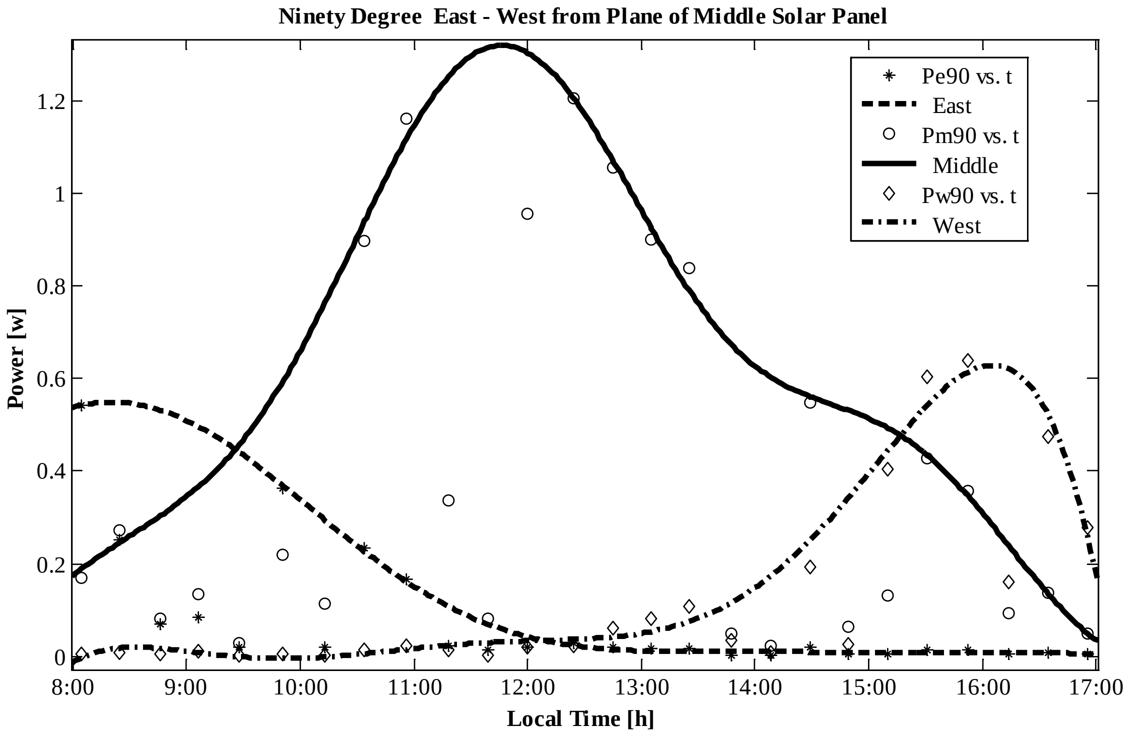

(c)

Figure 9. Power versus Time graph of East –West Orientation on 17/03/2013 shown as sample. (a) All the three panels on the same plane; (b) East – West facing panels oriented at 25^{o} from their respective references; (c) East and West facing panels oriented at 90^{o} from their respective references.

Values of energies (cumulative sums) obtained from power versus time graph, for the East/West for all predefined angles (0^{o} - 90^{o}) are given in Appendix II Table 3 and 4 for the months of March, April and May, respectively. The result depicted that best orientation angles that resulted in maximum power generated varied in each day but mostly ranged between ranged 0 and 10^o. In figure 16a all the three panels recorded identical powers. This is not surprising since orientations were the same for all the three and the panels are also of identical make. Figure 16b showed that East and West facing panels had significant contribution in the morning and afternoon hours, respectively. Their midday contributions were subdued. In figure 16c only early morning and late afternoon contribution were observed for East and West facing panels, respectively. The three together reveal that change in orientation is good to evenly distribute the power throughout the day.

4.2.1. East Facing Solar Panel

For the week of 17-22/03/2013, for East facing solar panel maximum powers were generated at 5^o, 10^o, 0^o, 10^o, 5^o, and 5^o, respectively. For the week of 15-20/04/2013, for East facing panel maximum powers were generated at 5^o, 0^o, 0^o, 10^o, 0^o, and 5^o, respectively (see Appendix II Table3). In March and April maximum powers were observed for orientation angles ranging between 0^o and 10^o. In May maximum powers were at higher angles of up to 20^o. Over all, the seasonal average ranged between 0^o and 10^o with more frequencies occurring between 0^o and 5^o.

Table 4. Cumulative power of P-t graph of east-oriented panel with orientation angles 0-90^o for the selected week of each month

Orientation Angle	March	April	May	Season average
0^o	6.2410	**5.7828**	4.5166	5.5135
5^o	**6.4651**	5.7543	**4.5289**	**5.5827**
10^o	6.3598	5.7420	4.4762	5.5260
15^o	6.1976	5.6963	4.4397	5.4445
20^o	6.1915	5.3365	4.3052	5.2777
25^o	6.1029	5.2770	4.2344	5.2048
30^o	5.7534	5.1217	3.9463	4.9405
35^o	5.1512	4.6768	3.5888	4.4723
40^o	4.9360	4.4675	3.4687	4.2907
45^o	4.9461	4.1278	3.1566	4.0769
50^o	4.2311	3.8277	2.9313	3.6633
55^o	3.9638	3.4866	2.5695	3.3400
60^o	3.4373	2.9565	2.3721	2.9220
65^o	3.2585	2.7678	2.1104	2.7122
70^o	2.7226	2.4473	1.7566	2.3088
75^o	2.5108	2.0430	1.5911	2.0483
80^o	1.9488	1.8353	1.2502	1.6781
85^o	1.5782	1.4385	1.0374	1.3513
90^o	1.1838	1.1485	0.6977	1.0100

Again in the summary table (Table 4) maximum power for East orientation were observed at 5^o more frequently during the season. Plots of energy versus orientation angles drawn for East oriented panel (figure 17) reveal that the energy linearly decreased with increase in orientation angle. It is clear from these graphs that a unique value exists for each month of the season for which the solar power is at a peak for the given month. Similar trend has been observed for the selected days of the months selected under present study (see Appendix IV figure 2).

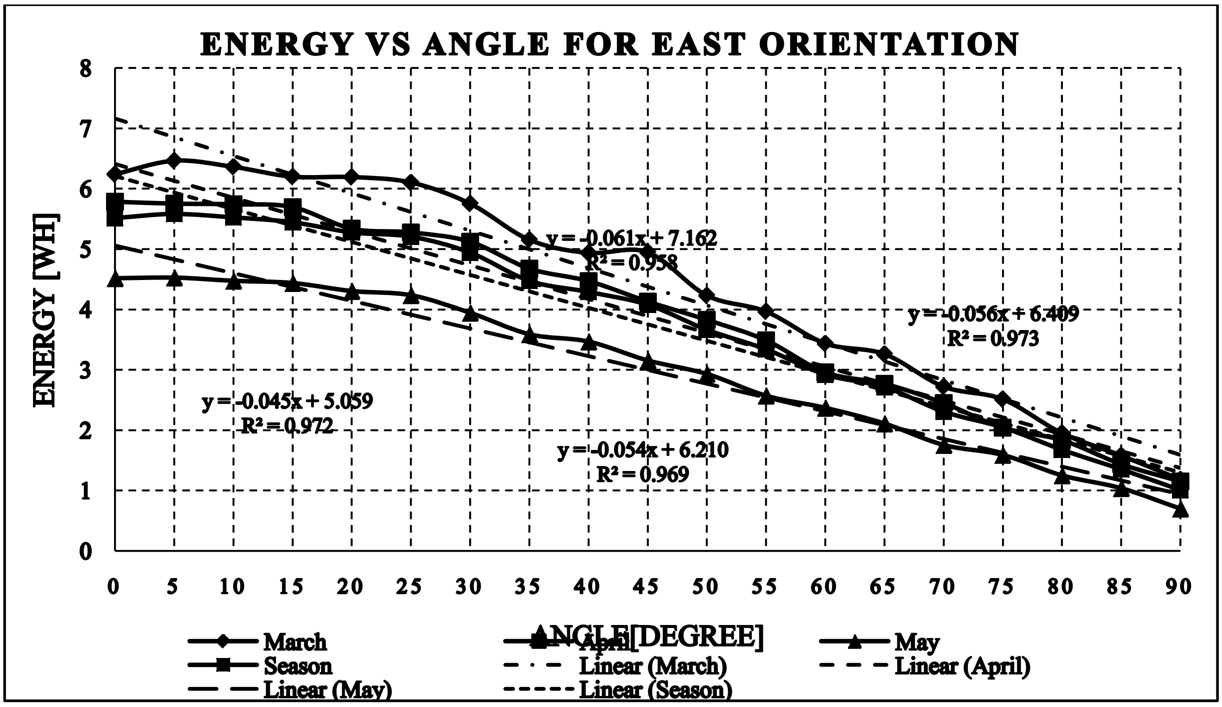

Figure 10. Graph of energy versus orientation angles and their trends for east-orientated panel

Analysis was performed to correlate the dependence of total energy received versus East orientation angles shown in figure 17.

Table 5. Trend coefficients and R^2 values of Energy versus angle graph

	a	b	R^2
March	-0.0619	7.1625	0.9581
April	-0.056	6.4097	0.9738
May	-0.0458	5.0596	0.9726
Season average	**-0.0545**	**6.2106**	**0.9692**

The corresponding regression constants obtained at 95% confidence intervals are given in Table 5. The result shows that optimum energy of a solar panel could be easily obtained as a function of east orientation angle by means of the coefficients and of a linear regression ($y = ax + b$). The negative slope for each day of the month shows that the energy decreased while east orientation angle increased. In the figure, the curve increased between 0^o to 5^o and decreased thereafter.

4.2.2. West oriented solar panel

As in the case of east-oriented solar panel, west-oriented panel yielded maximum energy when the orientation angle was between 0^o and 5^o. For the week of 15-20/05/2013, for west facing panel maximum powers were generated at 5^o, 5^o, 0^o, 15^o, 20^o and 0^o, respectively (see Appendix II Table 4). In March and April maximum powers were observed for orientation angles ranging between 0^o and 10^o. In May maximum powers were observed even when orientation angles increased up to 20^o. Over all, the seasonal averages were observed between 0^o and 10^o with height of frequencies occurring between 0^o and 5^o.

Table 6. Cumulative power under P-t graph in west-oriented for orientation angles of 0-90^o for the selected week of each month

Orientation Angle	March	April	May	Seasonal average
0^o	**6.3513**	**5.8183**	4.5964	**5.5887**
5^o	6.2104	5.6585	**4.6985**	5.5225
10^o	6.1329	5.7662	4.4466	5.4486
15^o	5.8592	5.4897	4.4907	5.2798
20^o	5.7637	5.0712	4.2900	5.0416
25^o	5.4678	5.2921	4.1187	4.9595
30^o	5.3130	4.9358	3.8058	4.6849
35^o	4.9113	4.7586	3.6561	4.4420
40^o	4.5654	4.7091	3.4249	4.2331
45^o	4.2797	4.1648	3.2457	3.8967
50^o	4.1304	3.9372	3.1278	3.7318
55^o	3.4686	3.4135	2.5807	3.1543
60^o	3.2024	3.0556	2.5935	2.9505
65^o	2.9435	2.8385	2.0667	2.6162
70^o	2.4729	2.4357	1.8567	2.2551
75^o	2.1627	2.2090	1.5778	1.9831
80^o	1.9105	1.9375	1.1874	1.6785
85^o	1.5729	1.6184	0.8703	1.3539
90^o	1.4923	1.4499	0.8624	1.2682

Plots of energy versus orientation angles drawn for west-oriented panel (figure 18) reveal that the energy linearly decreased with increase in orientation angle. It is clear from these graphs that a unique value exists for each month of the season for which the solar power is at its peak for the given month. Similar trend has been observed for the selected days of months selected under present study (see Appendix IV figure 3).

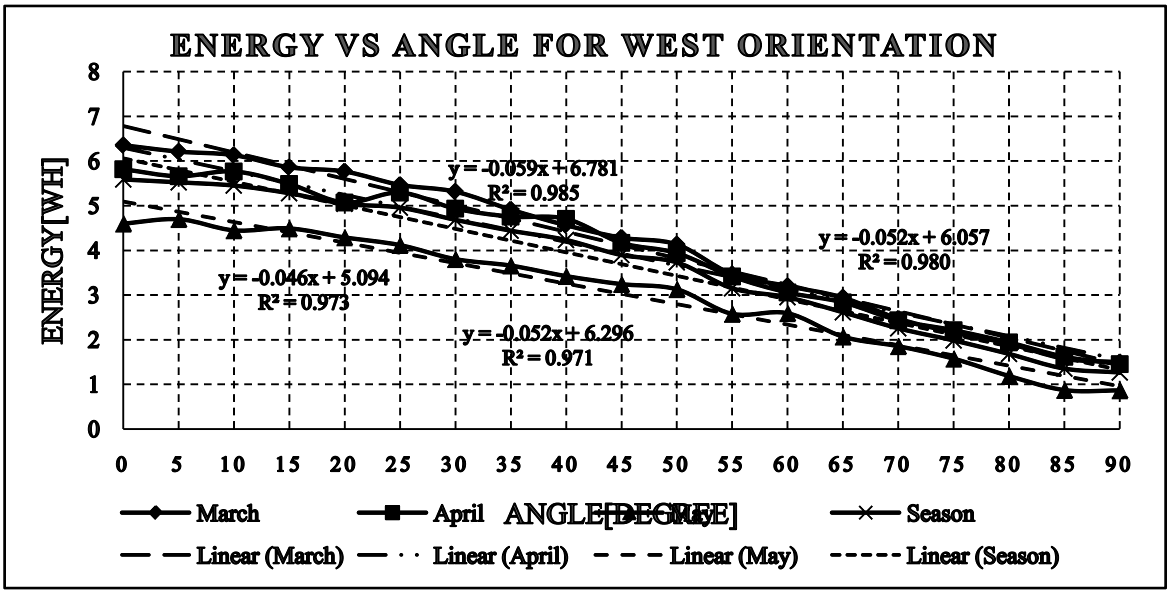

Figure 11. Graph of energy versus time and its trends of west orientation angles.

Regression constants obtained at 95% confidence intervals for west-oriented panel are given in Table 7. The result shows that optimum energy of a solar panel could be easily obtained as a function of orientation angle by means of the coefficients and of a linear regression ($y = ax + b$). The negative slope for each day of the month shows energy decreased while orientation angle increased. In the figure, the curve increased between 0^o to 5^o and decreased thereafter.

Table 7. Trend coefficients and R^2 value of Energy versus angle graph for West orientation

	a	b	R^2
March	-0.2961	7.0772	0.9859
April	-0.2635	6.5596	0.9713
May	-0.2298	5.3241	0.9734
Season average	**-0.2631**	**6.3203**	**0.9807**

4.3. Daily Maximum Power from Optimum East- West Orientation and Tilt Angle

An analysis was performed to determine the best east-west orientation angles that yield a maximum daily power. This was done by comparing the sum of powers of the three panels with three times the power of the middle panel (assuming all the three panels are on the same horizontal orientation).

As shown in Table 8 in March 4 out of six days orienting at least one of the two East and West panels at angles different from 0^o has yielded better than the power obtained when all the three panels are on the same plane.

Table 8. Tilt and East-West orientation angles for which maximum powers were obtained in March

March (3^o Tilt Angle)							
		17/03/2013	18/03/2013	19/03/2013	20/03/2013	21/03/2013	22/03/2013
East	Orientation Angle[^{o}]	5	10	0	10	5	5
	Energy[wh]	6.7126	5.7007	6.1313	7.1435	6.7210	7.5493
West	Orientation Angle[^{o}]	5	0	0	10	0	0
	Energy[wh]	6.4257	5.5749	6.1216	5.9945	6.7571	7.2976
Middle	Energy[wh]	6.3373	5.6939	6.1276	6.4339	6.6262	7.0371
	Sum (E +W +M)**	**19.4756**	16.9694	18.3805	**19.5719**	**20.1043**	**21.8840**
	3xMiddle***	19.0120	**17.0816**	**18.3828**	19.3016	19.8786	21.1113

* Middle's value=daily average value and 0^o orientation

** Sum (E +W +M) is the of power from east and west oriented panels added to the power of the middle panel

*** is three times the power of the middle panel, which is nearly the power obtained if the three panels were oriented on the same plane with the same tilt angle

Table 9. Tilt and East-West angles for which maximum powers were obtained in April

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April (0° Tilt Angle)							
		15/04/2013	16/04/2013	17/04/2013	18/04/2013	19/04/2013	20/04/2013
East	Orientation Angle[°]	5	0	0	10	0	5
	Energy[Wh]	6.4887	5.5872	5.7191	5.7337	5.4155	6.6248
West	Orientation Angle[°]	10	0	0	10	0	10
	Energy[Wh]	6.3391	5.3181	5.7339	5.6610	5.6506	6.6944
Middle	Energy[Wh]*	6.2031	5.3261	5.9856	5.6439	5.6132	6.3022
	Sum (E+W+M)**	**19.0309**	**16.2314**	17.4386	**17.0386**	16.6793	**19.6214**
	3xMiddle***	18.6094	15.9783	**17.9567**	16.9316	**16.8396**	18.9065

* Middle's value=daily average value and 0° orientation

** Sum (E +W +M) is the of power from east and west oriented panels added to the power of the middle panel

*** is three times the power of the middle panel, which is nearly the power obtained if the three panels were oriented on the same plane with the same tilt angle

Table 10. Tilt and East-West angles for which maximum powers were obtained in May

May (from 3° Tilt Angle)							
		15/05/2013	16/05/2013	17/05/2013	18/05/2013	19/05/2013	20/05/2013
East	Orientation Angle[°]	5	5	0	5	0	0
	Energy[Wh]	4.6770	4.8459	4.8175	4.7622	4.2512	4.3290
West	Orientation Angle[°]	5	5	0	15	20	0
	Energy[Wh]	5.4548	4.7854	4.9401	5.0126	4.2441	4.4177
Middle	Energy[Wh]*	4.7005	4.6851	4.7706	5.0134	4.2015	4.2446
	Sum (E+W+M)**	**14.8323**	**14.3164**	**14.5281**	14.7883	**12.6969**	**12.9912**
	3xMiddle***	14.1014	14.0553	14.3117	**15.0403**	12.6045	12.7337

* Middle's value=daily average value and 0° orientation

** Sum (E +W +M) is the of power from east and west oriented panels added to the power of the middle panel

*** is three times the power of the middle panel, which is nearly the power obtained if the three panels were oriented on the same plane with the same tilt angle

In April and May, as shown in Table 9 and 10 four and three out of six days orienting at least one of the two panels at angles different from 0° has yielded better than the power obtained when all the three panels are on the same plane, respectively. The maximum solar panel's output vary for the East and West orientation which is due to an asymmetric distribution of power before and after the midday. The orientation and tilt of the panels directly relates to the seasonal energy yield of the panels determined optimum tilt angle and orientation for solar photovoltaic arrays in order to maximize incident solar irradiance exposed on the array, for a specific period of time.

Table 11 shows in March, the maximum solar power output is for a solar panel with tilt 3^o and orientation angles of 5^o East and 0^o West, respectively. In April, the maximum solar power output is for a solar panel with tilt 0^o and orientation angles of 0^o East and 0^o West, respectively. In May, the maximum solar power output is for a surface with tilt 3^o and orientation angles of 5^o East and 5^{o}West, respectively. When the optimum orientation and tilt angle for March and May is considered, increase in the solar power output is 0.34% and 0.16% respectively compared with three times of Middle solar panel's output. Similarly for April, the reduction is 0.51%. In spring season, the solar power output is maximised for a surface with tilt angle of 3^o oriented 5^o east and 0^o West. When the optimum orientation and tilt for this season is considered, decline in the solar power output is 0.27% compared with Middle solar panel's output.

Table 11. Seasonal Tilt and East-West angles for which average maximum power were obtained

		March (3^o Tilt Angle)	April (0^o Tilt Angle)	May(3^o Tilt Angle)	Season
East	Orientation Angle[^{o}]	5	0	5	5
	Energy[Wh]	6.4651	5.7828	4.5289	5.5827
West	Orientation Angle[^{o}]	0	0	5	0
	Energy[Wh]	6.3513	5.8183	4.6985	5.5887
Middle	Energy[Wh]*	6.3760	5.8457	4.6026	5.6081
	Sum(E+M+W)**	**19.1924**	17.4468	**13.8300**	16.7795
	3xMiddle***	19.1280	**17.5370**	13.8078	**16.8243**

* Middle's value=daily average value and 0^o orientation
** Sum (E +W +M) is the of power from east and west oriented panels added to the power of the middle panel
*** is three times the power of the middle panel, which is nearly the power obtained if the three panels were oriented on the same plane with the same tilt angle

In March and May, one or both of East and West facing solar panels orientated at angle different from 0^o yielded maximum daily power when compared to all three panels oriented on the same plane. In spring, the PV output is maximised for a surface with tilt angle of 3^o oriented 5^o east. The maximum PV output is for the orientation slightly east of due south which is due to an asymmetric distribution of insolation before and after the midday during this season. However, the PV output varies only by 1.5% from the maximum PV output in this season, when the PV surface orientation lies within 30^o east or west from due south. For south-facing horizontal and vertical surfaces, PV outputs are 7.3% and 53% lower, respectively, than the maximum PV output in spring (Jayanta *et al.*, 2006).

4.4. Daily Distribution of Solar Energy

Analysis performed to determine daily distribution in solar energy received by the three solar panels at the monthly optimum tilt angles and East–West orientation angle indicate that difference in orientation of east and west panels from the middle panel improved solar energy reception during early morning and late afternoon (Fig.19a). However, it did not improve the total energy received during the day (Fig.19a). Detailed figures are given in Appendix IV figure 4. Although the voltage of the east/west solar panel deviates by up to 0.27% from the voltages of the solar panel with middle panel, the energy differences are very small, as can be seen in Table

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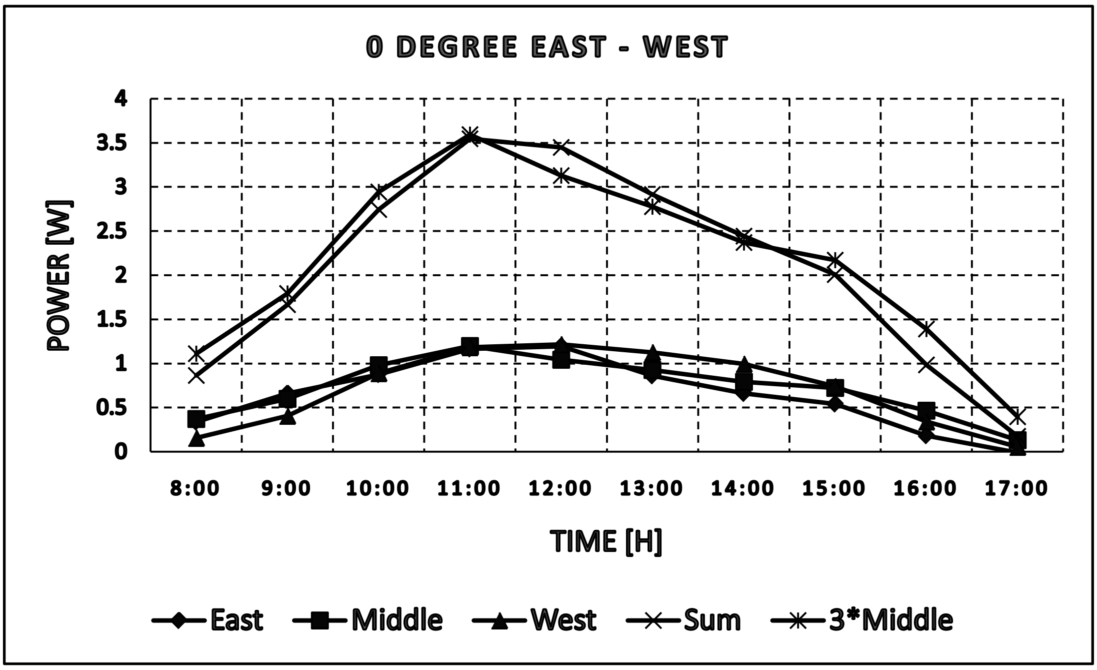
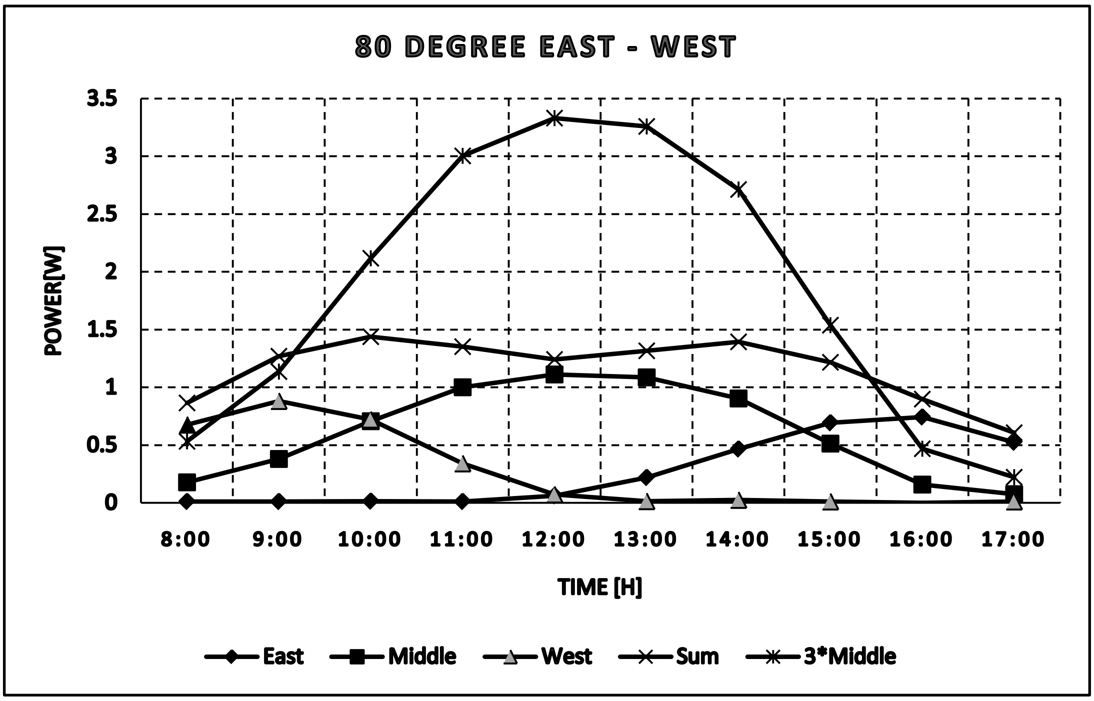
8-11. This is because the voltage of the east/west solar panel follows the voltage of the east solar panel in the morning and the voltage of the west panel in the afternoon.



(a)



*sum = sum of East, Middle and West

(b)

Figure 12. Daily Distribution of Solar Power

Table 12. East - West Angles for Daily distribution of Power

March	April	May	Seasonally

Date	Angle	Date	Angle	Date	Angle	
17/03/2013	90	15/04/2013	85	15/05/2013	75	
18/03/2013	85	16/04/2013	90	16/05/2013	75	
19/03/2013	80	17/04/2013	90	17/05/2013	70	
20/03/2013	80	18/04/2013	85	18/05/2013	85	
21/03/2013	85	19/04/2013	85	19/05/2013	85	
22/03/2013	85	20/04/2013	85	20/05/2013	90	
Mean	80		85		80	85

Solar power obtained by 3xmiddle is generally higher between 09:00 and 15:00 hours. But assuming that batteries can only store energy that can last a couple of hours with 3x middle solar panel power the battery is exploited for about 18 hours. However, if the solar power can kick in before 9:00 and also contribute after 15:00 hours the loss on the battery reduces and Photovoltaic panels can operate for longer hours. For East - West orientation between 75^o and 90^o early and late contribution of east and west panels respectively increase. But, this happens at the expense of power loss between 9:00 and 15:00 hours. The trade-off must be decided based on the capacity of the battery and the device that uses photovoltaic power.

5. Summary and Conclusion

The study was conducted to determine the optimal North – South tilt angle and East – West orientation angles for solar PV systems at Haramaya University. A total of sixteen tilt angles ranging between 0 and 45 (with 3^o intervals) and 19 orientation angles 0 to 90^o (with intervals of 5^o were used). Measurements were made for three weeks with one week from every month over three months of the spring season. The result shows that the tilt angle at which the solar panel generated maximum power output was 3^o in March and May and 0^o in April. The maximum solar power output is for a solar panel with orientation angles of 5^o East and 0^o West, 0^o East and 0^o West and 5^o East and 5^o West in March, April and May, respectively. The seasonal average of the North – South optimum tilt angle is 3^o, and East - West optimum orientation angle is 5^o East and 0^o West. When Solar panel set at the monthly tilt angle, there is increase of 9.15 %, 12.34% in March and May, respectively as compared to 0^o tilt angle. Similarly there is increase of 5.51% the PV array power output when the PV is set at seasonal tilt angle.

The power generated by a solar panel is dependent on the angle at which it is tilted and the orientation of the solar panel. Improper orientation of the solar panel would eventually lead to loss in power and poor return on investment. By implication, this means that solar energy conversion designed based on monthly average daily solar and weather data should be designed to track the solar radiation at the above mentioned angles for the months of March, April and May for optimum system performance. For maximum energy gain, solar panels should be inclined at optimal tilt angle and seasonal adjustment of the panel may lead to considerable gain in power obtained from solar energy. The optimum North – south tilt angle and East- West orientation angle is different for each months of the season and shows variation in the direction of sun with time of day and month of the season. The collected solar energy will be greater if we choose the optimum panel tilt for the season. For higher efficiency, the solar panel should be designed such that the angle of tilt can easily be changed at least on a seasonal basis, if not monthly.

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