ABUAD Journal of Engineering Research and Development (AJERD)
ISSN (online): 2645-2685; ISSN (print): 2756-6811

Volume 6, Issue 1, 31-37

Effect of Roof Inclination on Solar Panel's Energy Output in a South-Western Nigerian City

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Date Submitted: 17/03/2023
Date Accepted: 23/04/2023
Date Published: 01/05/2023

Abstract: *This work sets up four photovoltaic (PV)-based solar power systems with adjustable solar panel inclination angle stands. It also varies the inclination angle of the solar panel every five days while recording daily energy delivered by the panels. The study finally compares the output energy recorded for different angles. This was done with a view to studying the effect of building roof inclination on the energy deliverable by solar panel installed on it. The set up consists of PV-based solar power systems with adjustable inclination angle stands for four 10 W solar panels which are on the same axis. Each solar panel was connected to a 42 Ah battery through multimeter and charge controller. A 25 W load was used to discharge the battery at night to allow fresh charge from the panels during the day. The multimeter was used to monitor the daily energy delivered. The solar panels were subjected to 0°, 25°, 50° and 75° inclination angles and faced to South direction at the Renewable Energy Laboratory, Osun State University, Osogbo, Nigeria. Data were recorded daily for 20 days by subjecting all panels to the considered angles for five days. The results obtained showed that the average energy delivered by panels installed at the stated inclination angles are 35.35 Wh, 32.25 Wh, 24.1 Wh and 13.95 Wh, respectively. This means that, for a specific building energy need, the steeper the roof (intended for panel installation), the more the amount of solar panel required to meet such energy. The results also showed various expressions that can be used to estimate daily average sun hour (ASH) based on roof inclination. For example, the estimated daily (ASH) for Osogbo and environs can be taken to be 4.22 hour, 3.15 hour and 1.82 hour for 25°, 50° and 75° roof inclinations, respectively.*

Keywords: *Solar panel, inclination angle, energy, roof top, average sun hour.*

1. INTRODUCTION

The demand for electricity to meet the need of the society is increasing at a rapid rate in most countries of the world. In the developed world, there are energy provisions to meet up with these ever increasing demands. This energy comes from either the conventional or renewable sources. However, in the developing or underdeveloped nations, energy infrastructures are poor; hence, there are energy supply deficits to the populace. In recent times, there have been the adoptions of renewable energy sources (RES) by individuals and corporate organization to meet their energy needs. Examples of RES that are adopted are mainly solar and wind. While only few people adopted wind source, many are now using PV-based solar power systems. Though, it is expensive, the benefits outweigh the cost of installation in the long term. In addition to PV systems bridging the energy need gap, it has been observed that solar energy offers one of the best solutions to the problem of carbon emission that greatly influence climate change [1, 2]. The PV-based system comprises of solar panel, charge controller, battery, inverter and load. One major factor that affects efficient capturing of energy from the PV-based system is the tilt or inclination angle of the solar panel. This is the angle at which the solar panel makes with the horizontal. The tilt angle determines the solar radiation reaching the surface of the PV module [3]. If the solar panel is installed at a very good tilt angle, it is expected that the system will deliver a considerable amount of energy. One way to continually ensure good tilt angle is the installation of the solar panel with sun tracker [4-6]. Unfortunately, sun tracker makes the already expensive system to be more expensive and it consumes energy for its operation. As a result of these, it is expected of an installer that doesn't want to consider tracker to ensure that a good tilt angle is selected at the time of installation if possible. It is generally recommended that solar panel should be installed at a tilt angle equal to the latitude of the site [7, 8].

Due to its location in the world, Nigeria is a very suitable area for solar energy and if well harnessed, it could solve energy crisis for many of her populace [9]. In Nigeria, in order to save land space, most users of PV-based systems and installers of such systems usually install on available building roof spaces. The installed solar panels usually follow the roof inclination angle, not minding if the angle will affect the performance of the system or not. This work investigates the effects of roof inclination of the solar panel's output by monitoring the tilt angle of four different solar panels for a period of time in Osogbo, a South Western City in Nigeria.

The main objectives of this work are to:

a. set up four PV-based solar power system with adjustable solar panel inclination angle,
b. set the four solar panels to different tilt angles and record the energy outputs from the four systems,
c. ensure that each panel experience the four angles and
d. compare the output energy recorded for different tilt angles.

Several authors have carried out experimental works on the study of the effects of tilt angle on the output of solar panel and the results obtained were all promising ones. Mamun *et al.*, (2022) varied the module tilt under steady irradiation level of 750 W/m^2 and also varied the irradiation intensity at the maximum tilt set up [10]. The study was carried out both indoor and outdoor in a Malaysian city. The angle of study varied from 0^o to 80^o by means of a single-axis tracker. The findings by the authors showed that there is a power drop of 2.09 W and 3.45 W for every 5^o increment in tilt angle for indoor and outdoor, respectively. A major drawback of this work is its usage of one panel to achieve its objective. Better results could have been obtained if different panels are simultaneously subjected to the angles under study. In another work, Shareef (2017) studied the effect of varying the tilt angle from 0° to 90° in an Iraqi atmosphere [11]. The results obtained also confirm that as the angle increases, the output power decreases. Hasan *et al.*, (2023) studied the effect of solar radiance, shading, angle of tilt on the performance of a PV panel of 120 W in an Iraqi city of Al-Nasiriyah [12]. The impact of tilt angle showed that maximum power was achieved at 45 degrees. It should be noted that maximum power could be achieved at an angle during a particular time but same angle may not guarantee maximum daily energy. The effect of solar tilt angles on photovoltaic module performance of Tripura, in India using a behavioural optimization approach was carried out by Som *et al.*, (2020) [13]. The authors of the work used various mathematical models as against experimentation for the study. The study showed that maximum average solar energy is obtained about the horizontal east-west axis within 20° to 30° tilt angle. The effect of tilt angle on soiling of solar panels for Mesa, Arizona during a hot-dry climate was done by Cano *et al*., (2014) [14]. Two sets of solar panels were subjected to various tilt angles. A group was regularly cleaned and the other allowed accumulating dust. The study showed that solar panels of lesser tilt angles are more soiled (and experience more insolation losses) than the ones at higher tilt angles.

Few works have also been carried out on the subject matter locally. Ajao *et al*., (2013) determined the optimal tilt angle of solar photovoltaic panel in Ilorin, Nigeria [15]. In the study, one solar panel was set at 0° to the horizontal and the angle was gradually increased every 10 minutes in steps of 2° until it reaches 30°. The voltage and current generated were recorded during the experiment. The results obtained show that the average optimal tilt angle with a fixed solar panel installation for Ilorin is 22°. Abdullateef *et al*., (2022) varied the tilt angle of a 100 W panel while recording the power output in Anyigba town of Kogi State, Nigeria [16]. The results from the study showed that the best power was recorded when the panel was tilted between 0° and 10°. As enumerated earlier, adjusting one solar panel to obtain angle at best power delivery for few minutes or hours of study is not reliable as the optimal angle obtained from the studies may be because of the time of experiment which influences the position of the sun. Badamasi *et al.*, (2021) studied the effect of tilt angle on photovoltaic modules loses in Gwagwalada, Abuja, Nigeria and found out that the optimum tilt angle for the period under study is 20^o [17].

Aside all drawbacks pointed out in some previous works reviewed, it should be noted that the works were more focused on the output power as against energy. A particular angle that gives maximum power may be due to the position of the sun as at the time of measurement. Instead of focusing on the effect of tilt angle on the power that is a function of the time of measurement, why not focus on daily energy that captures all the power that the solar panel delivers in a day. Also, the results from the works have not been linked to sizing of solar panel for buildings with different roof top designs. This present study caters for the gaps mentioned.

2. MATERIALS AND METHODS

This section discusses the procedure used in carrying out this work. Four solar panels were monitored at four different tilt angles. The block diagram for each of the four set-ups is shown in Figure 1. The solar panels used are the 10 W, 17.5 V type. The solar panels were mounted on a rack stand in such a way that the panels tilt angle can be adjusted between 0 and 90 degrees. Four multimeters were placed in between the solar panels and a 20 A charge controller. This was done so as to capture the energy directly delivered by the solar panels. A 42 Ah battery was used as the load to accept the solar energy from the sun during the day and five pieces of 5 W DC light emitting diode (LED) bulbs were used to discharge the battery at night so as to create a vacuum in the battery that the solar panels are expected to fill up through charge during the day.

The 42 Ah battery was chosen so as to be able to accept the total energy from the four panels. Assuming an 100 percent output of 10 W from the solar panel and an average sun hour (ASH) of 5 hour, the total energy deliverable from the 4 solar panels are 200 Wh. Also assuming that this amount of energy is used to fill 50 percent depth of discharge (DOD) of the battery, the total capacity of the battery that can accept the charge from four 10 W solar panels is 400 Wh. This value corresponds to 33.33 Ah (i.e. 400 Wh ÷ 12 V). The next available battery size close to this is 42 Ah, 12 V Quanta battery. Every day, it is expected that 300 Wh (i.e. 5 × 5 × 12) is discharged from the battery with the automatic switching ON of five pieces of 5 W bulbs at night. The expected discharge energy of 300 Wh is definitely more than the expected charge energy of 200 Wh. With this design, it is expected that the 42 Ah battery will accept all the energy delivered by the four panels. The setting on the controller was done to automatically switch ON and OFF the loads at night and day, respectively.

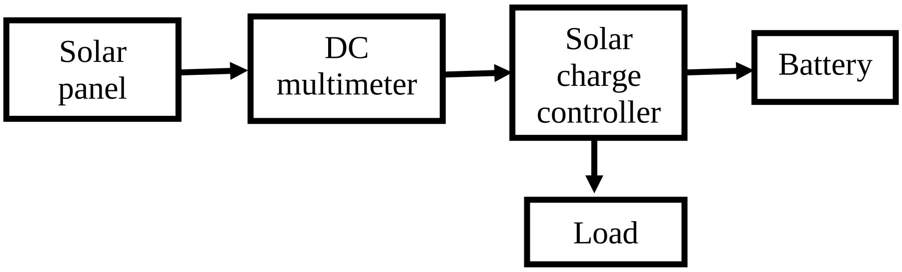

Figure 1: Block diagram of each the solar panels set-up

2.1 Indoor and Outdoor Units

The indoor unit of this work contains four solar panels attached to a rack stand for the adjustment of solar panel inclination angle. The rack stand was mainly constructed from mild steel pipe. The indoor unit consists of four multimeters, solar charge controller, battery and the five DC LED bulbs. The indoor and outdoor units are connected together through a two-core flexible cable. The units are shown in Figure 2. From the figure, it is obvious that the four panels are already inclined at different angles. The wiring diagram of both indoor and outdoor units is shown in Figure 3. The red and black lines, respectively, represent the positive and negative cable used for connection. The outdoor unit was installed at the top of the Renewable Energy Laboratory of the Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Nigeria. The indoor unit was installed inside the laboratory. Osun State University, Osogbo is on Latitude 7.7617 and Longitude 4.5986 [18].

(a) (b)

Figure 2: Experimental set-up (a) outdoor unit (b) indoor unit

2.2 Experimental Procedures Adopted

The following steps were carried out for the study.

a. The outdoor unit was placed on the roof top of the Renewable Energy Laboratory, Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Nigeria as shown in Figure 2.
b. The solar panels were inclined at different angles of 0°, 25°, 50° and 75° facing South direction. South has been reported as the best direction for solar panel installation for locations in the Northern hemisphere, which Nigeria falls under [19].
c. Energy data from each panel were captured each day for period of 5 days. Sample data on each multimeter is shown in Figure 4.

d. Steps B and C were repeated until all the solar panels experience the four angles of inclination. This was done with a view to ascertaining that the solar panels together with the connecting meters have similar characteristics. The inclination angle adjustment and energy monitoring were carried out for a 20 days period.

This study used four different inclination angle arrangements to analyse the results obtained. These are named: Arrangements 1, 2, 3 and 4. These arrangements are shown in Table 1. The implication of this is that arrangement 1 has solar panels (SP) 1, 2, 3 and 4 inclined at 0°, 25°, 50° and 75°, respectively. Similarly, arrangement 2 has solar panels (SP) 1, 2, 3 and 4 inclined at 75°, 0°, 25° and 50°, respectively. Arrangement 3 has solar panels (SP) 1, 2, 3 and 4 inclined at 50°, 75°, 0° and 25°, respectively. Lastly, arrangement 4 has solar panels (SP) 1, 2, 3 and 4 inclined at 25°, 50°, 75° and 0°, respectively. With these arrangements, each solar panel was subjected to the four inclination angles. It is important to note that, as generally known, no building roof top is inclined at 0°, however, the angle was used to serve as a reference for others.

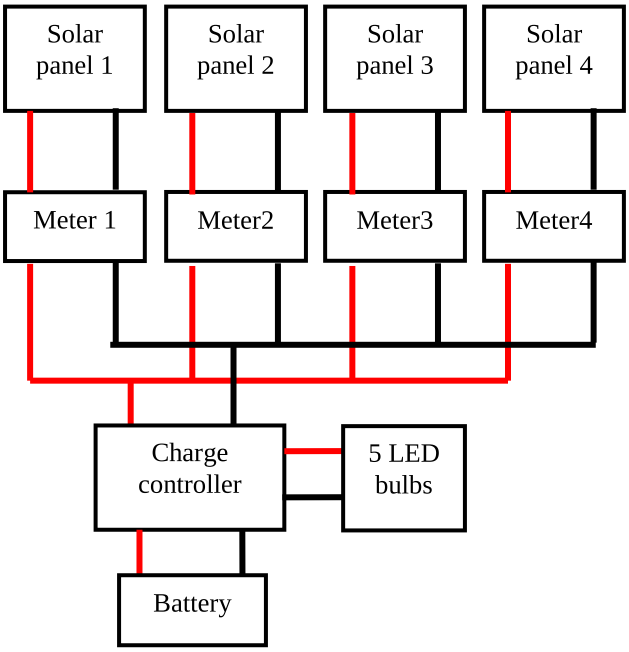

Figure 3: Electrical wiring of the experimental set-up

Figure 4: Sample multimeter readings during the day

3. RESULTS AND DISCUSSIONS

This section provides the explanation of the result obtained from the study. The results obtained from each arrangement is presented and discussed here. Each arrangement was monitored for five days and the results for all arrangements are shown in Tables 2 to 5. Table 6 shows the average energy recorded for the 20 days period. From Tables 1 to 6, it is obvious that making the solar panel to be at 0° returned the best result and as the inclination angle increases, the energy from the solar panel reduces.

Table 1: Solar panel arrangements

Arrangement	SP1	SP2	SP3	SP4
1	0°	25°	50°	75°
2	75°	0°	25°	50°
3	50°	75°	0°	25°
4	25°	50°	75°	0°

Table 2: Daily recorded energy for arrangement 1

Days	Energy (Wh) from SP1 at 0°	Energy (Wh) from SP2 at 25°	Energy (Wh) from SP3 at 50°	Energy (Wh) from SP4 at 75°
1	33	33	27	16
2	37	37	29	17
3	37	37	28	16
4	35	35	27	16
5	40	39	29	16
Average	36.4	36.2	28	16.2

Table 3: Daily recorded energy for arrangement 2

Days	Energy (Wh) from SP1 at 75°	Energy (Wh) from SP2 at 0°	Energy (Wh) from SP3 at 25°	Energy (Wh) from SP4 at 50°
1	11	45	38	28
2	10	43	36	27
3	13	37	37	29
4	11	39	37	25
5	10	34	33	24
Average	11	39.6	36.2	26.6

Table 4: Daily recorded energy for arrangements 3

Days	Energy (Wh) from SP1 at 50°	Energy (Wh) from SP2 at 75°	Energy (Wh) from SP3 at 0°	Energy (Wh) from SP4 at 25°
1	20	12	40	35
2	18	10	37	33
3	19	12	36	32
4	17	9	35	30
5	19	12	34	30
Average	18.6	11	36.4	32

Table 5: Daily recorded energy for arrangements 4

Days	Energy (Wh) from SP1 at 25°	Energy (Wh) from SP2 at 50°	Energy (Wh) from SP3 at 75°	Energy (Wh) from SP4 at 0°
1	31	30	22	36
2	26	24	19	31
3	25	23	16	29
4	22	21	18	26
5	19	18	13	23
Average	24.6	23.2	17.6	29

Table 6: Energy summary of the arrangements

Arrangements	0°	25°	50°	75°
1	36.4	36.2	28	16.2
2	39.6	36.2	26.6	11
3	36.4	32	18.6	11
4	29	24.6	23.2	17.6
Average	35.35	32.25	24.1	13.95

3.1 Effect of Roof Inclination Angle on Average Sun Hour

The implication of the variations in solar panel energy as the inclination angle varies is that the average sun hour (ASH) the panel is exposed to daily will also vary. This in turn affects sizing of solar panel needed for a building based on the inclination of the roof. For instance, if the ASH from 0^o inclination is T and used as the reference, the ASH for 25°, 50° and 75° inclinations are 0.9123T, 0.6818T and 0.3946T, respectively. These values are arrived at by dividing all average energy shown in Table 6 by the average energy of 0^o inclination (35.35 Wh). It is important to state that the value of T cannot be explicitly stated from the results obtained because the efficiency of the panel used is not known. However, the known and standard ASH for a specific location can be taken as T when the need arises. To get the ASH for inclinations in between the ones under study will require interpolation. Table 7 shows the experimental and interpolated (estimated) ASH values for other inclination angles not captured in the experiments. The ASH values in bolds are the experimental ones.

In a recent study carried out in same location [20], a roof inclination of 15^o was able to show an ASH of 4.38 hours. Using the expression for 15^o inclination in Table 7, T can be estimated to be 4.6232 hour (i.e. 4.38 ÷ 0.9474). If this value of T is to be used for Osogbo and environs, the estimated daily ASH for 25°, 50° and 75° roof inclinations are 4.22 hour (0.9123T), 3.15 hour (0.6818T) and 1.82 hour (0.3946T), respectively.

Table 7: Experimented and interpolated (estimated) ASH for different inclination angle

S/N	Angle (degree)	ASH (hr)	S/N	Angle (degree)	ASH (hr)
1	**0**	**T**	9	40	0.774T
2	5	0.9825T	10	45	0.7279T
3	10	0.9649T	11	**50**	**0.6818T**
4	15	0.9474T	12	55	0.6244T
5	20	0.9298T	13	60	0.5669T
6	**25**	**0.9123T**	14	65	0.5095T
7	30	0.8662T	15	70	0.452T
8	35	0.8201T	16	**75**	**0.3946T**

3.2 Effect of Roof Inclination Angle on Sizing of Solar Panel

Since solar panel experience different daily ASH based on the installed inclination angle, sizing of solar panel to meet specific energy need will also vary based on the roof's inclination angle. For instance, using the ASH determined in previous section, if a building intends to meet energy need of 5 kWh in a day, the size of solar panel (assuming an 100 percent solar panel efficiency) required for 25°, 50° and 75° roof inclinations are 1184.83 W (5000 ÷ 4.22), 1587.30 W (5000 ÷ 3.15) and 2747.25 W (5000 ÷ 1.82), respectively. The implication of this is that, if the roof top of a building is to be used for the installation of solar panel, the steeper the roof top, the more the solar panel required to meet up with specific energy need of the building.

4. CONCLUSION

This work has studied the variations in the energy delivered by solar panels installed at different tilt or inclination angle for 20 days. This study was carried out at the Renewable Energy Laboratory of the Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Nigeria. The work further used the information gathered to determine the effect on the daily ASH that solar panels at different inclination angles are exposed to. The ASHs were then used to size the solar panel required for sample energy need by a building. From the results obtained, it can be concluded that, the more the inclination angle of the panel, the lesser the energy it is capable of delivering. Also, the more the inclination of a building roof top, the more the amount of solar panel required to meet specific energy need of the building. Further work should look towards studying the effects of roof direction together with roof inclination angle.

ACKNOWLEDGMENT

The authors of this work acknowledge the Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Nigeria for providing us with space in their Renewable Energy Laboratory to conduct this research. We also acknowledge all those involved in the consideration of this manuscript.

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