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Design and Construction of a Cost Effective Solar Tracker

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Abstract:
To get the most energy from the sun, the solar PV panels and collectors must always be perpendicular to the direct beam irradiation from the sun. This means that the maximum power extracted from the sun is limited to the period when the direct beam from the sun is perpendicular to the solar collector. In order to obtain this maximum power, the solar PV array must be tilted and rotated at regular intervals to face the sun. This can be achieved by designing a trackable solar panel mounting frames. The thesis was aimed at designing a cost-effective solar tracker system with maximum efficiency.
The method employed involves the building of a tracker mounting frame coupled with a mechanical linear actuator. The entire system was controlled by a locally manufactured control board which signals the mechanical actuator to tilt the tracking frame at regular intervals of two (2) hours for an eight (8) hour daily period.
It was observed that the tracker generated 321.22 (W) with the motor action consuming a maximum of 0.3 (Wh) and an increase 25% in the efficiency as compared to an untracked solar array. A total cost of US $700 constituted the locally manufactured tracker but the imported tracker cost between US $1000 to US $1500 with the same efficiency and panel specification specifications.
Key Words**:**Solar PV, Solar Tracker, Efficiency, Cost Effective

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I. Introduction

The sun is an enormous nuclear reactor that continuously converts about 576 million tons of hydrogen into helium by thermonuclear fusion (Markvart and Klaus, 1994). Solar power is the most abundant and most renewable resource. The sun is about 150 million kilometers away from the earth and its effective blackbody temperature is estimated at 5,777 K (Goswami, 2000). It has been estimated that the energy radiated by the sun (all directions) is 8,000 to 10,000 times the current energy needs on earth. This means if we can extract 0.1% of the sun's energy it could supply the earth's entire energy requirement(Sawin, 2003). The sun has produced energy for billions of years and naturally energizes all the plants on the planet. These plants give energy to both man and animals through a process called photosynthesis. For decades now scientists have unlocked the secrets of how plants create energy through Photosynthesis and can duplicate that process using modern technology and silicon to generate electricity through solar cells. The technology of creating electricity from the sun by these cells can be relied upon to power our homes and cities effectively.

Solar cells are mainly semiconductor devices that convert light energy from the sun into electrical energy specifically Direct Current (DC) through photovoltaic phenomenon (Bagre, 2014). These cells are made up of semiconductor material layers positively and negatively doped.

The principle behind the technology from is that when the cells are subjected to sunlight through the metallic gridlines, electrons are freed from the negative layer of the semiconductor material. These electrons flow through, if provided, an external circuit back into the positive layer. The flow of electrons constitutes electric current. The current generated internally in the solar cell is proportional to the irradiation and weather condition at that particular time (Markvart and Klaus, 1994). Hence the energy from the solar cell is directly proportional to availability of both the direct and indirect solar irradiation.

Energy from the sun is proved not only renewable but assumes increased importance in the renewable resources because of its absence of fuel cost, little maintenance and no noise and wear due to the absence of moving parts(Zweibel, 1990). However, as every machine has its limitations, the downside to the photovoltaic principle is thehigh initial cost and low efficiency in energy conversion. In the photovoltaic system, the panel alone constitutes about 57% of the total cost, the battery and electrical system representing about 30% of the cost and other components such as the inverters, MPP- trackers, charge controllers e.t.c constitutes about 7% (Hua and Lin 2003). With this high cost of solar cells, there is the need to operate the PV module with high efficiency and at maximum power point (MPP). The output power of the solar cell is nonlinear because of its dependent on the irradiation levels, load voltage and the weather conditions which cannot be predicted (Markvart and Bogus 1994). Solar irradiation is high with direct sun light and low at a diffuse sun light. The current produced by solar panel is directly proportional to the solar irradiation. Hence, there is the need to align and site the solar panels perpendicular to the sun's apparent position at locations with high irradiation and power levels

The main objective of this project is to design a cost-effective single axis solar tracking system using local materials. For a yearly cycle, the sun makes an approximate of 46 degrees north and south movement. If we consider a fixed mounted panel with midpoint orientation between the two extremes, there will be a 23-degree sun motion on either side. This 23-degree displacement will result in an 8 % loss in the extracted power by a fixed solar panel(Lubitz, 2011).

The power produced by a solar panel is directly proportional to direct incident radiation falling on the modules. For solar panels in a fixed orientation between dawn and sunset a total sun motion of 75 degrees on either side will be observed. This means that the panel will lose 75% of the energy in the morning and evening (Lubitz, 2011). Efficiency of most modules installed in utility scale solar farms is 25% to 40% (SunShot Vision, 2012). This means that only 25-40% of the incident light is convertible to useful energy.

II. Material and Methods

There are various forms of tracking mechanisms, ranging from complex to very simple methods. But in all there are two basic parameters considered in solar tracking design; the mechanical framework (the frame) and the electrical/electronic driving system. The electrical/electronic part must generally exhibit reliability and tracking accuracy as the mechanical frame supports the entire structure firmly. The complex and broad nature of this project allowed for several considerations with its design alternatives.

This thesis will employ an active frame for the tracking process. A locally manufactured linear actuator, an analogue clock and controls will constitute the electrical and sensory section. The mechanical section will consist of frame to house two 55 Wp solar panels and a movable base to account for both the azimuth and zenith corrections. Hence, it is safe to categorize it under Active tracking.

To keep track of all considerations and ensure optimal design in the end, the solar tracker was split into three (3) main divisions. Each division had its own specific purpose and unique considerations. They are the mechanical support/mounting frame, the motor and linear actuation action and finally the control circuit.

The mechanical support/ mounting frame

Materials used to construct the mechanical structure:

1. Two "T" shaped 16"×24" threaded base support with the thread covering 10" of the rod from the top, as shown in Figure 3.1.
2. A "π" shaped 11" × 15" base structure, as shown in Figure 3.2, was also constructed.
3. A 22"×50", "U" shaped cross bar structure, as shown in Figure 3.3, to support the panel frame and the panel rest frame was constructed.
4. A 30" × 50" frame, to house two 15" × 47", 55Wp solar panels

T-shaped threaded bar, left and right, to support the cross bar at its ends by a bolt and nut action. Can be adjusted to tilt the cross bar at a preferred angle (maximum 20^{o}) left or right.

The π-Shaped middle base is bolted to the middle of the crossbar. It supports the cross bar at the middle and allow for free tilting of the cross bar left or right to make an angle to the horizontal.

Figure 1.0: T-Shaped threaded base

Figure 1.1: Pi-Shaped middle base

The crossbar as shown in Figure 1.2 is a 22”×50”, U shaped bar bolted in the middle to themiddle π-support and the panel frame rests on it. At the sides 8” away from both sides (left and right) is the T-shaped threaded base as shown in Figure 3.1 to support the weight of the panel and to allow for adjustments for proper mounting and accommodate for the yearly angular corrections. It allows for free movement at the joints to enable the tracking action.

Figure 1.2: U-shaped cross barFigure 1.3: Panel frame

The following steps were adopted to construct the mechanical structure;

1. The π-Shaped middle base was bolted to the middle of the crossbar, as shown in Fig 1.4to support the cross bar at the middle and allow for free tilting of the cross bar left or right to make an angle to the horizontal. This is to account for the yearly sun motion.
2. The T-shaped threaded bar, left and right, was screwed into the U-shaped support bar at its ends by a nut action. Figure 1.5 shows how exactly it was bolted.
3. The panel frame as shown in figure 1.3 is a 29” × 53” frame, designed to house two 13” × 51”, 55Wp solar panels which rests on the legs of the U- shaped cross bar by a bolt and nut action. An interlocker is attached to keep the panels locked and safely protected from strong winds. It is designed to accommodate standard solar panel sizes. See Appendix B tools for the 55Wp solar panels used for this project.
4. A stopper, 9” long, was welded at the side of the crossbar to secure the frame during strong winds. A spring joint was attached to the base of the crossbar and the tip of the panel frame. Two springs of different tensions and lengths are stretched over the crossbar and the panel frame spring joints. With this, the weight of the panel is balanced over the crossbar and also supports the weight during actuation.

Figure 1.5: Joint side support (Threaded rod and U-shaped cross bar)

Figure 1.4: Joint middle support (Pie shaped base and U-shaped cross bar)

Figure1.6: Base frame spring support

The supports are threaded so that by screwing the crossbar far down the thread on one side and far up the thread on the other side will affect an angular displacement of the crossbar. The total angle that can be made is limited but still enough to compensate for a 20^o seasonal change. The solar tracker frame was designed to make two motions; vertical motion to correct seasonal changes of the sun which is manually adjusted and checked during roof mounting and a horizontal motorized motion to compensate for the daily motion of the sun east to west automatically.

Motor and linear actuation

The entire weight of the panel is balanced on a three-legged mechanical frame with two springs supporting and balancing the panel frame and the base. The rotation of the solar tracker frame is done by a locally designed linear actuator. The linear actuator consists of a threaded rod, a hollow pipe, PVC pipe and two (2) end-cups, a 12V dc screwdriver motor, and bolt and nits (10 pieces).

The following steps were employed to construct the linear actuator.

1. Two bolts were welded at the ends of the hollow tube with one terminating the pipe at one end and the other bolt fixed at the other end such that the threaded rod can be bolted into the pipe.
2. The threaded rod was welded to the shaft of the 12v D.C motor such that it revolves with the shaft. The motor was then fixed into the PVC pipe with the shaft (rod) sticking out. The PVC pipe was terminated at the motor shaft end by the end-cup with the single hole such that it terminated the pipe but the shaft is allowed to revolve with the cup. The other side of the PVC pipe was also sealed water proof and glued permanently to the end-cup with two holes. The 12v D.C motor terminal leads passes through one hole of the end-cup and the other is bolted with a specially shaped eye-screw to be fitted to the base of the pie-shaped middle support.
3. The motor shaft (extended with the threaded rod) is screwed into the pipe and fixed to the solar panel frame so that the revolution of the motor causes the shaft to climb in and out of the pipe through the bolt, rendering the solar panel frame to move up and down on its axis.

Coupled on one side to the shaft of the 12V D.C. motor and the other side to the panel frame, the pipe moves so that as the motor action is initiated, the actuator pushes or pulls the panel frame linearly. This motion is converted horizontally by a joint action of the panel frame and the crossbar.

Figure 1.7: Single Axis Solar tracker

The control circuit

The control/ electrical part consists of a control circuit and an analogue clock. The analogue clock was designed to send positive signals to the control circuit at two (2) hour interval from 0800 GMT to 1700 GMT. A complete tracking process follows the process bellow:

1. The normal tracker default position is at 0800 GMT which should be 30^O S.E depending on the suns arbitrary position at the user’s location. The tracker remains at this position waiting for a 1000 GMT signal from the analogue clock to position the panel frame by means of the actuation action perpendicular to the

sun.

2. At 1000 GMT, a positive signal from the clock is sent to the control circuit which sends a signal to the actuator to position the tracker perpendicular to the sun. The result is the tracker tilting to the 1000 GMT position which should be 60^O S.E and wait for a 12noon signal.

3. At 12 noon, a positive signal from the clock is sent to the control circuit which also sends a signal to the actuator to position the tracker perpendicular to the sun. The result is the panel aligning parallel to the horizontal, thus 180^o. Tracking is then paused waiting for input from the clock at 1400 GMT.

4. At 1400 GMT and 1600 GMT, the positive signal from the clock aligns the panel 60^o and 30^o S.W respectively by means of the circuit control and the actuation action.

5. At 1700 GMT, the positive signal from the clock is inverted by the control circuit and sent to the actuator. This results in the reversing of the rotation of the tracker from clockwise to counter clockwise hence resets the tracker back to its default position, 30^O S.E and wait for a signal from the clock.

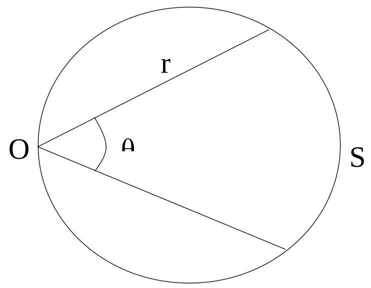
The control circuit was designed to: Initiate tracking sequence, control the timely start and stop operations of the tracking process with precision, and reset the tracking process after a complete tracking process is achieved for a day.

The tracking sequence is initiated by an “ON and OFF” switch. The tracker must be turned on in the morning before 0800GMT every day to allow tracking sequence to initiate and off every day after a complete tracking process is achieved. A complete tracking process is achieved when the tracking process returns/resets to its original position, 30^O S.E, after full tracking, dawn to sunset extremes, is accomplished.

To control the timely start and stop action of the tracker, the control circuit board was partitioned into conductive sections and non-conductive sections depending on the time signal from the analogue clock. Figure 3.14 shows the control circuit board. The circuit control was designed to conduct or send a continuous signal to the actuator so long as there remains a contact between the conductive sectors of the circuit. The conducting sectors were partitioned into six (6) isolated regions. Each sector receives a positive signal from the clock and a negative signal from the battery. In between the regions are separated by insulators. The length of a sector was calculated mathematically by:

$S = \theta \times r$

S	arc length
r	radius of the arc
Θ	arc angle
O	center of the circle



The distance between dawn and sunset is a complete revolution which is 360^o therefore one (1) day, from 0600 GMT to 1800 GMT makes 360^o, with the night also making another 360^o. Therefore, the difference between each hour for a 12-hour period is 30^o and 15^o for a 24-hour period. Arc length (S), as seen in the figure above, is calculated as the angle (θ) multiplied by the radius (r) of the circle. To find the length of the sectors, the proportional radius of the tracking frame (0.381m) was multiplied by 30^o, since the tracker would be tracking at a two (2) hour interval.

$S = 30\times 0.381$
$S = 11.43m$

For the reversing/resetting sector, the tracker has to make a total length of sum of all the sector lengths in reverse, which had a separate sector rout (sector R) for the reverse movement.

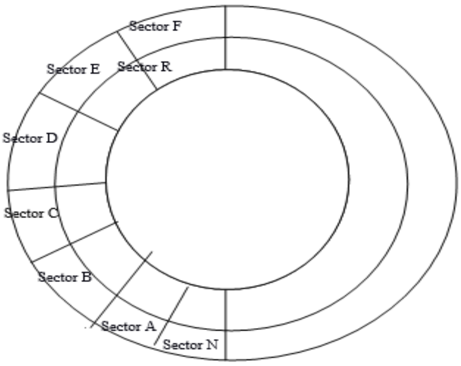


Figure1.8: Control Circuit Board Design

Figure1.9: Control Circuit Plate

Sector A 6a.m to 8a.m (positive signal from the clock)
Sector B 8a.m to 10a.m (positive signal from the clock)
Sector C 10a.m to 12 noon (positive signal from the clock)
Sector D 12 noon to 1400 GMT (positive signal from the clock)
Sector E 1400 GMT to 1600 GMT (positive signal from the clock)
Sector F 1600 GMT to 1800 GMT (positive signal from the clock)
Sector R Reverse (positive signal from the clock)
Sector N Neutral (negative signal from the battery)

III. Result

Based on the design configuration presented, the set up was mounted and the various parts were simultaneously tested. The experiment was carried out from February 10 to 24, 2015 and March 2nd to 6th, 2015. Four similar solar panels of the same electrical output were used. Two of the panels were paralleled to produce 110Wp, 12V array and attached to the solar tracking frame and the others also coupled together and mounted on a zenith- facing non-tracking surface. Data for current and voltage were recorded using appropriate meters at two (2) hour intervals, from 0800 GMT to 1600 GMT daily during the experiment. A solar irradiation meter and a thermometer recorded the horizontal solar irradiation and ambient temperature of the location consistently throughout the experimentation process. The experiment was performed on sunny, cloudy and severe overcast days.

Tracker and motor analysis:

Daily energy produced by the setups, separately was calculated using equation 4.1. The power consumed by the actuator was also calculated based on the time and number of movements made in a day including the reversing mode.

Energy (E) = Voltage (V) * Current (A) * time (s)

Voltage, steady state current and starting current were measured using a multimeter and an oscilloscope. The measurement of voltage, steady state current, starting current and time taken for total tracking by the actuator (climbing and descending) were measured. Table 4.1 shows the experimental results for the solar tracker.

Experimental results for tracked solar array:

The experimentation began at 6 a.m with irradiation of 50 Wp/m^2. A current and voltage of 0.3 A and 18.71 V were respectively recorded which resulted in a total power, at that hour, of 5.61 W. At noon where the irradiation peaked at 920 Wp/m^2, a current and voltage levels of 5.52 A and 19.3 V were recorded respectively which recorded a maximum power 106.54 W. At 4 p.m. when the irradiation shrunk to 483 Wp/m^2, a current and voltage level of 2.90 A and 18.74 V were recorded corresponding to power of 54.31 W. At 5 p.m. as the trackable reverses its path to the default mode, the irradiation level was 60 Wp/m^2, current and voltage levels of 0.33 A and 18.66 V respectively and a power of 6.15 W. On average for the day, a power of 61.09 was recorded.

Table 1: Average 2 hourly data for tracked solar array (February 10, 2015)

Time	Irradiation (Tracked) W/m^2	Current Amps	Voltage Volts	Power Watt
06:00	50	0.3	18.71	5.61
08:00	559	3.354	18.97	63.62
10:00	815	4.89	19.27	94.23

12:00	920	5.52	19.3	106.54
14:00	840	5.04	19.29	97.22
16:00	483	2.898	18.74	54.31
17:00	60	0.33	18.66	6.15
	Average			**61.09**

Total Energy produced = Average Voltage (V) * Average Current (I) * Time (s)
Time = 8 hrs
Energy produced = 61.09*8
= 488.72 Wh

Table 2: Average daily data log for tracked solar array (February 10th to February 24th)

Duration Days (8 hrs)	**Total Power Watts**
1 (Feb 10, 2015)	61.09
2 (Feb 12, 2015)	71.23
3 (Feb 13, 2015)	57.07
4 (Feb 22, 2015)	59.8
5 (Feb 24, 2015)	72.03
Total	**321.22**

Table3: Total Power consumption of actuator in a day

Duration (GMT)	**Time (s)**	**Power**	
		steady state (W)	**Starting (W)**
0800 to 1600	3[1]	3.78	12.78
Reverse	10	3.6	14.2
Total	**22**	**7.38**	**26.98**

The daily duration for the motor action is about 33 seconds. Hence, the total energy consumed for tracking in a day was calculated as:
Energy consumed by actuator = Power * Time

E (steady state) = 7.38*22
= 162.36 = 0.0451Wh
E (Starting) = 26.98*22
= 890.34= 0.1649 Wh

It was observed on the first day, that the tracker generation delivers 720.511Wh with the motor action consuming a maximum of 0.3 Wh per day.

Experimental results for the zenith facing untracked solar array

Table 4: Hourly data log of zenith facing solar array (February 10, 2015)

Irradiation (Zenith facing) W/m^2	**Current Amps**	**Voltage Volts**	**Power Watts**
13	0.09	18.12	1.73
140	0.84	18.56	16.22
540	3.24	18.9	61.59
920	5.52	19.3	106.14
802	4.812	19.27	87.86
200	1.2	18.82	21.85
60	0.33	18.67	6.16
Average			**43**

Table 5: daily data log for zenith facing solar array (February 10th to February 24th)

Duration Days (8 hrs)	**Total Power Watts**
1 (Feb 10, 2015)	43.07
2 (Feb 12, 2015)	46.86
3 (Feb 13, 2015)	19.08

[1] Time 3s is the time per two hourly movement of the motor. The total forward movement(8 a.m. to 4 p.m.) is 12s

4 (Feb 22, 2015)	33.89
5 (Feb 24, 2015)	36.56
Total	**179.47**

Comparative analyses of the tracked and untracked:

The overall power generated and the energy gain is shown in table 4.6. It can be noticed that for all weather conditions, the tracking panel gave the higher power generation. Factoring in the power consumption by the tracker, the margin decreased insignificantly.

Table 6: Percentage difference in extracted power between the two modes

Month (February,2015)	Daily mean solar irradiation (KWh/m^2-day)	Days	Power generation by untracked (W)	Power generation Tracker (W)	Percentage difference between generations (%)
February,2015	**5.066**	1 (Feb 10, 2015)	43.9	61.18	**39.36**
	5.103	2 (Feb 12, 2015)	46.86	71.23	**52.00**
	5.367	3 (Feb 13, 2015)	19.08	57.07	**+99**
	5.254	4 (Feb 22, 2015)	33.89	59.80	**76.45**
	5.735	5 (Feb 24, 2015)	36.56	72.03	**97.00**

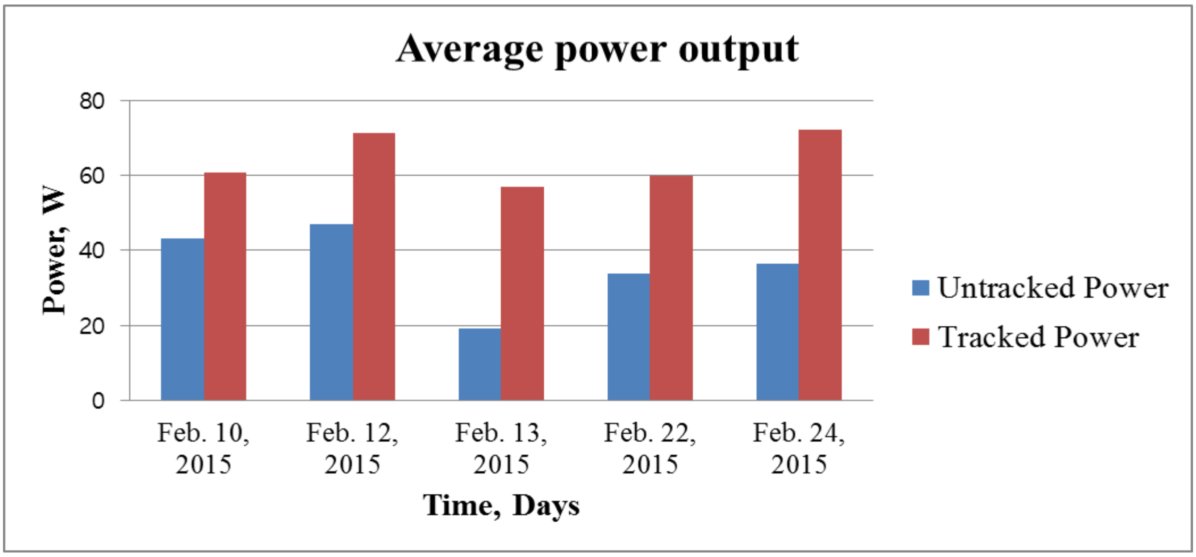


Figure 1: Panel Output Power vs. Time

For a cloudless sky, the graph of the power generated is parabolic but however, environmental effects such as cloudiness, dust and obstacles may influence the graph. There could be a few increments during certain time of the day and minimum in other periods. During sunny clear days, the power generation from the tracker showed encouraging results of 962.4 Wh, while the untracked module produced 551.6 Wh. The power generated by the zenith facing panel was low due to its orientation, thus losing most of the energy in the morning and sunset extremes. Moisture, dust and cloudiness reduce the irradiance spectrum received by the PV module during the afternoon for both the tracked and untracked solar panels.

On a cloudy day, where frequent overcast is experienced, the power generated was not constant due to the solar irradiation dropping and peaking uncontrollably. The result in power generation for the tracked and untracked panels was 880 Wh and 562 Wh respectively. The tracker proved useful during this weather condition. But in spite of this success, further improvements must be made in order to halt the tracker operation during severe overcast so as to save energy.

Cost analysis:

To make economic sense out of the use of the tracker, the increased energy harvested from the tracker must exceed the added cost of installation and maintenance of the tracker over the system's life time. The analysis of the different technological consideration can be very detailed but for comparison purposes, the approach employed here is much simplified. For the purpose of this thesis, all analysis are based only on the direct cost. The costs measured may vary by country due to accessibility of raw materials and the economic situation of the country. The cost considered includes.

1. Tracker frame equipment cost (actuator and trackable mounting frame).
2. Total installation cost.
3. Fixed and variable operating and maintenance costs.

Table 7: Tracker frame equipment used and cost

Equipment	Number	Unit Cost (US $)	Total cost (US $)
55Wp Solar Panel	2	50	100
Motor and actuator	1	56.42	56.42
Analog clock	1	2.82	2.82
Bolts and nut	5	1.42	7.1
Threaded Rod	3	4.23	12.69
Switches	2	0.71	1.42
Circuit Board	½ a meter	7.05	7.05
Cables	3 meters flexible multi-core cable	3.75	3.75
Cost of tracking frame	1	84.63	84.63
Labor / installation cost	3	56.42	169.26
Fixed and variable O&M	20	40	266.67
Total			**632.75**

IV. Conclusion

A cost effective single-axis solar tracker with improved efficiency was designed and constructed. The design consists of an adjustable mechanical frame to compensate for the yearly deviation of the sun by means of linked motor and actuation mechanism and an electrical circuitry to control the entire process. The entire structure is about 0.87 meters high and 1.35 meters wide to increase stability against wind gusts and reduce installation costs. The system can be ground mounted as well as be secured to the roof using bolt and nut action.

The tracker was locally designed and manufactured to suit the Ghanaian environment. The design stage was divided into Mechanical, Motor and actuation and the electrical stages to simplify the complex structure. Breaking the design process up into three smaller, more manageable subsystems made this complicated device a bit easier to handle. Simple electronics and mechanical geometric principles were employed. RETSCREEN, HOMER and other analysis tools aided in the determination of the solar resource assessment of the location. Again, the set up was experimented with zenith facing solar panels to confirm the efficiency of the tracker and it proved to increase the solar panel output power by up to 30%.

The budget for the tracker (without solar panels, inverters, charge controllers and batteries) was above US $529. Compared to the costs of an imported solar tracker of US $ 1500 to US $ 12000 (SunShot Vision, 2012)(Middleton, 2015), this tracker is less expensive. The tracker was designed to house even bigger panels. Hence, a bigger system will require just a few more stability adjustments.

The tracker can be applied in other systems requiring direct beam irradiation besides solar photovoltaic technology, such as measuring instruments, concentrated solar collectors and solar dryers.

V. Recommendation

Although the tests proved an increase in the solar panel efficiency throughout the day, the tracker can be improved to further increase the efficiency and reduce the losses and motor actuation energy consumption with little effects on cost. Below are a few recommendations;

1. Further studies and research should be conducted in the tracker technology.
2. The tracker could be programmed to pause/ stop motor actuation action during severe overcast and cloudy weather conditions where there is little or no direct sunlight.
3. Government subsidies on solar panels are encouraged since the panels make about 57% of the total cost.
4. The tracker should be combined with MPPT (Maximum Power Point Tracking) as well as cooling mechanisms to increase the maximum power extraction.

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