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Comparative performance analysis between static solar panels and single-axis tracking system on a hot climate region near to the equator

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ABSTRACT

Photovoltaic solar energy has been explored as an energy solution to the decline of energy production, as well as environmental concerns. However, generate electricity through the sun still considered uncompetitive freight to other sources, cause it presents low efficiency and high production cost. In attempt to make it more attractive from a financial point view, solar trackers has been used to increase the photovoltaic systems efficiency. Considering its facts, this paper aims to perform a comparative study between a static photovoltaic solar panel and a one-axis mobility panel, installed in the city of Mossoró/RN. The city in study is located in the Brazilian semiarid, under high solar radiation levels, in a dry climate and hot region, reaching high temperatures during the day. After assembly the proposed systems, were performed operating analysis and performance comparative study between the static and mobile systems, which allowed to conclude that the panel using the sun tracking showed a low average gain in power generated relative to the fixed panel to the region where the systems installed.

Contents

1. Introduction

The world energy consumption has shown high growth over the past decades, driven by technological progress and human

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development. This growth, together with the possibility of reducing the fossil fuels supply, and also the growing concern to the environment preservation, have been encouraging factors to research and development of alternative energy sources, less polluting, renewable and produce little environmental impact [1].

Faced with this global scenery, the use of solar energy, especially with regard to the generation of electricity through photovoltaic panels, is increasing the installed power each year, reaching approximately 139 GW in 2013 [2].

The electricity generation through the sun can bring benefits, such as the diversification of energy sources, reduction of environmental impacts and reducing fossil fuels dependence [3,4]. Despite the advantages presented, photovoltaic electricity generation find obstacles to its popularization. Two factors limit its use today, namely, the high production costs and low efficiency compared to others alternative energy sources [5].

Looking for increase photovoltaic systems efficiency, researches have been developed using solar trackers. These devices keep the panels almost always directed toward the sun in order to always keep the surface perpendicular to the solar rays. Thus, there is a greater uptake of solar energy and consequent increase in energy production [6].

The first tracker was completely mechanical and introduced by Finster in 1962. One year later, Saavedra presented a mechanism with an automatic electronic control, which was used to orient an Eppley pyrheliometer [7].

Bione et al. compared the pumping systems driven by fixed, tracking and tracking with concentration PVs. The PV–V-trough system, consisted of four cavities and two PV modules to track the sun along its north–south axis, tilted at an angle of 20° towards the north. A theoretical simulation, as well as experimental comparison between three cases, was performed. By analyzing the daily characteristic curve for three given modes, the results showed that for a given irradiance, the pumped water flow rate was significantly different from one another. They proved that the benefits ratios obtained for water volume were higher than that for collected solar energy. The fixed PV, the PV with the tracker and the concentrating-tracking systems pumped 4.9, 7.4 and 12.6 m^3/day, respectively [8].

Tomson analyzed the performance of the two-positional control of single stand-alone flat plate concentrator. The collector was rotated around its single tilted axis twice per day with predefined deflections. The effect of different tilt angles, initial tilt angle, initial azimuth, and azimuth angle of the deflected plane were evaluated on the daily and seasonal gain. The comparison of simulation and experimental results indicated that using a simple tracking drive with low energy input for a brief daily movement, increased the seasonal energy yield by 10–20% comparing to that of a fixed south facing collector tilted at an optimal angle [9].

Ai et al. proposed and compared the azimuth and hour angle three-step trackers. The day length on the south facing slope was divided into three equal parts in order to adjust the tilt angle. The sum of the direct radiation received in each time interval and the sky diffusion and ground reflection radiation during a day were considered to derive the mathematical formula for the three-step tracking system to estimate the daily radiation on planes. They concluded that for the whole year, the radiation on the slope with optimized tilt angle was 30.2% and that for the two-axis azimuth three-step tracking was 72% higher than that on the horizontal surface. No significant difference was found between one-axis azimuth three-step tracking and hour angle three-step tracking power [10].

Michaelides et al. investigated and compared the performance and cost effectiveness of a solar water heater with collector surface in four situations: fixed at 40° from the horizontal, the single-axis tracking with a vertical axis, fixed slope and variable azimuth and the seasonal tracking mode where the collector slope is changed twice per year. To analyze the system, they used computer simulations using the TRNSYS simulation program for a thermosiphon system. The simulation results showed that the best thermal performance was obtained with the single-axis tracking. In Nicosia, the annual solar fraction (fraction of load that is provided by solar radiation) with this mode was 87.6% compared to 81.6% with the seasonal mode and to 79.7% with the fixed surface mode, while the corresponding figures for Athens were 81.4%, 76.2%, and 74.4%, respectively. From the economic point of view, the fixed surface mode was found to be the most cost effective [11].

Lorenzo et al. designed a single vertical axis (azimuth axis) PV tracker and evaluated backtracking features. Each of 400 trackers installed in Spain used a 0.25 hp standard AC motor. The tilt angle of the PV surfaces remained constant. They mentioned that the energy collected by an ideal azimuth tracker was about 40% higher than that corresponding to an optimally tilted static surface and 10% higher than that of horizontal axis tracking. They calculated the E–W and N–S shadowing between two adjacent trackers occurred in the morning or afternoon. They recommended that when shadowing occurs, it can be avoided by moving the surface's azimuth angle away from its ideal value, just enough to get the shadow borderline to pass through the corner of the adjacent surface (backtracking). Their comparison showed that the azimuth tracking land was 40% greater than static surface while the corresponding energy cost can be significantly reduced [12].

Ibrahim constructed an electronically one-axis concentrating collector with an electric motor for forced circulation. The collector was hinged at two points for its tilt adjustment with a tightening screw to continuously track the sun from east to west through a range of 180°. The collector efficiency was measured for different values of mass flow rates. It was concluded that the collector efficiency increases (reaching the maximum value of 62%) as the mass flow rate increases [13].

Stern et al. designed, fabricated, tested and demonstrated a modular and fully integrated 15 kW, one-axis solar tracking PV power. The tracker used potentiometer and integral pendulum to provide a positive feedback signal to the tracker motor and actuator. It was concluded that single-axis solar tracking provides 20% more energy in a typical year than that of a fixed-axis PV system. Also, the net reduction in the total cost of single-axis solar tracking grid connected PV power system was found to be 23.3% [14].

2. Sun-tracking methods

Over the years, researchers have developed smart solar trackers to increase the amount of energy generation. Before the introduction of solar tracking methods, static solar panels were positioned with a reasonable tilted angle based on the latitude of the location. The introductions of automated systems improve existing power generation over 50% [15].

There are mainly two types of solar trackers on the basis of their movement degrees of freedoms. These are single axis solar tracker and dual axis solar tracker. Again these two systems are further classified on the basis of their tracking technologies. Active, passive, and chronological trackers are three of them [16,17]. Previous researchers used single axis tracking system which follows only the sun's daily motion [18].

There are several implementations of single axis trackers. These include horizontal single axis trackers, vertical single axis trackers, tilted single axis trackers and polar aligned single axis trackers [19–21].

Al-Mohamad designed a single-axis sun-tracking system based on a programmable logic controlling (PLC) unit to investigate the improvement in the daily output power of a photo-voltaic module. Two photo-resistive sensors were separated by a barrier to provide shadow for one of them. As solar radiation intensity increases the resistivity of the sensor decreases. Two output signals of the unit are connected directly to the analog inputs of the PLC and compared in order to produce a proper output signal to activate an electromechanical sun-tracking system. The tracker scans through an angle of about 120° east–west. For PLC, a proper program to control, monitor and to collect data was developed using special software. A special computer program for automatic detection and computer communication with RS-232 was developed using Visual Basic 5. The performance of the sun-tracker was evaluated and monitored. The output power showed a considerable increase during the early and late hours of the day. In fact, the overall improvement, in the tracking mode, exceeded 40% for the period from 6:00 to 10:00 a.m. and for the period from 15:00 to 17:00 p.m. However, the improvement was about 2–4% during mid-day. The average overall improvement during the whole day was better than 20% in comparison with that of a fixed module [22].

Konar et al. designed a one-axis microprocessor based sun-tracking device for using in PV flat plate solar panels or with parabolic reflectors. It was optimally tilted around one axis and controls the azimuth angle with another axis. They mentioned that this tracking device considerably saves the collected power and is independent from site circumstances such as geographical locations and temporal variation [23].

Kalogirou designed and constructed a one-axis sun-tracking system consisting of a control system with three light dependent resistor sensors and a DC motor. One sensor was responsible for direct beam detection; the second was cloud sensor and the third was daylight sensor. The control system consisted of relay, timer, many resistors and electronic parts. When any of the three sensors was shaded, the motor was switched on. The system tracked the sun in east-west direction and the final rotational speed of the collector was 0.011 rpm. Various tests of the solar collector showed that the tracking mechanism was very accurate [24].

But the earth follows a complex motion that consists of the daily and the annual motions. The daily motion causes the sun to appear in the east to west direction over the earth whereas the annual motion causes the sun to tilt at a particular angle while moving along east to west direction [25].

Solar tracking is best achieved when the tilt angle of the solar tracking systems is synchronized with the seasonal changes of the sun's altitude. An ideal tracker would allow the solar modules to point towards the sun, compensating for both changes in the altitude angle of the sun and latitudinal offset of the sun. So the maximum efficiency of the solar panel is not being used by single axis tracking system whereas double axis tracking would ensure a cosine effectiveness of one. The active/continuous tracking system tracks the sun for light intensity variation with precision. Hence, the power gain from this system is very high [26]. But to achieve this power gain the system uses two different motors continuously for two different axes. As a result, it always consumes a certain amount of extra power compared to time-based tracking system.

Dual axis trackers have two degrees of freedom that act as axis of rotation. There are some common implementations of dual axis trackers. They are classified by the orientation of their primary axis with respect to the ground.

Two common implementations are tip-tilt dual axis trackers and azimuth-altitude dual axis trackers [27]. Dual axis trackers allow for optimum solar energy levels due to their ability to follow the sun vertically and horizontally. It has two racks: one moves north-south and the other moves east-west side. Thus the primary benefit of a tracking system is to collect solar energy for the longest period of the day, and with the most accurate alignment as the sun's position shifts with the seasons.

Bingol et al. proposed, implemented and tested a microcontroller based two-axis solar tracking system. They used light dependent resistors as sensors, stepper motors as actuators and a microcontroller. In addition, the system was connected to a PC via RS-232 for sun position monitoring. The panel degree from vertical axis was fixed at 50°. The experimental study for two solar collector panels, one stationary and the other rotary were employed in the test. Temperature of the panels versus time was measured with a minute interval and 50 data were captured. The angle of intervals was almost 5.2°. A distinction of 9 °C between rotary and stationary panel was observed. This result verified that the rotary panel containing solar tracking system took more light density than the stationary panel [28].

Hamilton, in his thesis designed and constructed a microcontroller based sun-tracking device that used two motors to tilt the array in two planes of movement. The algorithm was designed to read and amplify sensor values and then to compare the data digitally to determine the exact position of the sun to activate the positioning uni-polar stepper motors. The sensor was a four sided pyramid in structure with solar cells mounted on each side. The microcontroller was programmed in C language. The device was tested both in the field and in the laboratory using a portable light source that was set up at 16 positions inside of a spherical area. The results showed that the sun-tracking system collected maximum energy throughout the day while stationary system collected maximum energy just when the sun was positioned overhead [29].

In active tracking or continuous tracking, the position of the sun in the sky during the day is continuously determined by sensors. The sensors will trigger the motor or actuator to move the mounting system so that the solar panels will always face the sun throughout the day. If the sunlight is not perpendicular to the tracker, then there will be a difference in light intensity on one light sensor compared to another. This difference can be used to determine in which direction the tracker has to be tilted in order to be perpendicular to the sun. This method of sun tracking is reasonably accurate except on very cloudy days when it is hard for the sensors to determine the position of the sun in the sky [30].

Passive tracker, unlike an active tracker which determines the position of the sun in the sky, moves in response to an imbalance in pressure between two points at both ends of the tracker. The imbalance is caused by solar heat creating gas pressure on a "low boiling point compressed gas fluid, that is, driven to one side or the other" which then moves the structure. However, this method of sun tracking is not accurate [31,47].

Mwithiga et al. designed and constructed a dryer with limited sun-tracking capability that operated manually. The dryer consisted of a gauge 20 mild steel flat absorber plate formed into a topless box. The drying unit was bolted onto a shaft which in turn was mounted on to a stand so as to face east-west direction. A selector disc on the stand allowed the tilt angle that the drying unit made with the horizontal, to be easily adjusted in increments of at least 15°. This way, the collector plate could be intermittently adjusted in order to track the sun during the day. Four dryer settings for tracking the sun were created. The dryer was set at an angle of 60° to the horizontal facing east at 8:00 a.m. They adjusted the angle of the dryer made with the horizontal either one, three, five or nine times a day when either loaded with coffee beans or under no load conditions. The results showed that the solar dryer can be used to successfully dry grains. Drying of coffee beans could be reduced to 2–3 days as opposed to sun drying without tracking system, which takes 5–7 days and the temperature inside the chamber could reach a maximum of 70.4 °C [32].

A chronological tracker is a time-based tracking system where the structure is moved at a fixed rate throughout the day as well for different months. Thus the motor or actuator is controlled to rotate at a slow average rate of one revolution per day (15°/hour). This method of sun tracking is more energy efficient [33].

Edwards examined the operation of a computer based sun following system for parabolic collectors. The computer of the system changes the speed of each of the collector actuators at regular intervals over the day. It is shown that for accurate sun following, the system requires a data output from the central controller of only 500 bit/s for ten thousand collectors [34].

In view of above, this paper proposes a comparative analysis between a static PV system, and one that makes use of a tracking system installed. Both systems were installed in a dry and hot climate region under high levels of solar radiation, and near line the equator, and its performances would be compared and analyzed in order to determinate its efficiency considering the local climate conditions.

3. Systems description

The research was developed in Mossoró city, located in the Brazilian semi-arid, its location defined by the geographical coordinates of 5° 11′ South Latitude (S) and 37° 20′ West Longitude (W), at an altitude of 18 m above the sea level. The city's climate is classified as dry, very hot and its rainy season in the summer, with an average annual temperature of 27.4 °C, average rainfall of 673.9 mm, and average air relative humidity 68.9% [35,36]. The city solar radiation average rate is 5.23 kWh/m^2, and the daily average insolation is 7.42 h per day [37,38]. Because the low-latitude region, therefore the proximity to the equator, there are no major changes in the sun's position throughout the year, or hours of sunshine per day.

The paper proposes to develop and analyze two distinct photovoltaic (PV) systems, as mentioned above, the first of a fixed solar panel, and the other with sun tracking mechanism using one-axis mobility azimuthal tracking strategy [39], to east-west direction. The Fig. 1 outlines the two assembled and analyzed systems. Both systems collect data on analyzes such as generated current and voltage, panel temperature and solar radiation [40]. The collected data is sent to the controller in this case uses an Arduino® board, stored and sent to a computer for further analysis.

For the case of the tracking system, the controller also receives information from the light intensity incident on the panels. If the controller identifies the capture of solar panels not being the maximum, this sends a command signal to the step motor installed on the structure. Detailed components and sensors are describe on Section 3.1.

3.1. Sensors and actuators

Sensors are devices responsible for collecting system data. In this case, the measurement variables are: current; tension; module temperature; solar radiation; and luminosity for positioning the panels.

3.1.1. Current measure

The ACS712ELC 30A sensor makes current measurement. It is powered by the controller board with 5 V input voltage. Two current sensors were installed, one for each photovoltaics panel in order to measure the current generated by the systems. The sensor can measure alternating or continuous currents up to 30A [41], and provides an output voltage proportional to the measured current. The proportion of the analog output for this sensor module is 66 mV/A.

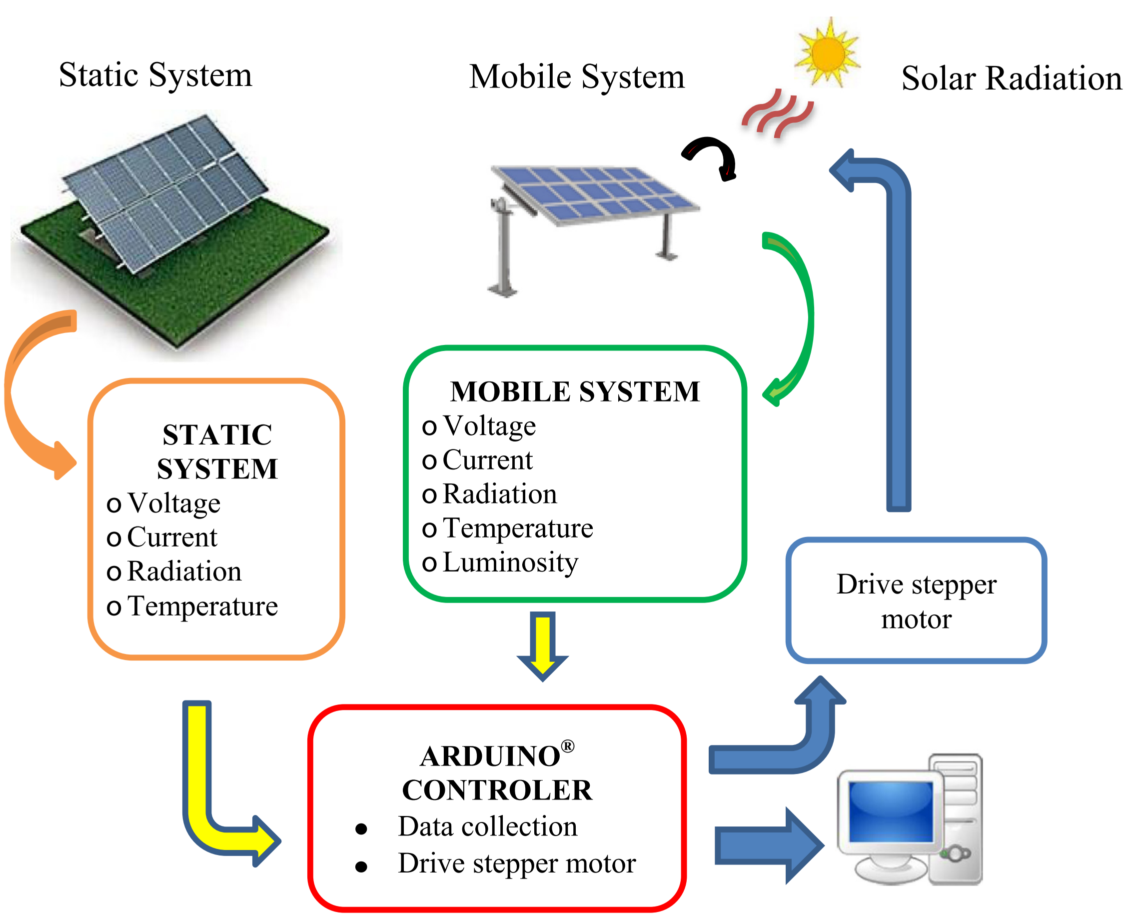

Fig. 1. Analyzed systems layout.

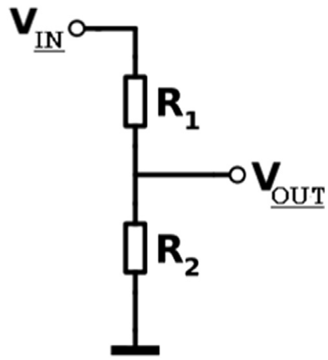

Fig. 2. Circuit voltage divider.

3.1.2. Voltage measurement

The voltage measurement is taken via a simple circuit voltage divider shown in Fig. 2. The input voltage V_{in} is the voltage generated in the photovoltaic module. To make the Arduino® board capable to read the voltage divider decrease the output voltage V_{out} so the maximum is 5 V.

The V_{out} voltage signal is read by the controller, and calculated the actual voltage value given by Eq. (1).

$$V_{out} = \frac{V_{in} \times R_2}{R_1 + R_2} \tag{1}$$

The maximum voltage V_{in} input corresponds to the open circuit voltage V_{oc} to the module uses of the project is 21.4 V, and the maximum voltage V_{out} that microcontrolled board receives is 5 V. Therefore, the resistors R_1 and R_2 must have respectivelly values of 33 kΩ and 10 kΩ [41].

3.1.3. Modules temperature measurement

The temperature of the PV modules is a factor that can influence the production of electricity in the panels, so it is a variable that should be monitored [42]. In the case of the current study, was used a LM35 temperature sensor. The sensor sends a signal which output voltage is linearly proportional to the temperature in Celsius degrees. The scale factor is 10 mV/°C with guaranteed precision of 0.5 °C.

3.1.4. Solar radiation measurement

The measurement was taken of solar radiation meter, developed by [43]. The solar radiation measurement system uses the same microcontrolled boardArduino® Mega using an LDR sensor (Light dependent resistor), also called photo resistive cell, or photo resistance. It is a semiconductor device which resistance varies linearly with incident light intensity. This device reduces its resistance when lighted, and increases as decreases to lightening.

According to [44] the Eq. (2) that converts the value read in Arduino® pine to solar radiation in W/m^2.

$$Rad = 4464,9 \times e^{-17,73 \times V_{out}} \tag{2}$$

Where:

Rad → Solar radiation
V_{out} → Output voltage read by Arduino®

An LDR sensor were installed dedicated to solar radiation measuring, the sensor signal will be sent to the controller, and Eq. (2), inserted in the controller command lines, will convert the value read for the solar radiation W/m^2.

3.1.5. Lighting intensity measurement positioning

The photovoltaic panel position of system studied is made through a pair of LDR sensors [44], separated by a shadier, similar to that illustrated in Fig. 3. As shown in Fig. 3, the LDR sensor 2 is shaded by the shield while the LDR 1 remains illuminated by the sun. The control circuit realizes this condition and sends drive signal of the stepper motor, until both LDR's are illuminated uniformly.

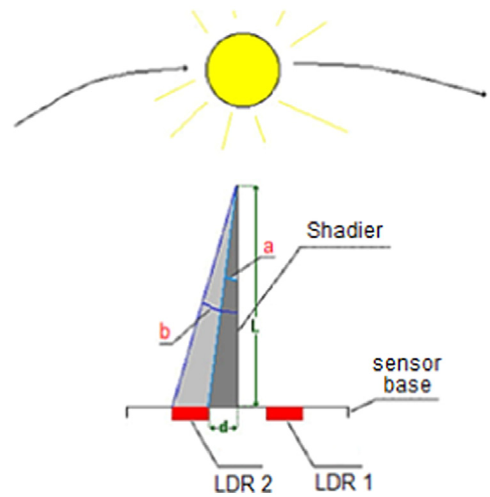

Fig. 3. Arrangement of LDR sensors to the structure positioning.

The angle “a” corresponds to the position in which the sensors are equally lighted, and depends on the distance between the LDR's and the preliminary stop length. So has the angle “a” is given by Eq. (3), wherein “d” is the distance between the sensor and the shadier, and L is the height thereof [45].

$$a = \tan^{-1} \frac{d}{L} \tag{3}$$

The angle “b” shown in Fig. 3, corresponds to the angle at which the LDR 2 is completely shadowed. The pair of sensors for guidance used in this study is shown in Fig. 4. The dimensions of the device are 5 × 3 cm, the shadier being located exactly in the center with 5 cm. The sensors are properly installed in the mobile PV module, and protected by an acrylic box, and a small plate the same material on its surface.

The controller board reads the sensor signal each 4 minutes, cause this is interval that the sun needs to move one degree [46]. When it identify different readings form the two LDR's, a signal is sent to the step motor, so it can move the PV module, and align to the best system efficiency.

Fig. 4. Positioning sensor used in the mobile PV panel.

3.1.6. Step motor

The stepper motor used in the system is HT23–397 Kalatec Automation Ltd. manufacturer. The basic features of equipment are: step angle is 1.8°; maximum current is 2 A; and maximum torque of 1.25 N m. The drive motor is made by a L298N stepper motor driver. The driver receives a signal from the microcontroller, and can run up to two stepper motors from 5 to 35 V in continuous tension, by a propels the current maximum 2 A, providing an output signal of 5 V.

3.1.7. PV Module

The photovoltaic panel used in the two-siste but analyzed is the STP020S-12/Cb facture Suntech model. The module's electrical characteristics are described in Table 1.

The technology of the cells composing the grindstone-module is monocrystalline silicon, with dimensions of 656 × 306 × 18 mm and weight of 2.5 kg.

4. Static PV panel assembly

The static PV panel assembly did not show any complications, and gave as had been projected. The system was set up, and sensors were installed to monitor the voltage, current, temperature, and incident solar radiation on the modules. Also were installed a light bulb of 32 V and 25 W of power as load to dissipate the power produced in the module. The static system is shown in Fig. 5.

Fig. 5(a) and (b) shows the inclination of 5° from the static module in this case regarding the location of the latitude, as described on Section 2.

5. Mobile PV panel assembly

The structure had been made with mobility on two axes, and to the research in question was used only east-west movement in order to track the sun's movement throughout the day. The stepper motor were installed axially to the drive axis, making it necessary to install a fixed axis gearbox for better stability of the structure and increasing the engine torque. The structure used is shown in Fig. 6.

Also two buttons are installed, one on each side of the path of the panel, in order to indicate the end of the travel trace and a light bulb, identical to the static system installed, such as load of a power consumption generated by the PV panel. After assembly of static and mobile systems, began collecting data for later performance analysis, described in Section 5.

6. Results and discussion

For both systems, eight days of data collection were performed in the period from 13 to 20 July 2014. The performance of the systems was observed from 8:00 to 17:30 h, with daily measurement intervals of four minutes each reading for position, and ten minutes to the others variables. It was not possible to observe the performance of the system at sunrise due to technical limitations such as shading of the modules in the first hours of the morning, caused by trees near the site where the experiment was conducted.

6.1. Static system performance

The static system performance is shown in Table 2 where it can be seen that the average power generated during the test days was approximately 146 Wh, significantly varies according to the weather condition.

The average static PV panel surface temperatures shown in Table 2 do not exceed the operating temperature of the cell, which is 50 °C according to Table 1. Fig. 7 illustrates the temperature curve on the panel and the energy generated over the days observed. Observing Fig. 7, the increase in power generation accompanied by increased average temperature during the days of experiment.

The performance of power and energy generated by the static system module can be seen in Figs. 8 and 9, the first graph generated on a cloudy day and the second on a sunny day.

Analyzing Figs. 8 and 9, it is observed that the fixed system, in both situations, generates power above rated module that is

Table 1
PV module electrical characteristics.

Maximum Power (P_{max})	20 Wp
Maximum Power Current (I_{mp})	1.19 A
Maximum Power Voltage (V_{mp})	16.8 V
Shot-Circuit Current (I_{sc})	1.21 A
Open Circuit Voltage (V_{oc})	21,4 V
Cell Operating Temperature	50 °C
Efficiency	10%

Fig. 6. Mobile System.

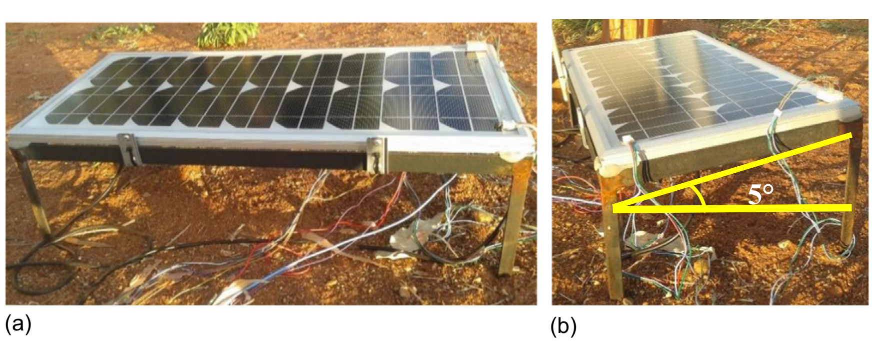

Fig. 5. Static PV system.

Table 2
Static system performance.

Day	Energy (W h)	Temperature (°C)	Global radiation (W/m^2)	Weather condition
13/jul	68.2	36.1	750.3	Cloudy
14/jul	162.7	42.8	888.6	Scattered clouds
15/jul	166.7	43.1	1261.3	Sunny
16/jul	149.3	41.3	1060.6	Sunny
17/jul	174.1	44.1	1037.7	Sunny
18/jul	159.2	41.7	958.7	Scattered clouds
19/jul	100.5	38.2	748.3	Cloudy
20/jul	189.8	43.1	1011.9	Sunny
Average	146.3	41.3	964.7	–

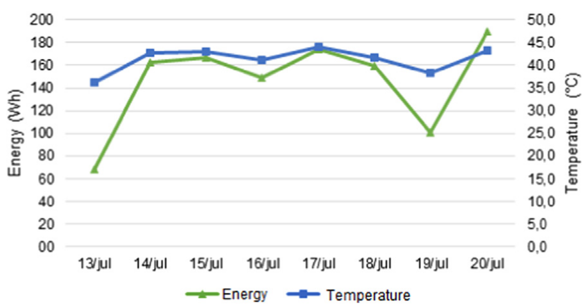

Fig. 7. Generated energy performance and temperature for the static system.

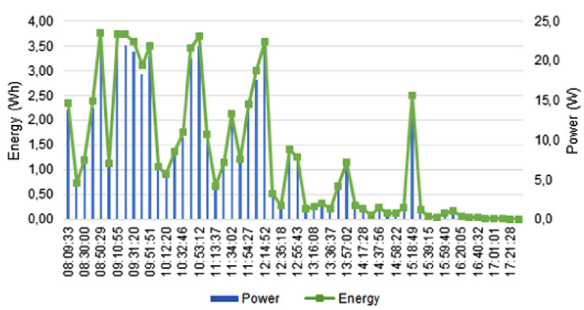

Fig. 8. Power curve and energy generated (cloudy day).

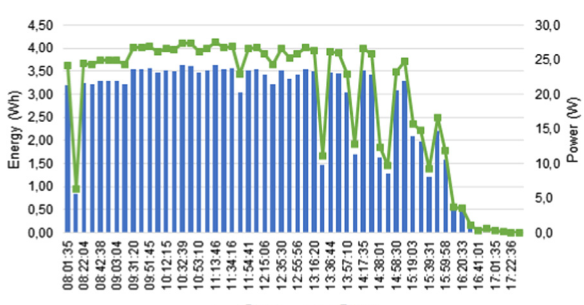

Fig. 9. Power curve and energy generated (sunny day).

20 Wp. This behavior was constant in all observation days, and can be explained by the high solar radiation levels from the region, as shown in Table 2.

Still analyzing the power generation performance can be observed points where the power and energy generated decreases abruptly. These moments of loss of income due to the cloudiness of the site, because even on sunny days, there is constant presence of clouds.

Table 3
Mobile system performance.

Day	Energy (W h)	Temperature (°C)	Global radiation (W/m^2)	Weather condition
13/jul	63.7	31.9	750.3	Cloudy
14/jul	195.4	40.4	888.6	Scattered clouds
15/jul	195.2	40.7	1261.3	Sunny
16/jul	177.0	38.7	1060.6	Sunny
17/jul	200.7	42.5	1037.7	Sunny
18/jul	149.9	40.2	958.7	Scattered clouds
19/jul	100.1	34.5	748.3	Cloudy
20/jul	223.1	42.6	1011.9	Sunny
Average	163.1	38.9	964.7	–

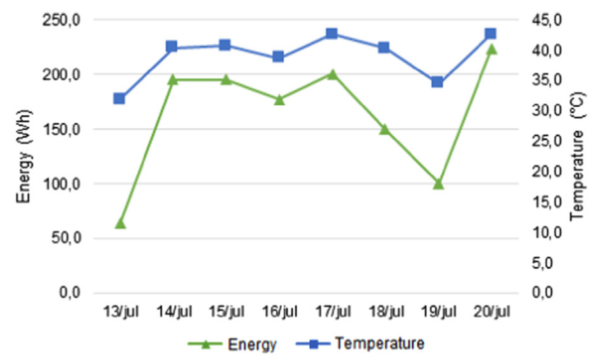

Fig. 10. Generated energy performance and temperature for the mobile system.

6.2. One-axis mobility system performance

The mobile system performance is shown in Table 3, which shows the average power generated during the days observed, reaching somewhere around 163 Wh also significantly varies according to weather conditions.

Table 3 shows that as well as with the static system, surface temperature averages were not higher than the PV module operation temperature, in this case 50 °C. Fig. 10 illustrates the average temperature curves of the module and the energy generated during the experimental period. It is observed that the average temperature accompanying the means of power generation, that is, when the surface temperature increases, the energy generated also increases, as well as with the static panel.

As shown in Fig. 10 the behavior of the power generation with respect to temperature was similar to the static system, i.e., the energy production accompanying the temperature rise, and the operating cell temperature was not reached.

Since the performance of power and energy generated in the module, Figs. 8 and 9 illustrate these curves, the first relating to a cloudy day and the second referring to a sunny day. It's worth noting that these days of measurement are the same for the static panel.

The curves shown in Figs. 11 and 12 are similar to the behavior exhibited by the static system, and the power and energy values generated slightly higher. The power generated at several times appears above the rated power of the module, i.e., 20 Wp, as well as in the static system, the behavior exhibited in everyday observation, and can also be justified by the average solar radiation levels, a few days of above standard observation in the case above 1000 W/m^2.

Another common mobile system behavior in relation to the static system refers to the sudden decrease of the power generated

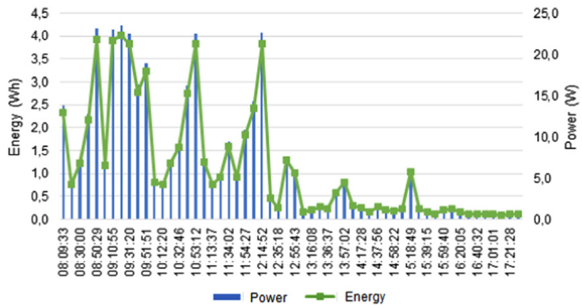

Fig. 11. Power performance and energy generated (cloudy day).

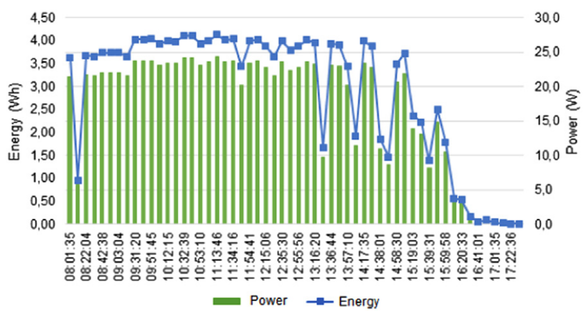

Fig. 12. Power performance and energy generated (sunny day).

Table 4
Performance of mobile photovoltaic systems and static.

Day	Mobile Sist. energy (W h)	Static Sist. energy (Wh)	Gain (%)	Weather condition
13/jul	63.7	68.2	−7	Cloudy
14/jul	195.4	162.7	20	Scattered clouds
15/jul	195.2	166.7	17	Sunny
16/jul	177.0	149.3	19	Sunny
17/jul	200.7	174.1	15	Sunny
18/jul	149.9	159.2	−6	Scattered clouds
19/jul	100.1	100.5	0	Cloudy
20/jul	223.1	189.8	18	Sunny
Average	163.1	146.3	11	

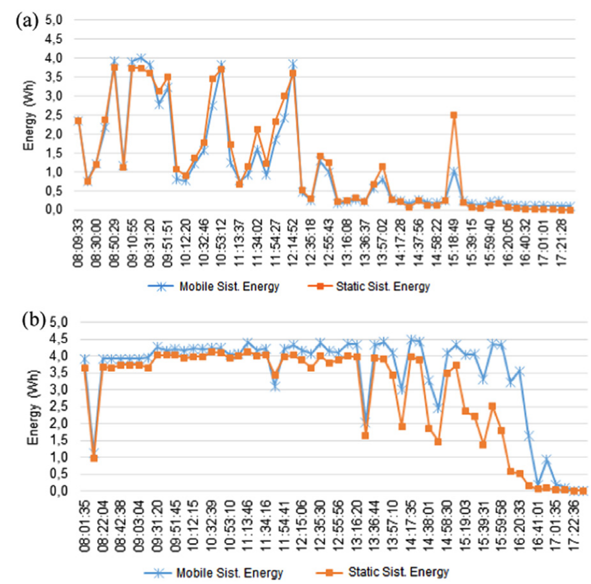

Fig. 13. Performance comparison of static and mobile systems day 1 (a) and day 2 (b).

at certain times of the day also occurred due to the cloudiness of the region.

Comparing the modules temperature shown on Tables 2 and 3, it is notice that the static system records higher temperature than the mobile system. This behavior can be explained by the modules disposal on the studied site. The static system has a shorter structure, closer to the ground, considering the hot climate region, the heat dissipation was harder than comparing to the mobile system, which has a higher structure, so the heat could be more easily dissipated by the wind.

Analyzing the performance of static and mobile systems, Section 6.3 will deal on the comparison between them.

6.3. Systems performance comparison

Table 4 shows the performance of the two photovoltaic systems, where it can be seen that the maximum percentages gained the logo of measurement days was 20%, and the efficiency increased average is 11%.

It can be said that the improved module performance tracking, comparing to the static system, is low in the region where the analysis was done, whereas in the literature are registered increases of up to 60%, as is the case of the research developed by [37].

The low average gain can also be justified by the high radiation levels in the region, as observed by the graphs in Figs. 5 and 6, in Section 6.1, and Figs. 8 and 9, in Section 6.2, which over almost all times of the day both modules operate at its rated capacity, or even above it. In addition, still must consider the linearity of the path traced by the sun over the horizon, due to proximity to the equator.

Still analyzing Table 4, it is observed that on cloudy days, the gain of the mobile system comparing to the static system is negative or zero. This behavior is related to the fact that on cloudy days, the radiation incident on the modules is diffuse solar radiation and not the direct solar radiation. Diffuse radiation make the tracking system loses its orientation, explaining the low or negative performance.

The energy produced by each system on a daily basis over the days observed is illustrated in Figs. 13–16.

In everyday observed in Figs. 14–16, the curves of power of static and mobile systems generation closely resemble, rectifying the low gain of income presented in the mobile system and compared to static, to the place in study. It is also noticed that are common to every day, and both systems, the sudden drops of power generation at times of the day, occurring in the same moment. Such behavior is due to cloudiness, as explained in Sections 6.2 and 6.3.

Another natural interference observed in the power generation, was the deposition of dust on the surface of the modules, leaving the opaque glass and therefore not absorbing the radiation incident on the module. The dust problem at the installation site is particularly important due to the influence of the salt desert, a high salinity of land and little vegetation on the coast near Mossoro [6]. In the survey, it was not possible to quantify the impact of dust on the generation of electricity, because although identified the presence of dust on the modules, they were cleaned daily.

Fig. 15(b) shows atypical behavior of the mobile system, for the energy generated in the morning is less than the energy generated in the static panel. This behavior was observed due to disorientation of the mobile panel, because it is a day of scattered clouds in the sky, which make the guidance system.

Finally, it can be seen from Figs. 14–16, the power generation mobile system presents significant difference from the static system around 15:00 h. This time is the time of day when starting the

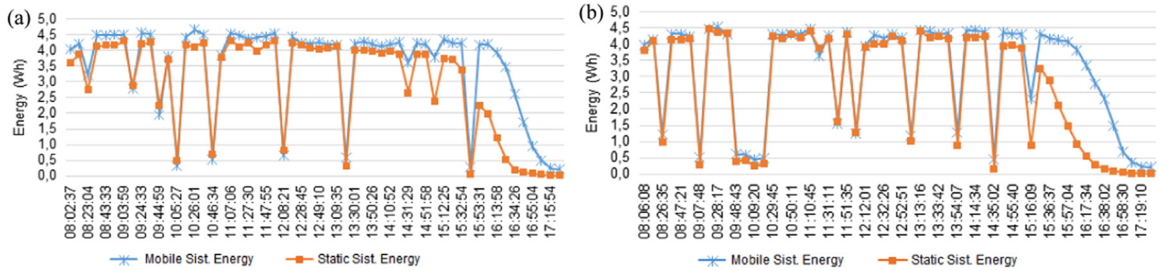

Fig. 14. Performance comparison of static and mobile systems day 3 (a) and day 4 (b).

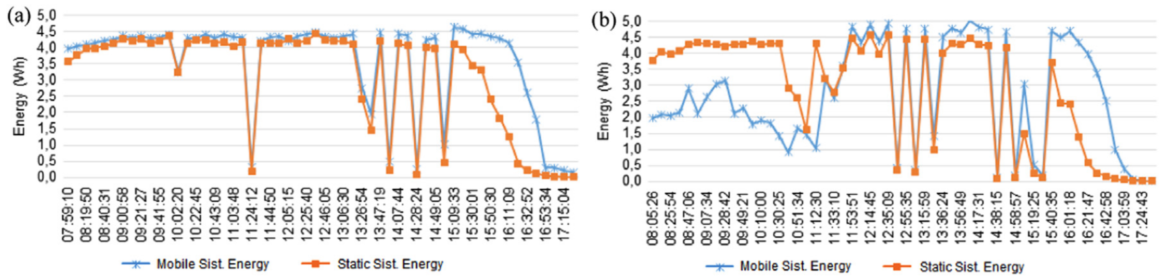

Fig. 15. Performance comparison of static and mobile systems day 5 (a) and day 6 (b).

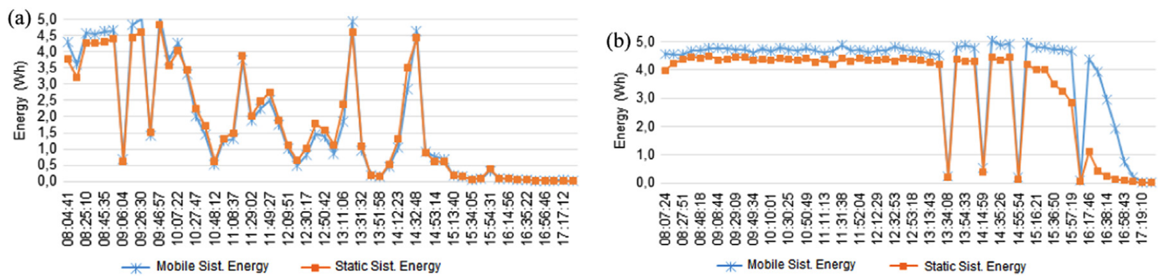

Fig. 16. Performance comparison of static and mobile systems day 7 (a) and day 8 (b).

sunset in the region, reducing the solar radiation and varying the angle of incidence of sunlight on the modules. It is important to highlight that energy consumption for the tracking mechanism was not recorded on the gain calculation. So if considered only the step motor powering, it consumes about 64 Wh, decreasing the average gain.

7. Conclusion

The performance shown in the mobile and static systems showed that the average surface temperature of the modules has not exceeded the operating condition of the cells at 50 °C and can be observed the increase in temperature of the panels together with the increased power output.

The power generated in the modules at various times of the day was above rated power, this fact can be explained by the high radiation incident in the region. As a consequence of increased power generation, the life of the panels, estimated at 25 years to a maximum radiation of 1000 W/m^2, can be reduced. It was also observed that the yield of the panels is considerably influenced by the cloudiness of the region, because even on sunny days, there is presence of clouds in the sky that eventually block the solar radiation.

When comparing the performance between the mobile system in relation to the static system, proved to be not very significant increase in performance in power generation, which is on average 11%, highlighting that the step motor consumption was not considering on this average. However, it is important to note that the daily observation period started at 8:00 am, so was disregarded the yield of the panels in the first hour of the day. Significant differences between the generated power could be observed only in times after 15:00 h.

On cloudy days were recorded negative or zero earnings mobile system in relation to static, this is due to solar radiation incident on the modules in this case be the diffuse solar radiation.

The low increase in mobile panel efficiency is also due to the region's proximity to the equator, because there is no large variations in the sun's position throughout the day or year, and still receives high average solar radiation.

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