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Advances in Solar Tracking System Efficiency for Photovoltaic Collection: A Focus on Sustainable Energy Solution for Equatorial Regions.

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Abstract: Ecuador is grappling with a severe energy crisis, marked by frequent power outages. A recent study explored solar energy efficiency in the coastal city of Manta, using an IoT real-time monitoring system to compare static photovoltaic (PV) systems with two single-axis solar tracking systems: one based on astronomical programming and the other using Light Dependent Resistors (LDR) sensors. Results showed that both tracking systems outperformed the static PV system, with net gains of 31.8% and 37.0%, respectively. The astronomical programming-based system had a slight edge, operating its stepper motor intermittently for two minutes per hour, while the LDR system required continuous motor energization. The single-axis tracker using astronomical programming demonstrated notable advantages in energy efficiency and complexity, making it suitable for equatorial regions like Manta. The study also suggested potential further gains by adjusting solar positioning at shorter intervals, such as every 15 or 30 minutes. These findings enhance understanding of solar tracking performance in equatorial environments, offering valuable insights for optimizing solar energy systems in regions with high solar radiation. By emphasizing customized solar tracking mechanisms, this research presents promising solutions to Ecuador's energy crisis and advances sustainable energy practices.

Keywords: Solar tracking system; Equatorial latitudes; IoT monitoring system

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1. Introduction

The urgency of finding sustainable and efficient energy solutions in equatorial regions is underlined by the current energy crisis in Ecuador and Colombia, characterized by frequent power outages throughout the country due to a prolonged drought and high hydroelectric dependency [1], [2]. Hydroelectric-dependent countries face significant energy challenges exacerbated by climate change. Shifts in precipitation patterns and glacier melt affect water availability, disrupting hydropower generation. Increased frequency of extreme weather events such as droughts and floods further strain hydroelectric infrastructure, highlighting the urgent need for diversified energy sources and robust climate adaptation strategies. Photovoltaic solar energy emerges as a promising alternative in diversifying the energy matrix of those countries, however, some challenges and obstacles need to be addressed for it to become more competitive with other energy sources. Two specific concerns often raised are high production costs and low-efficiency conversion [3], [4]. Regarding cost production, significant advancements in PV technology and economies of scale in production have led to a substantial decrease in costs over recent years. The cost of PV panels continues to decline, making solar energy more economically viable as a long-term energy solution to replace traditional energy sources [5], [6]. On the other hand, low efficiency has to do with the technology and process of converting solar energy into usable electrical energy. Crystalline silicon (c-Si) wafer-based technology is the most widely used worldwide due to its low cost and high availability in nature; however, its maximum energy conversion reaches only 26% at best [7]. Other emerging technologies with higher efficiency face challenges in scaling up the manufacturing processes for new photovoltaic materials, addressing manufacturing complexity, and reducing costs to achieve large-scale production [8].

Another historical approach to increase the efficiency of PV systems considers the use of solar tracker systems. By continuously orienting the solar panels to face the sun throughout the day, solar trackers maximize the amount of solar irradiation the PV panels receive. This enhances the electricity production of the PV system, [9], [10]. However, it is important to note that the implementation of solar trackers may add complexity and additional costs to the PV system, which must be considered in the overall economic and energetic analysis. According to [12], while solar tracking systems can have significant benefits in any location, certain regions may have specific characteristics that amplify the advantages of such systems, for instance, those located far north and south from the equatorial regions where most studies have been carried out. In some countries, the use of solar tracking systems can improve electricity generation by around 30% to 80% compared with fixed solar systems [10], [13]. On the contrary, there are very few studies focused solely on sun-tracking systems in equatorial regions [12]. In this region, the amount of solar radiation received through the years is generally high, with relatively stable sun trajectory and minimal seasonal variations [14]. As a result, the potential benefits of solar tracking systems in terms of increased energy production may not be as pronounced compared to regions with higher latitudes. However, it is worth noting that there are still advantages to implementing solar tracking systems in equatorial regions. For instance, a comparative simulation-based experiment in Ecuador between single and dual-axis tracking PV systems vs. fixed PV systems found improvements of 27.3% to 30% and 31.2% to 34.62% respectively [15,16]. Some other experimental studies in Ecuador and Brazil found that these energy improvements could be lower than those in simulation-based experiments. In Ecuador, a dual-axis PV system proved to be only 19,62% more efficient than a fixed PV system [9]; in Brazil, a single-axis tracking PV system showed an average enhancement of 11% than a fixed PV system [3]. As can be seen, there are certain discrepancies between simulated and experimental data regarding sun-tracing solar systems in equatorial regions. While it has been possible to compare the simulated and experimental information within the same country for dual-axis PV systems [9], it is still necessary to delve deeper into experimental data concerning single-axis PV systems.

This work is a follow-up of the last study [12] to fill the gap of knowledge regarding single-axis solar tracking systems operating in equatorial regions taking the city of Manta as a case study. This study aims to design a static photovoltaic system and two single-axis solar tracking systems: one using astronomical programming and the other with LDR sensors, to quantify the improvement in energy efficiency of the systems for each proposal.

This innovative proposal aims to quantify, through a six-month-long trial, the real-time energy monitoring of the system and the improvement in energy efficiency resulting from this proposal. This will shed light on the actual performance of solar tracking systems in these regions, especially in simpler tracking proposals compared to two-axis trackers. This addresses Ecuador's energy crisis and fosters energy resilience.

The structure of this paper is as follows. In Section 2 we examine the classification of solar trackers and describe the most common single-axis sun-tracking methods. In Section

3 we describe and compare the performance of the sun-tracking systems. In Section 4, results are presented and discussed. Finally, in Section 5, conclusions are presented.

2. Solar tracking classification

Knowing the available solar resource and meteorological conditions are crucial aspects for determining the best location for our generator. Many studies aim to shed light on this aspect. In some cases, an algorithm is designed that calculates the optimal tilt angle of the photovoltaic generator using artificial intelligence techniques [17]. This value is experimentally tested to improve the generator's efficiency. In other studies, through simulation, the best placement of the generator is determined before installing the farm to minimize the effect of cloud cover [18]. Other authors design covers where the architecture and arrangement of the modules show the best [19] performance, optimizing the distribution of radiation on the panel and increasing the energy received by the panel at all incidence angles. These works complement studies that propose tracking methods to improve the performance of photovoltaic systems [11].

Scientific studies classify solar tracking systems into passive and active tracking systems. The former are mechanical systems that do not require an external power source to operate and depend on manual adjustments or the movement of the solar panel guided by some physical principle. Their operation changes based on the position of the sun, so they are not used extensively. The latter, active tracking systems, use electrical energy to operate automatically. These systems incorporate components to track the sun's position, such as microprocessors, motors, gears, and sensors. They are more precise than passive tracking systems but are also more complex and costly. Active tracking systems are further divided into three categories: control drive-based systems, which optimize the orientation of solar panels to maximize energy capture; closed-loop and open-loop tracking systems, where the former use feedback control mechanisms to continuously monitor the position of the sun, while the latter rely on preprogrammed algorithms or schedules to determine the sun's position and adjust the solar panel orientation accordingly; and finally, hybrid systems, which combine open-loop and closed-loop control systems. [13-14,20].

An alternative and most common classification is based on the degree of freedom (DOF), which refers to the number of axes or directions along which they can move and orient solar panels to track the sun. The primary classifications are single-axis solar trackers (one degree of freedom), dual-axis solar trackers (two degrees of freedom), and fixed-tilt solar arrays (cero degree of freedom) [20]. From those, dual-axis tracking systems can adjust both the horizontal (azimuth) and vertical (elevation or inclination) axis; on the other hand, single-axis systems typically rotate along either the horizontal axis (east to west) or the vertical axis (north to south); these are the most common solar tracking systems [21]. The different types of angles and axes that play an important role in these tracking systems are (see Figure 1) zenith angle (z), Altitude angle (αs), declination angle (δ), angle of incident (i), azimuth angle (γ), and inclination angle (β) [15].

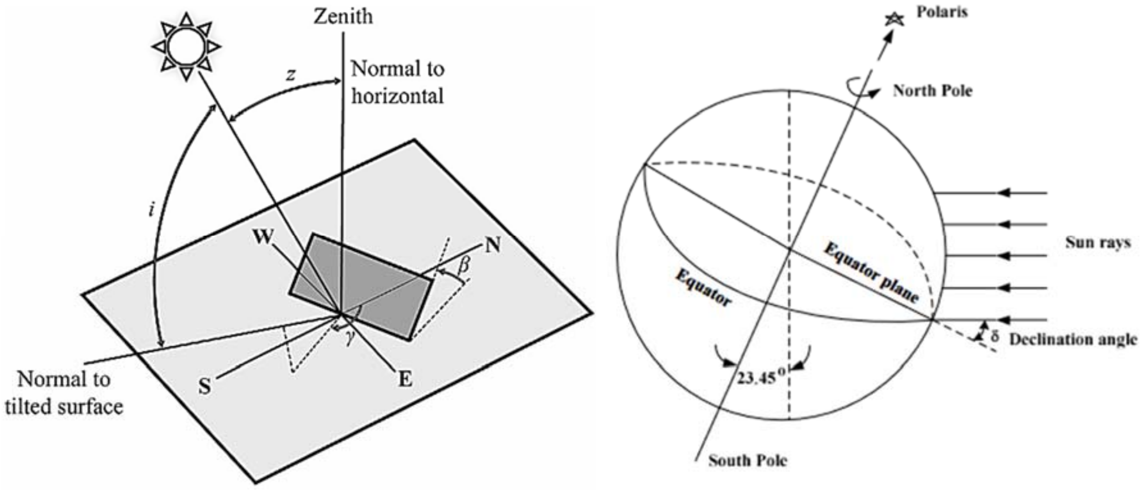

Figure 1. Angles and axes – a) zenith angle (z), Altitude angle (αs), angle of incident (i), azimuth angle (γ), and inclination angle (β) [21]; b) Declination angle (δ) [16]

Single-axis tracking systems offer improved energy capture compared to fixed solar installations by allowing solar panels to better align with the sun's position. They are more cost-effective and simpler to implement than dual-axis systems. These systems are often used in utility-scale solar farms, where maximizing energy output is crucial, but the complexity and cost of dual-axis tracking systems may not be justified. According to [21], this system is divided into three different types: horizontal single-axis tracking system (HSAT), vertical single-axis tracking system (VSAT), and tilted single-axis tracking system (TSAT). Figure 2 presents all types of single-axis solar tracking systems.

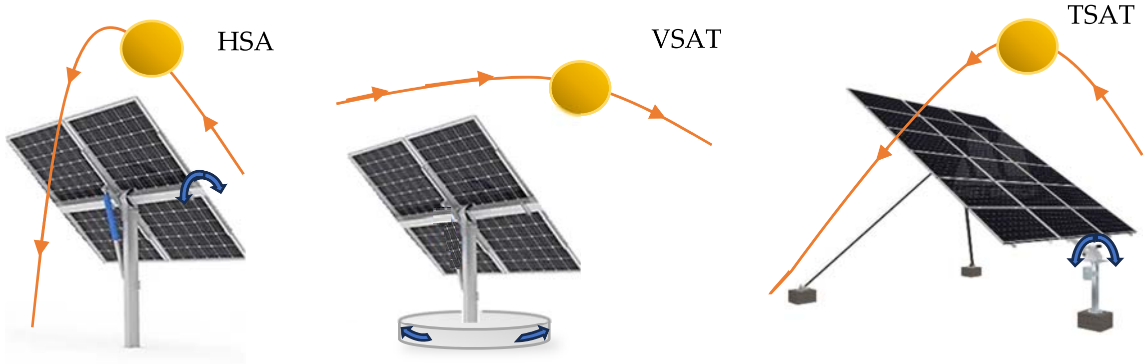

Figure 2. Single-axis tracking systems.

In this ongoing quest to enhance the efficiency of solar energy capture, the orientation and tracking of photovoltaic (PV) panels play a crucial role. Table 1 has been constructed to illustrate this. Various studies have approached the optimization of these systems through different methodologies, ranging from simulations to the design of experimental prototypes located in countries such as Turkey and Jordan, among others [22,23].

Table 1. Studies with Different Types of Tracking Simulations and Experimental Prototypes

Study	Methodology	Key Findings	Location
[22]	Simulated	30.4% - 34.6% efficiency improvement of the dual-axis tracking PV system compared to simulations on a fixed PV system.	Turkey
[23]		31.29% efficiency improvement of the dual-axis tracking PV system compared to simulations on a fixed PV system.	Jordan
[24]		1.86% - 31.52% efficiency improvement of the two-axis tracking PV system compared to simulations on an optimally tilted PV system	Nigeria
[25]		27.3% efficiency improvement of the single-axis and dual-axis tracking PV system 31.2%, compared to simulations on a fixed PV system	Ecuador
[26]		28.91 % the single-axis and dual-axis tracking PV system 33.11 % Comparative simulations between the fixed PV system	Kazakhstan
[27]		9.16-34.6% efficiency improvement of the dual-axis tracking PV system compared to simulations on a fixed PV system.	Malaysia
[3]	Experimental Prototype	11% range vs. fixed 20% sunny days	Brazil
[13]		13% more than fixed panels	India
[28]		23.3 % comparison fixed solar system	Egypt
[12]		19.62 % comparison fixed solar system	Ecuador
[29]		108.36 % more the stationary panel	Malaysia
[30]		41% superior to the traditional two-axis	Almaty – Kazakhstan
[31]		25% with respect to an axis 40 % comparison of fixed solar panels	India

The improvement in energy efficiency of PV systems using solar tracking mechanisms is considerable compared to fixed systems, with increases ranging from 1.86% to 108.36%, depending on geographical and climatic conditions. In Turkey, simulations revealed improvements of 30.4% to 34.6% [22]. In Jordan, other computational models indicated an increase of 31.29% [23]. In Nigeria, analyses showed increases ranging from 1.86% to 31.52% [24]. In Ecuador, simulations reflected improvements from 27.3% to 31.2% [25], and another study there found an increase of 19.62% [12]. In Kazakhstan, simulated comparisons reported improvements from 28.91% to 33.11% [26], and a study in Almaty showed an increase of 41% [30]. In Malaysia, simulations indicated increases from 9.16% to 34.6% [27], with another study reporting an improvement of 108.36% [29]. In Brazil, an experimental prototype showed improvements of 11% on cloudy days and 20% on sunny days [3]. In India, simulations indicated an increase of 13% [13], and another study reported improvements of 25% to 40% [31]. Finally, in Egypt, simulations indicated an increase of 23.3% [28]. These results highlight the importance of adopting solar tracking technologies to optimize PV energy production and improve the economic viability of solar projects globally. Given these findings, our solution stands out as it not only enhances efficiency but also provides a cost-effective alternative, addressing the challenges of the energy crisis prevalent in our country, making it a promising solution for sustainable energy production.

3. System realization and experimentation

This research was carried out in the facilities of the Universidad Laica Eloy Alfaro de Manabí, in Manta City, over the same location reported by [12]. Figure 3 shows the project assembled with each of the system components placed in an open area to avoid shadows. The block diagram of the proposed system is shown in Figure 4. It is composed of the following parts: an automatic weather station, two single-axis sun-tracking systems (based on Light Dependent Resistors (LDR), and astronomical programming), one fix-tilt solar system, and a data acquisition and monitoring system module.

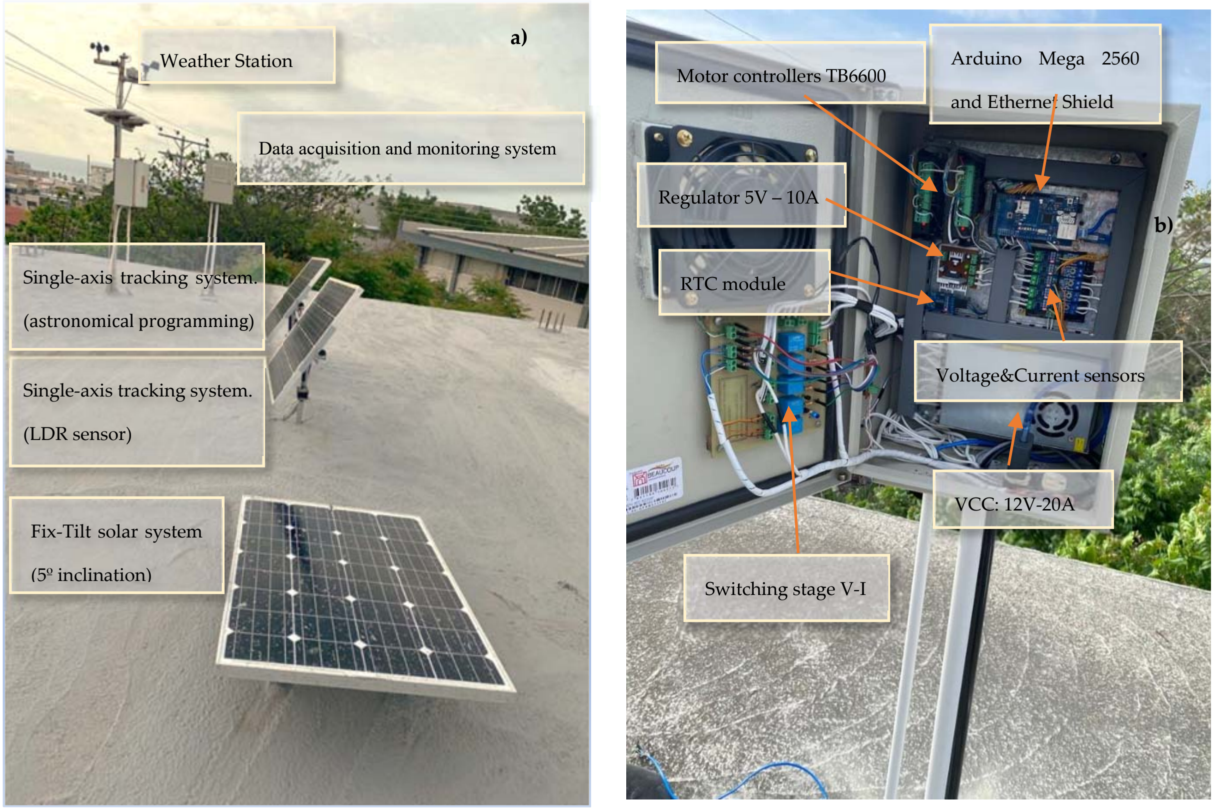

Figure 3. a) Automatic weather station, single-axis tracking systems and fixed-tilt solar system; b) data acquisition and monitoring system.

Automatic weather station

The IoT-based Automatic Weather Station (AWS) is an economical solution equipped with various instruments to gather and log meteorological parameters such as solar radiation, UV radiation, wind speed and direction, temperature, and humidity. A datalogger (based on Raspberry Pi3) is responsible for the collection and recording of all meteorological measurements and also, for processing and transmitting the data via the Ethernet network to our database. The AWS provides solar radiation and temperature reference for the whole system. The real-time data history is accessible to the university community through a web platform. For further details, refer to [32].

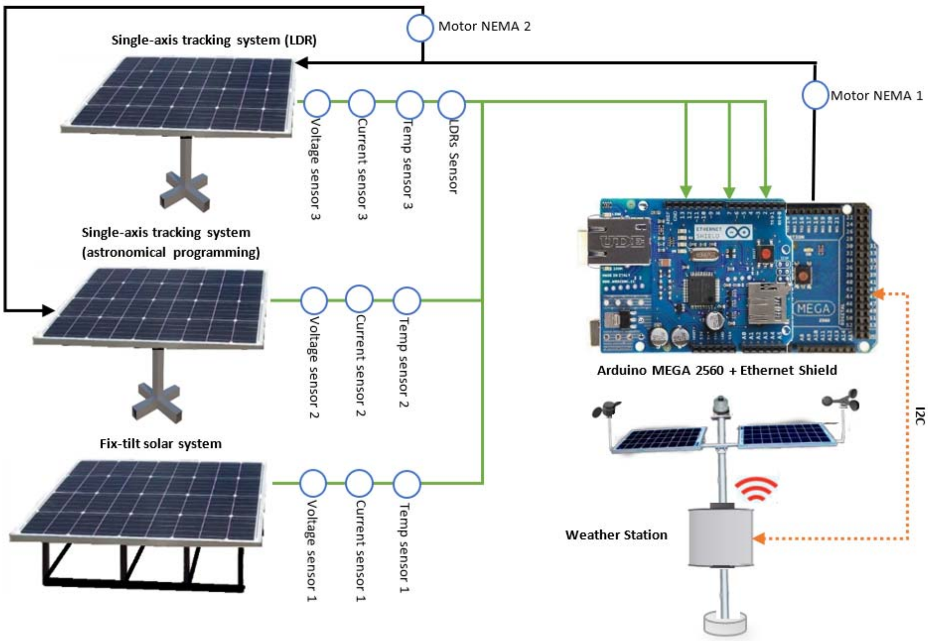

Figure 4. Schematic proposed system

3.2 Fix-tilt solar system

The fixed-tilt solar system is visible on the front side of Figure 3. This system comprises a monocrystalline PV panel and a stationary structure set at a 5° inclination, aligning with the latitude-based measurements detailed in [3]. The same PV panel is utilized in both the single-axis tracking system with LDR sensors and the Single-axis tracking system with the astronomical programming system; PV panel characteristics are outlined in Table 2.

Table 2. PV module characteristics [33]

Maximum Power (P_{max})	120 W_p
Maximum Power Current (I_{mp})	6.67 A
Maximum Power Voltage (V_{mp})	18.0 V
Short-Circuit Current (I_{sc})	7.20 A
Open Circuit Voltage (V_{oc})	22.5 V
Cell Operating Temperature	-40 ºC to +85 ºC
STC Efficiency	18.46 %
Dimensions	670 x 970 x 30 mm

3.3 Single-axis tracking system structure

The structure of the two single-axis solar tracking systems has been designed identically to compare the performance under equal technical conditions. The movement is carried out using an electric stepper motor in conjunction with a power screw. This will convert the rotational movement to linear movement, giving greater strength and precision to the movement of the solar panel. The base of the structure is a single post fixed to the installation site. Figure 5 shows the part of the structure.

Figure 5. Single-axis tracking system structure

The stepper motor chosen is a Nema 23 57HS41-2006 [34], which meets the design requirements to raise and lower the solar panel placed on the axis of rotation (torque greater than 0.08425 Nm). This motor is commanded by a TB6600 stepper motor driver controller [35], and this in turn connected and controlled by the Arduino Mega Module. The torque for a power screw with ACME thread or unified thread without a collar is expressed by (1) and the characteristics of the power screw are shown in table 3.

Table 3. Power Screw characteristics

F_m	D	d_m	p	μ	α (ACME)
63.7 N	10mm	9,25mm	1,5mm	0,2	30º

$$T = \frac{F_m * d_m}{2} * \frac{p + \pi * \mu * d_m * \sec\alpha}{\pi * d_m - \mu * p \sec\alpha} \quad (1)$$

So that:

Fm = force of mass
U = coefficient of friction (determined by table)
P = screw pitch
dm = average diameter
α = thread angle (unified thread)
T= input torque
D = diameter of the screw

To control the solar tracker system, the linear movement of the power screw must be correlated with the degrees of freedom established for the structure. The solar tracker system has 130° of freedom (δ=130°) and for its most extended position the power screw has a length of 29 cm; on the contrary, for its most collected position its length is 14.5 cm. Figure 6 shows the representation of the movement of the solar tracking system and the measurements of the oblique triangle formed by the power screw and the structure.

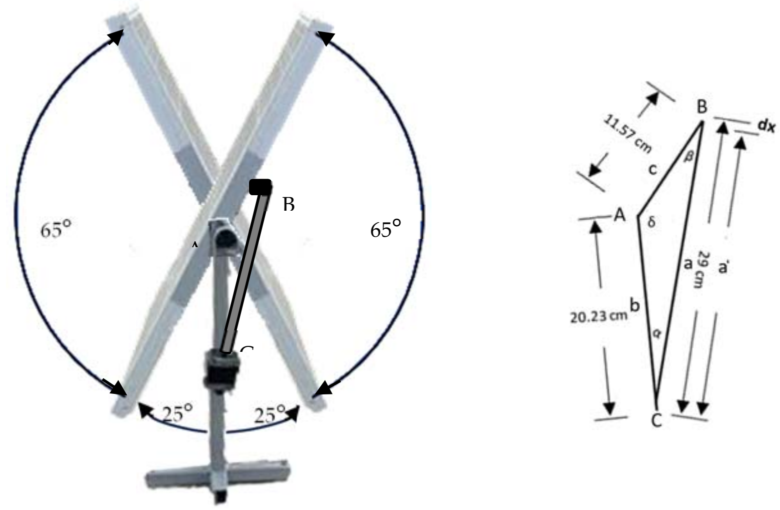

Figure 6. Movement of the single-axis solar tracker and the oblique triangle formed by the power screw and the structure.

To obtain the relationship of linear movement for each degree of inclination we assume a variation of 1° in angle δ (129°) so that distance "a" must be recalculated to find the variation of displacement dx. From the data shown in Figure 6 and equations (2-3), the linear movement per degree was computed.

$$(a')^2 = b^2 + c^2 - 2bc * \cos A \quad (2)$$

$$a' = \sqrt{b^2 + c^2 - 2bc * \cos A}$$

$$a' = \sqrt{20.23^2 + 11.57^2 - 2(20.23 * 11.57)\cos(129°)} = 28.98 \ cm$$

$$dx = a - a' \quad (3)$$

$$dx = 29 - 28.94 = 0.06 \ cm = 0.6 \ mm$$

Considering that the power screw has a pitch of 1.5 mm, it was concluded that for each complete turn of the stepper motor, the panel will tilt 2.5º.

a. Single-axis tracking system based on LDRs

This is an active tracking system based on a closed-loop control circuit. The tracking system uses a microprocessor and two photoresistors or photocells (LDRs). The photoresistor's resistance is inversely proportional to the light intensity falling on it, so it has very high resistance in darkness (≈1 MW), but it decreases to a few kW once it receives light (see Figure 7). The output signals from the LDRs are sent to the microprocessor where they are digitized and compared continuously to determine the position of the sun. Next, a signal proportional to this difference is sent so that the stepper motor executes the positioning of the solar panel perpendicular to the estimated position of the sun. Figure 7a) shows a representation of the operation of the LDRs and 7b) the LDRs measurement system and LDRs.

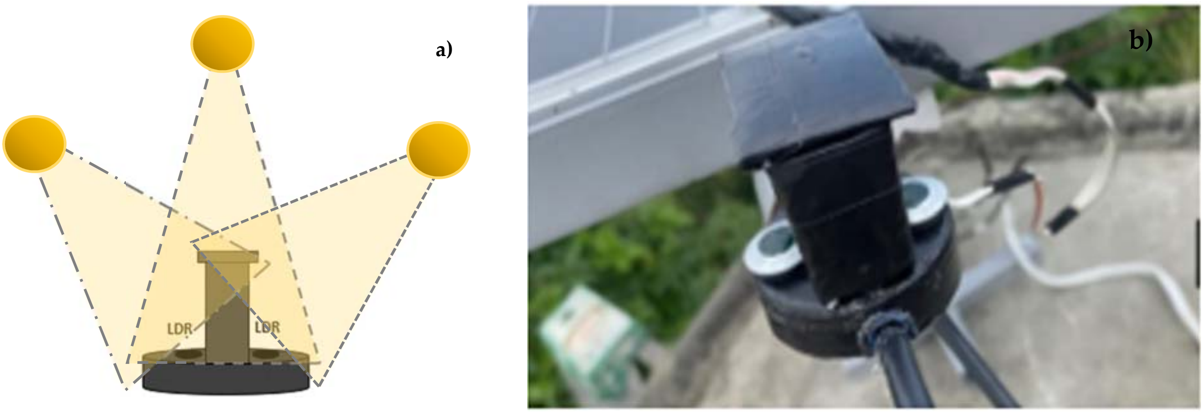

Figure 7. a) Representation of the operation of the LDRs; b) LDRs measurement system module.

b. Single-axis tracking system based on astronomical programming

This is an active tracking system based on an open-loop control circuit. The tracking system uses a microprocessor and a control algorithm. This system tracks the sun without physically following the sun through sensors. On the contrary, it uses a solar chart to calculate the solar angles of the sun. The solar chart is a table for a specific place on Earth that, according to the day of the year and the time, indicates the position of the sun using solar coordinates. There are numerous web tools to determine the solar table such as those shown in [36]. To know each specific time of the day, a Real-Time-Clock (RTC Arduino module) is used to provide the information needed at all times. Figure 8 shows the simulation of the sun path diagram for the selected location and Table 3 the sun coordinates throughout the year.

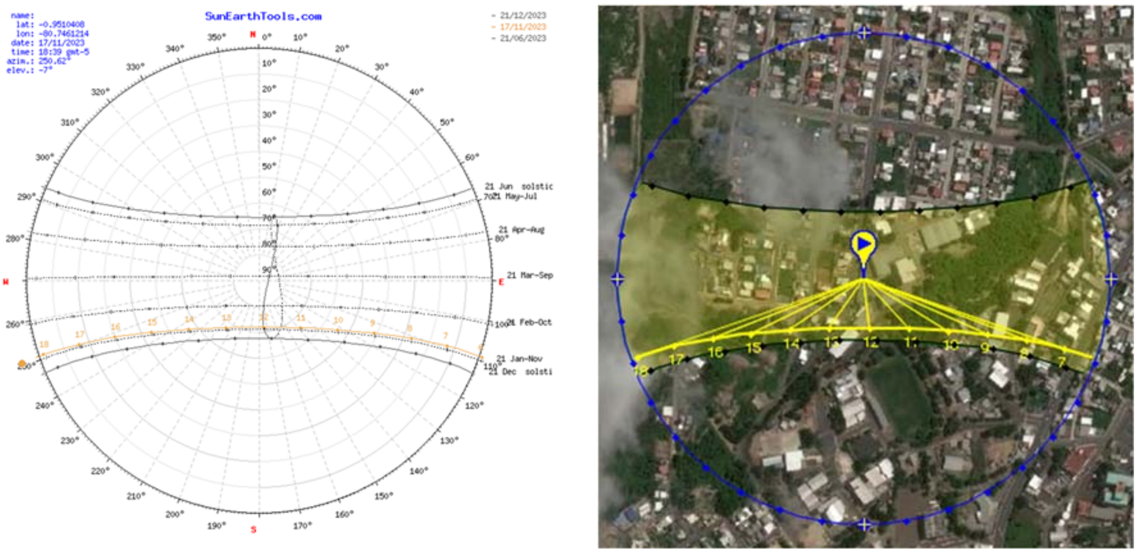

Figure 8. Sun path diagram (Manta, Ecuador) [37].

Table 4. Sun path coordinates. Adapted from [37]

Time of the day	Summer Solstice	Winter Solstice	Spring equinox	Autumn equinox	Average angle
6:00	-4.4°	-6.1°	-3.8°	-7.7°	-5.5°
7:00	9.5°	7.8°	11.2°	7.5°	9.0°
8:00	23.1°	21.4°	26.2°	22.4°	23.3°
9:00	36.5°	34.7°	41.2°	37.4°	37.5°
10:00	49.1°	47.2°	56.2°	52.4°	51.2°
11:00	60.2°	58.1°	71.2°	67.4°	64.2°
12:00	67°	64.9°	86.1°	82.4°	75.1°
13:00	65.6°	64.1°	78.8°	82.5°	72.8°
14:00	57.1°	56.4°	63.8°	67.4°	61.2°
15:00	45.4°	45.1°	48.8°	52.6°	48.0°
16:00	32.5°	32.4°	33.8°	37.6°	34.1°
17:00	19°	19°	18.8°	22.6°	19.9°
18:00	5.4°	5.4°	4°	7.7°	5.6°

As can be observed in Figure 8 and Table 4, the sun's path in equatorial latitudes presents a special profile where there is very little variation of the sun's path during the year. For this reason, the average angle for the entire year was taken as a reference; these data were then correlated with the degrees of freedom established for the single-axis solar tracker to finally send the corresponding command to the stepper motor to execute the movement of the solar panel hourly.

c. Sensing system

Based on what was presented in [12], three equal sensing systems were deployed to evaluate the efficiency of each system. The voltage, current and temperature of each solar system were evaluated, taking the average of 30 samples per minute from each sensor as the instantaneous value. Once the data has been processed, it is transmitted to the AWS using the I2C communication protocol to later be stored in the cloud. The structure and characteristics of these sensing systems are detailed below:

1. Current and voltage sensing system.

To measure voltage and current values, a set of relays were employed to control the acquisition of short-circuit current (I_Sc) and open-circuit voltage (V_oc) data for each solar system (see Figure 9). Voltage is measured using the FZ0430 circuit module [38]. This circuit is a straightforward voltage divider with values of 30 kΩ and 7.5 kΩ. Essentially, it implies that when the maximum input voltage is attained, the voltage sensed by the module is divided by a factor of five. The maximum resolution acquired is 4.89 mV (5V/1023) since the Arduino Mega ADC has a 10-bit resolution. For current detection, the ACS712ELC 20 A module was employed [39]. This sensor produces an analogue voltage output signal that changes proportionally with the detected current, whether it is alternating or continuous, up to 20 A. The sensor is composed of a precise, low-offset, linear Hall-effect sensor circuit featuring a copper conduction path (internal resistance 1.2 mΩ) situated close to the die's surface. Operating at 5 VDC, this sensor generates an analogue voltage (66 mV/A) centred at 2.5 V (Vcc/2), exhibiting a typical error of 1.5%.

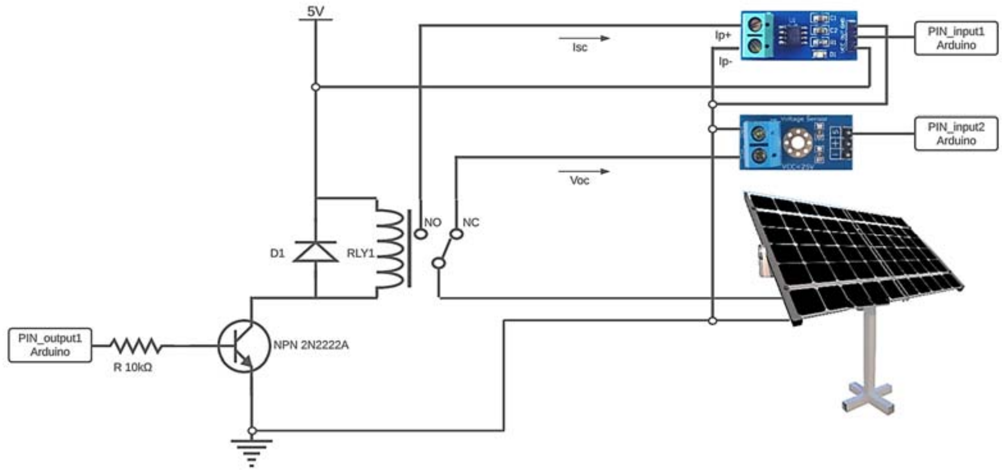

Figure 9. Switching circuit and voltage-current measurement

2. Temperature sensing system.

One of the most relevant factors that affect the efficiency of the solar panel is the operating temperature, when the temperature increases the efficiency decreases. The ideal operating temperature of a solar panel is frequently around 25ºC, when this value is exceeded the output power never reaches the maximum value specified by the manufacturer [40], [41] To verify and compare the working temperature of the solar panels, three LM35 sensors were used on each of the solar panels. This sensor is a highly accurate integrated circuit with an output voltage that linearly corresponds to the instantaneous temperature in Celsius degrees. Its temperature range spans from -55°C to +150°C, and it operates with a scale factor of 10 mV/C.

4. Result and Discussion

According to [12], the fact that Ecuador does not have four seasons, and there are no extreme weather conditions throughout the year (only cloudy and sunny days in the summer and sunny and rainy days in the winter), allow us to undertake the study by considering a collection period of 6 months (three from each station) as a sample of the performance of these systems in areas close to the equator.

The system's performance was monitored from 6:00 am to 6:00 pm, with measurements taken at one-minute intervals each day to obtain temperature, short-circuit current (I_Sc) and open-circuit voltage (V_oc). Measurements of solar radiation in W/m2 were taken by the AWS, which were used as a control element for the energy produced by the solar systems. Apart from the data obtained from the three solar systems, to complement this study, a record of the state of the sky was made according to cloudiness: sunny, partly cloudy, and cloudy (through qualitative observation). With the evaluation carried out, there is enough data to provide a representative sample of the behaviour of the three systems.

Systems Comparison Performance

For this analysis, one of the months studied will be taken as an example and the behaviour of the tracking and fixed systems will be presented for a typical sunny, partially cloudy, and cloudy day. Figures 10 and 11 compare the system performance of the two single-axis tracking PV system with the static PV system on a sunny day, while Figures 12 and 13 show the same comparison on a partially cloudy day, and Figures 14 and 15 on a cloudy day. The energy production of these systems is influenced by solar radiation, which changes depending on the sky conditions.

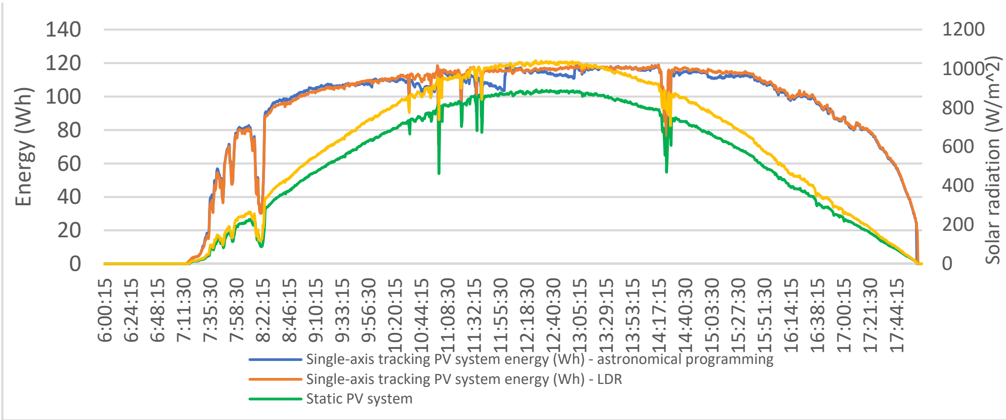

Figure 10. Generated energy performance on a sunny day (day 17).

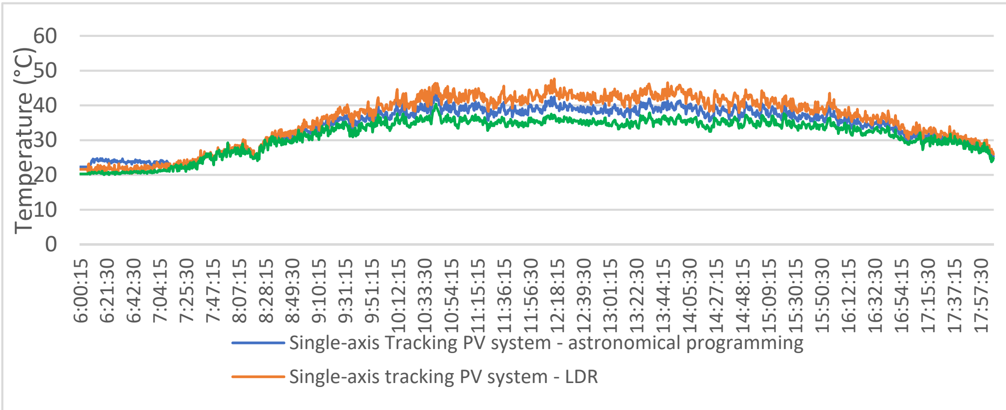

Figure 11. Temperature performance on a sunny day (day 17).

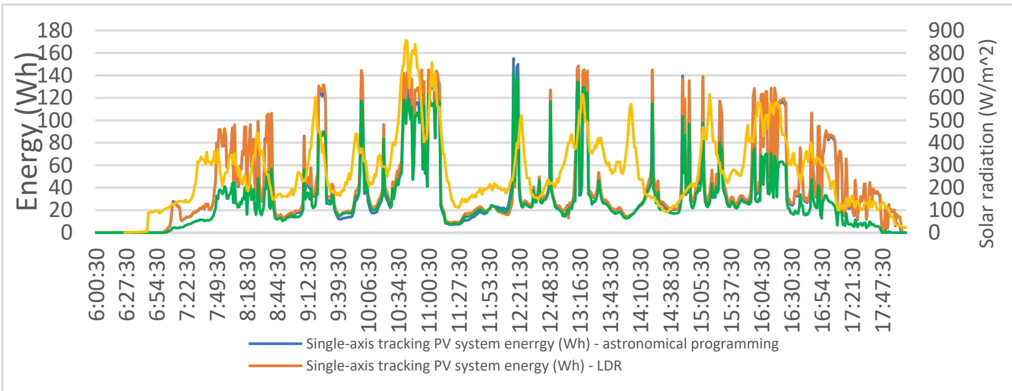

Figure 12. Generated energy performance on a partially cloudy day (day 15).

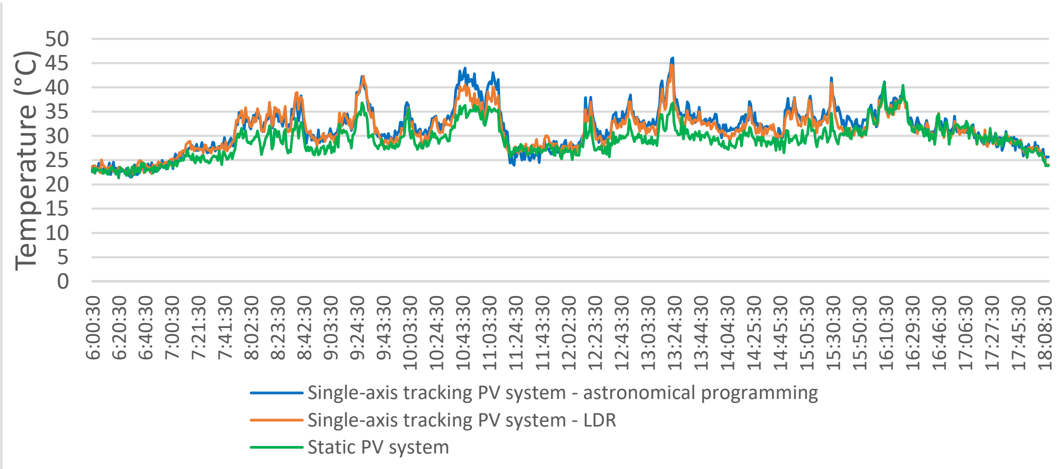

Figure 13. Temperature performance on a partially cloudy day (day 15).

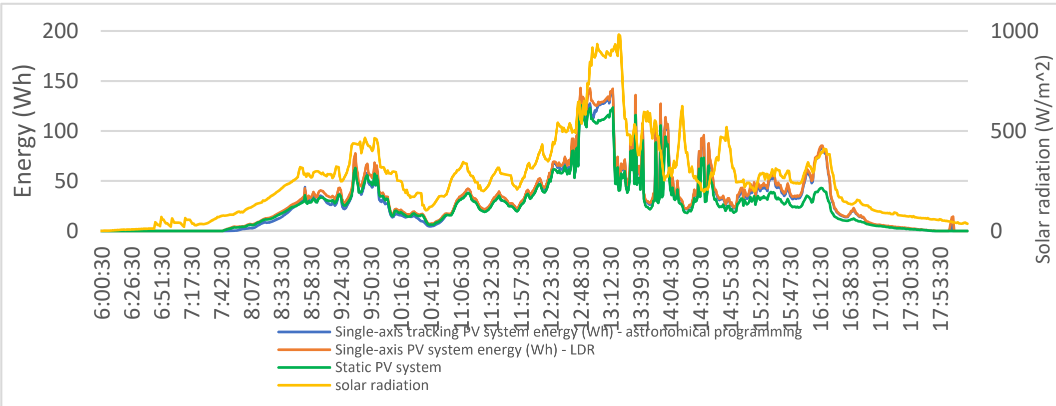

Figure 14. Generated energy performance on a cloudy day (day 4).

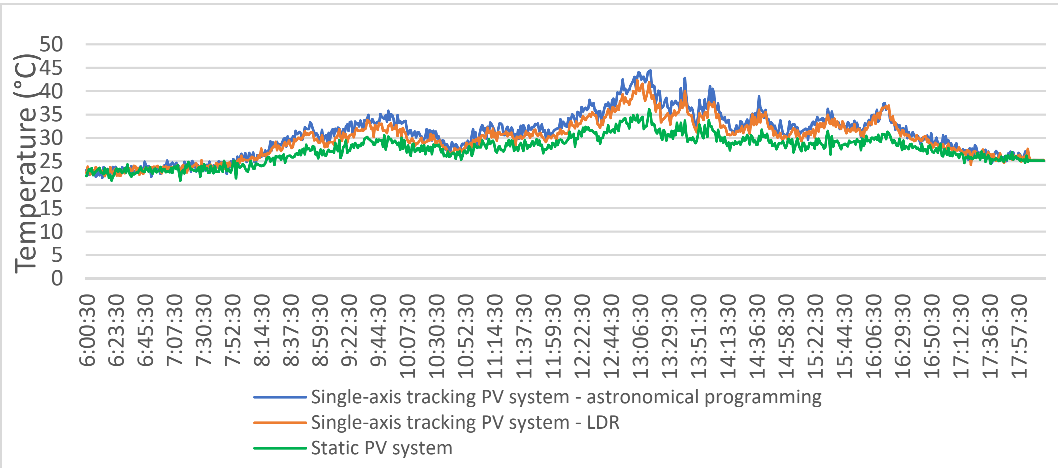

Figure 15. Temperature performance on a cloudy day (day 4).

Table 5 shows the average performance of the three systems, which have different solar production and percentage of gain on different days with different sky conditions. Figure 16 presents their energy and temperature performance. For calculation purposes, Energy (Wh) and Gain (%) have been estimated considering the following equations:

$$\boldsymbol{Energy\ \ (Wh)} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{E(min)_i} \tag{4}$$

$$\boldsymbol{Gain}(\%) = \frac{[\boldsymbol{Energy(Wh)_{Dual-axis\ \ PV}}] * \boldsymbol{100}}{\boldsymbol{Energy(Wh)_{Static\ \ PV}}} - \boldsymbol{100} \tag{5}$$

Table 5. Systems average performance

	S-A_TPV1*		S-A_TPV2**		S PV***		S PV vs S-A_TPV1	S PV vs S-A_TPV2	
Day	**Energy (Wh)**	**Temp (°C)**	**Energy (Wh)**	**Temp (°C)**	**Energy (Wh)**	**Temp (°C)**	**Gain1 (%)**	**Gain2 (%)**	**State of the sky**
1	463.52	29.92	491.49	31.16	373.56	29.47	24.08	31.57	Cloudy
2	573.19	29.40	592.13	30.85	421.25	30.03	36.07	40,57	partially cloudy
3	172.95	24.30	182.40	24.35	172.65	23.25	0.17	5.65	Cloudy
4	628.07	30.14	649.69	30.81	523.98	2847	19.87	23.99	partially cloudy
5	283.33	28.70	292.38	28.46	239.92	27.93	18.10	21.87	Cloudy
6	487.44	32.72	516.16	37.76	347.38	26.68	40.32	48.58	Cloudy
7	434.62	30.29	455.83	32.53	353.69	27.05	22.89	28.88	Cloudy
8	451.96	30.76	480.57	31.45	382.30	29.06	18.22	25.71	Cloudy
9	334.59	28.62	350.42	28.98	284.02	27.26	17.81	23.38	Cloudy
10	370.55	29.14	393.24	29.86	298.83	27.42	24.00	31.59	Cloudy
11	641.71	31.22	667.83	32.23	494.05	29.22	29.89	35.17	partially cloudy
12	875.04	32.70	901.69	34.10	620.76	30.30	40.96	45.26	Sunny
13	474.72	29.46	495.44	30.34	391.94	27.59	21.12	26.41	Cloudy
14	686.33	32.25	711.01	33.18	500.56	30.31	37.11	42.04	partially cloudy
15	672.36	32.04	708.79	33.42	499.72	29.66	34.55	41.84	partially cloudy
16	430.35	29.97	440.35	30.89	357.97	28.05	20.22	23.01	Cloudy
17	106.,8	32.05	1082.81	32.74	703.66	30.36	51.19	53.88	Sunny
18	471.43	29.26	488.84	31.20	294.01	26.32	60.35	66.27	Cloudy
19	401.80	30.57	421.46	32.92	313.66	27.22	28.10	34.37	Cloudy
20	611.14	31.25	638.41	32.32	464.08	29.18	31.69	37.57	partially cloudy
21	407.06	29.89	428.94	30.99	340.00	27.79	19.72	26.16	Cloudy
22	807.52	32.11	834.20	33.11	567.98	30.11	42.17	46.87	Sunny
23	308.25	27.70	328.03	28.60	258.50	25.80	19.25	26.90	Cloudy
24	352.64	28.72	375.44	29.53	315.46	26.90	11.79	19.01	Cloudy
25	1062.6	33.12	1077.36	34.61	693.96	30.63	53.13	55.25	Sunny
26	1100.7	32.82	1116.13	34.46	694.21	30.17	58.55	60.78	Sunny
27	1016.1	32.80	1029.92	33.40	695.21	31.20	46.17	48.14	Sunny
28	819.31	30.85	849.55	31.56	627.39	29.14	30.59	35.41	Sunny

29	843.58	32.89	857.38	33.95	532.66	30.83	58.37	60.96	Sunny
30	980.02	32.33	999.61	32.92	700.08	30.74	39.99	42.78	Sunny
Average	607.20	30.60	628.58	31.76	448.78	28.60	31.88	37.00	---

* Single-axis tracking PV system (Astronomical Programming)

** Single-axis tracking PV system (LDRs)

*** Static PV system

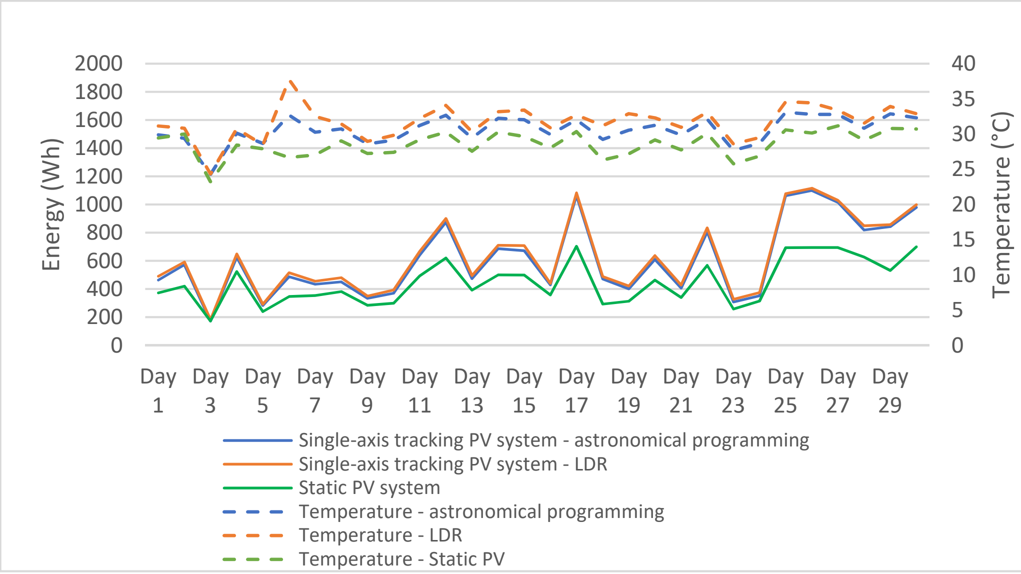

Figure 16. Generated energy and temperature performance of the systems.

According to these data, single-axis tracking systems exhibit higher energy production compared to static solar systems under similar conditions. Solar tracker system employing astronomical programming and the one utilizing LDR sensors demonstrate energy enhancements of 31.8% and 37.0% respectively; this confirms the simulated data from the studies presented by [17] and [18]. The highest values of gain for both systems are achieved on day 26 (Sunny) with 58.55% and 60.96%, and the lowest values on day 5 (Cloudy) with 18.10% and 21.87% respectively. The superior performance of the LDR-based solar tracker system in contrast to the astronomical programming-based counterpart is attributed to the former consistently aligning itself perpendicular to the sun, while the latter updates its position hourly. Conversely, from an energy point of view, the one-axis solar tracking system based on astronomical programming has greater efficiency due to its simplified design and low energy consumption, which gives it a great advantage for use in equatorial regions. Table 6 shows the energy consumption of the electronic components used for each solar tracker system, and Table 7 shows their total gains and losses.

Table 6. Energy consumption per component

Name	Consumption (W)	Usage time (h)	Energy (Wh)
Arduino Mega + RTC	1.2	24	28.8
LDR sensor	0.1	12	1.2

S-A_TPV1: Stepper motor + TB6600 Controller	0.28	12	3.36
S-A_TPV2: Stepper motor + TB6600 Controller	2.37	12	33.18

Table 7. Electrical consumption per system

Name	Gain (%)	Energy losses (Wh)	Losses (%)	Total Gain (%)
Energy S-A_TPV1	31.88	32.16	6.46	25.42
Energy S-A_TPV2	37.00	63.18	12.78	24.22

Based on the presented energy data, the net gain, factoring in losses, exhibits notable similarity between the two systems; 25.42% for the solar tracker system employing astronomical programming and 24.22% for the tracker system relying on LDR sensors (refer to Table 6). It is noteworthy that in the former system, the stepper motor is activated intermittently, for 2 minutes per hour, whereas in the latter, the motors require continuous energization for real-time correction of the panel's position relative to the solar perpendicular.

From both an energy and complexity standpoint, the single-axis solar tracker system utilizing astronomical programming demonstrates advantages suitable for deployment in equatorial regions. Furthermore, there is potential for an increased gain in this system by refining the solar positioning adjustment to a more frequent interval, such as every 15 or 30 minutes.

4.1 Comparative Analysis: Two-Axis vs. Single-Axis Solar Tracking Systems

In the pursuit of enhancing solar energy harvesting efficiency, the choice between two-axis and single-axis solar tracking systems plays a crucial role, particularly in equatorial regions like Manta, Ecuador. This subsection delves into a comparative analysis between these two tracking methodologies, shedding light on their respective advantages, challenges, and overall performance. While previous studies have focused on the efficacy of two-axis tracking systems [12], recent advancements have brought single-axis solutions to the forefront, offering promising alternatives with potentially superior energy gains and operational simplicity. By examining the nuances between these tracking systems, we aim to provide insights into optimal solar energy harvesting strategies for equatorial environments, ultimately contributing to the advancement of sustainable energy solutions. Table 8 provides a comprehensive comparison of the two-axis monitoring system and each of the single-axis monitoring systems studied, including their respective energy efficiency enhancements, energy consumption, complexity, operational adaptability, and overall performance.

Table 8. Comparative analysis

Aspect	Two-Axis system	Single-Axis system (LDR-Based)	Single-Axis System (Astronomical Programming)
Location	Coastal city of Manta, Ecuador	Coastal city of Manta, Ecuador	Coastal city of Manta, Ecuador
Tracking System Type	Dual-axis	Single-axis	Single-axis
Monitoring System	Real-time IoT-based	Real-time IoT-based	Real-time IoT-based
Tracking Mechanism	Mechanical and electronic closed-loop based on LDRs	Mechanical and electronic closed loop based on LDRs	Mechanical and electronic open loop based on astronomical programming
Energy Efficiency Enhancement	Average: 19.62%	Average: 37.0%	Average: 31.88%
Energy Consumption	72Wh	63.18Wh	32.16Wh
Complexity	Higher	Lower	Lower
Weather Condition Sensitivity	Susceptible to wind disturbances and cloudy days	Stable operation, less affected by weather conditions	Stable operation, less affected by weather conditions
Potential for Further Improvement	Limited	Moderate	Significant
Applicability in Equatorial Regions	Viable, but limited efficiency gains	Highly suitable, notable efficiency gains	Highly suitable, notable efficiency gains
Overall Performance	Good, but with small room for improvement	Good, with potential for further enhancements	Excellent, with potential for further enhancements

The comparative analysis reveals distinct efficiency outcomes between the two-axis monitoring system and the proposed single-axis solutions. While the two-axis monitoring system achieved notable energy gains of approximately 19.62%, its complexity and energy consumption were relatively higher due to dual-axis tracking mechanism. In contrast, the single-axis systems, both based on LDR sensors and astronomical programming, exhibited promising efficiency gains of around 37% and 31,88%. The LDR-based system showcased slightly higher energy enhancements, likely due to its continuous real-time adjustments, albeit with increased energy consumption. Conversely, the astronomical programming-based system offered simplified design and lower energy consumption, demonstrating significant potential for equatorial regions. These findings underscore the viability of single-axis solar tracking system, particularly those leveraging astronomical programming, in enhancing energy capture efficiency, thus presenting a promising avenue for sustainable energy solutions in equatorial regions like Manta, Ecuador.

On the other hand, one of the things that stands out in this comparison is the low gain of the two-axis tracking system compared to the single-axis tracking systems presented in this study. The main causes identified include an inadequate mechanical positioning system unable to withstand constant winds, which generated imbalances that hindered achieving greater gains. Additionally, it was found that on cloudy days, the system had problems positioning itself correctly, which also negatively influenced the energy efficiency of the system. However, although efficiency was improved with a more robust mechanical system, it was found that this system reported high energy consumption and cost compared to the single-axis tacking systems, which suggest that it is not the best option for equatorial region.

5. Conclusions

This research conducted a comparative analysis involving a static photovoltaic (PV) system and two single-axis PV tracking solar systems, each employing distinct approaches, operating within an equatorial region. An automated monitoring system was utilized to systematically evaluate energy production under standardized conditions. The motivation for this investigation stems from the limited existing studies addressing the utilization of sun-tracking solar systems in proximity to equatorial latitudes. Consequently, it was imperative to undertake additional investigations to elucidate the operational dynamics of these solar systems in enclaves near Ecuador.

A real-time IoT monitoring system was effectively deployed to acquire pertinent variables for the purpose of performance comparison between a static solar system and two single-axis solar tracking systems: a single-axis solar tracking system based on astronomical programming and based on Light Dependent Resistors. The outcomes revealed an average gain of 31.88% and 37% respectively in comparison to the static solar system. Taking into account losses, the study reveals a marginal difference between them, with the former achieving 25.42% and the latter 24.22%. Notably, the intermittent activation of the stepper motor for two minutes per hour in the astronomical programming-based system contrasts with the continuous energization requirement for the LDR sensor-based system. Considering both energy efficiency and system complexity, the single-axis solar tracker system with astronomical programming emerges as advantageous for deployment in equatorial regions. The findings suggest that potential exists for further gains by refining the solar positioning adjustment to occur at more frequent intervals, such as every 15 or 30 minutes. These observations underscore the importance of optimizing single-axis solar tracking mechanisms to enhance energy capture in equatorial environments, where precise solar alignment is crucial for maximizing overall system performance.

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References

[1] El Universo, "Crisis energética en Ecuador, una historia que se repite cada quince años," https://www.eluniverso.com/noticias/economia/las-crisis-energeticas-que-vivio-ecuador-durante-los-ultimos-32-anos-nota/.

[2] El Pais, "Colombia se enfrenta al riesgo de quedarse a oscuras ante la falta de energía," https://elpais.com/america-colombia/2024-04-18/colombia-se-enfrenta-al-riesgo-de-quedarse-a-oscuras-ante-la-falta-de-energia.html.

[3] R. G. Vieira, F. K. O. M. V. Guerra, M. R. B. G. Vale, and M. M. Araújo, "Comparative performance analysis between static solar panels and single-axis tracking system on a hot climate region near to the equator," *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 672–681, 2016, doi: 10.1016/j.rser.2016.06.089.

[4] S. Malge, K. Bhole, and R. Narkhede, "Designing of dual-axis Solar tracking system with remote monitoring," *2015 International Conference on Industrial Instrumentation and Control, ICIC 2015*, no. Icic, pp. 1524–1527, 2015, doi: 10.1109/IIC.2015.7150991.

[5] SPE, "Solar Power Europe. Global market outlook for solar power 2017-2021." Accessed: Nov. 20, 2017. [Online]. Available: https://static1.squarespace.com/static/597512eb579fb3d3de0207aa/t/5980696c46c3c486918975af/1501587836470/Global+market+outlook+2017.pdf

[6] BNEF, "Bloomberg New Energy Finance. Investing Trillions in Electricity's Sunny Future." Accessed: Nov. 18, 2017. [Online]. Available: https://about.bnef.com/blog/investing-trillions-electricitys-sunny-future/

[7] NREL, "National Renewable Energy Laboratory - National Center for Photovoltaics. Research Cell Efficiency Records." Accessed: Jul. 05, 2021. [Online]. Available: https://energy.gov/eere/solar/photovoltaics-research-and-development

[8] J. Jean, P. R. Brown, R. L. Jaffe, T. Buonassisi, and V. Bulović, "Pathways for solar photovoltaics," *Energy Environ Sci*, vol. 8, no. 4, pp. 1200–1219, 2015, doi: 10.1039/c4ee04073b.

[9] C. Y. Lee, P. C. Chou, C. M. Chiang, and C. F. Lin, "Sun tracking systems: A review," *Sensors*, vol. 9, no. 5, pp. 3875–3890, 2009, doi: 10.3390/s90503875.

[10] S. Racharla and K. Rajan, "Solar tracking system–a review," *International Journal of Sustainable Engineering*, vol. 10, no. 2, pp. 72–81, 2017, doi: 10.1080/19397038.2016.1267816.

[11] M. A. Ponce-Jara, C. Velásquez-Figueroa, M. Reyes-Mero, and C. Rus-Casas, "Performance Comparison between Fixed and Dual-Axis Sun-Tracking Photovoltaic Panels with an IoT Monitoring System in the Coastal Region of Ecuador," *Sustainability (Switzerland)*, vol. 14, no. 3, Feb. 2022, doi: 10.3390/su14031696.

[12] P. Sharma and N. Malhotra, "Solar tracking System using Microcontroller," Kalyani, India, 2014, pp. 77–79.

[13] GAISMA, "Sun Path Diagram - Manta, Ecuador." Accessed: Oct. 05, 2021. [Online]. Available: https://www.gaisma.com/en/location/manta.html

[14] S. Seme, K. Sredenšek, B. Štumberger, and M. Hadžiselimović, "Analysis of the performance of photovoltaic systems in Slovenia," *Solar Energy*, vol. 180, pp. 550–558, Mar. 2019, doi: 10.1016/j.solener.2019.01.062.

[15] A. Awasthi *et al.*, "Review on sun tracking technology in solar PV system," *Energy Reports*, vol. 6. Elsevier Ltd, pp. 392–405, Nov. 01, 2020. doi: 10.1016/j.egyr.2020.02.004.

[16] A. K. Abdelaal, A. I. A. Alhamahmy, H. E. D. Attia, and A. A. El-Fergany, "Maximizing solar radiations of PV panels using artificial gorilla troops reinforced by experimental investigations," *Sci Rep*, vol. 14, no. 1, p. 3562, Feb. 2024, doi: 10.1038/s41598-024-53873-9.

[17] A. A. Periola, A. A. Alonge, and K. A. Ogudo, "Cloud Resolution and Solar Location Diversity," in *2024 32nd Southern African Universities Power Engineering Conference (SAUPEC)*, IEEE, Jan. 2024, pp. 1–6. doi: 10.1109/SAUPEC60914.2024.10445065.

[18] A. Alblawi and M. Talaat, "Experimental and Simulation Study Investigating the Effect of a Transparent Pyramidal Cover on PV Cell Performance," *Sustainability*, vol. 14, no. 5, p. 2599, Feb. 2022, doi: 10.3390/su14052599.

[19] C. Rus-Casas, J. D. Aguilar, P. Rodrigo, F. Almonacid, and P. J. Pérez-Higueras, "Classification of methods for annual energy harvesting calculations of photovoltaic generators," *Energy Convers Manag*, vol. 78, pp. 527–536, 2014, doi: 10.1016/j.enconman.2013.11.006.

[20] N. AL-Rousan, N. A. M. Isa, and M. K. M. Desa, "Advances in solar photovoltaic tracking systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 2548–2569, Feb. 01, 2018. doi: 10.1016/j.rser.2017.09.077.

[21] S. Seme, B. Štumberger, M. Hadžiselimović, and K. Sredenšek, "Solar photovoltaic tracking systems for electricity generation: A review," *Energies (Basel)*, vol. 13, no. 6, pp. 1–24, 2020, doi: 10.3390/en13164224.

[22] Ö. Gönül, F. Yazar, A. C. Duman, and Ö. Güler, "A comparative techno-economic assessment of manually adjustable tilt mechanisms and automatic solar trackers for behind-the-meter PV applications," *Renewable and Sustainable Energy Reviews*, vol. 168, p. 112770, Oct. 2022, doi: 10.1016/j.rser.2022.112770.

[23] B. Hammad, A. Al-Sardeah, M. Al-Abed, S. Nijmeh, and A. Al-Ghandoor, "Performance and economic comparison of fixed and tracking photovoltaic systems in Jordan," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 827–839, Dec. 2017, doi: 10.1016/j.rser.2017.05.241.

[24] C. O. Okoye, A. Bahrami, and U. Atikol, "Evaluating the solar resource potential on different tracking surfaces in Nigeria," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1569–1581, Jan. 2018, doi: 10.1016/j.rser.2017.05.235.

[25] F. Ordóñez, C. Morales, J. López-Villada, and S. Vaca, "Assessment of the Energy Gain of Photovoltaic Systems by Using Solar Tracking in Equatorial Regions," *J Sol Energy Eng*, vol. 140, no. 3, Jun. 2018, doi: 10.1115/1.4039095.

[26] N. Praliyev, K. Zhunis, Y. Kalel, D. Dikhanbayeva, and L. Rojas-Solórzano, "N. Praliyev, K. ZhunImpact of One- and Two-axis Solar Tracking on Techno-Economic Viability of On-Grid PV Systems: Case of Burnoye-1, Kazakhstan," *International Journal of Sustainable Energy Plannig and Managementt*, vol. 29, no. IJSEPM, pp. 79–90, Sep. 2020.

[27] L. Zaghba, M. Khennane Benbitour, A. Fezzani, and A. Borni, "Simulation and experimental study of grid-connected photovoltaic power plants in a hot desert climate with fixed and dual-axis tracking," *Smart Science*, pp. 1–16, May 2024, doi: 10.1080/23080477.2024.2350808.

[28] Y. M. Safan, S. Shaaban, and M. I. Abu El-Sebah, "Performance evaluation of a multi-degree of freedom hybrid controlled dual axis solar tracking system," *Solar Energy*, vol. 170, pp. 576–585, Aug. 2018, doi: 10.1016/J.SOLENER.2018.06.011.

[29] M. Alif Ismail, K. A. Ramanathan, M. Hafizi Idris, K. Ananda-Rao, M. Mazlan, and N. Fairuz, "Improving the performance of solar panels by the used of dual axis solar tracking system with mirror reflection," *J Phys Conf Ser*, vol. 1432, no. 1, p. 012060, Jan. 2020, doi: 10.1088/1742-6596/1432/1/012060.

[30] A. Saymbetov *et al.*, "Dual-axis schedule tracker with an adaptive algorithm for a strong scattering of sunbeam," *Solar Energy*, vol. 224, pp. 285–297, Aug. 2021, doi: 10.1016/J.SOLENER.2021.06.024.

[31] Ms. N. Yadav, S. Bhatia, M. Tyagi, R. Kumar, and A. Kumar, "Dual Axis Solar Panel Weather Monitoring System," *Int J Res Appl Sci Eng Technol*, vol. 10, no. 5, pp. 1397–1402, May 2022, doi: 10.22214/ijraset.2022.42520.

[32] M. Ponce-Jara, A. Talavera, C. Velásquez, and D. T. Peralta, "Prediction of Solar Radiation Using Neural Networks Forecasting," Lima: Springer, Cham, 2021, pp. 181–194. doi: 10.1007/978-3-030-76228-5_13.

[33] PROSTAR, "PMS120W energía del sol placas solares 120w 12v monocristalino." [Online]. Available: https://www.prostarsolar.net/es/producto-detalles/prostar-pms120w-energia-del-sol-placas-solares-120w-12v-monocristalino

[34] NEMA, "Stepper motor Nema 23." Accessed: Oct. 07, 2021. [Online]. Available: https://components101.com/sites/default/files/component_datasheet/NEMA23 Stepper Motor.pdf

[35] SOROTEC, "Stepper Motor Driver TB6600." Accessed: Oct. 07, 2021. [Online]. Available: https://components101.com/sites/default/files/component_datasheet/TB6600-Datasheet.pdf

[36] HelioEsfera, "Coordenadas y carta solar." Accessed: Nov. 16, 2023. [Online]. Available: https://www.helioesfera.com/coordenadas-y-carta-solar/

[37] SunEarthTols, "Sun Position." Accessed: Nov. 16, 2023. [Online]. Available: https://www.sunearthtools.com/dp/tools/pos_sun.php?lang=es#txtEarth_2

[38] Altronics, "Voltage Sensor for Arduino FZ0430." Accessed: Oct. 09, 2021. [Online]. Available: https://altronics.cl/sensor-voltaje-fz0430

[39] Allegro, "ACS712 Current Sensor." Accessed: Oct. 09, 2021. [Online]. Available: https://pdf1.alldatasheet.com/datasheet-pdf/view/168326/ALLEGRO/ACS712.html

[40] J. Adeeb, A. Farhan, and A. Al-Salaymeh, "Temperature effect on performance of different solar cell technologies," *Journal of Ecological Engineering*, vol. 20, no. 5, pp. 249–254, 2019, doi: 10.12911/22998993/105543.

[41] A. W. Kandeal *et al.*, "Photovoltaics performance improvement using different cooling methodologies: A state-of-art review," *Journal of Cleaner Production*, vol. 273. Elsevier Ltd, Nov. 10, 2020. doi: 10.1016/j.jclepro.2020.122772.