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Performance Comparison between Fixed and Dual-Axis Sun-Tracking Photovoltaic Panels with an IoT Monitoring System in the Coastal Region of Ecuador

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Abstract: Solar photovoltaic (PV) energy systems are one of the most widely deployed renewable technologies in the world. The efficiency of solar panels has been studied during the last few decades, and, to date, it has not been possible to displace the production of energy using crystalline silicon wafer-based technology whose efficiency has reached values around 26.1%. Moreover, using solar tracking PV systems has become a feasible alternative to increase the electric output of PV silicon technologies instead of using the conventional fixed PV installation on a flat or sloping surface. The following study has compared fixed and dual-axis sun-tracking PV panels in order to quantify the enhancement associated with the amount of energy harvested when using dual-axis tracking PV systems in the city of Manta, located in a coastal region of Ecuador. In order to carry out this study, an IoT monitoring system based on Raspberry Pi3 and Arduino platforms was used. Measurements of solar radiation (W/m^2), light intensity (Lux), temperature ($^{\circ}C$), short-circuit current (A), and open-circuit voltage (V) were taken every minute for both systems. The results prove that the dual-axis tracking PV system produces, on average, 19.62% more energy than the static PV system. These results present an 8.62% energy increase with respect to a previous study carried out in an equatorial region with similar characteristics to those of the city of Manta, where a one-axis tracking PV system was used.

Keywords: solar radiation; fixed solar panel; sun-tracking solar panels; equatorial latitudes

Citation: Ponce-Jara, M.A.; Velásquez-Figueroa, C.; Reyes-Mero, M.; Rus-Casas, C. Performance Comparison between Fixed and Dual-Axis Sun-Tracking Photovoltaic Panels with an IoT Monitoring System in the Coastal Region of Ecuador. *Sustainability* **2022**, *14*, 1696. <https://doi.org/10.3390/su14031696>

Academic Editor: Manosh C. Paul

Received: 12 November 2021

Accepted: 26 January 2022

Published: 1 February 2022

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1. Introduction

Solar energy is the most abundant and widely dispersed form of energy available on earth [1]. Currently, solar photovoltaic (PV) power generation has become the fastest-growing energy technology in the world due to its maturity and its scalability [2]. Due to its relatively low cost, this technology is forecasted to lead power generation technology investments in the period of 2017–2040. PV-installed capacity is expected to exceed nuclear, wind, and gas generation capacity worldwide [3,4]. Nevertheless, further system-level cost reduction is required to continue decreasing costs while maintaining crystalline silicon (c-Si) wafer-based technology (90% of the global production), whose maximum energy conversion reaches 26% [5]. Even though various emerging technologies promise lower-cost manufacturing and deployment, no one has yet reached large-scale commercial production, and most face many challenges regarding PV material scaling limits, manufacturing complexity, and cost [2]. According to [6,7], despite c-Si wafer-based technology showing many advantages to reduce global environmental impacts, two factors limit its use today: the high production cost and low efficiency compared to alternative sources. Figure 1

shows a PV technology classification scheme based on material complexity and its energy conversion efficiency.

Figure 1. Alternative PV technology classification scheme based on material complexity and energy conversion efficiencies (%). Adapted from [5,8].

Considering the aforementioned obstacles, other methods to increase the efficiency of PV systems, such as the use of solar tracker systems, have been carried out. These systems keep the panels always looking at the sun. This provides a greater increase in electricity production because the electrical energy generated by a PV system is directly proportional to the solar irradiation received in the generator panel and to the installed nominal power [9]. The literature provides many studies regarding the use of solar tracking systems capable of following the trajectory of the sun throughout the day on a year-round basis [10,11]. The solar tracking system is one of the most suitable methods to increase solar panel efficiency by controlling the orientation angle (azimuth) and elevation angle (zenith) of the PV system [7,12]. The azimuth is the compass angle of the sun, which moves from east to west over daytime, and the zenith is the angle of the sun looking up from the horizon or ground level (it varies throughout the day, roughly 0° at sunrise, 90° at midday, and 180° at sunset) [13]. In some countries, this method could allow cost reduction in terms of

locating additional solar panels to increase the output since it could improve the electricity generation around 30–82% more than the fixed-angle PV system [11,14]. Furthermore, when combined with other renewable generators (e.g., wind turbines) and energy storage devices (e.g., batteries or electric vehicles), it can become an excellent model to improve the economic dispatch and provide a good energy management system that is able to minimize the grid energy costs [15,16]. On the other hand, very few studies involving the enhancement of electrical energy production with sun-tracking solar systems have been carried out in regions close to equatorial latitudes. Some simulation-based analyses have reported improvements between 27 and 34% [17,18], while other technical research has shown an average enhancement of 11% using a single-axis tracking PV system [6], as presented in Table 1.

Table 1. Published studies regarding tracking PV systems in equatorial regions.

Title	Type	Country	Findings
Comparative performance analysis between static solar panels and single-axis tracking system in a hot climate region near to the equator [6]	Experimental	Brazil	The efficiency of a single-axis tracking PV system proved to be, on average, 11% higher than a fixed PV system. In this study, the consumption of the solar tracker was not taken into consideration.
Improvements in photovoltaic systems using solar tracking in equatorial regions [17]	Simulation	Ecuador	Comparative simulations between the fixed PV system and the single-axis and dual-axis tracking PV system showed efficiency improvements of 27.3% and 31.2%, respectively. Given that the difference is only 4%, single-axis tracking PV systems are recommended.
Assessment of the energy gain of photovoltaic systems using solar tracking in equatorial regions [18]	Simulation	Ecuador	Comparative simulations between the fixed PV system and the single-axis and dual-axis tracking PV system showed efficiency improvements of 30% and 34.62%, respectively.

Moreover, Table 1 shows that Ecuador and Brazil are the only two countries that have developed either experimental studies or studies based on simulations.

Taking into consideration that the sun's path in the equatorial latitudes presents a very special profile that differs considerably from latitudes located further south or north (Figure 2), this work intends to fill the gap in knowledge regarding improvement in sun-tracking solar systems in equatorial regions, taking the city of Manta as a case of study.

Figure 2. Sun path diagram (Manta, Ecuador) [19].

This work is based on information obtained in real time from both a static and a dual-axis PV system operating in an equatorial region. Not many studies have been carried out on this area. It has resulted in an efficiency enhancement of 19.62% since the average electric output for the dual-axis tracking PV system was 9838.35 W, whereas the static PV system provided 8326.18 W.

The structure of this paper is as follows: after a brief introduction, (Section 1), the different sun-tracking methods will be presented, (Section 2). Section 3 describes and compares the performance of a fixed and a dual-axis sun-tracking solar system developed by the authors of this work; in addition, the automatic IoT monitoring system built with the low-cost RaspberryPi3 and Arduino platforms will be described. Results are presented and discussed in Section 4. Finally, in Section 5, conclusions are presented.

2. Sun-Tracking System

Recent research on solar systems classified sun-tracking systems in the following way [20]:

1. Based on drives
 - a. **A passive** sun-tracking system uses the pressure difference of special liquids or gases created by the thermal differences of the shaded and illuminated sides of the tracking system to move solar panel systems towards the sun position. These do not need an additional power supply and are rarely used since their accuracy is relatively low.
 - b. **An active** sun-tracking system uses electrical drivers and mechanical assemblies to operate, such as a microprocessor, an electric motor, gearboxes, and sensors.
2. Based on the degree of freedom
 - a. **Fixed PV systems** are the most common systems mounted directly on the roofs of buildings or houses, most of the time at the same slope as the roof and south-oriented, inclined at a certain angle, depending on the latitude and longitude.
 - b. **Single-axis tracking PV systems** have only one degree of freedom, which serves as an axis rotation. These systems are divided into three different types: (1) horizontal single-axis tracking system (HSAT); (2) vertical single-axis tracking system (VSAT); and (3) tilted single-axis tracking system (TSAT).
 - c. **Dual-axis tracking PV systems** have two degrees of freedom, which serve as axes of the simultaneous rotation left–right (azimuth angle) and up–down (zenith angle) directions. Two common types are the azimuth–altitude tracking system (AADAT) and tip-til tracking system (TTDAT).
3. Based on strategies
 - a. **The open-loop control system** uses a mathematical algorithm to determine the precise position of the sun; the use of this system implies not having any control to correct the errors that could occur during the tracking process.
 - b. **The closed-loop control system** is based on a light intensity sensor feedback control system; through an algorithm loaded in a microprocessor, the position of the sun is evaluated from the data of the sensors to move the axes of the solar system towards its position.

From these groups, the most common classification is according to their degree of freedom [12]. Single-axis solar tracking was the first technology used to follow the sun's daily motion. Afterwards, this system was developed into a dual-axis tracking system to be able to track both the daily and annual motions of the sun's path [13,21]. According to [17], the main mechanisms of the solar tracking system are (1) the tracking algorithm, (2) the control unit, (3) the positioning system, and (4) sensing devices. The tracking algorithm is responsible for determining the position of the sun-tracking system; it can be done using astronomical algorithms (mathematical algorithms based on astronomical references) or using real-time light intensity algorithms (based on real-time light intensity measurements). The control unit and the positioning system are responsible for executing the algorithm and

positioning the tracking device towards the calculated sun position. Finally, the sensing device gathers a group of sensors that are able to measure ambient conditions, such as light intensity, temperature, humidity, etc.

Since dual-axis tracking PV systems are the most frequently used technology in areas located far from the equator and are those associated with higher efficiency, they represent an interesting opportunity for further study in the equatorial region. Single-axis solar tracking systems' performance has been previously explored in this area, with promising results [6].

3. System Realization and Experimentation

3.1. Research Location

The research was carried out in Manta, located in the Ecuadorian coastal region. Its location is defined by the geographical coordinates of $0^{\circ}57.72'$ south latitude (S) and $80^{\circ}42.73'$ west longitude (W), at an altitude of 6 m above sea level. The city's climate is considered dry tropical, with an average annual temperature of 23.9°C and average air relative humidity of 79% [22]. The city solar annual radiation average rate is 4.88 kWh/m^2 [23].

3.2. Proposed System

The block diagram of the proposed system is shown in Figure 3, and the real system installed in the facilities of the Universidad Laica Eloy Alfaro de Manabí (ULEAM) in the city of Manta is shown in Figure 4. The system can be divided into two major units: the automatic weather station and the energy production comparison system, which compares a dual-axis tracking PV system and static PV system. Both PV systems were placed at an open area in order to avoid shadows from the surrounding buildings and trees.

Figure 3. Proposed system.

The automatic weather station (AWS) is an IoT low-cost facility provided with a series of instruments that collect and record meteorological variables, such as solar radiation, UV radiation, wind velocity and direction, temperature, and humidity. All measurements carried out in the meteorological weather station were read and recorded by a data logger (Raspberry Pi3), which is also in charge of processing and sending data through the ethernet network to the servers of ULEAM and to those of the National Institute of Meteorology and Hydrology (INAMHI). The data history is displayed in real time on a web platform to the university community. In addition, all the sensors used were calibrated under rigorous processes performed by the INAMHI. Additional information can be found at [24].

Figure 4. Automatic weather station, dual-axis tracking PV system and static PV system.

This paper suggests that the AWS can be used as a bridge to automatically monitor the temperature and the energy production of a dual-axis tracking PV system vs. a static PV system. In order to achieve this, the AWS is linked via i2c communication protocol to an Arduino platform that serves as a data acquisition system for the static and dual-axis PV system; it also ensures that the dual-axis tracking system is always looking at solar position. Moreover, detailed components and sensors are described in the following subsections.

3.2.1. Static PV System

The static PV system can be observed on the right side in Figure 4. This system is made of a monocrystalline PV panel and a fixed structure with a 5° inclination, following the latitude location measurements described above and presented by [6]. The PV panel is used in both the static PV system and the dual-axis tracking PV system; the properties of this solar panel are described in Table 2.

Table 2. PV module electrical characteristics [25].

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°C to $+85^\circ\text{C}$
STC Efficiency	18.46%
Dimensions	$670 \times 970 \times 30$ mm

3.2.2. Dual-Axis Tracking PV System

The proposed solar tracking PV system shown in Figure 5 includes a mechanical structure and an electronic closed-loop system. The mechanical structure consists of both fixed and movable elements that allow the system to track the movement of the sun. The fixed structure part is made of aluminum, and it is responsible for supporting the weight of the solar panel, gears, motors, and other accessories. The movable parts are associated with azimuthal and zenithal movements linked to the stepper motors NEMA23 [26], which are commonly used in precision control applications. Both motors are commanded by a TB6600 stepper motor driver controller [27], and this is in turn connected and controlled by the Arduino module. The loop is closed by four Light Dependent Resistors (LDR) used to evaluate the sun's position and accordingly move the solar positioning system, as suggested by the authors in [12,28].

Figure 5. (a) Dual-axis tracking PV system; (b) LDR's system position; (c) Azimuthal rotation system; (d) Zenithal rotation system.

3.2.3. Light Dependent Resistors Sensing System

The Light Depending Resistor (LDR) is a photoresistor or photocell whose resistance varies depending on light intensity. The resistance of this sensor is inversely proportional to the light intensity falling on it, so it has very high resistance in darkness ($\approx 1 \text{ M}\Omega$), but it decreases to a few $\text{k}\Omega$ once it receives light. In the dual-axis tracking PV system, four LDRs were placed on one of the sides of the solar panel, as shown in Figure 6. The intensity of the light is sensed during the day and evaluated by the Arduino Uno to position the solar panel in the direction of the sun using the stepper motors. Thus, the electronic circuit works as a comparator of light intensity in such way that, depending on the position of the sun, one part of the LDR sensors will be more shaded than the others, which will consequently allow for the best possible outcome.

Figure 6. Light Dependent Resistor system.

3.2.4. Voltage, Current, and Temperature Sensing System

To compare the performance of the static and dual-axis tracking PV systems, three sensors were installed on each system to collect voltage, current, and temperature data. The temperature sensor was installed on the back of the solar panels. An average of 60 samples per minute was taken as an instantaneous value.

To measure voltage and current values, a series of relays was used to control the acquisition of the short-circuit current and the open-circuit voltage data by interleaving these measurements every second for one minute. Thus, an average of 30 samples per minute was taken as an instantaneous value. Finally, these data were sent via i2C protocol communication to the AWS. Table 3 shows the sensors, their schematic circuits, and their characteristics.

Table 3. Voltage, current, and temperature sensors.

Image	Circuit Configuration	Characteristics
FZ0430 voltage sensor [29] <ul style="list-style-type: none"> - Supply voltage: 0 to 25 V - Resolution: 0.00489 V_{DC} - Minimum input detection voltage with Arduino Uno: 24.41 mV
ACS712ELC current sensor [30] <ul style="list-style-type: none"> - Supply voltage: 5 V - Maximum current: 20 A - Sensitivity: 66 to 185 mV/A - Output error: 1.5 % at 25 °C - Internal resistance: 1.2 mΩ
LM35 temp. sensor [30] <ul style="list-style-type: none"> - Supply voltage: 4 to 30 V - Temp. range: −55 to 150 °C - Accuracy: ±2 °C - Output: +10 mV/ °C

Voltage is measured using the FZ0430 circuit module. This is a simple circuit voltage divider with 30 kΩ and 7.5 KΩ, which means that the voltage perceived by the module is divided by a factor of five when the maximum input voltage is reached. Since the Arduino Uno ADC has a 10-bit resolution, it is possible to map input voltages between 0 and 5 volts to integer values between 0 and 1023. Therefore, the resolution is approximately 4.89 mV (5 V/1023), so the minimum voltage value to detect is 24.45 mV.

To sense current flow, the ACS712ELC 20 A module is used. The sensor provides an analog voltage output signal that varies linearly with sensed current, which can be either alternating or a continuous current up to 20 A. The sensor consists of a precise, low-offset, linear Hall-effect sensor circuit with a copper conduction path (1.2 mΩ typical) located near the surface of the die. When a current is applied, the copper conduction path generates a magnetic field, which is sensed by the integrated Hall-effect sensor and is then converted into a proportional voltage. This sensor operates with 5 VDC and outputs an analog voltage (66 mV/A) centered at 2.5 V (V_{cc}/2) with a typical error of 1.5%.

According to [31], temperature is one of the main parameters that affects the performance of the solar cell. Its capacity to produce energy decreases with increasing temperatures. Therefore, an LM35 temperature sensor was used in order to evaluate the system that operates better in the city of Manta, considering its average temperature. This sensor is a precise integrated-circuit whose output voltage is linearly proportional to the instantaneous temperature in Celsius degrees. The temperature range of this sensor goes from $-55\text{ }^{\circ}\text{C}$ to $+150\text{ }^{\circ}\text{C}$ and has a scale factor of $10\text{ mV}/^{\circ}\text{C}$.

4. Results and Discussion

Ecuador is not a four-season country, and there are no extreme opposite weather conditions throughout the year besides cloudy and sunny days in the summer and sunny and rainy days in the winter. This fact is supported by the data obtained from the meteorological weather station located at ULEAM (Manta), for a period of 2 years. This information allowed us to approach the study considering 6 months of collected data (three from each station).

The static PV system, the dual-axis tracking PV system, and the AWS have collected enough data to provide a sample of those days with the most representative conditions for a complete assessment; therefore, a record of the state of the sky according to cloud cover was carried out: sunny, partially cloudy, and cloudy (using qualitative observation). The performance of the system was observed from 6:00 am to 6:00 pm, with daily measurement intervals every minute; an average of 60 samples per minute for the temperature and 30 samples per minute for the Voc and Isc were taken as instant values. Measurements of solar radiation in W/m^2 were taken by the AWS (orange curve), and an average of 60 samples per minute were taken as instant values.

Systems Comparison Performance

System performance of the dual-axis tracking PV system and static PV system are shown in Figures 7 and 8 for a cloudy day, in Figures 9 and 10 for a partially cloudy day, and in Figures 11 and 12 for a sunny day. It can be seen that energy production follows a pattern defined by solar radiation, and the amount of energy varies significantly according to the state of the sky. However, the dual-axis tracking PV system is slightly higher.

Conversely, a slightly higher temperature is observed for the dual-axis tracking PV system during the days evaluated. The temperature of both systems oscillates approximately between $20\text{ }^{\circ}\text{C}$ (at sunrise and sunset) and $35\text{ }^{\circ}\text{C}$ (at midday) and therefore does not exceed the operating temperature of the cell, shown in Table 2.

Table 4 shows the average performance of both systems, and Figure 13 presents their energy performance and temperature. According to these data, the dual-axis tracking PV system has a better performance than the static PV system (this does not consider the system's consumption).

Figure 7. Generated energy performance on a cloudy day (day 2).

Figure 8. Temperature performance on a cloudy day (day 2).

Figure 9. Generated energy performance on a partially cloudy day (day 10).

Figure 10. Temperature performance on a partially cloudy day (day 10).

Figure 11. Generated energy performance on a sunny day (day 16).

Figure 12. Temperature performance on a sunny day (day 16).

Table 4. Dual-axis tracking PV system and static PV system average performance.

Day	Global Radiation (W/m ²)	Gain (%)	State of the Sky	Dual-Axis Tracking PV System		Static PV System	
				Energy (Wh)	Temperature (°C)	Energy (Wh)	Temperature (°C)
1	182.82	31.00	cloudy	259.26	25.61	197.91	24.24
2	199.45	26.58	cloudy	291.39	27.16	230.20	26.00
3	346.61	42.68	partially cloudy	473.46	28.62	331.83	27.29
4	223.75	38.96	cloudy	138.99	23.80	100.02	23.19
5	418.8	16.57	sunny	613.95	28.62	526.69	26.83
6	393.95	22.88	partially cloudy	476.70	23.83	387.93	26.61
7	318.1	8.74	partially cloudy	329.30	26.72	302.84	25.00
8	303.47	11.44	partially cloudy	302.85	29.15	271.77	25.31
9	412.49	23.61	sunny	720.99	28.50	583.28	26.94
10	302.01	19.04	partially cloudy	456.08	25.96	383.13	25.75
11	358.45	12.20	partially cloudy	508.48	29.71	453.20	24.47
12	402.93	13.03	sunny	687.85	27.00	608.53	25.54
13	235.61	13.88	cloudy	371.70	24.98	326.37	23.6
14	300.41	16.20	partially cloudy	493.03	27.91	424.30	26.61
15	293.18	21.45	partially cloudy	414.59	27.78	341.38	26.48
16	405.69	14.70	sunny	703.30	29.25	613.18	27.95
17	287.96	13.98	partially cloudy	488.63	26.77	428.68	25.36
18	524.89	15.87	sunny	765.09	29.25	660.31	27.94
19	396.72	22.55	partially cloudy	512.40	27.98	418.12	26.68
20	494.42	11.11	sunny	511.35	29.68	460.24	28.43
21	391.38	15.46	partially cloudy	318.99	27.79	276.27	26.56
Average	342.52	19.62	—	468.49	27.43	396.48	26.03

Figure 13. Generated energy and temperature performance for both systems.

Table 4 additionally states that the electric output went as high as 765.09 W on a sunny day for the dual-axis tracking PV system, while the output power obtained by the static PV system the same day was 660.31 W. Additionally, the dual-axis tracking PV system went as low as 259.26 W on a cloudy day, whereas the static PV system decreased to 197.91 W the exact same day.

The maximum percentage obtained was 42.68% (day 3), and the minimum was 8.74% (day 7). On average, the energy efficiency of this system increases up to 19.62%. This percentage is higher than the 11% mentioned by [6], and, consequently, the dual-axis tracking PV system has better performance in equatorial regions compared to the one-axis tracking PV system. Nevertheless, this 8.62% improvement could still be very low, since dual-axis tracking PV systems require more energy consumption in the motion system and more mechanical mechanisms that need to be implemented, as mentioned by [18].

In addition, according to the observations performed in these systems, it is important to highlight the continuous disturbances received from the wind speed and the disorientation of the system on very cloudy days (losses light reference) in the study area; this makes it difficult to track the solar path and could also increase energy consumption.

Regarding the temperature, it can be observed that there is a slight difference of approximately one degree in the temperature between the dual-axis and the static solar panels. This small rise in the dual-axis tracking PV system could be due to the higher energy production registered with this system. The maximum difference recorded was 3.84 °C (day 8), and the minimum was 0.61 °C (day 4).

For calculation purposes, *Energy (Wh)* has been estimated considering the following:

$$\text{Energy (Wh)} = \sum_{i=1}^n E(\min)_i \quad (1)$$

where $E(\min)$ corresponds to the energy measured per minute, and $n = 720$ is the number of samples considered.

On the other hand, *Gain (%)* is calculated as follows:

$$\text{Gain (\%)} = \frac{[\text{Energy(Wh)}_{\text{Dual-axis PV}}] \times 100}{\text{Energy(Wh)}_{\text{Static PV}}} - 100 \quad (2)$$

The values previously stated do not consider the energy consumption associated with elements, such as the stepper motors and the stepper motor driver, that allow for the tracking system to locate the right angle of incidence and whose cost implication in the overall system is minimal since these elements are not expensive and are easily found in electronics stores. Moreover, this element's consumption is approximately 72 Wh, and, when taken into account, results in both systems providing very close energy values, which supports the statement that it is not feasible to use such technologies in equatorial regions.

5. Conclusions

This study presented a comparison between a static and a dual-axis PV system operating in an equatorial region using an automatic monitoring system to evaluate energy production under equal conditions; given the few studies regarding the use of sun-tracking solar systems in regions close to equatorial latitudes, it is necessary to carry out further studies to show the operation of solar PV systems in any type of enclave near Ecuador.

A real time IoT monitoring system was successfully implemented using an automatic weather station and a data acquisition system to obtain all the necessary variables to compare the performance of a static and dual-axis tracking PV system, resulting in an average electric output of 9838.35 W for the dual-axis tracking PV system. Conversely, the static PV system generated 8326.18 W, consequently providing an efficiency enhancement of 19.62%.

Manta is considered to have high solar radiation levels. Moreover, solar tracking systems in equatorial latitudes do represent an alternative; however, dual-axis tracking PV systems are not the best choice for this specific location since evidence provided in

this study suggests that the energy efficiency enhancement does not offer a significant improvement either from an energy or an economic point of view.

Power generation using dual-axis tracking PV systems allows for values as high as 765.09 W on a sunny day and as low as 259.26 W on a cloudy day; moreover, further study throughout the year is of great relevance in order to provide a complete assessment of the performance of this type of system.

Given the location where the prototype is currently working, additional procedures intended to improve the sun-tracking system's outcome in weather conditions such as Manta's are an important consideration. Additionally, factors such as wind velocity, typical of coastal areas and cloudy days, could significantly affect the operation and energy production of an LDR system; furthermore, disturbances related to wind speed make the correct solar path difficult to find. Therefore, further studies locating different weather stations in areas near Manta could allow for a better understating and relocation of future projects regarding dual-axis tracking PV systems.

Lastly, additional work aimed to improve the performance of one-axis tracking PV systems for equatorial regions is recommended to find the best cost-effective system, improve energy efficiency, and, consequently, obtain a better and stronger alternative for countries such as Ecuador.

Author Contributions: All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Universidad Laica Eloy Alfaro de Manabí (Proyecto de Investigación-Análisis de los recursos energéticos en los catones Manta, Montecristi y Jaramijó con fines de generación eléctrica) and the University of Jaén (Programa Operativo Proyectos de I+D+i en el marco del Programa Operativo FEDER Andalucía 2014/2020. Project Contribución al abastecimiento de energía eléctrica en pequeñas y medianas empresas de Andalucía. AcoGED_PYMES (Autoconsumo fotovoltaico y Generación Eléctrica Distribuida en PYMES). Ref: 1380927 and CEAETEMA).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge anonymous reviewers for their kind and interesting comments, which have helped us to improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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