Performance enhancement of PV generator using a sensor based dual axis solar tracking system in Algeria

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ABSTRACT

This article presents the implementation of a two-axis solar tracking system and its impacts to increase the performance of the photovoltaic system in northern Algeria. The system enhances the efficiency of solar systems by optimizing their exposure to sunlight making the sunbeam perpendicular to solar panel. The main objective of the study is to develop a technically proficient and economically viable solution to increase solar energy production. The design relies on integrating light sensors and motors controlled by an Arduino board, enabling automatic adjustment of solar panel positions. This approach offers dynamic and precise orientation, based on light dependent resistor (LDR) sensor design and threshold value, resulting in a significant increase in energy output. The results show that the dual-axis solar tracking system can capture 60.64% more solar energy, taking into account the power consumption of the two electric actuators. The findings of this study will positively influence the promotion of clean and sustainable energy sources while providing a practical solution for more efficient utilization of solar energy in Algeria.

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1. INTRODUCTION

Solar energy has become an increasingly attractive solution to meet the world's growing energy needs while reducing our carbon footprint. Solar photovoltaic and thermal systems are becoming more and more widespread, providing a renewable and environmentally friendly source of energy. However, to maximize the effectiveness of these systems, it is essential to capture sunlight optimally throughout the day. It is in this context that solar trackers play a crucial role.

The path of the sun changes throughout the day and varies with the seasons. A solar tracker makes it possible to precisely follow this trajectory, where sunbeam is perpendicular to the face of the photovoltaic (PV) module. Thus ensuring optimal positioning of the solar panels for maximum absorption of sunlight. The challenge lies in the search for effective, sustainable and economically viable solutions to address this problem. Many works have been tried to improve the performance of solar tracker system using different techniques based on drive passive or active [1], [2], based on degree of freedom single or dual axis solar tracking system, tracking strategies sensor-based or sensorless using date and time [1], [3]. Using control strategies closed or open loop solar tracking system [4]–[6]. Based on a digital hemispherical imager as studied in [7] which presents a design and implementation of a solar tracker using a computer vision technique where the sun position is determined using a camera equipped with a fisheye lens.

Kuttybay *et al*. [8] examines solar tracking system from different aspects, methods and designs, efficiency, geographical locations, climatic conditions, complexity and cost. In addition, the evaluation of the effectiveness of different types of solar tracking systems is classified in tables according to the availability equipment, climatic conditions, energy consumption and prevalence in world practice. Solar tracking system (STS) has a considerable effect on improving the efficiency of solar energy system and their potential in promoting sustainable energy [9]. The control algorithms implemented in active solar tracking systems are classified according to three strategies: open loop, closed loop and combined open and closed loop schemes [10]. Closed loop strategie is the most used one by the rate of 54.39%.

The single axis solar tracking method has a lot of interest and attract many works [11]–[14]. An implementation of single axis automatic solar tracking system with three manipulation modes (manual, light dependent resistor (LDR), programmed real-time clock (RTC)) is investigated in [15]. Zhu *et al*. [16] discusses a novel tilted-rotating single axis tracking structure for a PV system. The latter had a ratio of incident solar radiation relative to that of the two-axis tracked panel of approximately 96.40%. A study of the effect of discrete three-position single-axis solar tracking using the Hay–Davies–Klucher–Reindl (HDKR) isotropic and anisotropic models is covered in [17]. The energy gain produced by this system represents approximately 91-94% of the solar energy collection of a single-axis continuous solar system. Since the system only operates three times per day in the azimuthal plane to track the sun, it reduces the starting torque of the motors, which reduces energy consumption. Although the single-axis solar tracking system improves the performance of the solar PV system, the utilization of the sun's radiation is less than we intended.

In contrast, dual-axis solar tracking systems have been developed to overcome the limitations of movement directions of single-axis solar tracking systems. The system has two axes allowing full rotation while the tilt angle is between 0° and 90° and the azimuth angle between 0° and 360° [18]. Altitude and azimuth angles were taken into account to track the exact position of the sun, increasing energy harvest [19]. Many works are discussing this issue from different points [20]. Ray and Tripathi [21] describes the design, development and fabrication of a single-axis and dual-axis solar tracking controllers to power mobile batteries. The tilted single axis tracking system increases the efficiency of solar panel up to 30%, whereas, the azimuth altitude dual axis solar tracking system augments the efficiency of solar panel up to 40%. A novel online sensorless dual-axis sun tracker was proposed in [22]. The study proves that both sensor-based and sensorless solar tracking have advantages. In addition, it reduces the tracking error to 0.11°. Dual-axis solar tracking system with different control strategies was described in [23]. Simulation and link (SIMULINK) platform and SOLIDWORKS platform are used for designing real-life solar tracking systems. The results of this work, Mamodiya and Tiwari [23] show the strength of the system against high wind speed. A sensorless dual-axis solar tracking system using particle filter has been proposed [24]. Power generation performance was increased (after accounting for operational power consumption) by 20.1% compared to the fixed flat-plate system. Dahli *et al*. [25] proposes optimal tracking intervals for solar tracking system that consumes less than 0.15% of the energy produced, thus improving energy efficiency, reducing unnecessary energy consumption.

In addition, the use of recent technologies in the solar tracking system is essential to keep pace with technological development. The introduction of notion of artificial intelligence was incorporated through the development of algorithms based on artificial intelligence in controlling a solar tracker is investigated in [26], [27]. The advanced fuzzy logic with adaptable rules was used in order to replace proportional–integral–derivative (PID) controller. The assessment of a dual-axis tracker with smart algorithms called maximum light detection (MLD) applied in the solar energy generation system is discussed in [20].

Integrating internet of things (IoT) into a solar tracking system can also increase energy production and efficiency, remote monitoring and control, improve reliability, and consequently reduce operating costs. Rouibah *et al*. [28] presents a system using IoT for remote and real-time monitoring of solar PV installations and shows the potential of IoT-enabled monitoring to improve energy efficiency. Shi *et al*. [29] proposes a solar-powered and radio frequency (RF) energy transmission-based IoT management system for roadside parking space. The objective of the study is to reduce the costs of the system, relieve installation difficulties and achieve complete autonomy in the power supply. Rao *et al*. [30] explains the role of energy management in smart architecture and focuses on IoT in photovoltaic power generation. It presents an overview of smart energy management techniques for hybrid, connected, and off-grid renewable energy. Additionally, it focuses on IoT in photovoltaic power generation. IoT can be used in solar cities, smart villages, microgrids, and solar street lighting to facilitate remote control and increase efficiency, accuracy, and economic gains [31].

Despite the considerable development of solar tracking systems and numerous studies in this field, the use of this device remains very limited in our country. It is therefore necessary to explain and present its advantages in local meteorological conditions. In this context, a novel sensor based dual axis solar tracker is proposed. The study emphasizes the reliability of the system and the low consumption of the actuator. In the contrast, the study shows a huge increase in energy harvest. The tracker can be used in all application that need maximum of radiation like photovoltaic systems in agriculture, water pumping or solar concentrators and water disinfection system. It has been implemented and evaluated to show its performances comparing to fixed ones in our area. Moreover, the economic study is done for fair comparison in the power production. The impact of the cloudy sky in the system operation is presented. Although, the cost of energy generated by a photovoltaic tracking system is higher than that of energy produced by a fixed system, the system remains advantageous. The initial cost of the tracking system implemented is 105 $ higher than that of the fixed system. The paper is organized as follows, details of the construction is presented in section 2. Section 3 presents results and discussion, and conclusions are drawn in section 4.

2. SENSOR BASED DUAL AXIS SOLAR TRACKING SYSTEM DESCRIPTION

Figure 1 shows the realized sensor-based dual-axis solar tracking system and its various elements. The developed tracking system consists of an electronic part which controls two electric actuators using LDR sensors. These actuators orient a mechanical structure that supports two solar panels along two axes, in the direction of the sun. Our mechanical structure rests on a "[" shaped rod which supports a square metal frame. Additionally, a sturdy leg provides a stable base, while an H-shaped aluminum bracket rises above the frame with dimensions of 2 m by 1 m to support our solar panels. The solar panel positioning system consists of two separate mechanisms that use a pair of electrical actuators. One of these actuators is dedicated to azimuth translation, while the other manages elevation.

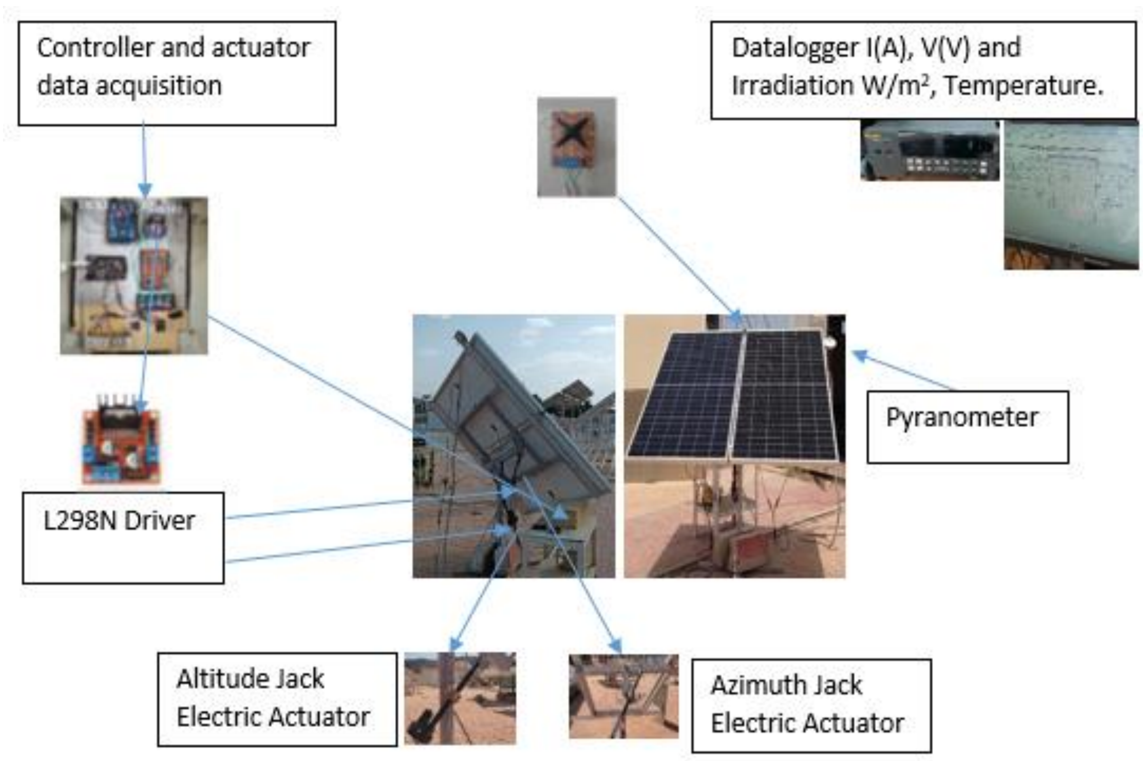

Figure 1. Proposed solar tracking system

The characteristics of solar panels, actuators, driver and controller are presented below. The control strategy is also explained in detail.

2.1. PV module

JingAo (JA) solar PV module (JAM72S10 395-415/MR) has been used in this study. The technical specifications of PV module JA solar under standard test condition (STC): solar irradiance G ¼ 1000 W m^2, air mass (AM) 1.5 solar radiation spectrum, cell temperature T=25 °C, and solar angle qz ¼ 48.19) extracted from its datasheet are summarized in Table 1.

Table 1. Parameters of the PV module JA solar

Parameter	Specification / value
Type	JAM72S10-415/MR
Rated maximum power (Pmax) [W]	415
Maximum power voltage (Vmp) [V]	42.18
Maximum power current (Imp) [A]	9.84
Open circuit voltage (Voc) [V]	50.41
Short circuit current (Isc) [A]	10.51

2.2. Jack electric actuator

The electric actuator uses the electrical energy generated by a photovoltaic module to produce linear motion. It is mainly composed of two fundamental elements: an electric motor and a motion transmutation mechanism, which converts the rotary motion of the motor into linear motion. It is controlled by the driver. The parameters of the Jack electric actuator are shown in Table 2.

Table 2. Parameters of Jack electric actuator

Parameter	Specification / value
Input voltage	36 V DC
Charge capacity	3000 N
Static load	4500 N
Length	30.5 cm

2.3. Driver

The L298N H-bridge controls the opening and speed of both actuators. It is ideal for connecting to a microcontroller requiring only two control lines per motor. The controller processes data from the LDR sensor and independently controls two motors up to 2 A each in both directions.

2.4. Controller

The control box of our dual-axis solar tracker system plays a central role. It integrates an Arduino Mega as the main control unit, housing our essential program and handling key instructions based on the input data arrived from the LDR sensor. Movement control is provided by the L298N motor driver, which translates signals from the Arduino into precise rotations for the motors, ensuring precise solar tracking. To monitor energy consumption, we have integrated current and voltage sensors, allowing us to know the consumption of the actuators in real time. Additionally, an Arduino WiFi facilitates connectivity, receiving and transmitting sensor data over a local network.

2.5. System control strategy

Figure 2 shows the flowchart of the Arduino program that controls our entire system. It uses information received from LDR sensors via analog ports to detect luminosity in different directions : east, west, north, and south. The threshold value between the LDR sensors is selected after different measurements to select the best one that can follow the sun's ray optimally and at the same time reduce the consumption of the actuators. The program then adjusts the motors accordingly to maintain optimal luminosity balance. The steps of program are indicated below :

- Read the values of the analog sensors.
- Calculate the luminosity differences between pairs of north-south and east-west sensors.
- If a limit switch is not activated, correct the deviations by adjusting the appropriate motors to reduce the difference in luminosity.
- Once equilibrium is reached in each direction, the motors are stopped.
- If the limit switch is activated, the program performs a return movement to the starting position using the motors.
- A delay is included to avoid frequent operations after returning to the starting position.

The program allows the system to follow the light source by adjusting the motors according to the sensor values and return to the initial position if the limit switch is activated. The flowchart below emphasize steps.

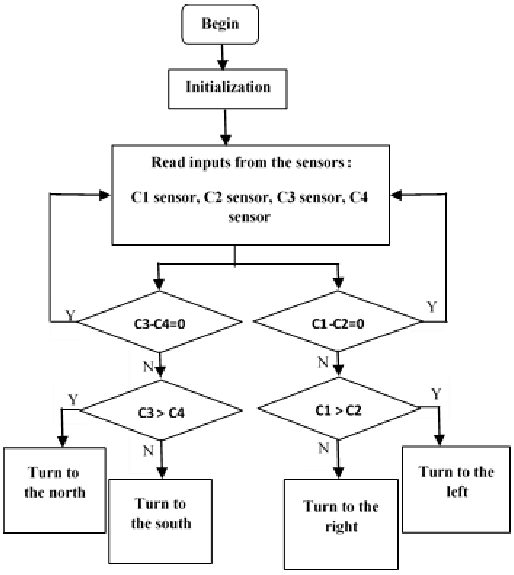

Figure 2. Flowchart of dual axis solar tracker

3. RESULTS AND DISCUSSION

In this study focuses on the development of a two-axis solar tracking system to improve the performance of the photovoltaic field in northern Algeria. Additionally, a fair comparison was made between the developed dual-axis solar tracking system and a conventional fixed system to demonstrate the effectiveness of the tracking system in energy harvesting. Acquisition of electrical parameters; voltage, current and other relevant parameters were carried out at the same time and the tracking and conventional systems were installed at the same location in order to have similar weather conditions.

The aim of the study is to quantify and analyze the energy produced during the experiments between the two systems taking into account the power consumed by the electrical actuators to show the percentage of energy gain. This comparison offers valuable information to optimize technological choices in the implementation of solar energy solutions. The study emphasizes the relation between irradiation and the produced power for the tracking system. The additional cost of the developed tracking system was also calculated.

3.1. Solar irradiation on a fixed plane and on a tracking system

Figure 3 represents solar irradiation on a fixed plane and on a plane, which follows the trajectory of the sun (tracking system). It is clear that the amount of radiation following the sun tracker is greater than that of the fixed system. According to the figure, the difference in irradiation between the tracking system and the fixed system is significant in the morning and in the afternoon but at noon this difference in irradiation is reduced.

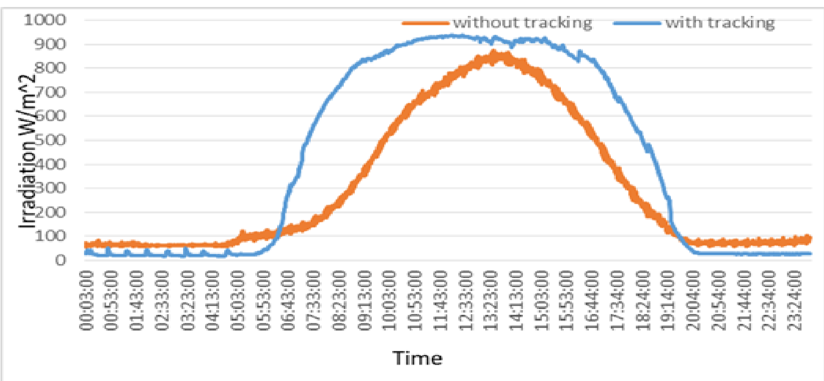

Figure 3. Solar irradiation with and without tracking for a sunny day

3.2. Energy evaluation of the tracking system
3.2.1. Ambient temperature

The influence of temperature on photovoltaic solar panels is significant. An increase in temperature tends to reduce the power produced by the PV generator. Figure 4 presents the ambient temperature measured during the day of July 20, 2023 using temperature sensor and datalogger. The value of the temperature varies between 40 °C and 37 °C during the morning until 03:55 p.m. and it began to decrease to reache 31°C at 08:00 p.m.

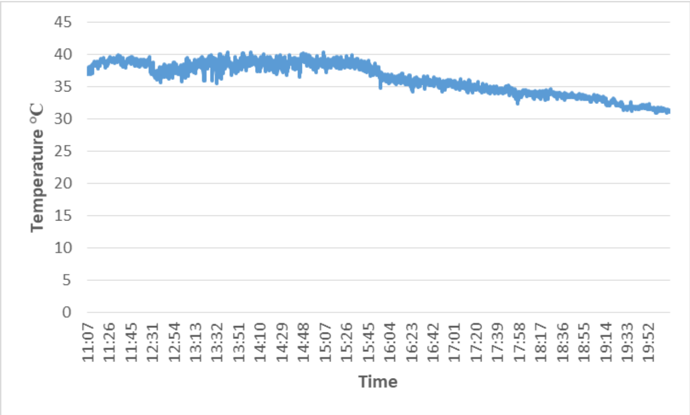

Figure 4. Ambient temperature measured during the day of July 20, 2023

3.2.2. Solar irradiation

Figure 5 gives the solar irradiation using a pyranometer and datalogger. An increase in solar irradiation leads to a simultaneous increase in voltage and current. These variations are due to the intrinsic properties of solar cells. Overall, higher temperature can affect the output voltage, while higher solar irradiation improves both the voltage and current produced by the panels. Understanding these influences is essential to assess the PV system.

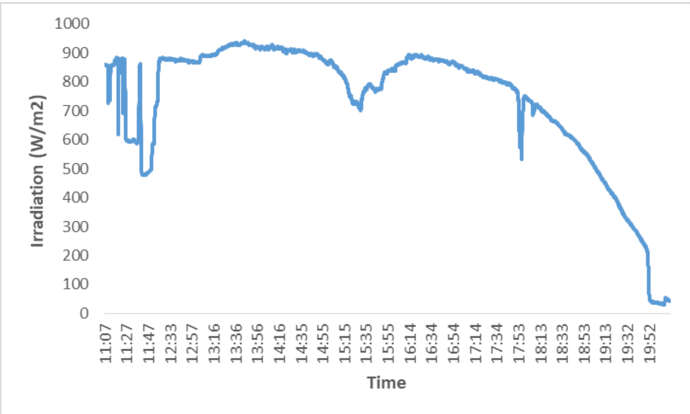

Figure 5. Solar irradiation using a pyranometer placed on a sun tracking system during the day of July 20, 2023

3.2.3. Power produced

Figure 6 represents the evolution of the power as a function of time of our solar tracking system. In the morning, the weather was cloudy, so the amount of energy fluctuated between the maximum value of 700 W and the minimum value of 263.32. We noticed that the maximum power is 778.63 W reached at 12:45 and the power varies between 778 and 700 W between 11:54 and 17:00 and it began to decrease gradually to a small value over time until reaching 2.82 W at 20:11.

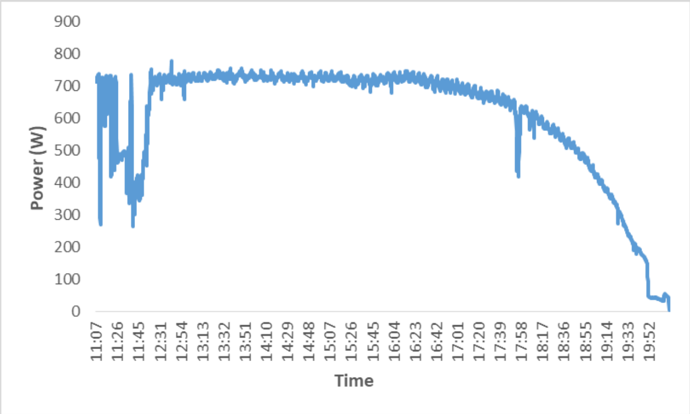

Figure 6. Power harvested using a sensor-based solar tracking system during the day of July 20, 2023

3.3. Comparison between the electrical production of the sun tracking system and a fixed system inclined to the south

3.3.1. Solar radiation measured on the sun tracking system

Figure 7 represents the solar radiation collected during the day on a plane that follows the path of the sun (tracking system). The x-axis represents time in hours, while the y-axis represents solar radiation intensity (W/m²). It is clear that the quantity of radiation is low during the morning; it varies between 110 W/m^2 and 400 W/m^2 because it was marked by unfavorable weather conditions, characterized by cloudy skies and persistent humidity. In the afternoon the irradiation is significant, it reaches 1000 W/m^2 at 1:30 p.m.

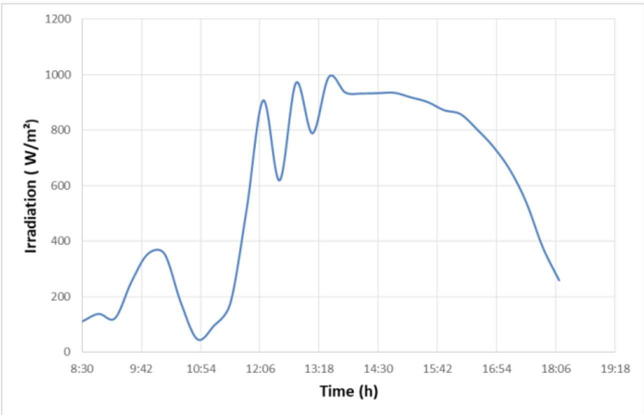

Figure 7. Solar irradiation on a plane, which follows the trajectory of the sun

3.3.2. Ambient temperature measured

Figure 8 shows the change in temperature throughout the day during our experiment. The x-axis represents time in hours and the y-axis represents temperature in degrees Celsius (°C). The temperature varies between a maximum value of 37.9 °C and a minimum value of 25.5 °C.

3.3.3. Comparison of the power produced by the solar tracking system and the fixed system inclined to the south

Figure 9 comparatively illustrates the energy production of the two systems, the solar tracker and the fixed system, during one day. The data is presented in the form of two superimposed curves: the blue curve represents the power generated by the solar tracker, while the green curve represents the production of the fixed system. During the morning, when solar radiation was low, both systems generated relatively low power, but the power provided by the tracking system was higher than that of the fixed system. This is likely due to unfavorable weather conditions, where the amount of sunlight reaching the solar panels was limited between 110 and 400 W/m².

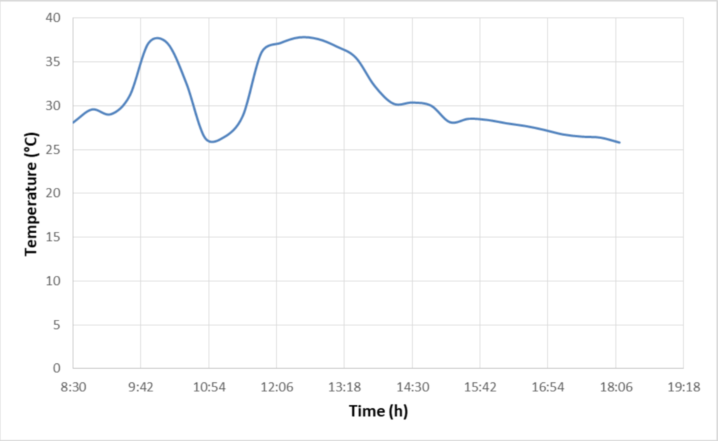

Figure 8. Ambient temperature measured during the day

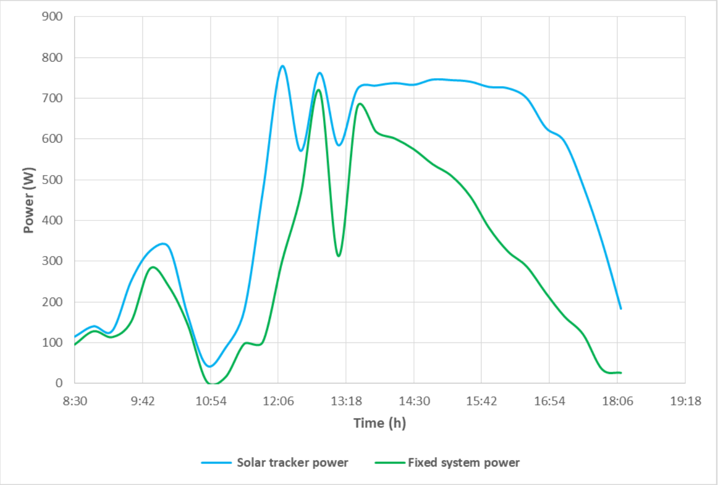

Figure 9. Comparison between PV module output powers in sensor-based tracking modes and fixed mode

Around noon, the power difference between the solar tracker and the fixed system decreases but we notice that the power of the tracker remains slightly higher due to its ability to better follow the exact trajectory of the sun, even when it is near the zenith. From 1:30 p.m. until 6 p.m., when the sky became clearer with better solar radiation, the difference in power generated between the two systems became remarkable. It is clearly observable that the solar tracker produces a considerably higher amount of energy than the fixed system.

The important observation is that the two-axis solar tracker generated more power than the fixed system during this period of the experiment. This suggests that the solar tracker was more efficient at tracking the sun's path and maximizing the absorption of sunlight, resulting in greater energy production. Percentage increase in power is calculated using the energy production for both fixed and tracking system and the following formula:

$$Percentage = ([E\_tracking - E\_fixed\,] \,/\, E\_fixed\,) \times 100 \qquad (1)$$

Figure 10 shows us the evolution of energy gain percentage as a function of time. We see that there are two peaks. The first is due to the cloud but the second is due to the inclination of the fixed panels. At noon, the energy difference between the tracking system and the fixed system is reduced.

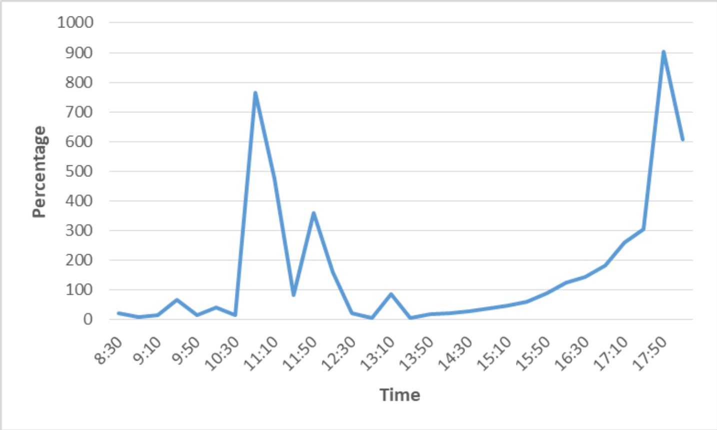

Figure 10. Percentage increase in power

In summary, even when there was low solar radiation due to unfavorable weather conditions, the two-axis solar tracker maintained superior performance compared to the fixed system. This finding highlights the solar tracker's ability to optimize solar energy capture, demonstrating its superior efficiency throughout the day. The solar tracker produced shows its effectiveness in following the trajectory of the sun from sunrise to sunset.

3.3.4. Calculation of consumption of electric actuators

Figure 11 presents an analysis of the consumption of the actuators during the operation of the solar tracker. The blue graph represents the consumption of the east-west actuator, while the red graph represents the consumption of the north-south actuator. It is important to note that the consumption of the actuators must be subtracted from the power generated by the solar tracker to obtain the net power available for electricity production. The total sum of the consumption of the two actuators, in watts, can be calculated by adding the values of the power consumed. In our case, the total sum of the power consumed by the actuators is 505.43 Watts.

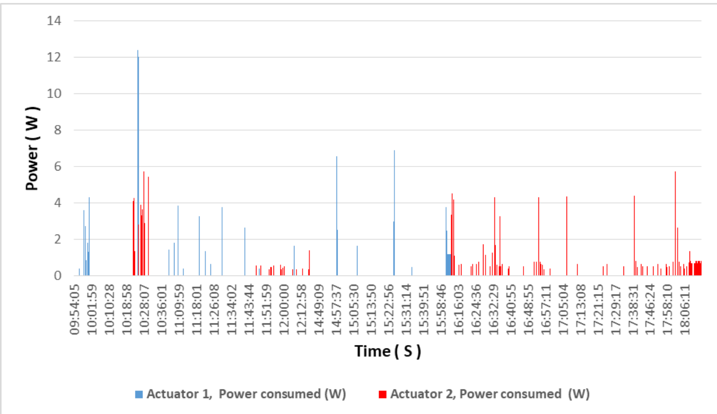

Figure 11. Power consumed by the tracking system actuators

$$E\_(tracking\ value\ pure) = E\_tracking - E\_(consumed\ by\ actuators) \tag{2}$$

$$Percentage = ([E\_(tracking\ value\ pure) - E\_fixed\ ] \ /\ E\_fixed\ ) \times 100 \tag{3}$$

$$Percentage = 60.64\% \tag{4}$$

In the Bou-Ismail study site in northern Algeria, the dual-axis solar tracking system can capture 60.64% more solar energy than a stably operating system. These results improve the performance of the tracking system compared to the previous results of [32], where the energy gain reaches 21.86% in summer. These results prove the accuracy of the two-axis solar tracking system implemented. Also, the decrease in ambient temperature compared to that of the Ghardaïa Sahara in Algeria [32] contributes to increasing the energy produced. In addition, the panels used are new and cleaned before the experiment. These findings encourage us to conduct the study in all seasons to test the system performance in windy and cloudy weather for a fair comparison.

4. CONCLUSION

A novel dual axis solar tracker with a data acquisition and control system is proposed. Bou-Ismaïl from Algeria is taken as a sample area where the solar tracker is placed. The analysis of the data collected during this experiment clearly demonstrates that the solar tracker outperforms the fixed system in terms of energy performance. The solar tracker generated higher solar power throughout the day, even after accounting for the actuator's power consumption required for accurate solar tracking.

This superior efficiency of the solar tracker makes it a particularly attractive option for applications where maximizing solar energy production is essential. Although the fixed system is oriented in the optimal direction, the proposed dual-axis solar tracking system outperforms it in terms of energy harvesting, contributing to more efficient use of solar energy and reduced energy costs. The proposed tracker increases the energy gain by 60.64% and can reduce the manufacturing price, complexity and power dissipation of the system. This system is highly recommended for use in photovoltaic power plants, agriculture, and water pumping to reduce the use of fossil fuels.

For further evaluation, the system will be tested in windy conditions to determine the actuator's power consumption when the wind direction is opposite that of the tracker. Further research and development will utilize artificial intelligence to improve system performance, particularly in adverse weather conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [initials, AB], upon reasonable request.

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