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Design, development and evaluation of electronic solar tracker: A sustainable energy generation

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ABSTRACT

Improving the efficiency of photovoltaic (PV) systems is essential for maximizing renewable energy generation, particularly in off-grid and small-scale applications where energy availability is limited. This study aimed to design, develop, and experimentally evaluate a low-cost Arduino-based electronic solar tracker capable of automatically orienting a photovoltaic panel toward the sun to enhance electrical energy production. An experimental research design was employed to fabricate the tracker using commercially available components, including an Arduino Uno microcontroller, light-dependent resistor (LDR) sensors, DC geared motors, and a dual-axis tracking mechanism. The performance of the developed system was compared with that of a fixed-mounted solar panel under identical environmental conditions from 06:00 AM to 06:00 PM. Hourly voltage, current, and power outputs were measured, and the data were analyzed using descriptive statistics and paired *t*-tests. The electronic solar tracker consistently outperformed the fixed-mounted system, producing higher average voltage (18.85 V vs. 17.15 V), current (1.50 A vs. 0.93 A), and power output (32.05 W vs. 16.69 W). Statistical analysis confirmed that these improvements were highly significant ($p < 0.001$) for all measured electrical parameters. The enhanced performance resulted from the continuous alignment of the photovoltaic panel with incident solar radiation, enabling more efficient solar energy harvesting. The findings demonstrate that the proposed electronic solar tracker is a technically feasible and cost-effective solution for improving photovoltaic performance and has considerable potential for application in off-grid, educational, and small-scale renewable energy systems.

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INTRODUCTION

The increasing global demand for electricity, coupled with concerns over climate change and the depletion of fossil fuel reserves, has accelerated the transition toward renewable energy technologies. Among the available renewable energy resources, solar energy has emerged as one of the most promising options because it is abundant, environmentally friendly, and widely accessible. Photovoltaic (PV) systems convert solar radiation directly into electricity without producing greenhouse gas emissions during operation, making them an important component of sustainable energy development. Nevertheless, the efficiency of photovoltaic systems remains strongly dependent on the intensity and angle of incident solar radiation, which vary continuously throughout the day and across seasons (Şen, 2004; Kalogirou, 2014).
Conventional fixed-mounted photovoltaic panels are installed at predetermined tilt and azimuth angles that represent a compromise between seasonal solar positions. Although this configuration offers structural simplicity and relatively low installation costs, it cannot maintain an optimal orientation to the sun throughout the day. Consequently, the angle of incidence between incoming solar radiation and the panel surface increases during morning and afternoon hours, reducing the amount of solar energy intercepted and lowering electrical output. These optical losses become particularly important in locations where maximizing energy production from limited photovoltaic capacity is essential (Mousazadeh *et al.*, 2009; Green, 2002).

Solar tracking technology has been developed to overcome this limitation by continuously orienting photovoltaic panels toward the sun, thereby maximizing incident solar irradiance and improving energy conversion efficiency. Depending on the tracking strategy, solar trackers may operate along a single axis or two orthogonal axes. Dual-axis tracking systems generally provide the highest energy yield because they continuously compensate for both the daily and seasonal apparent motion of the sun (Rubio *et al.*, 2007; Wang and Lu, 2013). Recent reviews have reported that appropriately designed tracking systems can substantially increase photovoltaic energy production compared with fixed-mounted installations, although the magnitude of improvement depends on geographic location, tracking accuracy, weather conditions, and system design (Mousazadeh *et al.*, 2009; International Energy Agency, 2024).

Advances in low-cost microcontrollers, embedded electronics, and sensor technologies have further enhanced the practicality of automatic solar tracking systems. Platforms such as the Arduino Uno enable the development of intelligent control systems capable of processing sensor signals and precisely positioning photovoltaic panels with relatively low hardware complexity and cost. These developments have expanded the potential application of solar trackers in off-grid electrification, rural energy systems, educational laboratories, and small-scale renewable energy installations, particularly in developing countries where reliable electricity access remains a challenge (Kalogirou, 2014; Alam *et al.*, 2010).

Despite considerable progress in solar tracking technology, several studies have primarily focused on tracker design, control algorithms, or simulation-based performance analysis, with relatively fewer investigations providing an integrated experimental evaluation that combines prototype development, electrical performance testing, and statistical validation under actual operating conditions. Furthermore, many existing studies emphasize energy yield while providing limited quantitative comparison of voltage, current, and power outputs throughout the complete daytime operating period. There is also a need for practical, low-cost tracking systems that can be fabricated using commercially available components while maintaining reliable performance and suitability for educational and small-scale renewable energy applications (Mousazadeh *et al.*, 2009; Wang and Lu, 2013).

Although previous studies have demonstrated the potential advantages of solar tracking systems, limited research has experimentally evaluated low-cost, Arduino-based dual-axis electronic solar trackers using commercially available components under real operating conditions while simultaneously comparing voltage, current, and power outputs with those of a conventional fixed-mounted photovoltaic panel through statistical analysis. Addressing this gap is important for determining whether an economically feasible tracking system can significantly improve photovoltaic performance and provide a practical solution for decentralized renewable energy generation.

Therefore, this study aimed to design, develop, and experimentally evaluate an Arduino-based electronic solar tracker for sustainable photovoltaic energy generation. Specifically, the study sought to: (i) design and fabricate a functional electronic solar tracker using commercially available components; (ii) compare the voltage, current, and power outputs of the electronic solar tracker with those of a fixed-mounted solar panel under identical operating conditions; (iii) determine whether the observed differences in electrical performance were statistically significant; and (iv) assess the operational feasibility of the developed system as a practical and sustainable renewable energy solution for off-grid and small-scale photovoltaic applications.

MATERIALS AND METHODS

Study design

This study employed an experimental research design to design, fabricate, and evaluate an electronic solar tracker intended to improve the energy conversion efficiency of a photovoltaic (PV) system. The experimental approach enabled direct comparison of the electrical performance of the developed electronic solar tracker with that of a conventional fixed-mounted solar panel under identical environmental conditions. The methodology comprised the design and construction of the tracking system, functional testing, electrical performance evaluation, and statistical analysis of the measured outputs. Similar experimental approaches have been widely adopted for evaluating photovoltaic tracking systems because they provide reliable assessment of device performance under real operating conditions (Mousazadeh *et al.*, 2009; Kalogirou, 2014).

Design and fabrication of the electronic solar tracker

The electronic solar tracker was designed as a self-powered dual-axis photovoltaic tracking system capable of automatically maintaining the solar panel perpendicular to incident sunlight throughout the day. The system consisted of a 30-W photovoltaic module, an Arduino Uno microcontroller, light-dependent resistor (LDR) sensors, comparator circuit, relay driver circuit, DC geared motor, voltage regulator, solar charge controller, deep-cycle battery, power inverter, electrical wiring, and supporting mechanical components (Table 1).

Table1. List of supplies and materials

Quantity	Unit	Component
2	Pieces	DC geared motor
1	Piece	Solar panel (30 Watts)
1	Piece	Arduino Uno
1	Piece	Comparator circuit
1	Piece	Relay driver circuit
1	Lengths	12 Volts to 5 volts regulator circuit
1	Piece	Solar charge controller (5Amperes)
1	Piece	Deep cycle battery
1	Piece	Power inverter 100 watts
10	Meters	Electrical wire (#18)
10	Meters	Shielded wire

The system architecture and operational workflow of the tracker is illustrated in Fig. 1–5. Four LDR sensors continuously monitored light intensity from different directions. Variations in sensor output were processed through the comparator circuit and transmitted to the Arduino Uno microcontroller, which executed the programmed control algorithm. The controller subsequently actuated the DC geared motors to rotate the solar panel until the sensors detected balanced illumination, indicating that the panel was oriented nearly perpendicular to the incoming solar radiation. To improve operational reliability, limit switches were incorporated to prevent excessive rotation and cable entanglement while allowing the tracker to return automatically to its default east-facing position at the end of the day.

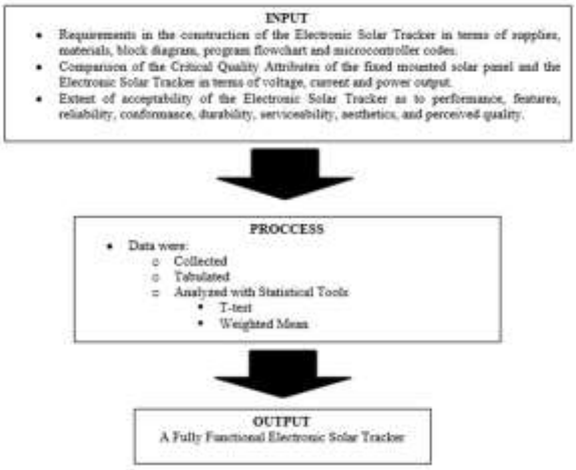

Fig. 1. Flow of the study

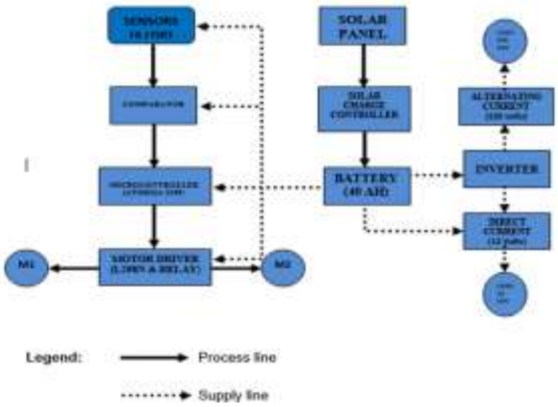

Fig. 2. Block diagram of the electronic solar tracker

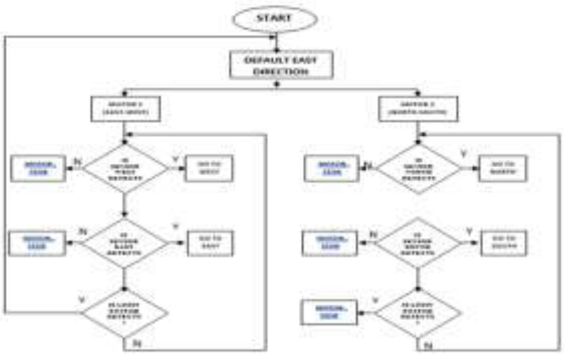

Fig. 3. Microcontroller program flowchart

Fig. 4. Arduino Uno

Fig. 5. The functional solar tracker

The photovoltaic module supplied electrical energy to a deep-cycle battery through a solar charge controller, which regulated battery charging and protected the system from overcharging. A power inverter enabled the stored direct current (DC) electricity to supply alternating current (AC) loads when required.

Experimental procedure

Performance evaluation was conducted by comparing the fabricated electronic solar tracker with a fixed-mounted photovoltaic panel of identical capacity. Both systems were tested under the same environmental conditions during daylight hours, from 06:00 AM to 06:00 PM, to minimize variations arising from weather and solar irradiance.

For the voltage test, the open-circuit voltage of each photovoltaic module was measured hourly using a calibrated digital voltmeter before connection to the solar charge controller. Output current was measured hourly using a DC ammeter connected in series between the photovoltaic module and the charge controller. Output power was subsequently calculated using the standard electrical relationship:

$$P = V \times I$$

Where P is power (W), V is voltage (V), and I is current (A).

Hourly measurements were recorded for both systems throughout the experimental period, and daily average values were calculated to facilitate comparison.

Statistical analysis

Descriptive statistics, including the mean, standard deviation (SD), and standard error (SE), were computed for voltage, current, and power outputs. A paired Student's *t*-test was performed using Minitab statistical software to determine whether significant differences existed between the electronic solar tracker and the fixed-mounted photovoltaic panel.

Statistical significance was evaluated at the 1% significance level ($\alpha = 0.01$). The null hypothesis stated that no significant difference existed between the two systems, whereas the alternative hypothesis proposed that the electronic solar tracker produced significantly different electrical outputs. Ninety-five percent confidence intervals (95% CI) for the mean differences were also calculated to quantify the magnitude and precision of the observed effects.

Ethical considerations

This investigation involved engineering equipment and performance testing without the participation of human or animal subjects. Therefore, institutional ethical approval and informed consent were not required.

RESULTS AND DISCUSSION

The electronic solar tracker was designed using commercially available electronic and mechanical components, including an Arduino Uno microcontroller, light-dependent resistor (LDR) sensors, comparator and relay driver circuits, a DC geared motor, a solar charge controller, and a 30-W photovoltaic module (Table 1). The system architecture and operational workflow are illustrated in Fig. 1-5, demonstrating the integration of the sensing, control, and actuation units for automatic sun tracking. The dual-axis tracking mechanism continuously adjusted the solar panel to maintain a near-perpendicular orientation to incoming solar radiation throughout the day, thereby maximizing solar energy capture. This design is consistent with previous studies reporting that microcontroller-based dual-axis tracking systems improve photovoltaic performance by maintaining optimal solar incidence angles (Mousazadeh *et al.*, 2009; Wang and Lu, 2013).

Table 2. Comparison of output voltage between fixed mounted solar panel and the electronic solar tracker

Hour	Fixed mounted Voltage output (in volts)	Electronic solar tracker-mounted Voltage output (in volts)
06:00AM	14.00	15.00
07:00AM	18.00	20.00
08:00AM	18.00	20.00
09:00AM	18.00	20.00
10:00AM	18.00	20.00
11:00AM	18.00	20.00
12:00PM	18.00	20.00
01:00PM	18.00	20.00
02:00PM	17.00	19.00
03:00PM	18.00	19.00
04:00PM	18.00	20.00
05:00PM	17.00	19.00
06:00PM	13.00	13.00
AVERAGE	17.15	18.85

The comparison of output voltage between the electronic solar tracker and the fixed-mounted solar panel is presented in Table 2. The electronic solar tracker consistently generated higher voltages during most daylight hours, with an average output of 18.85 V compared with 17.15 V for the fixed-mounted panel. The largest improvements were observed during the morning and afternoon periods, whereas both systems produced similar voltages at 6:00 PM when solar irradiance was minimal. These findings indicate that continuous solar alignment enhanced voltage generation by maintaining favorable incident angles. Similar improvements in photovoltaic voltage have been reported for solar tracking systems that minimize cosine losses associated with fixed installations (Mousazadeh *et al.*, 2009; Rubio *et al.*, 2007).

As shown in Table 3, the electronic solar tracker also produced substantially higher current than the fixed-mounted panel throughout the evaluation period. The average current increased from 0.93 A for the fixed system to 1.50 A for the tracking system, with the greatest differences occurring during peak solar radiation hours. Because photovoltaic current is strongly influenced by the amount of incident solar energy, the higher current output confirms that the tracking mechanism improved solar energy collection efficiency. These observations agree with previous research demonstrating that dual-axis tracking systems increase current generation by maintaining optimal exposure to sunlight throughout the day (Huang *et al.*, 1999; Mousazadeh *et al.*, 2009).

Table 3. Comparison of output current between fixed mounted solar panel and the electronic solar tracker

Hour	Fixed mounted Current output (in amperes)	Electronic solar tracker-mounted Current output (in amperes)
06:00AM	0.05	0.15
07:00AM	0.10	1.00
08:00AM	1.00	2.20
09:00AM	1.70	2.25
10:00AM	1.70	2.25
11:00AM	2.00	3.00
12:00PM	1.80	2.27
01:00PM	0.90	2.00
02:00PM	0.60	1.90
03:00PM	1.30	2.00
04:00PM	0.50	0.90
05:00PM	0.40	1.00
06:00PM	0.10	0.30
AVERAGE	0.93	1.50

The improvements in voltage and current translated directly into higher power production (Table 4). The electronic solar tracker achieved an average power output of 32.05 W, nearly double that of the fixed-mounted solar panel (16.69 W). Peak power output reached 60.00 W at 11:00 AM for the tracking system compared with 36.00 W for the fixed-mounted panel. This substantial increase demonstrates the effectiveness of continuously orienting the photovoltaic module toward the sun to maximize energy conversion. Similar gains have been widely documented in photovoltaic tracking studies, where dual-axis tracking significantly enhances daily energy yield compared with stationary systems (Mousazadeh *et al.*, 2009; Wang and Lu, 2013).

The statistical comparison further confirmed these performance improvements. As presented in Tables 5–7, paired t-tests revealed highly significant differences between the electronic solar tracker and the fixed-mounted solar panel for voltage (t = 9.68, p < 0.001), current (t = 6.67, P < 0.001), and power output (t = 6.82, p < 0.001). In all cases, the calculated t-values exceeded the critical value, indicating that the observed improvements were unlikely to have occurred by chance. These results provide strong statistical evidence that the tracking mechanism significantly enhanced photovoltaic performance under the experimental conditions. Similar statistically significant improvements have been reported in comparative evaluations of solar tracking technologies, supporting the effectiveness of active tracking systems for increasing photovoltaic energy production (Rubio *et al.*, 2007; Mousazadeh *et al.*, 2009).

Table 4. Comparison of output power between fixed mounted solar panel and the electronic solar tracker

Hour	Fixed mounted Power output (in watts)	Electronic solar tracker-mounted Power output (in watts)
06:00AM	0.70	2.25
07:00AM	1.80	20.00
08:00AM	18.00	44.00
09:00AM	30.60	45.00
10:00AM	30.60	45.00
11:00AM	36.00	60.00
12:00PM	32.40	45.40
01:00PM	16.20	40.00
02:00PM	10.20	36.10
03:00PM	23.40	38.00
04:00PM	9.00	18.00
05:00PM	6.80	19.00
06:00PM	1.30	3.90
AVERAGE	16.69	32.05

The operational performance of the completed prototype is illustrated in Fig. 5, which demonstrates the functionality of the fabricated electronic solar tracker under field conditions. The successful integration of the sensing, control, and mechanical tracking components enabled the system to operate automatically while maintaining continuous solar alignment. Combined with the significantly higher voltage, current, and power outputs, these results demonstrate that the developed electronic solar tracker is an effective and practical approach for improving photovoltaic energy harvesting. Such systems have considerable potential for off-grid renewable energy applications where maximizing energy production from limited photovoltaic capacity is essential.

Table 5. T for output voltage of electronic solar tracker and output voltage of fixed mounted

	N	Mean	StDev	SE Mean
Electronic solar tracker-V	13	18.846	2.230	0.619
Fixed-V	13	17.154	1.676	0.465
Difference	13	1.692	0.630	0.175

95% CI for mean difference: (1.311, 2.073)

T-Test of mean difference= 0 (vs not= 0): T-value= 9.68, *p*-value= 0.000

Table 6. T for output current of electronic solar tracker and output current of fixed mounted

	N	Mean	StDev	SE Mean
Electronic solar tracker -I	13	1.632	0.867	0.240
Fixed-I	13	0.935	0.705	0.195
Difference	13	0.698	0.377	0.105

95% CI for mean difference: (0.470, 0.926)

T-Test of mean difference= 0 (vs not= 0): T-value= 6.67, *p*-value= 0.000

Table 7. T for output power of electronic solar tracker and output power of fixed mounted

	N	Mean	StDev	SE Mean
Electronic Solar Tracker -P	13	32.05	17.67	4.90
Fixed-P	13	16.69	12.80	3.55
Difference	13	15.36	8.11	2.25

95% CI for mean difference: (10.45, 20.26)

T-Test of mean difference= 0 (vs not= 0): T-value= 6.82, *p*-value= 0.000

CONCLUSION

The present study successfully designed, fabricated, and experimentally evaluated an Arduino-based electronic solar tracker for sustainable photovoltaic energy generation. The developed system effectively integrated light-dependent resistor (LDR) sensors, a microcontroller-based control unit, and a dual-axis tracking mechanism to automatically orient the photovoltaic panel toward the direction of maximum solar irradiance throughout the day.

The experimental results demonstrated that the electronic solar tracker consistently outperformed the fixed-mounted solar panel in terms of electrical performance. Compared with the stationary system, the tracker produced higher average voltage (18.85 V vs. 17.15 V), current (1.50 A vs. 0.93 A), and power output (32.05 W vs. 16.69 W), indicating a substantial improvement in photovoltaic energy harvesting. Statistical analysis further confirmed that these improvements were highly significant ($p < 0.001$), providing strong evidence that continuous solar tracking significantly enhances the electrical performance of photovoltaic systems under the tested conditions.

The findings are consistent with established photovoltaic principles, whereby maintaining the solar panel close to a perpendicular angle relative to incident sunlight reduces optical losses and increases energy conversion efficiency. The successful operation of the prototype also demonstrates that a low-cost tracking system constructed from commercially available components can provide a practical and reliable solution for improving photovoltaic performance.

Overall, the developed electronic solar tracker represents a technically feasible and effective approach for increasing solar energy utilization in small-scale and off-grid photovoltaic applications. Its improved energy output combined with its relatively simple design and automated operation, highlights it's potential for deployment in educational institutions, rural electrification projects, and other decentralized renewable energy systems where maximizing photovoltaic efficiency is essential. Future studies should evaluate the long-term reliability, economic feasibility, and energy yield of the system under different climatic conditions and investigate the integration of advanced control strategies, higher-efficiency photovoltaic modules, and Maximum Power Point Tracking (MPPT) technology to further optimize overall system performance.

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