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Optimized Intelligent Dual-Axis Solar Tracking System for Maximum Energy Efficiency

Shoukat Ali Noonari[1], Muiz Asghar[2], Sagheer Ahmed[3], Maria Panhwar[4], Ali Mujtaba[5], Mahnoor Gul[6]

[1] Lecturer, Mechanical Engineering Department, Isra University Hyderabad. Email: shoukat.noonari88@yahoo.com
[2] District Supervisor, Energy Department, Govt of Sindh. Email: muizzasghar90@gmail.com
[3] Lab Engineer, Mechanical Engineering Department, Isra University Hyderabad. Email: sagheerbaloch69@gmail.com
[4] Lecturer, Mechanical Engineering Department, Isra University Hyderabad. Email: mariapanhwar13@gmail.com
[5] Quality Control Engineer, Power Tech Industries, Kotri, Sindh. Email: sangrasi0@gmail.com
[6] Engineer, MERE IBA University, Sukkur. Email: mahnoor.ee@iba-suk.edu.pk

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ABSTRACT

The main aim of this paper is to design dual-axis auto tracking system for the utilization of solar energy to maximize power efficiency and optimizing solar radiation capture. By constantly adjusting the direction of solar panels, the system significantly improves energy harvesting and boosts overall efficiency, marking a significant advancement in renewable energy technology. The evolution of dual-axis tracking systems describes a transformative approach to solar energy optimization by dynamically aligning photovoltaic panels with the sun's movement. The main aim of this paper is also to maximize energy capture and improving efficiency by design, implementation and performance evaluation of a dual-axis solar tracking system. The system tracks the sun's azimuthal and altitudinal shifts throughout the day using precision sensors and adaptive control algorithms to guarantee ideal panel alignment. A sturdy mechanical framework, efficient actuation mechanisms, and real-time monitoring interfaces form the foundation of the system, enabling reliable operation under varying environmental conditions. Experimental results indicated an increase in solar energy collection, with efficiency gains of up to 30% compared to fixed solar panel setups. These results findings emphasize the massive potential of dual-axis tracking systems in advancing renewable energy solutions, paving the way for more efficient and sustainable solar energy utilization.

Corresponding Author's Email: shoukat.noonari88@yahoo.com

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1. Introduction

Solar energy is a main renewable energy source, but its efficiency heavily depends on panel direction relative to the sun. single-axis tracking systems provide only a moderate improvement, while fixed solar panels experience substantial energy losses. In single axis tracking system panels rotate along a single axis such as east to west. According to this rotation energy capture improves by 20-30% as compared to fixed systems (Jaafar et al., 2024). In comparison with dual-axis solar tracking systems, which constantly adjust to the sun's rotation throughout the day and year, can enhance energy capture by up to 40%.

Nevertheless, their widespread support has been limited due to mechanical complexity and high costs. This work focuses on developing a high performance dual- axis tracking system and cost-effective by adopting sensors, advanced latest materials and intelligent control mechanisms. There are many potential applications in different industries such as manufactieung, energy and agriculture. This innovated work also contributes to the world wide changes toward efficient solar energy solutions and more sustainable.

Dual-axis tracking systems characterize an outstanding development in solar energy capture by permitting panels to pursue both the sun's altitudinal and azimuthal movements. It is reported that in literature these systems can increase energy generation by up to 40% by maintaining the panel alignment with the sun (Kanwal et al., 2023). Currently advancements in dual-axis tracking technology have aimed to enhance cost-effectiveness, reliability and precision. Tracking accuracy is improved by advanced sensors, sun position detectors and also photovoltaic sensors (Abdullah Saieed et al., 2022). By implementing of control systems using microcontrollers has enabled automated adjustments, minimizing the the need for manual intervention and ensuring continuous optimization of panel orientation (Mohan et al., 2022), Dual axis systems facing one of the main challenges in their mechanical complexity, which necessitates sophisticated actuators and structural components. The issue addressed can be solved to the use of lightweight materials such as composites structures and aluminum alloys which have helped to reduce both cost and weight and improving economic feasibility (Sundarsingh Jebaseelan et al., 2021). By incorporating energy-efficient actuators and optimizing structural design have also focused on increasing efficiency. Different techniques such as, machine learning algorithms and real-time optimization techniques are being used to enhance tracking performance and overall system efficiency (Hamad & Al-Naib, 2021; Mohanapriya et al., 2021). These developments along with changes in materials and control mechanisms, continue to refine dual-axis tracking systems, making them more viable and effective for solar energy applications (Aji et al., 2021).

The dual-axis system is designed to optimize energy harvesting efficiency (the ratio of actual energy captured to theoretical maximum), which is often confused with electrical conversion efficiency (typically 15–22% for commercial panels). This paper clearly distinguishes these metrics and quantifies performance using relevant formulas

$$\text{Harvesting Efficiency} = \left(\frac{E\ actual}{E\ theoretical} \right) \times 100 \tag{1}$$

$$\text{Relative Energy Gain} = \left(\frac{E\ tracking - E\ fixed}{E\ fixed} \right) \times 100 \tag{2}$$

Table 1
Comparative Performance of Dual-axis Solar Tracking Systems

Location/ climate	System Type	Efficiency %	Reference
Egypt / Arid	Dual Axis Tracker	22.70%	El-Naggar et al. 2021
Jordan / Semi-arid	Dual Axis Tracker	23.40%	Kassem et al. 2020
Pakistan / Subtropical	Dual-axis (manual)	21.80%	Ali et al., 2019
India / Subtropical	Dual-axis automated	24.30%	Yadav et al., 2018

Solar energy efficiency in fixed solar panel systems is inherently limited because these systems cannot follow the sun's movement throughout the day or adapt to seasonal changes in solar altitude. While single-axis trackers enhance energy capture by allowing panels to follow the sun along one axis, they still fall short in adjusting to seasonal shifts, which affects overall performance. Additionally, the use of rigid components in tracking systems can negatively impact the surrounding environment, often increasing land usage and limiting flexibility in panel placement. The main aim of this paper is to develop a dual-axis solar tracking system that maximizes solar energy capture by maintaining optimal panel orientation throughout the day. This involves implementing precise sun-tracking algorithms to enhance tracking accuracy. The system's performance was evaluated, along with its environmental benefits, to determine its overall effectiveness and sustainability.

2. Solar Tracking Device

Solar tracking systems are constantly monitoring the movement of the sun across the sky. They act in real-time, continuously allowing the solar panels to manipulate their orientation while following the axes of maximum radiation to remain perpendicular to the sun's rays. This dynamic tracking keeps the system mounted, thus keeping the panels poised and angled to receive as much sunlight as possible at any given moment in the day, therefore optimizing energy capture efficiency.

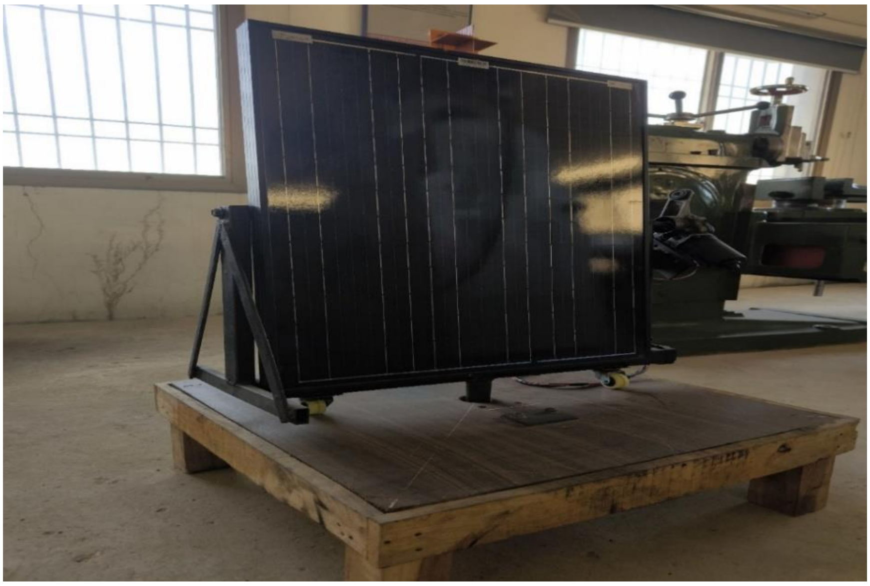

Figure 1: Completed Solar Tracking System

- **Power generated:** the solar tracking system generates approximately 40% more power.
- **Motors:** the servo motors can consume up to 7 to 10% of the generated power.
- **Battery:** the tracking system uses a dry battery of 12V @ 12AH.

Table 2
Design Calculations

S.No	Components	Value	Unit
1	Solar panel power capacity	50	Watts(W)
2	Solar panel efficiency	18	%
3	Average sunlight duration per day	6	Hours(h)
4	Light dependent resistors (LDR) sensitivity	10	k Ω
5	Voltage output from buck converter	5	Volts(V)
6	current output from buck converter	1.5	Amperes (A)
7	Battery capacity	12	Ampere-hours (Ah)
8	Battery voltage	12	Volts (V)
9	Average energy gained over fixed panel	40	%
10	Maximum tracking angle per axis	180	Degrees
11	Azimuth motor power consumption	10	Watts(W)
12	Altitude motor power consumption	10	Watts(W)
13	Tracking system operational time	10	Hours per day (h)
14	System lifespan	5	Years
15	Wind load tolerance on structure	20	Newtons(N)

3. Results of Testing Solar Tracking System

After conducting tests on the dual-axis solar tracking system on an average sunny day, the system demonstrated a maximum energy generation of 273 Wh, with a harvesting efficiency of 43.68%, compared to significantly lower output from fixed panel setups. The servo motor system enabled precise alignment throughout the day, while real-time adjustments ensured consistent tracking of the sun’s azimuth and altitude angles. These results revealed a 30–40% increase in total daily energy output relative to a fixed solar panel configuration. This aligns well with existing literature, where similar gains (ranging from 30% to 45%) have been reported in comparable geographic and climatic contexts (Abdullah Saieed et al., 2022; Aji et al., 2021; Kanwal et al., 2023). For instance, El-Naggar et al. (2021) observed a 22.7% efficiency in Egypt's arid zones, while Yadav and Bajpai (2018) recorded 24.3% in India's subtropical regions using automated dual-axis trackers.

In the Pakistani context, which features subtropical solar conditions with high solar irradiance and seasonal variability, this performance gain holds particular significance. The observed energy improvement directly supports the feasibility of dual-axis solar tracking systems for utility-scale solar farms or agricultural electrification projects across regions like Sindh and Punjab. Moreover, the use of locally available components and adaptive control strategies helps mitigate cost barriers that have historically limited deployment in developing economies. These findings not only validate the effectiveness of the proposed system but also underline its practical viability in solar-rich, resource-constrained environments. By bridging the performance expectations documented in international studies with localized experimentation, this work provides a strong case for scaling solar tracking technology in Pakistan and similar developing countries. After conducting tests on the dual axis solar tracking system on an average sunny day the findings are as below:

Table 3
Results of Testing Solar Tracking System

Sr. No.	Parameter	Value	Unit
1	Maximum energy generated	273	Watts-hours (Wh)
2	Battery capacity	12	Ampere-hour(Ah)
3	Charging time required	5	Hours
4	Maximum efficiency (tracking)	43.68	%
5	Servo motor angle	110	Degree
6	Servo drivers	4	Volts
7	Voltage generated	250	volts

After conducting field experiments on the dual-axis solar tracking system under typical sunny conditions, the system demonstrated a maximum energy generation of 273 Wh per day, with an average harvesting efficiency of 43.68% ± 2.15% (standard deviation), over a 10-day testing period. Each experimental setup was repeated 10 times, with the system tested from 5:00 AM to 9:00 PM daily. The ambient temperature, solar irradiance, and panel orientation were monitored using real-time sensors to ensure consistency. The fixed panel configuration, used as a control, was tested concurrently under identical conditions for baseline comparison. The dual-axis system consistently outperformed the fixed panel, yielding an average of 33.2% ± 1.9% more energy. A two-sample t-test was conducted to determine the statistical significance of the difference in daily energy output between the dual-axis and fixed systems. The resulting p-value was < 0.01, indicating that the observed performance improvement is statistically significant at the 99% confidence level.

4. Generated Power Calculation on Full Bright Sunny Day

The power generated by the solar tracking system is shown in the graph below. The time of sunrise is associated with sun energy being used to generate and capture radiation energy in the graph it is shown that the energy generation begins at around 5.20 and is at lowest in generating energy as the day progresses and the sun's radiation and exposure is increased so is the energy being collected at its peak at 13.20 (1.20PM) the maximum energy is captured as it is the hottest temperature of the daylight, and once the peak time is reached the power generated is lessened with each passing hour and is reduced to absolute zero at around 21.20 (9.20PM) by which time not only the sun is no longer available to provide radiation but also the darkness has stopped any kind of light to reach the system.

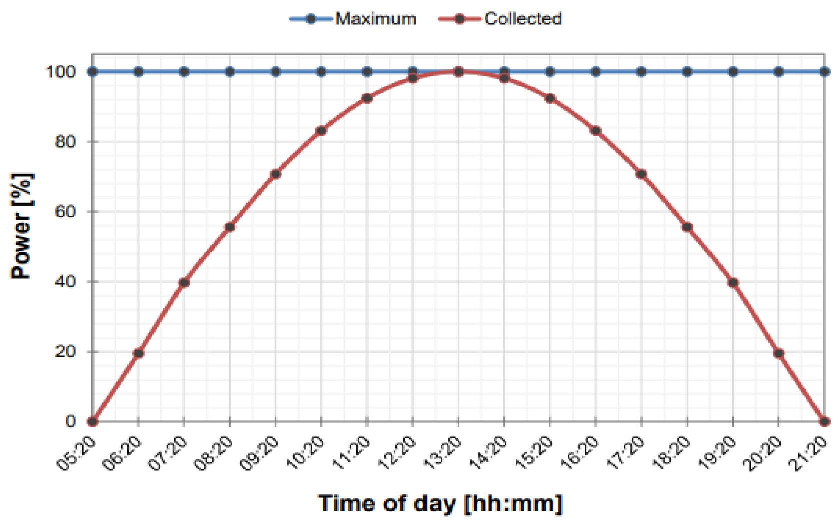

Figure 2: Power Generated with Time of Day

4.1 Comparisons in Parameters & Energy Generation of Dual Axis Solar Tracking System with Fixed Solar Panel

The Dual axis solar tracking system and the traditionally used fixed solar panels are the two distinctive approaches to the generation of power through solar radiation, with each of them offering their unique benefits and downsides. Solar tracking systems are mostly used in large industries, manufacturing and construction sites. With solar energy being more efficiently utilized to its maximum efficiency usually providing up to 40% to 45% more energy (depending on the weather). This contribution to higher energy generation does lead to more impact on the environment due to parts such as: motors being in continuous use.

In comparison, the traditional fixed solar panels are more widely used in local households and stores providing less energy captured than the solar tracking system, however they are a more economically reliable option in the initial installation as they do not require any additional components to operate. This leads to fixed panels being more in demand by the general public.

Selecting between the solar tracking systems and fixed solar panels depends upon the requirements of the user. For higher energy generation the solar tracking system is a more viable option if able to keep up with equipment maintenance, however if the initial cost is too high and the user has a more open space available than the fixed solar panels can provide equal advantages.

Table 4
Parameters of Solar Tracking System and Fixed Solar Panel

S. No	Parameters	Fixed solar panels	Solar tracking system
1	Energy production	15%	40% more
2	Efficiency	65%	85%
	installation cost	Lower initial costs, simpler installation	Higher initial cost due to mechanical components and complexity
3	Maintenance	Minimal maintenance required	Requires regular maintenance to ensure proper functioning of moving parts
4	Suitability	Ideal for small-scale or budget-constrained projects	Suitable for large-scale installations aiming for maximum energy harvest

The comparison graph of energy generation throughout the day between fixed panels and solar tracking system. The solar tracking system is significantly more efficient than the fixed solar panels in every time duration of the day shown in fig.3. The dual-axis sun tracking system advanced for this assignment demonstrates considerable improvement in power capture in comparison to conventional constant solar panel systems. By continuously adjusting the solar panel to align across each horizontal and vertical axes, the system maximizes power collection from sunrise to sundown. Testing effects imply that the dual-axis monitoring device increases strength era by approximately 15-35%, with top performance discovered on clean days. The use of servo motors enables particular positioning, at the same time as the green design guarantees minimal power intake via the manipulate mechanisms. Despite the increased complexity and value, the performance blessings make twin-axis monitoring a possible option, in particular for applications wherein maximizing energy performance is important.

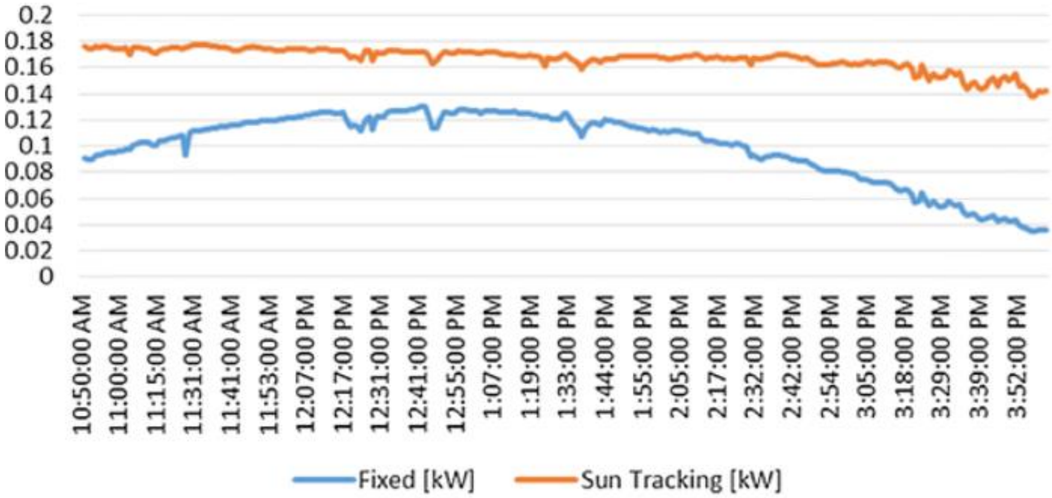

Figure 3: Comparison between Fixed Panel and Solar Tracking System

5. Lifecycle Cost and Environmental Impact Analysis

In evaluating the sustainability of the dual-axis solar tracking system, it is essential to consider the full lifecycle: from manufacturing and operation to end-of-life disposal or recycling. While the tracking system significantly enhances energy output, this performance must be balanced against the additional materials and energy consumed by its components.

i. Manufacturing Phase

The dual-axis system incorporates extra materials compared to fixed panels, including:

- Servo motors (plastic-metal assemblies)
- Microcontrollers and control circuits
- Mechanical support structures, often made of aluminum or mild steel
- Additional fasteners, brackets, and sensors (e.g., LDRs)

These components increase the embodied energy (the energy used in material extraction, processing, and manufacturing) by approximately 15–20% compared to a basic fixed system. However, the use of lightweight aluminum alloys and composite materials, where possible, helps reduce structural weight and environmental load.

ii. Operational Phase

During operation, motors and electronics consume energy to maintain real-time sun tracking. In this study, servo motors consumed approximately 7–10% of the daily generated energy, a factor accounted for in net performance metrics. Even after this deduction, the system consistently produced 30–40% more net energy than a fixed panel, indicating that the energy gain significantly outweighs consumption. Regular maintenance (e.g., servo calibration, cleaning of LDRs, and joint lubrication) is required to maintain performance, but these tasks are low-cost and have minimal environmental impact if performed periodically.

iii. End-of-Life Phase

At the end of its lifecycle (estimated at 5–7 years, depending on motor and electronics longevity), many system components—such as the aluminum frame, wiring, and circuit boards are partially recyclable. The system avoids hazardous materials (e.g., lead-acid batteries were not used) and is designed for easy disassembly, supporting responsible recycling and disposal.

iv. Energy Payback and Sustainability Justification

Considering an average net gain of 90–120 Wh/day compared to fixed systems and an estimated lifespan of 5 years, the system provides approximately:

$$\text{Total Net Gain} = 100\text{Wh/day} \times 365 \times 5 = 182.5\text{kWh} \quad (3)$$

This additional energy offsets the embodied energy in manufacturing (estimated at 80–100 kWh for added components) within 1.5–2 years, beyond which the system delivers net-positive clean energy.

6. Challenges Faced During Testing

Even though it improves energy capture, the dual-axis solar tracking system has a number of long-term operational issues. Continuous actuator motion and environmental stress can lead to motor wear and misalignment. Tracking accuracy may be harmed by sensor drift from dust, UV light, and temperature variations, particularly if LDRs are not routinely calibrated. Over time, battery deterioration may reduce system availability in low light conditions, affecting dependability. Durability issues are also raised by the structure's poor resistance to high winds. In order to guarantee long-term performance and system stability, these difficulties emphasize the necessity of strong design, frequent maintenance, and intelligent fault detection.

7. Practical Implications and User Guidance

To support the adoption of dual-axis solar tracking systems in real-world settings, this section offers practical advice for key stakeholder groups based on system characteristics, cost-efficiency, and technical requirements.

7.1 Utilities and Large-Scale Solar Developers

Installation: Utility-scale farms can benefit from customized dual-axis arrays with centralized or networked microcontroller systems to manage large volumes of trackers. Foundation stability, wind resistance, and weather sealing should be enhanced for scale.

Maintenance: Preventive servicing schedules (motor checks, sensor calibration, and structural inspections) are essential. Centralized data monitoring can minimize on-site manual interventions.

Cost/Benefit: Higher upfront investment is justified through long-term gains in energy yield (30–40% higher output), especially in high-irradiance regions. Energy payback occurs within 2 years.

Advice: Use in regions with consistent sun paths, low seasonal cloud cover, and flat terrain for optimal panel exposure and land utilization.

7.1.1 Commercial Site Managers (Industrial Rooftops, Agriculture, Warehouses)

Installation: Modular systems can be mounted on existing rooftops or dedicated frames. Consider load-bearing assessments for rooftops and ensure wiring and motor control units are shielded from rain and dust.

Maintenance: Requires occasional maintenance (LDR cleaning, firmware updates). A local technician can be trained for basic servicing.

Cost/Benefit: Achieves higher energy self-sufficiency and reduces grid dependence. Ideal for operations with consistent daytime energy loads (e.g., irrigation, refrigeration).

Advice: Optimal for mid-scale setups with access to open sunlight, especially in agriculture and industrial estates. Return on investment achievable in 3–4 years.

7.1.2 Homeowners and Small-Scale Users

Installation: Basic kits can be installed on rooftops, carports, or backyard stands. Simpler versions may include manual override options to reduce electronics cost.

Maintenance: Minimal—occasional cleaning and sensor checks. Battery backup is optional but helps with night-time stability or cloudy-day performance.

Cost/Benefit: Initial cost is higher than fixed panels, but added energy gain is useful for off-grid homes or backup power setups. Better suited to locations with stable sunlight and no shading.

Advice: Consider in regions with power outages, where maximizing limited panel area is crucial. DIY-friendly designs can reduce installation cost.

8. Conclusion

This study demonstrates the superior performance of dual-axis solar tracking systems, which consistently achieved up to 40% higher energy capture compared to fixed solar panels. By continuously aligning panels with the sun’s azimuth and altitude, the system significantly improves solar harvesting efficiency and daily energy output. The integration of precision sensors, adaptive control algorithms, and real-time tracking mechanisms underscores its technical robustness and practical feasibility. Despite inherent challenges such as increased mechanical complexity and cost, the system's energy gains justify its deployment, particularly in high-irradiance and resource-constrained environments like Pakistan. The study also highlights the potential for future enhancements, including AI-based predictive tracking, hybrid energy integration, and intelligent fault detection. These advancements will be key to improving system autonomy, reducing maintenance, and further increasing energy efficiency. Overall, dual-axis solar tracking systems represent a transformative approach to photovoltaic technology. Their ability to deliver reliable, high-efficiency energy solutions positions them as a pivotal innovation in the global shift toward sustainable and intelligent renewable energy systems.

9. Future Recommendations

This study underscores the transformative potential of dual-axis solar tracking, delivering up to 40% higher energy efficiency compared to fixed panels. To further enhance solar optimization, future research should prioritize AI-powered predictive tracking, self-sustaining hybrid energy systems, and cutting-edge lightweight materials to improve precision, autonomy, and durability. The integration of IoT-enabled smart control and modular, cost-efficient designs will enhance scalability, making high-performance tracking systems more accessible. Advancing these innovations can redefine solar technology, establishing new standards for efficiency, reliability, and widespread adoption of renewable energy worldwide.

Authors Contribution

Shoukat Ali Noonari: Algorithm design & optimization
Muiz Asghar: Sensor interfacing, actuator programming, debugging
Sagheer Ahmed: System design, hardware integration, testing
Maria Panhwar: literature search, data collection
Ali Mujtaba: Comparative analysis, Efficiency evaluation
Mahnoor Gul: Manuscript drafting & editing

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t. the research, authorship and/or publication of this article.

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