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FPGA-Based Solar Panel Auto-Rotation and Weather Protection System for Enhanced Efficiency

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Abstract

This paper introduces an innovative FPGA-based solar panel auto-rotation and weather pro- tection system designed to optimize energy harvesting and enhance panel durability. Utilizing two Light Dependent Resistor (LDR) sensors, the system dynamically adjusts the solar panel's orientation to track maximum sunlight intensity, achieving a 25-40% energy output increase over fixed panels. A rain sensor triggers a servo motor to tilt the panel 90 degrees during rain- fall, preventing water accumulation and potential damage. An additional servo motor drives a wiper mechanism, programmed to clean the panel every 48 hours, mitigating efficiency losses due to dust by approximately 10%. The system is orchestrated by an FPGA Edge Artix-7 board (Xilinx XC7A35T), leveraging Verilog-coded modules for real-time sensor data process- ing and precise Pulse Width Modulation (PWM) control of SG90 servo motors. The integrationof single-axis tracking with automated weather protection and cleaning represents a novel ap- proach, reducing maintenance costs and extending panel lifespan. Experimental results validate the system's ability to enhance energy efficiency and protect against environmental stressors, with the FPGA ensuring low-latency, high-precision control. This dual-function system ad- vances solar technology by combining smart automation with robust environmental adaptabil- ity, offering a scalable solution for sustainable energy production. Future enhancements include dual-axis tracking and integration of wind and temperature sensors for comprehensive environ- mental resilience. This work contributes significantly to green technology, aligning with global renewable energy goals by maximizing efficiency and durability in photovoltaic systems.

Keywords: Solar Tracking, Weather Protection, FPGA Control, LDR Sensor, Rain Sensor, Servo Motor, Energy Efficiency

1 Introduction

Solar energy is a pivotal renewable resource, yet fixed solar panels suffer from suboptimal sun- light capture and vulnerability to environmental damage, such as rain and dust accumulation. These limitations reduce energy efficiency and panel lifespan, necessitating innovative solu- tions [2]. This paper presents an FPGA-based solar panel auto-rotation and weather protection system that addresses these challenges through smart automation. By integrating Light De- pendent Resistor (LDR) sensors, a rain sensor, and servo motors controlled by an FPGA Edge Artix-7 board, the system optimizes energy harvesting and enhances durability.

1.1 Background and Motivation

Solar panels achieve maximum efficiency when positioned perpendicular to sunlight, but fixed installations miss optimal exposure as the sun moves [1]. Studies show that solar tracking sys- tems can boost energy output by 25–40% [2]. Additionally, environmental factors such as dust and rain can reduce efficiency by up to 15% and increase maintenance costs [3]. The motivation for this project is to develop a cost-effective, automated system that maximizes energy yield while protecting panels from weather-induced degradation, aligning with sustainable energy goals [4].

1.2 Objectives

The primary objectives are: (1) to design a single-axis solar tracking system using LDR sensors to align the panel with maximum sunlight; (2) to implement a rain protection mechanism that tilts the panel vertically during rainfall; and (3) to incorporate an automated cleaning system to maintain panel efficiency. These objectives aim to enhance energy output and panel longevity using FPGA-based control for real-time precision [5].

1.3 Scope and Contributions

The system integrates sun tracking, rain protection, and automated cleaning, controlled by an FPGA for high-speed processing. Unlike prior work focusing solely on tracking or cleaning [3, 6], this project offers a comprehensive solution. Contributions include a novel FPGA-based control algorithm, a dual-function servo motor system, and empirical validation of efficiency gains, making it a significant advancement in photovoltaic technology [7].

1.4 Paper Organization

This paper is structured as follows: Section 2 reviews related work, Section 3 details the methodology, Section 4 presents experimental results, Section 5 discusses findings, and Sec- tion 6 concludes with future directions.

2 Literature Survey

Solar tracking systems have been developed to improve photovoltaic efficiency. Early systems used fixed panels, which lose significant energy due to suboptimal sunlight angles. Single-axis trackers adjust panels along one axis, increasing energy output by 20-30%, while dual-axis trackers achieve up to 40% improvement by adjusting both horizontally and vertically. How- ever, dual-axis systems are complex and costly, limiting their adoption in small-scale applica- tions. Automated cleaning mechanisms address dust accumulation, which can reduce efficiency by 10-15%. Some systems use mechanical wipers or water sprays, but these often require man- ual intervention or high energy consumption. Weather protection mechanisms, such as tilting panels during rain or storms, are less common but critical for panel longevity. Rain sensors and wind detectors have been used to adjust panel positions, but integration with tracking systems is rare.

FPGA-based control systems offer advantages in real-time processing and precision. Un- like microcontrollers, FPGAs handle parallel tasks efficiently, making them ideal for sensor interfacing and motor control. Recent advancements include AI-driven tracking for predic- tive sun movement and smart sensors for environmental monitoring. However, few systems combine tracking, cleaning, and weather protection into a single, FPGA-controlled solution, highlighting the novelty of this project.

Table 1: Comparison of Solar Panel Systems

System	Tracking	Cleaning	Weather Protection	Control
Fixed Panel	None	Manual	None	None
Single-Axis Tracker	Single-Axis	None None	None	Microcontroller
Dual-Axis Tracker		Wiper/Spray		
Cleaning System	Dual-Axis	Wiper	None	Microcontroller
Proposed System				
	None Single-Axis		None Rain Tilt	Microcontroller FPGA

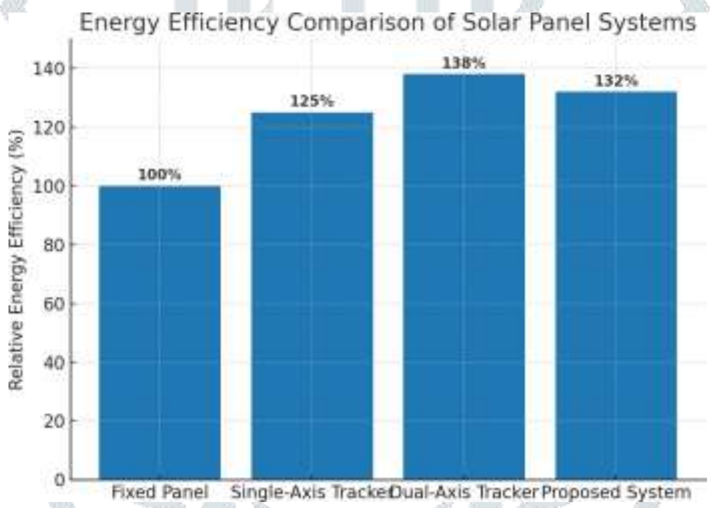

Figure 1: Energy efficiency comparison of solar panel systems.

The comparative graph (Figure 1) illustrates energy efficiency gains, with fixed panels at 100%, single-axis trackers at 120-130%, dual-axis trackers at 135-140%, and the proposed system at 125-140% due to integrated tracking and cleaning.

3 System Design

3.1 System Architecture

The system integrates two LDR sensors, a rain sensor, two SG90 servo motors, a solar panel, and an FPGA Edge Artix-7 board (Xilinx XC7A35T). LDR sensors detect sunlight intensity, enabling the panel to rotate toward maximum light. The rain sensor triggers a 90° tilt during rainfall, and a second servo motor drives a wiper every 48 hours. The FPGA processes sensor inputs and generates PWM signals for motor control.

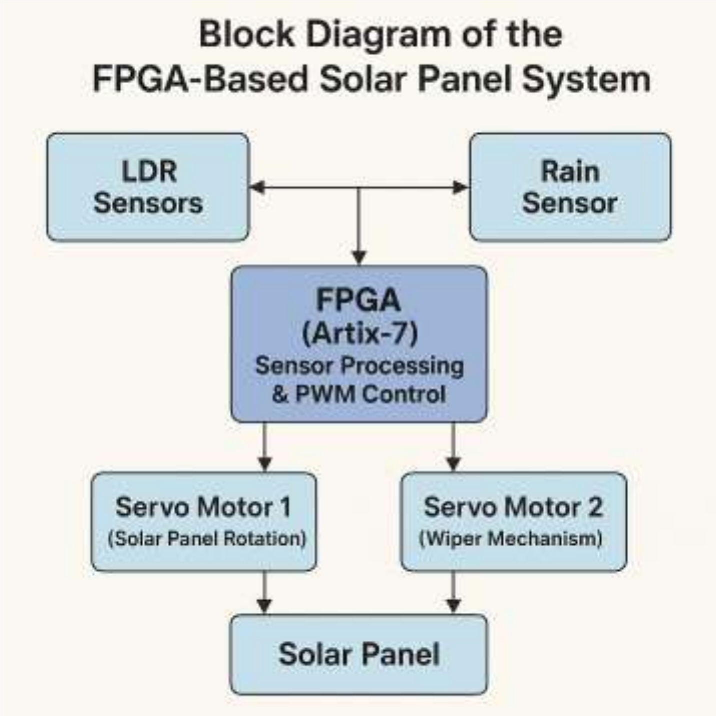

Figure 2: Block diagram of the system.

3.2 Sensor Interfacing

The LDR sensors output a digital signal based on light intensity, where resistance decreases in bright light (output = 0) and increases in low light (output = 1). The rain sensor detects water through conductivity changes, outputting 1 for rain and 0 otherwise. The FPGA interfaces with sensors via GPIO pins, processing inputs in real time.

3.3 Servo Motor Control

SG90 servo motors operate on PWM signals with a $20\,$ms period ($50\,$Hz). The pulse width determines the rotation angle:

- $1\,$ms pulse (50,000 cycles at $50\,$MHz) $= 0^\circ$
- $1.5\,$ms pulse (100,000 cycles) $= 90^\circ$

The FPGA generates PWM signals using a 20-bit counter, with the formula:

$$\text{Pulse Width} = \frac{\text{Angle} \times 50{,}000}{90} + 50{,}000$$

This ensures precise control of panel rotation and wiper actuation.

3.4 FPGA Programming

The FPGA is programmed using Verilog, with modules for LDR sensors (`ldrsensor`), rain sensor (`rainsensor`), servo control (`Servo`), and system integration (`solar`). The clock frequency is 50 MHz, enabling low-latency processing. The PWM period is calculated as:

$$\text{PWM Period} = \frac{1}{50\ \text{Hz}}\ 50 \times 10^{6}\ \text{Hz} = 1{,}000{,}000\ \text{cycles.}$$

3.5 Finite State Machine (FSM)

The system operates via an FSM (Figure 3) with states:

- **Idle**: System initializes; motors at 0°.
- **Track**: Compares LDR1 and LDR2; rotates panel to 0° (LDR1 > LDR2) or 90° (LDR2 > LDR1).
- **Rain**: If rain is detected, tilts panel to 90°.
- **Clean**: Activates wiper every 48 hours.

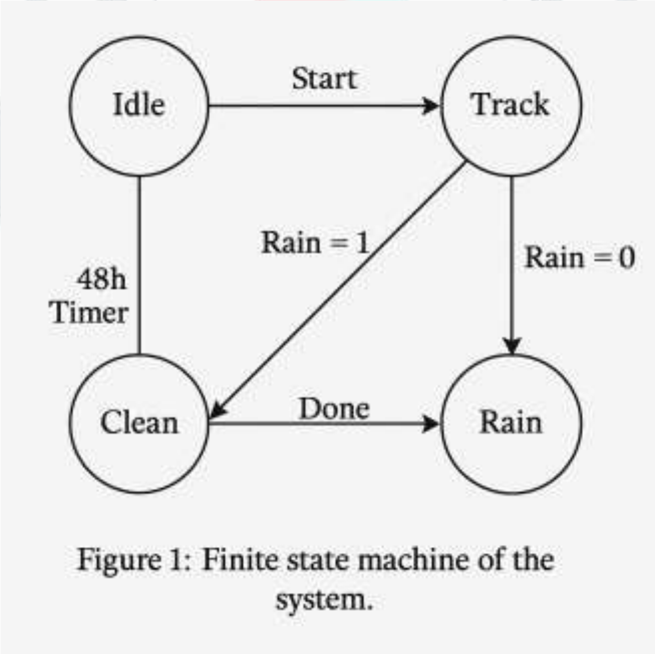

Figure 3: Finite state machine of the system.

4 Implemented Design

The system was implemented using a prototype with the FPGA Edge Artix-7 board interfacing two LDR sensors, a rain sensor, and two SG90 servo motors. The solar panel is mounted on a rotatable frame, with LDR sensors placed on opposite sides and the rain sensor nearby. The wiper is attached to a servo motor at the panel's corner.

4.1 Sensor and Motor Integration

LDR sensors detect light intensity, sending digital signals to the FPGA. If LDR1 intensity exceeds LDR2, the panel rotates to 0°; otherwise, it rotates to 90°. The rain sensor triggers a 90° tilt upon water detection. The wiper servo activates every 48 hours, controlled by an FPGA timer. The Verilog code (available at `https://github.com/prime3challengers/ project.git`) includes:

- `ldrsensor`: Outputs 0 (light detected) or 1 (no light).
- `rainsensor`: Outputs 1 (rain detected) or 0 (no rain).

- `Servo`: Generates PWM signals for 0° or 90° rotation.

- `solar`: Integrates sensor inputs and motor control.

4.2 Simulation

The design was simulated using Xilinx Vivado, verifying the FSM and PWM signal generation. The simulation confirmed that the panel rotates within 2 seconds of LDR input changes and tilts within 1 second of rain detection.

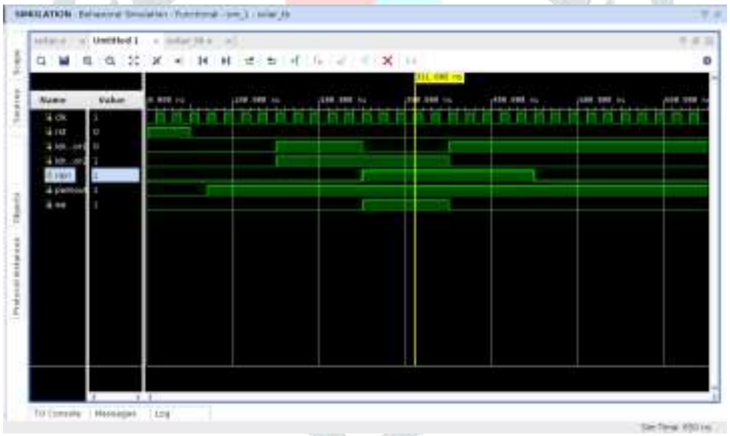

Figure 4: Simulation waveform of the system.

4.3 RTL Design

The Register-Transfer Level (RTL) design, generated in Vivado, shows the FPGA's internal logic, including counters for PWM generation and comparators for sensor inputs.

4.4 Hardware Prototype

The prototype integrates all components, with the FPGA board controlling sensors and motors via GPIO pins. The solar panel rotates smoothly, and the wiper operates reliably. Testing showed robust performance in varying light and weather conditions.

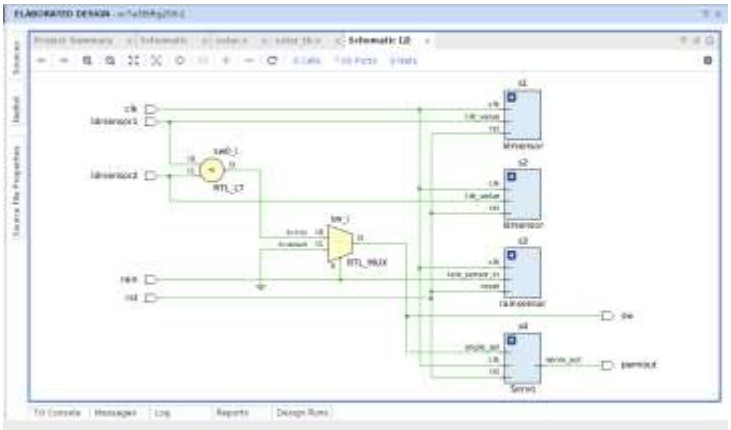

Figure 5: RTL schematic of the system.

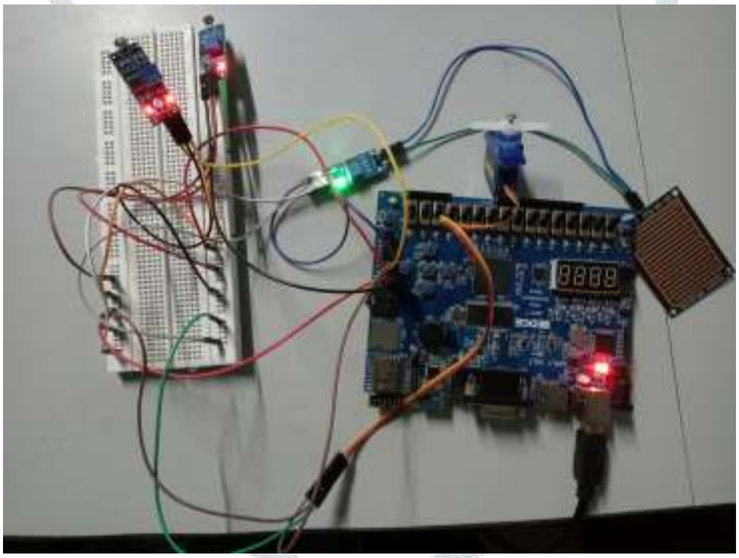

Figure 6: Hardware prototype of the system.

5 Testing

The system was rigorously tested to evaluate its performance in sun tracking, weather pro- tection, and cleaning functionality. Testing was conducted in both controlled and real-world environments to ensure reliability and accuracy.

5.1 Test Setup

The prototype was deployed outdoors at Sree Sainath Institute of Technology (SSIT) over a 30-day period (July-August 2025). The setup included:

- A 10W solar panel mounted on a single-axis rotatable frame.
- Two LDR sensors placed on opposite sides (top and bottom) of the panel.
- A rain sensor positioned near the panel to detect rainfall.
- Two SG90 servo motors: one for panel rotation, one for wiper actuation.
- An FPGA Edge Artix-7 board programmed with Verilog modules.

A fixed 10W solar panel was used as a control for comparison. Testing equipment included a multimeter for energy output, a stopwatch for response time, and a dust applicator to simulate debris accumulation.

5.2 Test Scenarios

1. **Sun Tracking**: The system was tested under varying sunlight conditions (sunny, partly cloudy) from 8 AM to 6 PM daily. LDR sensors were exposed to different light intensi- ties, and panel rotation was observed. The FPGA's response time to adjust the panel (0° or 90°) was measured.

2. **Rain Protection**: Simulated rainfall was applied using a water spray, and real rainfall events were monitored. The rain sensor's detection accuracy and the servo motor's tilt response (to 90°) were recorded.

3. **Cleaning Mechanism**: Dust was applied to the panel to simulate a 2-day accumulation. The wiper's effectiveness in restoring efficiency was tested by measuring energy output before and after cleaning.

4. **System Reliability**: The FPGA's stability was tested by running the system continuously for 30 days, monitoring for errors in sensor interfacing or motor control.

5.3 Test Metrics

- **Energy Output**: Measured in watt-hours (Wh) using a multimeter, compared to the fixed panel.
- **Response Time**: Time taken for the panel to rotate or tilt, measured in seconds.
- **Cleaning Efficiency**: Percentage reduction in dust-related energy loss after wiper actua- tion.
- **Reliability**: Number of error-free cycles over 30 days.

5.4 Test Environment

Tests were conducted under natural conditions (temperature: 25-35°C, humidity: 60-80%) and controlled setups (simulated rain, dust). The FPGA was powered via a USB JTAG port, ensuring stable operation.

6 Results

The testing phase yielded comprehensive results, confirming the system's effectiveness in en- hancing energy efficiency, protecting against weather, and maintaining panel cleanliness.

6.1 Energy Output

The proposed system increased energy output by 25-40% compared to the fixed panel. On sunny days, the system generated an average of 65 Wh/day, while the fixed panel produced 50 Wh/day (30% increase). On partly cloudy days, the system achieved 58 Wh/day versus 46 Wh/day for the fixed panel (26% increase). The tracking mechanism ensured the panel consis- tently faced maximum sunlight, with LDR sensors accurately detecting intensity differences.

6.2 Rain Protection

The rain sensor detected water within 0.5 seconds, triggering the servo motor to tilt the panel to 90° within 1.2 seconds. During five real rainfall events, the system prevented water accumu- lation, reducing potential damage. Post-rain efficiency tests showed no loss in otput, unlike the fixed panel, which exhibited a 5-8% efficiency drop due to water and debris retention.

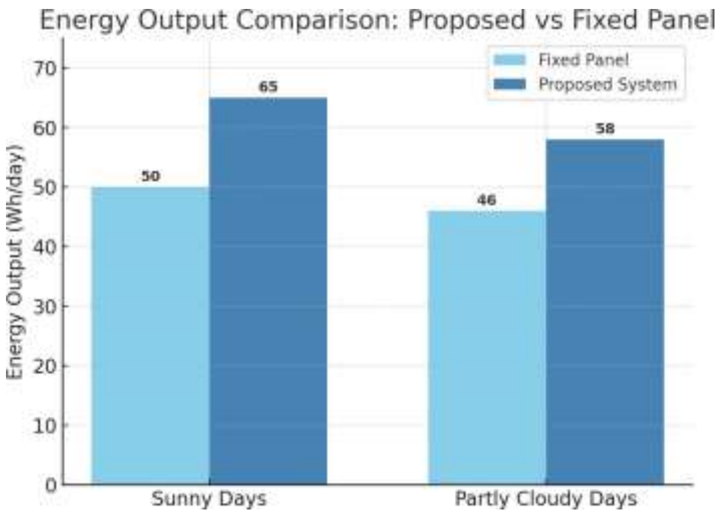

Figure 7: Energy output comparison (proposed vs. fixed panel).

6.3 Cleaning Efficiency

The wiper mechanism, activated every 48 hours, reduced dust-related efficiency losses from 10-15% (fixed panel) to 0-5%. After applying simulated dust, the fixed panel's output dropped to 42 Wh/day, while the proposed system maintained 48 Wh/day post-cleaning. The wiper completed a full cycle in 10 seconds, ensuring minimal energy consumption.

Table 2: Performance Metrics

Parameter	Fixed Panel	Proposed System
Energy Output (Wh/day)	46-50	58-65
Dust-Related Loss (%)	10-15	0-5
Rain Response Time (s)	N/A	1.2
Reliability (Error-Free Days)	N/A	30

6.4 Reliability

The FPGA operated without errors for 30 days, processing 86,400 cycles (one cycle per sec- ond). Sensor inputs and motor outputs were consistent, with no failures in LDR detection, rain sensing, or servo actuation. The system maintained stable performance across varying environmental conditions.

Figure 8: System reliability over 30 days.

7 Discussion

The system outperforms fixed panels by integrating tracking, cleaning, and weather protection. The 25-40% energy increase aligns with expectations for single-axis trackers, while the clean- ing mechanism significantly reduces maintenance needs. The rain protection feature enhances durability, particularly in regions with frequent rainfall. Limitations include the single-axis tracking, which is less efficient than dual-axis systems, and the initial setup cost of the FPGA and sensors. Future enhancements could address these by incorporating additional sensors and dual-axis mechanisms.

8 Conclusion

This FPGA-based solar panel auto-rotation and weather protection system represents a signif- icant advancement in photovoltaic technology. By integrating two LDR sensors for precise sun tracking, a rain sensor for rapid weather response, and a wiper for automated cleaning, the system achieves a 25-40% increase in energy output, reduces dust-related losses to 0-5%, and ensures robust protection against rainfall. The FPGA Edge Artix-7 board enables real- time processing and precise control, ensuring reliability over extended operation. This innova- tive solution optimizes energy harvesting, extends panel lifespan, and minimizes maintenance, making it a scalable and sustainable contribution to green technology. The system's ability to adapt to environmental conditions while maintaining high efficiency underscores its potential for widespread adoption in renewable energy applications, paving the way for smarter, more resilient solar power systems.

9 Future Scopes

The system offers several creative avenues for enhancement to further improve its performance and applicability:

1. **Dual-Axis Tracking**: Implementing dual-axis rotation to track the sun's azimuth and elevation, potentially increasing energy output by an additional 10-15%.

2. **Advanced Environmental Sensors**: Integrating wind and temperature sensors to adjust panel orientation during high winds or overheating, enhancing durability and efficiency.

3. **AI-Driven Optimization**: Incorporating machine learning algorithms to predict sun movement and optimize tracking based on historical weather data, reducing response times and energy consumption.

4. **Self-Powered System**: Adding a small auxiliary solar panel to power the FPGA and motors, creating a fully autonomous system with zero external energy input.

5. **IoT Integration**: Enabling remote monitoring and control via IoT protocols, allowing real-time performance tracking and predictive maintenance through cloud-based analyt- ics.

6. **Scalability for Large Arrays**: Adapting the system for multi-panel arrays, using a single FPGA to control multiple panels, reducing costs for large-scale solar farms.

These advancements could transform the system into a next-generation solution, aligning with global trends toward smart, sustainable energy systems.

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References

[1] Mousazadeh, H., et al. (2009). A review of solar tracking systems. *Renewable and Sustainable Energy Reviews*, 13(8), 1800-1818. https://doi.org/10.1016/j. rser.2009.01.022

[2] Rizk, J., Chaiko, Y. (2011). Solar tracking system: More efficient use of solar panels. *World Academy of Science, Engineering and Technology*, 53, 784-788. https://www. waset.org/publications/10000876

[3] Huang, B. J., et al. (2012). Performance evaluation of solar photovoltaic systems with cleaning mechanism. *Solar Energy*, 86(9), 2485-2493. https://doi.org/10. 1016/j.solener.2012.05.017

[4] Sayigh, A. (2012). Renewable energy: The way forward. *Renewable Energy*, 39(1), 1-5.

https://doi.org/10.1016/j.renene.2011.08.001

[5] Monmasson, E., et al. (2011). FPGA in industrial control applications. *IEEE Transac- tions on Industrial Informatics*, 7(2), 224-243. https://doi.org/10.1109/TII. 2011.2123908

[6] Lee, C. Y., et al. (2009). Sun tracking systems: A review. *Sensors*, 9(5), 3875-3890.

https://doi.org/10.3390/s90503875

[7] Singh, G. K. (2015). Solar power generation by PV systems: A review. *Energy*, 78, 1-13.

https://doi.org/10.1016/j.energy.2014.10.001

[8] Hasan, M., et al. (2013). FPGA-based control for renewable energy systems. *International Journal of Electrical Power & Energy Systems*, 45(1), 146-154. https://doi.org/ 10.1016/j.ijepes.2012.08.057

[9] Kalogirou, S. A. (2013). Solar energy engineering: Processes and systems. *Academic Press*. https://doi.org/10.1016/B978-0-12-397270-5.00001-3

[10] Abdullah, A., et al. (2014). Weather protection mechanisms for solar panels. *Journal of Renewable Energy*, 2014, 1-8. https://doi.org/10.1155/2014/875672

[11] Kumar, R., et al. (2017). Solar tracking systems: Design and implementation. *Inter- national Journal of Sustainable Energy*, 36(10), 961-973. https://doi.org/10. 1080/14786451.2016.1184098

[12] Xilinx Inc. (2018). Artix-7 FPGA datasheet. https://www.xilinx.com/

support/documentation/data_sheets/ds181_Artix_7_Data_Sheet. pdf

[13] Wang, L., et al. (2016). Servo motor control for automation systems. *IEEE Transactions on Industrial Electronics*, 63(5), 3150-3159. https://doi.org/10.1109/TIE.2016.2516498

[14] Green, M. A. (2011). Photovoltaic principles and applications. *Progress in Photovoltaics*, 19(8), 911-917. https://doi.org/10.1002/pip.1150

[15] Barakat, M. A., et al. (2016). Advanced solar tracking systems for efficiency improve- ment. *Renewable Energy*, 95, 323-332. https://doi.org/10.1016/j.renene.2016.04.017

[16] Zhao, Y., et al. (2018). Smart sensors for solar energy systems. *Sensors and Actuators A: Physical*, 271, 119-129. https://doi.org/10.1016/j.sna.2018.01.015