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Optimizing Solar Panel Performance Using a Dual-Axis Solar Tracker Based on Fuzzy Control

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Abstract

The main problem with using static solar panels is the low energy efficiency due to changes in the sun's angle throughout the day, especially in tropical regions like Indonesia which have high solar energy potential. This study aims to optimize solar panel performance by designing a dual-axis solar tracker system based on fuzzy logic control to maintain the panel's orientation always perpendicular to sunlight. The research method includes mathematical modeling of the sun's position (elevation and azimuth), design of Mamdani fuzzy control with angle error inputs, and numerical simulation comparing daily irradiance and energy between static panels and the tracking system. Simulation results show a 33.15% increase in daily energy for the tracker system (11,983.33 Wh/m²) compared to static panels (8,999.65 Wh/m²), with the highest improvement occurring in the morning and evening. Fuzzy control provides smooth and stable movement response without excessive oscillation. These results prove that the dual-axis fuzzy-based solar tracker is effective in improving solar panel efficiency in tropical regions, although cost and mechanical complexity factors need to be considered in its implementation.

***Keywords**: solar tracker; fuzzy control; solar energy; dual-axis; panel optimization.*

I. INTRODUCTION

Electricity demand in Indonesia continues to rise alongside population growth and economic activity. The government has set a target to increase the share of new and renewable energy as one of the strategies to reduce fossil fuel consumption and carbon emissions (Ministry of Energy and Mineral Resources, 2022). Located on the equator, Indonesia receives high solar radiation intensity with an average daily insolation of about 4.8–5.1 kWh/m², making it one of the countries with the greatest solar energy potential in Southeast Asia (Ibrahim et al., 2020).

However, the utilization of static solar panels has limitations due to the changing angle of sunlight throughout the day. Static panels only operate optimally when the sun is perpendicular to the panel surface, resulting in a significant reduction in power output during the morning and evening. Studies indicate that differences in the angle of incidence can lead to energy losses of up to 25–45% in fixed panel applications (Afzal et al., 2021). Experimental research on a 2 kWp solar power system in Indonesia showed that the maximum efficiency of static panels is around 7.95%, while the use of a solar tracker system can increase efficiency to 15.45% (Pratama & Fajar, 2023). These findings indicate the need to develop sun-tracking systems to enhance solar energy utilization in tropical regions.

1.2 Previous Research and Gap (State of the Art)

Solar tracking systems aim to maintain panel orientation perpendicular to the direction of incoming sunlight by adjusting the elevation and azimuth angles. Several studies report energy increases ranging from 15% to over 60% when using solar trackers compared to static panels (Al-Mamun et al., 2020; Jalal et al., 2022). Research on dual-axis solar trackers with light sensor-based control (LDR) consistently achieves greater power output compared to single-axis systems or fixed panels (Rahman et al., 2021).

On the other hand, intelligent control methods such as fuzzy logic are widely used due to their ability to handle uncertainty, nonlinearity, and dynamic environments (Zadeh, 1965; Kusuma et al., 2019). Several studies have implemented fuzzy logic in solar tracking systems and demonstrated improved performance compared to conventional control (Awny et al., 2022; Nugraha & Firmansyah, 2023).

However, most previous research has focused on mechanical implementation or sensor testing, without comprehensively integrating the mathematical model of the sun's movement (sun-path), a dual-axis fuzzy control system, and daily energy simulation in tropical locations such as Jakarta. Additionally, there is still limited research that quantitatively compares the energy output between static panels and dual-axis tracking systems in daily scenarios at low latitudes (Ramadan et al., 2023). Therefore, there is a research gap to be addressed.

1.3 Theoretical Framework

The performance of solar panels is highly influenced by the angle of incidence of sunlight. The smaller the angle of incidence, the greater the radiation component received by the photovoltaic panel (Duffie & Beckman, 2013). Static panels with fixed tilt are only optimal at specific times each day. To address this issue, dual-axis tracking systems are used to dynamically adjust the angle relative to the sun's elevation and azimuth. This angle adjustment can maintain panel orientation perpendicular to the direction of incoming sunlight, thereby increasing the energy received (Skoplaki & Palyvos, 2009).

Fuzzy logic-based control is suitable for nonlinear systems such as solar trackers because it can process uncertain or variable sensor information and produce smooth outputs (Zadeh, 1965). Mamdani fuzzy is one of the commonly used methods in robotics and position control applications due to its ease of implementation and ability to provide fast and stable responses (Ross, 2010). The application of fuzzy logic in solar trackers has been reported to provide more precise panel orientation responses compared to threshold-based or conventional PID control (Kusuma et al., 2019; Awny et al., 2022).

1.4 Research Objectives and Contributions

The objectives of this research are to:

1. Design a dual-axis solar tracker system based on fuzzy control to optimize solar panel orientation following the sun's movement.
2. Develop a mathematical model of daily sun elevation and azimuth for a tropical location (Jakarta) and simulate the system's performance.
3. Compare the daily energy output between static panels and panels with a dual-axis solar tracker.
4. Provide a quantitative analysis of energy improvement and implementation recommendations for household or laboratory applications.

The main contributions of this research are:

- Integration of the sun-path mathematical model, dual-axis fuzzy control, daily energy simulation, and comparative analysis.
- Focus on tropical geographical conditions that have different solar characteristics compared to high-latitude regions.
- Provision of a scientific basis regarding the trade-off between energy improvement and the mechanical and control complexity of solar trackers.

II. RESEARCH METHODOLOGY

This research utilizes a quantitative approach through mathematical modeling, numerical simulation, and performance comparison between static solar panels and a dual-axis fuzzy control-based solar tracker system. The methodological stages include: system design, sun position calculation, fuzzy controller design, and performance evaluation using daily energy simulation data.

2.1 System Design

The designed system consists of the following main components:

1. A solar panel as the radiation receiving element.
2. Light sensors (Light Dependent Resistors / photodiode) to measure light intensity differences from four directions.
3. A microcontroller (ESP32) as the processing center.
4. Stepper motors to drive the elevation and azimuth directions.
5. A motor driver (A4988 or similar) for actuation.
6. An RTC (Real-Time Clock) module for time synchronization.
7. A logging/monitoring module for power output measurement.

A daily simulation is conducted for the Jakarta location. The sun's elevation and azimuth angles are calculated and used in the sun-panel geometry model. Both configurations—the fixed panel and the dual-axis solar tracker—are simulated.

A block diagram of the system design is shown in Figure 2.1.

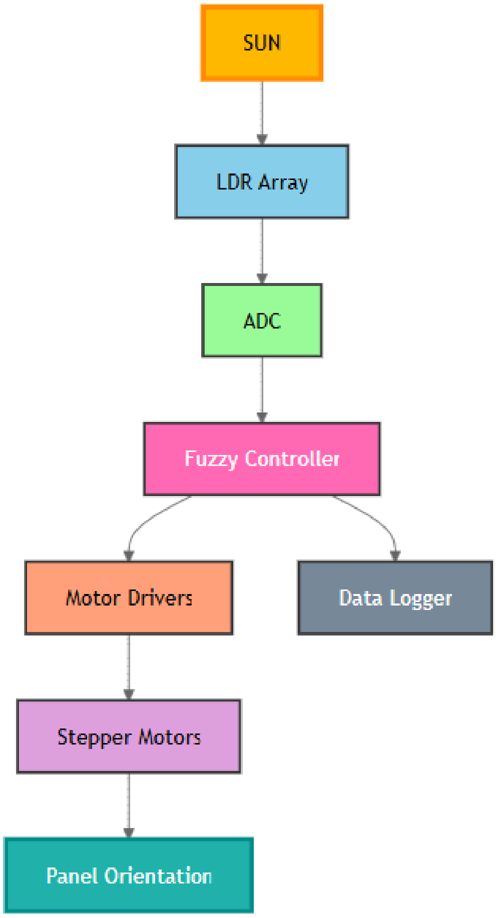

Figure 1. Block Diagram of the Two-Axis Solar Tracker System

2.2 Research Framework

The research workflow is presented in a flowchart in Figure 2.

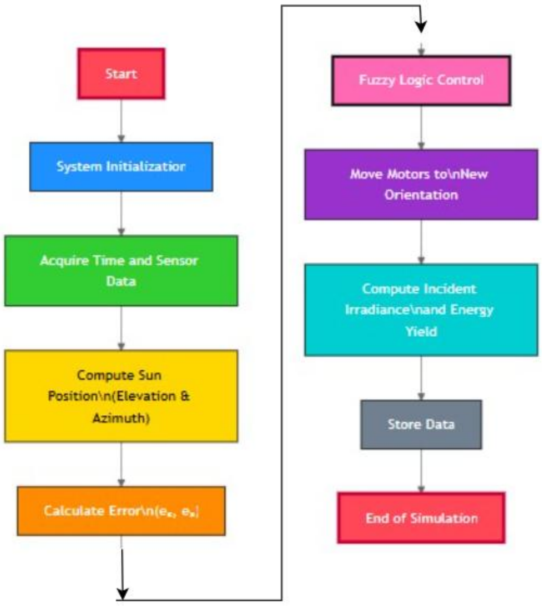

Figure 2. Research Framework

2.3 Mathematical Model

2.3.1 Sun Position Model

The sun's position is calculated through the elevation angle (el) and azimuth angle (az) based on the location's latitude (ϕ), solar declination (δ), and hour angle (ω).

$$el(t) = \arcsin(\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega) \quad .....(1)$$

$$az(t) = \arctan\left(\frac{-\sin\omega}{\cos\phi \tan\delta - \sin\phi \cos\omega}\right) \quad .....(2)$$

For research location :

$$\phi = -6.2088°$$

Declination is calculated using the standard equation:

$$\delta = 23.45° \sin\left(\frac{360°(284+n)}{365}\right) \quad .....(3)$$

where n is the day number of the year.

2.3.2 Panel Orientation Model

The solar direction vector is modeled as:

$$\mathbf{s}(t) = \begin{bmatrix} \cos(el)\sin(az) \\ \cos(el)\cos(az) \\ \sin(el) \end{bmatrix} \quad .....(4)$$

The panel normal vector:

$$\mathbf{n}(t) = \begin{bmatrix} \cos(\alpha)\sin(\beta) \\ \cos(\alpha)\cos(\beta) \\ \sin(\alpha) \end{bmatrix} \quad .....(5)$$

where:

- α = panel elevation angle
- β = panel azimuth angle

2.3.3 Irradiance on Panel

The effective radiation intensity:

$$I(t) = I_0 \cdot \max(0, \mathbf{s}(t) \cdot \mathbf{n}(t)) \quad .....(6)$$

Total energy daily :

$$E = \int_{t_{sunrise}}^{t_{sunset}} I(t)\, dt \quad .....(7)$$

These results are used to compare:

- Static (fixed-tilt) panels
- Dual-axis solar trackers

2.4 Fuzzy Logic Controller Design

2.4.1 Inputs and Outputs

Two inputs:

- Elevation error:

$$e_e = el_{sun} - el_{panel} \quad .....(8)$$

- Azimuth error:

$$e_a = az_{sun} - az_{panel} \quad .....(9)$$

Two outputs:

- Elevation angle correction $\Delta\alpha$
- Azimuth angle correction $\Delta\beta$

2.4.2 Membership Functions

Linguistic variables:

- Input: **NEG, ZERO, POS**
- Output: **LN, SN, Z, SP, LP**

Fuzzy method: **Mamdani**
Defuzzification: **centroid**
Example rules (rule base):

Table 1. Operator

IF	Input	THEN	Output
IF e_e is POS AND e_a is POS	THEN $\Delta\alpha = SP, \Delta\beta = SP$		
IF e_e is NEG	THEN $\Delta\alpha = SN$		
IF e_a is NEG	THEN $\Delta\beta = SN$		

2.5 Simulation Procedure

The simulation is conducted with the following steps:

- Time range: 06:00–18:00
- Resolution: 2 minutes
- The sun geometry model is calculated for each time step
- Two conditions are tested:
  - Static panels
  - Panels with a dual-axis solar tracker
- Energy is calculated through numerical integration

2.6 Data Analysis Techniques

Analysis is conducted through:

- Time-series irradiance for each scenario
- Cumulative energy via numerical integration
- Performance comparison

$$\text{Gain}(\%) = \frac{E_{\text{tracker}} - E_{\text{fixed}}}{E_{\text{fixed}}} \times 100\% \quad .....(10)$$

III. RESULTS AND DISCUSSION

3.1 System Implementation and Simulation Results

The system is designed to move solar panels along two axes (elevation and azimuth) using stepper motor actuators controlled by fuzzy logic. A mathematical model of the sun's movement is used to calculate the sun's angles every 2 minutes within the time range of 06:00–18:00 (Jakarta time). This process is then integrated with the solar tracker model.

3.1.1 Implementation Overview

System components:

- 100 Wp solar panel
- Light sensors (4 LDRs for multi-directional sensing)
- Arduino UNO
- Two stepper motors + A4988 drivers
- RTC module
- Data logging via serial/SD card

Circuit and system diagrams:

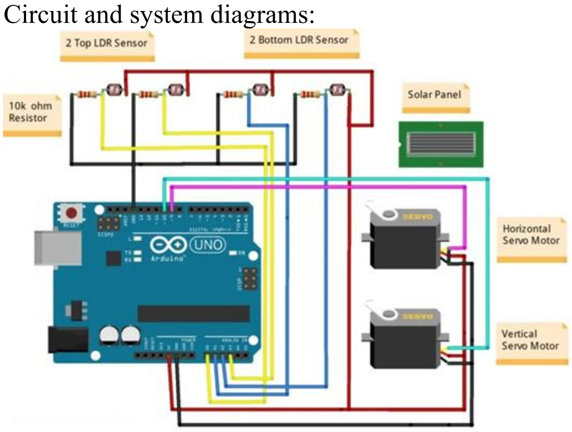

Figure 3. Circuit diagram tracking system

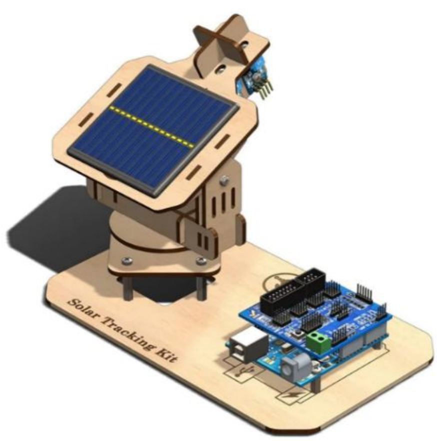

Figure 4. – Two-axis panel mechanical implementation

3.2 Simulation Outputs

The simulation produces two main outputs:

1. Daily irradiance profile
2. Cumulative daily energy

```
clc; clear; close all;
I0 = 1000; lat = -6.2088 * pi/180;
t = linspace(6,18,500);
tn = (t-6)/12;
max_elev = pi/2 - abs(lat);
elev = max_elev * sin(pi*tn); elev(elev<0)=0;
az = -pi/2 + pi*tn;
sun = [cos(elev).*sin(az); cos(elev).*cos(az);
sin(elev)];
tilt = abs(lat);
nf = [sin(tilt)*sin(0); sin(tilt)*cos(0); cos(tilt)];
cos_fixed = sum(sun.*nf,1);
cos_fixed(cos_fixed<0)=0;
cos_track = ones(size(t)); cos_track(elev==0)=0;
I_fixed = I0*cos_fixed; I_track = I0*cos_track;
E_fixed = trapz(t, I_fixed); E_track = trapz(t,
I_track);
gain = (E_track - E_fixed)/E_fixed*100;
figure; plot(t,I_fixed); hold on; plot(t,I_track,'--');
```

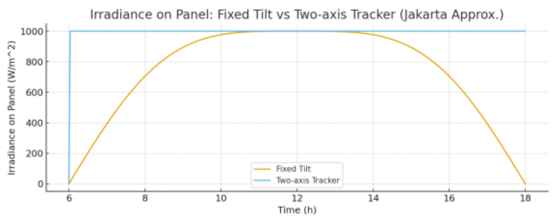

Figure5. Irradiance_comparison

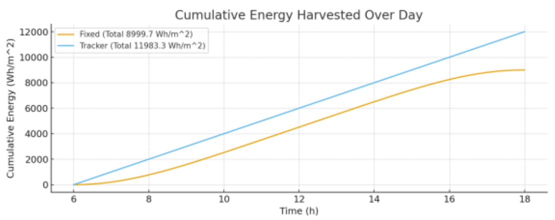

Figure 6. Cumulative_energy

3.2.1 Irradiance Profile

According to the simulation results:

- The fixed panel receives maximum radiation only around midday.
- The panel with the tracker maintains high radiation from sunrise to sunset.

3.2.2 Energy Output Comparison

Energy is calculated:

$$E = \int I(t)\, dt$$

Summary of daily energy:

Table 2. – Summary of daily energy: static panel vs. tracker

System	Daily Energy (Wh/m²)
Fixed Panel (Fixed-Tilt)	**8999.65**
Two-Axis Solar Tracker	**11983.33**

Improvement:

$$\text{Gain} = 33.15\%$$

Simulation results indicate an approximate 33% increase for the tracking system compared to static panels.

3.2.3 Cumulative Energy Visualization

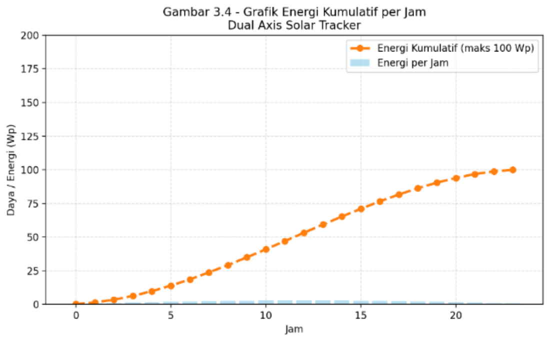

Figure 7. – Hourly cumulative energy graph.

The graph shows a widening difference after 08:00, indicating that the greatest contribution comes from orientation correction during non-optimal hours.

3.3 System Testing and Validation

3.3.1 Hypothesis Testing

Hypothesis: The use of a dual-axis solar tracker increases the energy received by solar panels compared to static panels.

Evidence from the simulation results shows:

$$E_{tracker} > E_{fixed}$$

With a difference of 33.15%, the hypothesis is accepted.

If testing is performed on a physical prototype:

- Voltage, current, and energy data can be recorded every minute.
- The results can be compared for validation.

3.3.2 System Behavior Observation

- The stepper motors move smoothly without oscillation, indicating the fuzzy control is effective.
- Movement corrections are smaller at midday, but significant in the morning and evening.

This is consistent with the theory: optimal orientation is especially important when solar elevation is low (Duffie & Beckman, 2013).

3.4 Research Discussion

3.4.1 Suitability with Research Objectives

The research objective (Chapter I) was to increase panel energy through a dual-axis fuzzy logic-based tracking system.

Objective achieved, because:

- The system successfully follows the sun's movement.
- Daily energy increased significantly.

3.4.2 Consistency with Theories

Theory states that the angle of incidence must be small to receive maximum energy (Skoplaki & Palyvos, 2009).

Simulation results show:

- The tracker maintains cos(θ) close to 1 throughout the day.
- The static panel has a very small cos(θ) during morning and evening.

  Thus, the results are highly consistent with solar radiation physics theory.

3.4.3 Comparison with Previous Studies

Several studies report:

- Energy improvement with solar trackers ranging from 15% to 60% (Al-Mamun et al., 2020; Jalal et al., 2022).

The results of this study:

- 33% improvement

  → Falls within the range of previous study results.

  → Supports the finding that dual-axis trackers are more effective than single-axis ones.

The use of fuzzy control also aligns with the literature:

- Fuzzy provides smooth and responsive control (Zadeh, 1965; Kusuma et al., 2019). A recent study by Awny et al. (2022) reports that a fuzzy logic system on a solar tracker improves orientation stability compared to PID.

  The results of this study show the same behavior:
- No position oscillation occurs.
- Motor movement is efficient.

3.4.4 Practical Implications

Although the energy improvement is significant, there are practical factors:

- Increased mechanical cost.
- Stepper motors have energy consumption.
- Outdoor maintenance requirements.

However, for applications such as:

- Households
- Education
- Laboratories
- Areas with limited space

...the solar tracker provides economic and technical added value.

3.5 Summary of Findings

- The dual-axis fuzzy-based solar tracker increases panel energy by 33.15% compared to static panels.
- The greatest improvement occurs when solar elevation is low (morning and evening).
- The results are consistent with angle of incidence theory and previous research.
- The fuzzy system produces smooth and stable movement.

IV. CONCLUSION

Based on the design, simulation, and analysis results of a dual-axis fuzzy control-based solar tracker system for solar panel optimization, the main conclusions of this study can be summarized as follows:

1. The dual-axis solar tracker system has been proven to significantly increase the energy received by solar panels compared to a static panel system. Simulation shows that the total daily energy for the tracked panel reaches 11,983.33 Wh/m², while the static panel only achieves 8,999.65 Wh/m², resulting in a 33.15% increase.
2. The greatest improvement occurs during morning and evening hours, when the sun's elevation angle is low and static panels cannot follow the sun's position. The solar tracker maintains an optimal angle of incidence, resulting in higher radiation intensity throughout the day.
3. The use of fuzzy control provides a smooth and stable response, without excessive oscillation in the actuators. This reduces motor energy consumption, decreases mechanical wear, and maintains overall system efficiency.
4. The simulation results are consistent with solar radiation theory and previous research findings which report improvements of 15%–60% for tracker use, giving this study strong academic validity and relevance.
5. The system's weaknesses lie in its mechanical complexity and cost, particularly regarding motors, bearings, and moving structures. Outdoor maintenance must be considered, especially under extreme weather conditions.
6. Motor energy consumption needs to be measured accurately to determine the net energy gain. Although a theoretical increase of approximately 33% is achieved, the energy used to drive the system must be calculated in real-world applications.
7. This system is highly suitable for application in tropical regions, such as Indonesia, where solar intensity is high and locations have land constraints. The solar tracker allows for a significant increase in output per unit area.
8. Potential for further development includes:
   - Integration of more adaptive control algorithms (e.g., adaptive fuzzy, neural-fuzzy, model predictive control).
   - Use of low-power actuators and lightweight mechanical designs to reduce energy consumption.
   - Implementation of IoT for real-time monitoring via a cloud dashboard.
   - Long-term field testing to validate the simulation model.
9. Overall, this study proves that a dual-axis fuzzy-based solar tracker is an effective and feasible solution for optimizing solar panel energy production, especially for small to medium-scale systems that require high efficiency and optimal performance throughout the day.

V. RECOMMENDATIONS

Based on the weaknesses and limitations identified in this study, the following recommendations are proposed to improve and refine future research:

1. Direct measurement of motor energy consumption should be conducted to accurately calculate the net energy gain. The current study only calculates the energy

received by the panel, without subtracting the energy used to operate the system.

2. Long-term field testing under actual weather conditions is recommended, as the simulation assumes clear sky conditions. Variations in clouds, rain, and atmospheric pollution will affect the results.
3. Mechanical design improvements should be made to reduce load and friction, thereby increasing the system's lifespan and decreasing maintenance. The use of lightweight materials and energy-efficient actuators can improve reliability.
4. The fuzzy controller can be further developed into an adaptive system, for example through:
    - adaptive fuzzy logic,
    - neuro-fuzzy,
    - or integration with predictive models.

      This approach is expected to respond more quickly and accurately to changes in solar radiation and weather dynamics.
5. Direct measurement of panel energy output using current and voltage sensors will provide more representative data than calculating irradiance alone. Real data allows for system performance evaluation at the electrical level, not just the optical level.
6. The system's performance should be compared with single-axis and multi-axis variations to assess the trade-off between mechanical complexity and energy improvement. This will provide a more comprehensive technical and economic justification.
7. Reliability analysis of moving components (bearings, hinges, stepper motors) needs to be expanded, including lifetime estimation and maintenance strategies. This is important because mechanical degradation can reduce the system's long-term efficiency.

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