Journal of Electrical Vocational Education and Technology
Volume 8 Issue 1, June 2025
DOI: https://doi.org/10.21009/JEVET.0081.03
e-ISSN: 2745 - 9373

Received : 20 April 2025
Revised : 25 April 2025
Published : 25 April 2025
Issued : 30 June 2025

Design of Prototype Solar Tracking System Dual Axis Based on Positioning System (GPS) for Energy Optimization on 100WP Solar Panel

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Abstract

Static solar panels have a disadvantage in capturing solar radiation intensity optimally because they do not follow the movement of the sun. This study aims to design and develop a GPS-based dual-axis solar tracker prototype to optimize energy on a 100WP solar panel. The system tracks the sun's position in real-time based on azimuth and elevation angles using a stepper motor as an actuator, employing the R&D research method and the ADDIE approach. The results show that the solar tracker increases the energy generated compared to the static system. On December 20, 2024, energy increased by 9.6% after accounting for system power consumption. Meanwhile, on December 18, 2024, the energy increase was 5.11%, and on December 19, 2024, it was 1.0%, but these values were before deducting power consumption. The stepper motor's power consumption of 16.125Wh over 9 hours of operation affected net energy efficiency. Testing showed a tracking error of 1.74%, with an accuracy rate of 98.26%. This study concludes that the GPS-based dual-axis solar tracker can improve the energy output of solar panels with a high tracking accuracy rate.

Keywords: dual axis, energy optimization, solar panel, solar tracker

Introduction

In 2023, Indonesia has a population of 278.8 million people and is ranked fourth in the world in terms of population according to the Central Statistics Agency (BPS). With a large population, the demand for electrical energy will also be high (Belmin et al., 2024). The average actual energy consumption per person in Indonesia is estimated to reach 1,285 kWh/capita in 2023, with a target of 1,408 kWh/capita in 2024 (Ramadhan et al., 2024). PT Perusahaan Listrik Negara (PLN) as a supplier of electrical energy in Indonesia has power plants with a total installed capacity of 73,343.76 MegaWat (MW) in 2022 (Taruna et al., 2025). Of the total installed capacity, Steam Power Plants (PLTU) fulfill about 50.72% of it, and Gas and Steam Power Plants (PLTGU) about 19.49% (Bartnik et al., 2024). The main raw material in PLTU and PLTGU is fossil fuel. Based on the study of greenhouse gas emissions at PLTGU and PLTU Muara Karang, CO2 is the main emission produced by these power plants from their fuel. PLTGU block 2 produces the most greenhouse gas emissions of the three blocks at this location, amounting to 1,952,852.78 CO_2 (Tu et al., 2024; Ramly et al., 2025).

Earth's air temperature can increase due to excessive CO_2 concentration in the atmosphere (Filonchyk et al., 2024). This happens because the earth's temperature is increasing and has the potential to cause global warming due to the high concentration of greenhouse gases that reflect heat back to the planet (Ganguly & Gupta, 2024). Therefore, to reduce CO2 gas waste caused by power plant exhaust emissions, additional generating capacity from renewable energy is needed (Huan et al., 2024). Solar Power Plant (PLTS) is one of the EBT plants. Converting solar energy into electrical energy is the basic idea behind PLTS generators (Xu et al., 2024). Besides being renewable due to its unlimited supply, solar energy is also environmentally friendly as it produces electricity without CO_2 emissions (Mostafa & Aboelezz, 2024). Given that Indonesia is in the tropical zone and receives sunlight throughout the year, there is great potential for the development of solar energy utilization (Imtihan et al., 2024).

However, the use of solar panels still has weaknesses, one of which is the static (stationary) installation. The inability of static solar panels to capture the entire intensity of solar radiation is one of its weaknesses. If the solar panel is oriented perpendicular to the light source, it will obtain the maximum amount of radiation. Therefore, making the solar panel move according to the position of the sun is one way to increase the quantity of energy received from sunlight (Hammas et al., 2025). Therefore, a solar tracker must be included to increase the energy produced by the solar panel. A device called a solar tracker rotates the solar panel automatically based on the position of the sun.

To make a solar tracker that can adjust to the sun's position accurately, location, time of day and season variables are needed (Santos et al., 2024), therefore this research will use a global positioning system (GPS) on a dual axis solar tracker to automatically track the sun even if the device is placed in a different location and improve the accuracy of sun tracking (Wu et al., 2025).

Methods

In this study, the research and development method was used. The research and development method conceptually comes from two terms, namely research and development. Research is a scientific endeavor conducted in accordance with generally accepted research guidelines or criteria. Development, on the other hand, is the process of improving an activity or object both in terms of quantity and quality. The ADDIE (Analysis, Design, Development, Implementation, Evaluation) development model is one of the R&D development models used in this study.

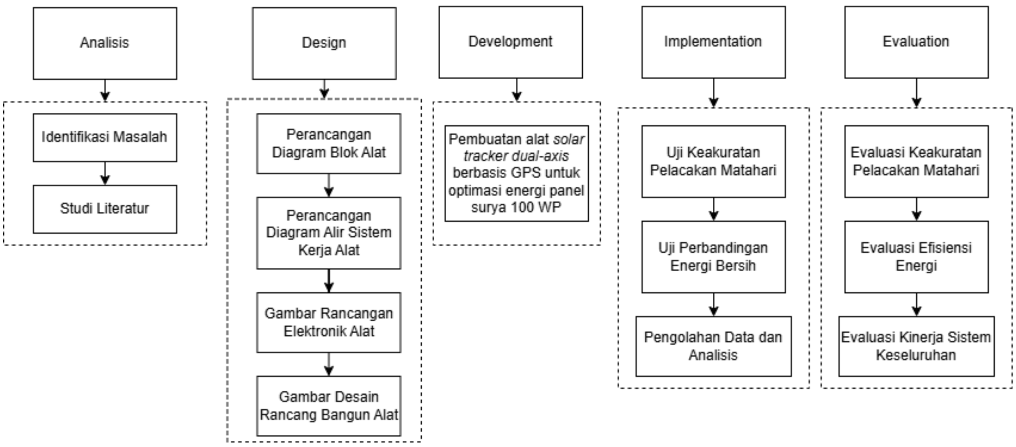

Figure 1. Research Flow

Analysis

This stage involves searching or analyzing previous research through literature studies. This analysis includes identifying weaknesses in the movement method of the solar tracker in previous studies.

Design

- A system design consisting of several major components is being implemented at this stage to facilitate the manufacture of a GPS-based dual-axis solar tracker. This stage includes:
- Tool Block Diagram: Designing a system block diagram that illustrates the relationship between the main components, such as the GPS module, microcontroller, drive motors for the dual-axis as well as additional sensors. This diagram provides a comprehensive overview of the system.
- Flowchart of the tool's working system: Develop a flowchart of the tool's working system that explains the operational steps, starting from the capture of location data by the GPS module, calculation of azimuth and elevation angles, to controlling the motor to drive the solar panel according to the position of the sun.
- Electronic Design of the Tool: Create an electronic circuit scheme that includes the wiring of the GPS module, motor driver, current sensor for power consumption measurement, and microcontroller-based control system.
- Tool Design Drawing: Develop the mechanical design of the device, including the solar panel mount, as well as the support structure that supports the stable movement of the device.

Development:

At this stage, the process of making a GPS-based dual-axis solar tracker for energy optimization of 100 WP solar panels is carried out. This stage includes the implementation of the results of the previous design.

Implementation

At this stage, a series of tests were carried out on the GPS-based dual-axis solar tracker. Tests include:

- Sun tracking accuracy test, measuring the azimuth and elevation angles of the sun produced by the tool, then comparing with reference data from the Suncalc application or platform. This test aims to ensure that the GPS-based sun tracking system is able to determine the position of the sun in real-time.
- Net energy comparison test, a net energy comparison is carried out between solar panels that use solar trackers and static solar panels. Net energy is calculated by subtracting the energy consumption of the solar tracker system from the total energy produced by solar panels. This test aims to determine the increase in energy produced by solar tracker solar panels compared to static panels.

Evaluation

At this point, the performance and effectiveness of the GPS-based dual axis solar tracker is evaluated through analysis of the test results. This evaluation includes:

- Solar tracking accuracy, by assessing the degree to which the azimuth and elevation angles generated by the device match the reference data from Suncalc.

- Energy efficiency, by evaluating the net energy comparison between solar panels with solar trackers and static solar panels. The results of the analysis were used to confirm that the use of the tracker provided a significant increase in net energy compared to the static system.
- Overall system performance, by identifying strengths and weaknesses in system integration.

Results and Discussion

This research produces a dual axis solar tracking system that is able to move solar panels to be perpendicular to the direction of sunlight by making solar panels follow the sun based on the azimuth angle and altitude angle of the sun obtained based on the location where the solar tracker is placed using the Global Positioning System (GPS).

Figure 2. Solar Tracking System Dual Axis

Data from the energy comparison test results of static solar panels with solar tracker solar panels are presented in the following graph.

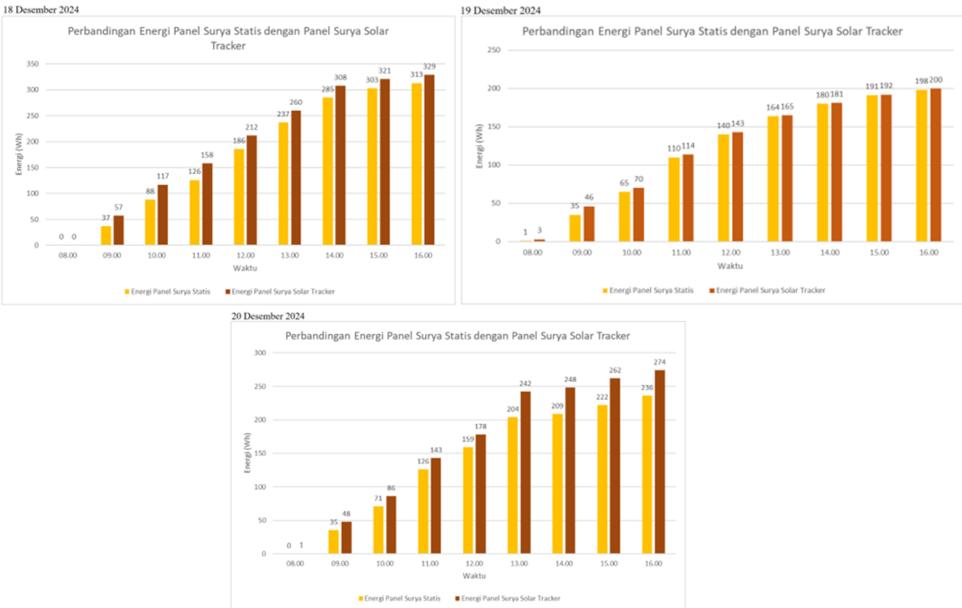

Figure 3. Energy Comparison Testing Data of Static Solar Panels and Solar Tracker Solar Panels

Graph of energy test results of static solar panels with solar tracker solar panels that move every one hour. Based on the graph, we can see the difference in energy produced by the two solar panels. The energy produced by solar tracker solar panels has a significant increase compared to static solar panels. There was an increase in energy in the solar tracker solar panel of 5.11% on December 18, 2024, 1.0% on December 19, 2024, and 16.1% on December 20, 2024, so the average increase in energy was 7.4%. This proves that the tilt angle and direction of the solar panel greatly affect the energy produced by the solar panel.

Furthermore, to find out the net energy produced by solar tracker solar panels, energy

Figure 4. Net Energy Data Results

The energy produced by the solar tracker solar panel will be reduced by the energy needed to move the solar tracker. To calculate the total energy consumed by solar tracker tools based on the power used can use the following calculation.

Total Energy = Power (W) X Operating Time (Hours)

The operating period of the solar tracker tool is for 9 hours from 08.00 WIB to 16.00 WIB with operating time for 5 minutes per hour. Then the operating time in a day is 16.125Wh.

Table 1. Comparison of Net Energy of Solar Tracker Solar Panels with Static Solar Panels

Datel	Energy Used by Solar Tracker Tool (Wh)	Total Solar Tracker Solar Panel Energy (Wh)	Total Net Energy of Solar Tracker Solar Panels (Wh)	Total Static Solar Panel Energy (Wh)
18/12/2024	16,125	329	312,875	313
19/12/2024	16,125	200	183,875	198
20/12/2024	16,125	274	257,875	236

Based on Table 1, on December 20, 2024 the net energy produced by the solar tracker solar panel is 9.6% greater than the energy produced by the static solar panel. Whereas on December 18, 2024 and December 19, 2024 the net energy produced by the solar tracker solar panel is smaller than the energy of the static solar panel.

Table 2. Solar Tracker Sun Tracking Accuracy Test Results Compared to SunCalc

Date	December 18, 2024					
Location (latitude, longitude)	(-6.194141)(106.877975)					
Time	**Altidude Angle (*Solar Tracker*)**	**Altidude Angle (SunCalc)**	***Error***	**Azimuth Angle (*Solar Tracker*)**	**Azimuth Angle (SunCalc)**	***Error***
08.00	33,75	32,41	4,13%	112,33	113,81	1,30%
09.00	48,85	45,87	6,50%	117,62	117,47	0,13%

10.00	59,22	58,6	1,06%	126,42	126,04	0,30%
11.00	70,03	69,11	1,33%	143,36	146,66	2,25%
12.00	73,32	72,61	0,98%	188,83	188,2	0,33%
13.00	66,39	65,82	0,87%	222,22	222,8	0,26%
14.00	53,43	54,21	1,44%	237,43	237,81	0,16%
15.00	43,2	41,12	5,06%	243,52	244,16	0,26%
16.00	26,63	27,55	3,34%	246,39	246,78	0,16%
Rata-Rata	2,74%			0,57%		

The data from testing the accuracy of sun tracking on the solar tracker tool aims to compare the results of tracking the azimuth angle and elevation/altitude angle of the sun on the solar tracker tool with the results of tracking the azimuth angle and elevation/altitude angle of the sun in the SunCalc application. SunCalc application is an application that shows the movement of the sun and the phase of sunlight on a particular day in a particular place. The SunCalc application can display the position of the sun based on the azimuth angle and altitude/elevation angle of the sun, besides that this application also displays sunrise time, sun peak time and sunset time.

This test was conducted from 08.00 WIB to 16.00 WIB with data collection every one hour. Based on Table 2, the average error in tracking the elevation/altitude angle is 2.74% and the error in tracking the azimuth angle is 0.57%, so the average percentage error in the azimuth angle value and the elevation/altitude angle of the sun solar tracker tool is 1.74%. Then the accuracy value of tracking the azimuth angle and elevation angle / altitude of the sun on the solar tracker tool is 98.26%.

Table 3. Test Results of Solar Tracker Sun Tracking Accuracy in Different Locations Compared with SunCalc

Date	December 16, 2024					
Location (latitude, longitude)	(3.588432)(98.673507)					
Time	**Altidude Angle (*Solar Tracker*)**	**Altidude Angle (SunCalc)**	***Error***	**Azimuth Angle (*Solar Tracker*)**	**Azimuth Angle (SunCalc)**	***Error***
08.00	21,89	21,06	3,9%	115,57	116,66	0,93%
09.00	34,18	34,14	0,11%	121,7	121,43	0,22%
10.00	46,42	46,35	0,15%	130,83	129,79	0,8%
11.00	57,05	56,61	0,7%	145,46	144,65	0,56%
12.00	64	62,60	2,2%	168,83	169,38	0,32%
13.00	59,56	61,47	3,1%	198,58	198,88	0,15%
14.00	54,08	53,39	1,2%	219,36	220,58	0,55%
15.00	39,74	42,89	7,3%	234,18	233,12	0,45%
16.00	31,91	30,35	5,1%	240,07	240,20	0,05%
Rata-Rata	2,67%			0,45%		

Testing the accuracy of sun tracking in different locations on the solar tracker tool aims to test the accuracy in tracking the position of the sun based on the location of the solar tracker tool placed. This test is done by entering location data manually in the program. In this test, researchers entered location data in the city of Medan as a sample.

Based on Table 3, the average error in tracking the elevation/altitude angle is 2.67% and the error in tracking the azimuth angle is 0.45%, so the average percentage error in the azimuth angle value and the elevation/altitude angle of the solar tracker tool is 1.56%. Then the accuracy value of tracking the azimuth angle and elevation angle / altitude of the sun on the solar tracker tool is 98.44%.

Conclusion

The GPS-based dual-axis solar tracker prototype was successfully designed and demonstrated the ability to accurately track the sun's movement based on geographic coordinates (latitude and longitude), with test results showing an average error of 1.74% (98.26% accuracy) in one location and 1.56% (98.44% accuracy) in different locations; furthermore, the dual-axis tracking system increased the energy output of solar panels compared to static systems, with energy gains of 5.11% on December 18, 2024, 1.0% on December 19, 2024, and 16.1% on December 20, 2024 before accounting for power consumption, and after factoring in the system's power consumption of 16.125 Wh over a 9-hour operation period (08:00 to 16:00 WIB), the net energy produced by the solar tracker system on December 20, 2024 still showed a 9.6% increase, while on December 18, 2024 the net energy was nearly equal to that of the static system, and on December 19, 2024 the static system produced slightly more net energy, indicating that under low solar radiation conditions such as rainy weather, static solar panels may yield more net energy due to the power consumption of the tracking mechanism.

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