Design and Development of an Automatic Solar Tracker with Power Measurement and Analysis as an Effort to Optimize Renewable Energy in Line with Sustainable Development Goal 7

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ABSTRACT
Electricity is essential to modern society, yet stationary solar panels can lose 20–40% of their energy potential due to changes in the sun's position. This study develops an automatic solar tracker to optimize renewable energy generation in support of SDG 7.2. Using the Research and Development (R&D) method and the 4D model (Define, Design, Development, Disseminate), the prototype integrates two Light Dependent Resistor (LDR) sensors, a microcontroller, a servo motor, and an INA219 sensor to track light intensity and measure electrical parameters. Testing showed responsive tracking and voltage variations consistent with light intensity. Negative current readings occasionally occurred, likely due to sensor polarity, offset, or reverse current, rather than tracking failure.

ABSTRAK
Energi listrik merupakan kebutuhan penting bagi masyarakat modern. Namun, panel surya statis dapat kehilangan 20–40% potensi energinya akibat perubahan posisi matahari. Penelitian ini mengembangkan pelacak surya otomatis untuk mengoptimalkan pembangkitan energi terbarukan guna mendukung SDG 7.2. Penelitian menggunakan metode Research and Development (R&D) dengan model 4D (Define, Design, Development, Disseminate). Prototipe mengintegrasikan dua sensor Light Dependent Resistor (LDR), mikrokontroler, motor servo, dan sensor INA219 untuk mengikuti intensitas cahaya serta mengukur parameter listrik. Pengujian menunjukkan bahwa sistem mampu mengikuti arah cahaya secara responsif dan perubahan tegangan konsisten dengan intensitas cahaya. Pembacaan arus negatif sesekali terjadi, yang diduga disebabkan oleh polaritas sensor, offset yang belum terkalibrasi, atau arus balik dari panel, bukan karena kegagalan mekanisme pelacakan.

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KEYWORDS
Automatic solar tracker, LDR sensor, SDG 7.2.

INTRODUCTION

Electricity is a vital need for society and remains the most efficient resource for a wide range of activities, as almost every human activity depends on its availability. Electricity use is driven by its relatively affordable price and its ease of use compared with other energy sources (Suryadi et al, 2020). As technology has advanced, the use of electrical energy has expanded to cover more sophisticated applications such as electric vehicles, smart homes, and the many electronic devices that support daily life, so that demand for electricity continues to grow alongside technological development and rapid urbanization (Muzayanah et al., 2022).

Indonesia's demand for electrical energy has continued to increase every year. Data from the Ministry of Energy and Mineral Resources (ESDM) of the Republic of Indonesia show that per-capita electricity consumption has risen consistently, as illustrated in the following figure.



Figure 1. Electricity Consumption Increases Every Year
(Source: Ministry of ESDM)

Limited availability of electricity restricts access to information, education, and health services. Economic activities such as agriculture, trade, and small-scale industry, which have the potential to boost the local economy, are also affected (Suryadi et al., 2020). If this situation continues, it may hinder Indonesia's progress toward the Sustainable Development Goals.

The use of solar panels to generate electricity greatly helps Indonesia meet its electricity needs. However, because the sun moves from east to west, the angle of incidence of sunlight continuously changes throughout the day, while conventional solar panels are static and unable to adjust their orientation. This mismatch in angle significantly reduces the light intensity received by the panel, so that energy conversion efficiency is not optimal. Research shows that static solar panels can lose 20–40% of their potential energy because they are not positioned perpendicular to the sun (Sadeghi et al., 2025). An automatic solar tracker system capable of following the sun's position is therefore needed to maximize light absorption and increase the power output produced.

Optimizing the use of solar energy is very important for society, particularly in Indonesia, which still faces challenges related to electricity supply, rising electricity costs, and heavy dependence on fossil fuels (IEA, 2023). A more efficient solar tracker can help communities obtain an independent energy source, reduce monthly electricity expenses, and provide more stable energy access for remote areas not yet reached by the state electricity grid (PLN). So, using solar energy isn't just a technical solution for providing electricity, it can also have social and economic impacts for communities by improving access to electricity, empowering people, and developing local economic potential (UNDP Indonesia, 2021).

Based on this analysis, we propose an innovative and creative idea entitled "Design and Development of an Automatic Solar Tracker with Power Measurement and Analysis as an Effort to Optimize Renewable Energy in Line with Sustainable Development Goal 7." This idea is proposed to help address the energy crisis anticipated in 2030 and to help provide renewable energy to meet the community's electricity needs. This aligns with the objective of SDG target 7.2, namely to ensure universal access to affordable, reliable, and modern energy services by 2030, and to substantially increase the share of renewable energy in the global energy mix by 2030.



Figure 2. SDG Target 7.2 (Source: Sustainable Development Goals)

Based on the background described above, the problems addressed by this research are as follows: (1) how can an automatic solar tracker system be designed to follow the sun's movement in real time in order to maximize energy absorption by the solar panel; (2) how does the LDR sensor perform in detecting sunlight intensity to accurately orient the solar panel; (3) how is the electrical power (voltage and current) generated by the solar panel measured when using the automatic solar tracker system; and (4) how does the design of this automatic solar tracker contribute to optimizing renewable energy in line with Sustainable Development Goal (SDG) 7?

The objectives of this research are to design and develop an automatic solar tracker prototype with power measurement and analysis capable of generating electricity sustainably; to test and evaluate the performance of the LDR sensor in detecting differences in light intensity in order to move the solar panel; to measure the electrical power produced by the solar panel in both automatic and static modes; and to analyze the difference in power output between a static solar panel and one equipped with an automatic solar tracker. The benefit of this research is to improve the efficiency of solar panels by enabling them to adjust their position to follow the sun's movement throughout the day.

Target 7.2 of the SDGs emphasizes the importance of significantly increasing the share of renewable energy within the global energy system by 2030, as part of a global effort to address climate change and to create sustainable economic growth through the transformation of energy systems (United Nations, 2023). Renewable energy sources, such as ocean wave power, are part of an energy diversification strategy to address the challenge of ensuring the availability of clean energy in the future (IRENA, 2021).

A solar tracker is an integrated system composed of several components, including a solar panel, sensors, actuators, and a microcontroller. It is designed to detect and follow the direction of the sun so that the solar panel's position remains perpendicular to the sun at all times, which increases the power output generated by the panel.

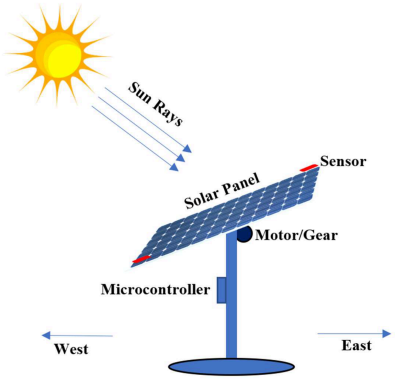


Figure 3. Solar Tracker
(Source: Inspiredpencil)

Solar trackers can be classified according to the number of rotational axes they use: single-axis and dual-axis systems. A Light Dependent Resistor (LDR) is an electronic component whose resistance changes in response to variations in the light intensity it detects, so it can also be regarded as a light sensor. The resistance of an LDR changes whenever the light falling on it changes. LDRs are typically made of cadmium sulfide, a semiconductor material whose resistance varies according to the amount of light it receives. In darkness, an LDR's resistance typically reaches around 10 Ω. Its resistance is inversely proportional to the illumination it receives, and in general an LDR operates based on the intensity of light striking the sensor.

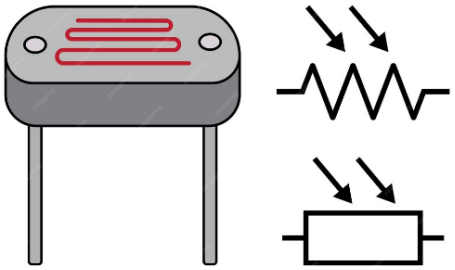


Figure 4. LDR Sensor
(Source: Freepik)

The magnitude of light intensity affects the magnitude of the LDR's resistance, and this effect follows an exponentially decreasing relationship; the resulting change in resistance produces a change in voltage, which is used to regulate the intensity of household lighting (Al Ghifari et al, 2022). The working principle of an LDR is fairly simple: when light is dim or absent, the LDR's resistance is high, blocking the incoming current so that the input value becomes zero and no voltage flows. When light is received, however, the resistance decreases toward zero, so that there is effectively no resistance (Annas, 2022).

The INA219 is a sensor module capable of measuring voltage, current, and power simultaneously. It works by reading the current flowing through an internal copper wire, which generates a magnetic field that is captured by an integrated magnetic-field IC and converted into a proportional voltage (Habiburosid et al, 2019).

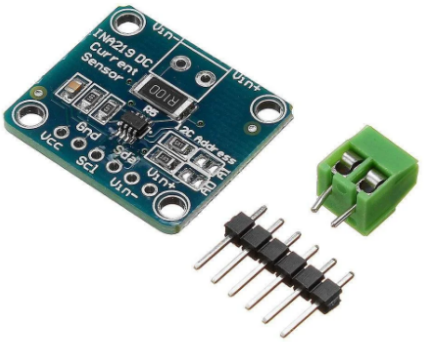


Figure 5. INA219 Sensor
(Source: Circuit.pk)

The potential power generated by a solar panel equipped with a solar tracker can be calculated using the equation $P = V \times I$, where P is the power produced, V is the voltage, and I is the current output from the solar panel (Nugroho, 2025). The power received by the solar cell (P_{in}) depends heavily on the intensity of solar radiation received relative to the surface area of the solar panel, expressed as $P_{in} = I_r \times A$, where P_{in} is the input power due to solar radiation (Watt), I_r is the intensity of solar radiation (Watt/m²), and A is the surface area of the solar panel (m²). Meanwhile, the power output of the solar panel (P_{out}) is the product of voltage and current, expressed as $P_{out} = V \times I$, where P_{out} is the power generated by the solar panel (Watt), V is the voltage produced by the solar panel (V), and I is the current produced by the solar panel (A) (Ulum, 2025).

METHODS

This research was conducted in DKI Jakarta, an area selected for its potential ocean-wave energy that can be used to generate electricity. The research period extended from the planning and preparation of the proposal through the completion of the research report in November 2025, and all research activities, including equipment testing, were carried out during this period.

The hardware components utilized in this study consist of a 3D printer and its corresponding filament. Additionally, the electronic setup integrates a servo motor, an LDR sensor, an INA219 power sensor, and connecting cables. For the design and development phase, the software applications employed are Fusion 360 and KiCad 9.0. Finally, Draw.io was used to create the system diagrams and visual documentation.

Research and Development (R&D) is a type of research used to create a specific product and test its effectiveness. In this study, we used the 4D development model, an acronym for Define, Design, Development, and Disseminate. This model is well suited to the requirements of product development (Harjanto et al, 2022).

The development of the solar tracker prototype followed the 4D model, which was applied for the following purposes: (1) to conduct a needs analysis based on the literature and interviews; (2) to design the device using relevant software; and (3) to design and develop the prototype based on information gathered from the literature.

In the Analysis (Define) stage, we conducted a needs analysis to gather information on the current state of energy in Indonesia and the innovation gaps that could be addressed, then reviewed literature to support the design and development of this solar tracker.

In the Design stage, the device was designed, producing a flowchart, an electronic circuit diagram, and a casing design for the solar tracker, as shown in Figures 6 and 7.

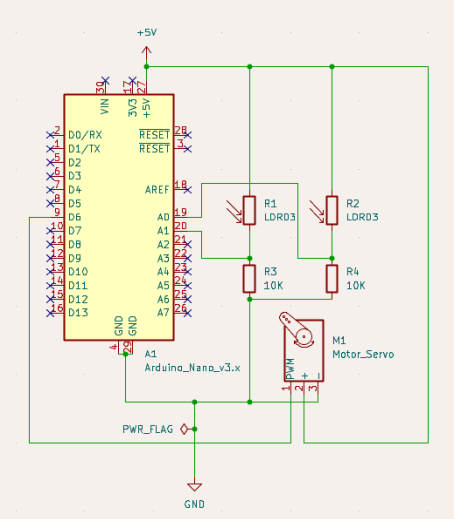
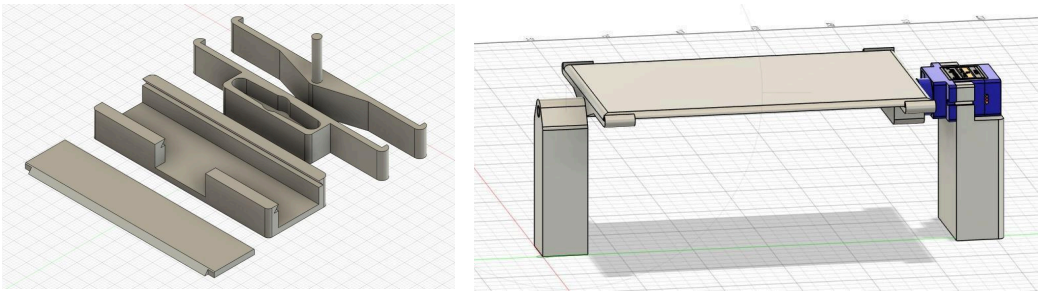


Figure 6. Wiring Diagram Schematic of the Solar Tracker Circuit



(a) (b)

Figure 7. 3D Casing Design of the Solar Tracker: (a) Exploded View, (b) Assembled View

In the Development stage, the researchers calibrated the LDR and INA219 sensors to be used. After calibration, all components were assembled into a single unit. The next stage was testing, in which the solar tracker's responsiveness and its power, current, and voltage measurement results were evaluated.

Disseminate is the final stage of the 4D development method. Once the product has passed testing at the development stage, received a positive assessment from experts, and demonstrated consistently proven performance, it can be considered to have reached the final stage of production (development), and is ready for widespread use once proven suitable.

RESULTS AND DISCUSSIONS

The performance of the developed solar tracker system is presented in the following subsections, covering its tracking behavior, its voltage and power measurements, and an analysis of the negative current readings observed during testing.

Solar Tracker System Performance

The solar tracker designed in this study successfully operated as intended. The system was able to automatically move the solar panel to follow the direction of incoming sunlight using two LDR sensors positioned on the left and right sides of the panel. The microcontroller read the difference in light intensity between the two LDR sensors and drove a servo motor until the panel reached the position with the highest light intensity.

During testing, the solar panel was able to move responsively in line with changes in the position of the light source, demonstrating that the control algorithm based on comparing light intensity worked optimally. The servo movement was smooth and stable, so that the panel consistently oriented itself toward the point of maximum light intensity.

Voltage and Solar Panel Power Measurement

Power measurement was carried out using two parameters: voltage (V) and current (I). Test results showed that the voltage values measured by the sensor behaved normally, increasing when light intensity was high and decreasing when light conditions were reduced.

However, the current measurement exhibited a phenomenon of negative value readings. This was the only component that did not function entirely as originally designed.

Analysis of the Cause of Negative Current Readings

Based on observation and the characteristics of the current sensor (INA219), negative current values can be caused by the following technical factors.

1. Reversed current direction at the sensor: the current sensor has a specific polarity. If the current input wiring is connected in reverse, for example, with the load on the IN–side and the source on the IN+ side — the sensor will read the current as reverse current, producing a negative value. This is the most common cause.
2. Uncalibrated sensor offset: Hall-effect–based current sensors have a zero-current midpoint value that should ideally sit at the center of the ADC reading. If this offset is not properly calibrated, small current readings can appear negative even when the actual current is not negative.
3. Reverse current in the solar panel: a solar panel produces forward current when exposed to light, but when the panel's voltage is lower than that of the load, a small current can flow back toward the panel. The sensor detects this reverse current as a negative value. This condition is normal when the system does not use a blocking diode.

CONCLUSIONS

Overall, the solar tracker system developed in this study performed very well in directing the solar panel to its optimal position. The increase in voltage values shows that the light-tracking mechanism worked as intended. The only shortcoming was found in the negative current readings, which stem from technical characteristics of the sensor rather than from the performance of the solar tracker itself. It can therefore be concluded that the solar tracker successfully increased the potential power output of the panel, and that improving the current sensor is a logical next step toward obtaining a more accurate power analysis.

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