

Design and Performance Analysis of Dual-Axis Solar Tracking to Enhance PV Efficiency Using Mamdani Fuzzy Logic Method

Seflahir Dinata^{1,2*}, Ahmad Faisal Mohamad Ayob², Fariq Alamsyahid Al Ghiffari¹, Didik Krisyanto¹, Heranudin¹, Sunardi¹

¹Department of Electrical Engineering, Pamulang University, Tangerang Selatan, Banten, Indonesia

²Faculty of Ocean Engineering Technology, University Malaysia Terengganu, Terengganu, Malaysia

*Corresponding author, e-mail: dosen01138@unpam.ac.id

Abstract— The efficiency of a solar panel (PV) depends on solar radiation. In general, the solar panels will produce maximum power with radiation of 1000 W/m^2 at a temperature of 25°C . The sun's relative position will affect the strength of solar radiation received by the PV. This work aims to implement Mamdani fuzzy logic to optimize sunlight detection by dual-axis solar tracking (DAST) movement. The designed solar tracker consists of a light sensor (light-dependent resistor/LDR) as the input, an Arduino Mega as the controller, and a linear actuator to drive the solar panels. The solar panels used are 100 Wp monocrystalline. Data collection was carried out for 10 hours with time intervals every 10 minutes, starting from 7.00 am to 17.00 pm. Efficiency optimization is reviewed by comparing the output voltage of solar panels using and without sunlight tracking. The test results show that the solar tracker shows significant performance in maximizing the capture of sunlight so that the PV gets optimum radiation. The energy generated by fixed and solar trackers is 0.63 kWh and 0.92 kWh. The solar tracker also result higher efficiency 4.17% more, it shows that the use of the proposed method can increase the PV efficiency.

Keywords: Dual-Axis Solar Tracking, Linear Actuator, Mamdani Fuzzy Logic, PV efficiency

This article is licensed under the [CC-BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.

1. Introduction

The generation of electrical energy in solar panels is directly proportional to the dimensions and the amount of solar radiation received by the solar panels [1]. In designing a solar power generation system, the angle of inclination of the solar panel (tilt angle) is an important consideration for optimal solar radiation reception [2], [3], [4]. Figure 1 shows three components of solar radiation on an inclined plane, direct irradiation that hits the panel plays a major role as a main component in maintaining the electrical energy generated throughout the day [4]. The optimum condition for absorbed solar radiation occurs when a perpendicular angle is formed between the direction of incoming sunlight and the solar panel [5], [6], [7]. However, this is not possible in solar power generation systems where the solar panels are installed permanently, because of the change in the sun's movement from east to west every day. Therefore, the generation of electrical energy from solar panels can be increased by creating a system that moves the solar panels following the movement of the sun, namely solar tracking[8], [9], [10].

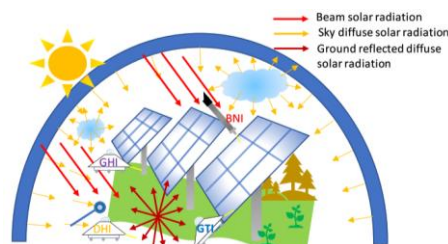


Figure 1. Solar Irradiation Components [4]

The essence of solar tracking aims to regulate the size of the angle formed between the PV and incoming solar radiation, in other words, increasing the solar radiation received [11]. The operation of the solar tracking system can be divided into four types, namely based on the type of drive, based on the angular movement, based on the control strategy, and based on the sunlight tracking strategy [12]. Based on the tracking strategy, the solar tracking system works based on date and time, light sensor, time and light sensor and time [13]. Based on the drive system, it is divided into active and passive tracking [14]. Based on the control strategy, solar tracking systems are divided into open-loop, closed-loop, and hybrid tracking [15]. Based on its angular movement, solar tracking is categorized into two, namely single and dual-axis configurations [16]. Single-Axis solar tracking is a mechanical system that moves photovoltaic panels along one axis of rotation (horizontal, vertical, or tilted) using a single drive motor to follow the sun's daily path [17]. A DAST system is an automated system designed to increase energy production by precisely moving photovoltaic (PV) panels to follow the position of the sun [18]. Due to the revolution and rotation of the earth, it causes two degrees of freedom of the apparent motion of the sun, and the dual-axis tracker can realize more optimal tracking of the sun's movement to optimize the absorption of sunlight [19]. DAST are gaining popularity in solar energy applications, due to the tracker's ability to continuously align the PV perpendicular to the sun, thereby maximizing sunlight exposure and solar panel efficiency [19], [20].

The application of the fuzzy logic method (FLM) in DAST has been used to increase electrical energy production and solar panel efficiency [21], [22], [23]. The study [21]The sensorless fuzzy logic controllers application on DAST systems has been proven to be effective in optimizing power production. This research successfully implemented the Fuzzy Logic Controller (FLC) on a DAST using the Takagi-Sugeno method to optimize the capture of sunlight via tilt angle movement from 8 am until 4 pm. This system is proven to increase power generation compared to static systems through adaptive motor control. In [22], this research successfully improved the electricity generation using two control strategies for DAST. Simulink and SolidWorks platform used to design an electrical and mechanical system DAST. By using two LDR sensors, the motor will rotate to east or west based on the output voltage of the LDR sensor. In [23], a low-cost DAST was designed to use four LDR sensors as inputs to control the tracking. The strategy of tracking based on the logic sensors (design of digital logic) to rotate the primary and secondary axis. The implementation of DAST has been shown to significantly increase current output and daily energy absorption compared to static solar panel systems. The panel's ability to precisely track the sun's movement optimizes energy conversion throughout the day.

For this reason, the research designs a DAST system based on Arduino Mega 2560 using Mamdani fuzzy logic controller. This method is used to regulate the movement of the linear actuator to be more precise in detecting the movement of the sun based on the results of the four LDR sensor reading. Solar tracking performance is measured by comparing the output voltage and current values of the solar panel directly at its output terminal using a voltmeter and an ammeter. Measurement of solar radiation, tilt, and temperature received by solar panels using the Seaward Solar Survey 200R measuring instrument. Solar tracking performance analysis is carried out by comparing the efficiency between solar panels in the tracking system and fixed solar panels. Likewise, the impact of solar panel movement on the solar panel's solar radiation reception is analyzed to show that changing its angle can increase solar radiation reception, thereby increasing output power, efficiency, and energy generated.

2. Method

This research was conducted on the roof of building B, Pamulang Viktor University campus at the coordinate point -6.3377, 106.6912 ° as shown in Figure 2. The Arduino circuit board used in this research is the Arduino Mega. Because this board has the advantages of being flexible, low-cost, and easy to use, it can be integrated into various electronic projects.



Figure 2. Satellite Image of Research Location

Figure 3 shows the wiring between the input, process, and output sections of the tracking system. There are four LDRs placed on the 4 sides of the solar panel to detect sunlight. The output signal from the LDR is processed by the Arduino Mega to control the movement of the linear actuator (output) on each axis.

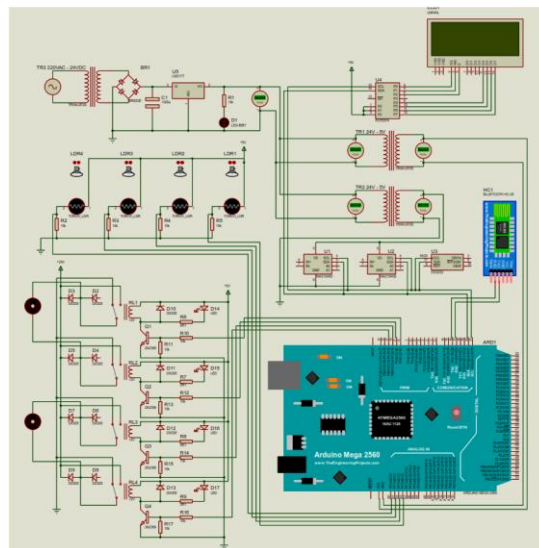


Figure 3. Integration Circuit between Input, Processor, and Actuator

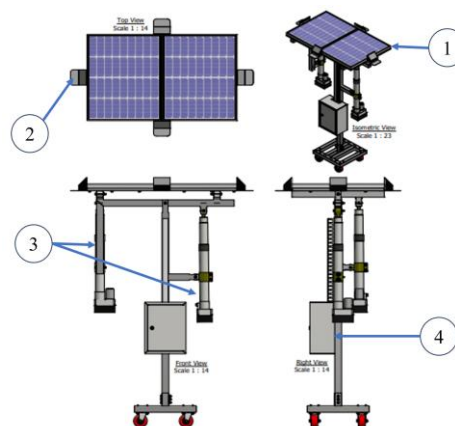


Figure 4. Components in the Tracking System

A linear actuator is a device for converting rotational motion into forward or backward linear motion with input provided by the system. The forward and backward actions allow the device to pan, tilt and lift the PV by controlling the actuators. Figure 4 is a design of a DAST tool consisting of 1) a solar panel, 2) an LDR sensor, 3) a linear actuator, and 4) a control circuit panel box.

In the Mamdani method, 4 stages are required to obtain output, namely forming a fuzzy set, determining the degree of membership, establishing rules, and defuzzification. The input and output sets and their membership are written using the millis function to determine the Arduino input and output as Figure 5.

```

158 if (currentMillis - previousMillis >= interval) {
159   // save the last time you blinked the LED
160   previousMillis = currentMillis;
161   // Read Input: kn
162   g_fisInput[0] =ldr_2;
163   // Read Input: ki
164   g_fisInput[1] =ldr_4;
165   // Read Input: bw
166   g_fisInput[2] =ldr_1;
167   // Read Input: at
168   g_fisInput[3] =ldr_3;
169
170   g_fisOutput[0] = 0;
171   g_fisOutput[1] = 0;
172
173   defuzzy();
174
175   if (g_fisOutput[0] >= 0) {
176     kanan();
177   } else if (g_fisOutput[0] == 0.5) {
178     stop();

```

Figure 5. Input and output defuzzyfication

Next, Figure 6 show the Mamdani fuzzy logic design was carried out using the MATLAB program. Input design is carried out by creating appropriate input variables, namely right, left, middle, and bottom, with high, medium, and low membership values. The output is determined based on the fuzzy logic output. The membership consists of left, still, and right, for each actuator with membership values of 0, 0.5, and 1, respectively. Determination of Mamdani fuzzy logic rules is carried out to determine the movement of the actuator according to the input function using the IF and THEN statements.

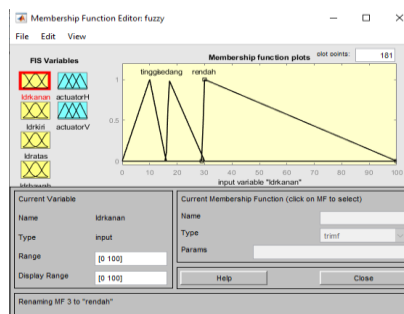


Figure 6. Fuzzy logic input set



Figure 7. Rule Viewer Fuzzy

After determining the input, output and rules, the final step is to carry out a fuzzy simulation to determine the rules that are in accordance with fuzzy logic. Figure 7 shows that the sensor input is in

the medium range, in accordance with the established rules. Therefore, the output of both actuators is 0.5, which is the same as being at rest.

To measure the performance of the tracking system, tests were carried out using two identical solar panels (using tracking and fixed) with the data listed in Table 1.

Table 1. The PV Data Sheet

Model	SP100-18M
Peak Power	100 W
Open Circuit Voltage (Voc)	21.8 V
Short Circuit Current (Isc)	6.05 A
Maximum Power Voltage (Vmp)	17.8 V
Maximum Power Current (Imp)	5.62 A
Cell Efficiency	16.93%
STC irradiance	1000 W/m ²
Operating Temperature	-4°C + 85°C

Testing is carried out by measuring the open circuit voltage and short circuit current of the PV using a DC voltmeter and a DC ammeter. Meanwhile, the performance of solar panels is analyzed using an equation approach. To determine the efficiency value of PV, the equation is used [24].

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \quad (1)$$

Where the fill factor FF value is taken from the data sheet on the PV, the value of which is [25].

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (2)$$

The amount of energy in Watt Hours generated by each PV is calculated using the equation [26].

$$E = P_{out} \times t \quad (3)$$

While the output power is obtained from [27].

$$P_{out} = \eta \times A \times I \quad (4)$$

3. Result and Discussion

Result of Testing dan Measurement

This solar tracker was tested to determine its performance. Data collection was carried out using the measuring instruments mentioned in the introduction. Measurements were carried out for one day, starting at 07:10 am until 17:00 pm with a 10-minute interval for each data. The parameters measured on solar panels consist of solar panel temperature, ambient temperature, open circuit voltage, short circuit current, radiation, and tilt angle.

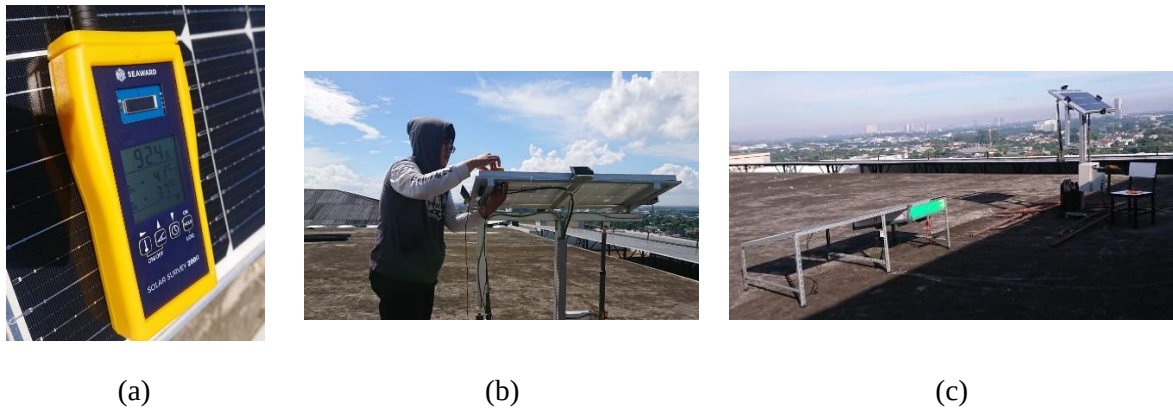


Figure 8. Data Collection (a) Measurement of Radiation, PV Tilt, PV Temperature, and Environmental Temperature via Seaward Isolar Survey 200R, (b) DAST System, (c) PV Testing with Tracker System and Fixed

The intensity of solar radiation has an impact on the output power of PV and increases its surface temperature as seen in Figure 9.

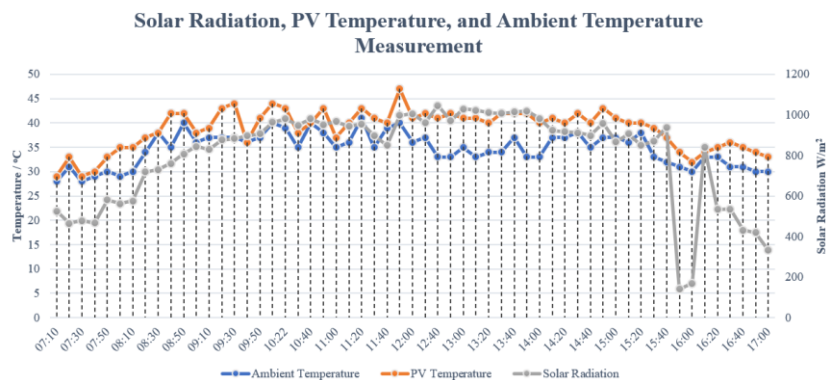


Figure 9. Results of radiation measurements, PV temperature, and environmental temperature

With the scorching hot weather during the test, the intensity of solar radiation experienced an increasing trend from the beginning of data collection to a peak value of 1046 W/m² at 12: 40 pm. Likewise, the temperature of the solar panels and the ambient temperature increased from morning to noon, with the highest values of 47 °C at 11: 50 am and 41 °C at 11: 20 am, respectively. Then from noon to evening, there was a decreasing trend in the intensity of solar radiation, the temperature of the solar panels, and the ambient temperature, and obtained an average of 804.51 W/m², 38.77 °C, and 34.68 °C respectively.

The intensity of solar radiation significantly impacts the increase in open circuit voltage generated by solar panels, as shown in Figure 10. During the test, it was seen that the solar tracker system was able to maintain optimal sunlight capture so that the open circuit voltage of the solar panels produced was higher than that of solar panels without trackers, namely 23.7 Volts and 22.5 Volts, respectively. When compared to the average open circuit voltage during the test, the solar panel with tracking produced 23.12 Volts, and the fixed solar panel still produced 21.65 Volts. From these values, it was found that the tracker system produced a higher average open circuit voltage of 1.47 Volts.

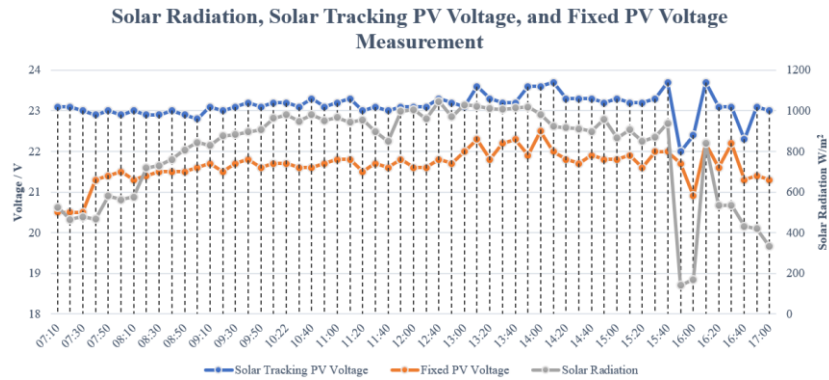


Figure 10. Results Of Measuring Solar Radiation, Open Circuit Voltage of The PV Tracking System, And Open Circuit Voltage Of The Fixed Solar Panel

The short-circuit current of solar panels increases significantly with the increase in solar radiation intensity, as shown in Figure 11. With 57 measurement data, it can be seen that the increase in solar radiation intensity is directly proportional to the short-circuit current. The highest short-circuit current of the tracking system solar panel is 7.01 A, which occurs at the highest solar radiation intensity of 1046 W/m^2 , while the fixed PV produces the highest short-circuit current of 6.53 A. In addition, when viewed from the average value of the short-circuit current, the tracking system and fixed system produce currents of 5.22 A and 3.83 A, respectively. In other words, the tracking system has a higher average short-circuit current value of 1.39 A.

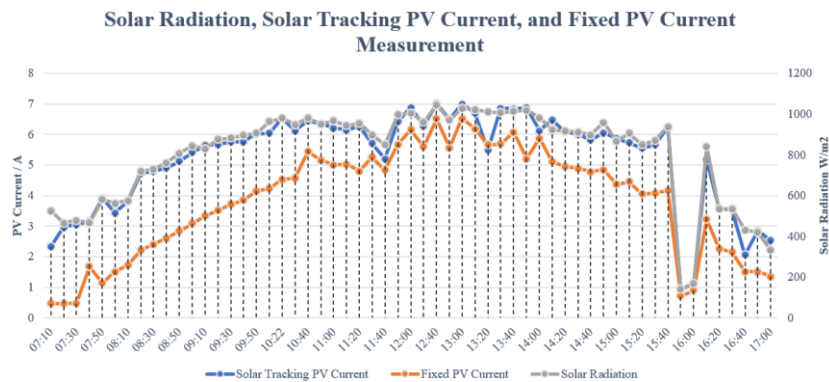


Figure 11. Results Of Measuring Solar Radiation, Tracking Solar Panel Short Circuit Current, And Fixed Solar Panel Short Circuit Current

Based on the solar panel data sheet and equations 1 and 2, the fill factor value is 0.76, while the efficiency of the solar panel with the tracking system and the efficiency of the fixed solar panel are as shown in Figure 12.

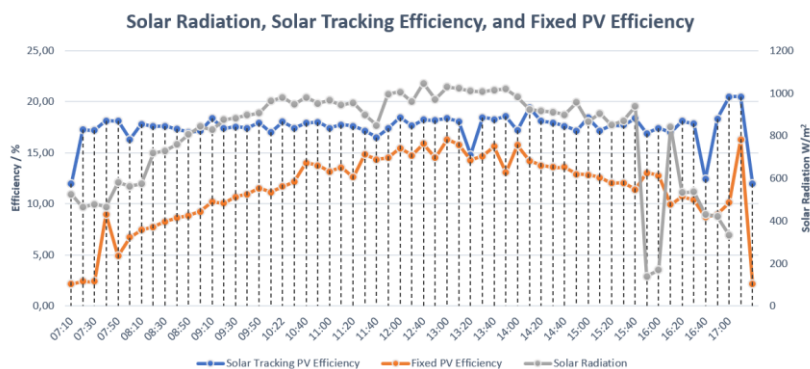


Figure 12. Relationship Between Solar Radiation And Solar Panel Efficiency

As stated in the introduction, the solar tracking system aims to increase the capture of solar radiation received by solar panels. This ensures optimum efficiency during peak sun hours. Figure 12 shows that the solar tracking system produces a 4.17% higher efficiency than the fixed system, with the highest efficiencies of the two systems being 20.49% and 16.32%, respectively. This optimization of sunlight capture can also be seen from the significant difference in the average efficiencies of the two systems, which are 17.53% for the tracking system and 11.53% for the fixed system.

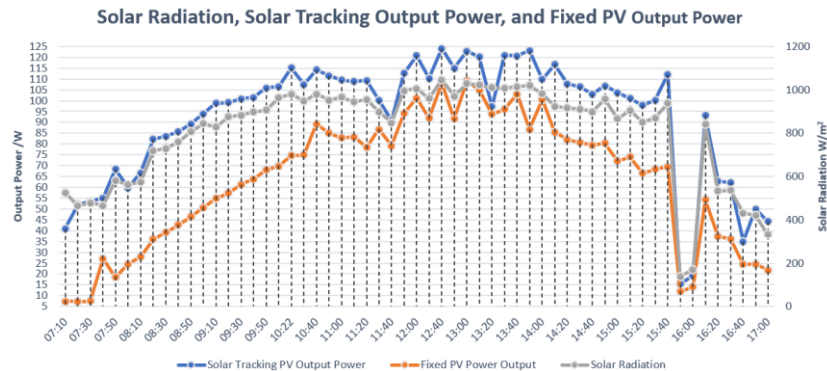


Figure 13. Relationship Between Solar Radiation And PV Output Power

Figure 13 shows a comparison of the PV output power between the tracking system and a fixed system. The tracking system shows that the optimization of solar radiation has an impact on the output power produced. For 10 hours, it can be seen that the highest output power for solar panels using a tracking system and a fixed system is 124.13 Watts and 109.18 Watts, respectively, and the average power is 92.05 Watts and 63.33 Watts. In other words, there is an increase in average power of 28.71 Watts after using the tracking system. By using equation 3, a significant difference in energy generation by the two solar panels is obtained. The application of the tracking system is able to increase energy by 45.34%, where in the fixed system, the solar panel generates energy of 0.63 kWh, while the tracking system produces energy of 0.92 kWh.

Optimizing sunlight capture is the primary objective of implementing a two-axis tracking system, as it maximizes solar radiation reaching the solar panels. This is linearly correlated to increased efficiency, output power, and energy generated by the solar panels. The application of Mamdani fuzzy control to control the movement of linear actuators based on LDR sensor readings has shown a significant impact on optimizing solar panel performance. Figure 14 shows the changes in solar panel angles generated by the designed two-axis tracking system. The angular changes observed during the study indicate that the system is able to track the sun's movement effectively. These angular changes also indicate that the PV system's tilt varies, resulting in maximum exposure to solar radiation from morning to evening.

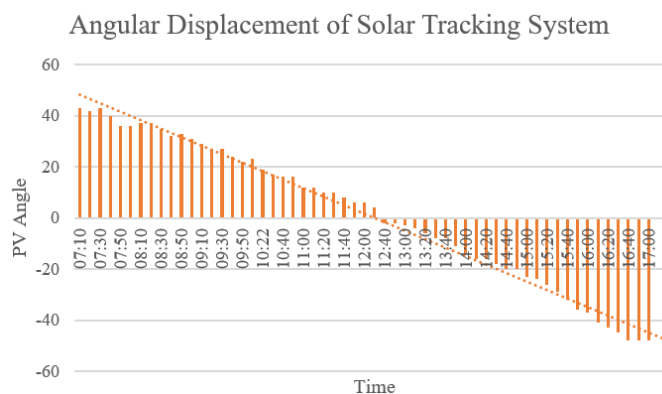


Figure 14. PV Tilt Variations Generated By The Two-Axis Tracking System.

Validation and Discussion

Based on the test and measurement data, the following discussion is conducted to evaluate the solar tracking system data. The evaluation uses four main graphs, which include: Time-Series Plot to view the solar radiation profile throughout the day, Scatter Plot to view the correlation between radiation and short-circuit current, Scatter Plot to view the relationship between PV temperature and Voc, and Line Plot to view changes in the PV Tracker angle over time. The four graphs are shown in Figures 15 until 18.

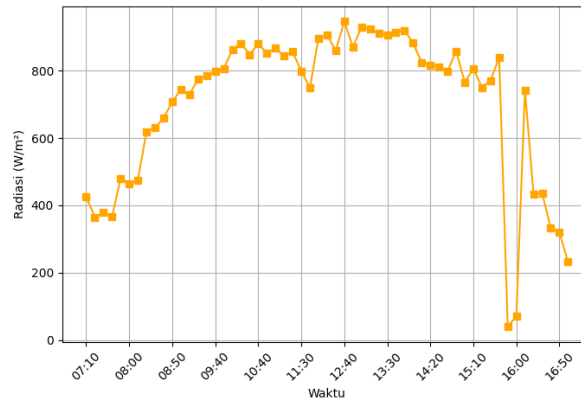


Figure 15. Solar Radiation Profile

Figure 15 is used to validate environmental conditions. The solar radiation profile forms a bell curve indicating a sunny day, but there is a drastic decrease at 15:50 (40 W/m²) and 16:00 (70 W/m²) before finally jumping back to 742 W/m² at 16:10. Using the cross-validation method, looking back at the electricity data, at 15:50, the I_{sc} value also plummeted to 0.92 A. Because both measurement results (radiation and short-circuit current) show a decrease at the same time, this proves that the data is physically valid because there is a real phenomenon (shadow) by thick clouds that block the sunlight.

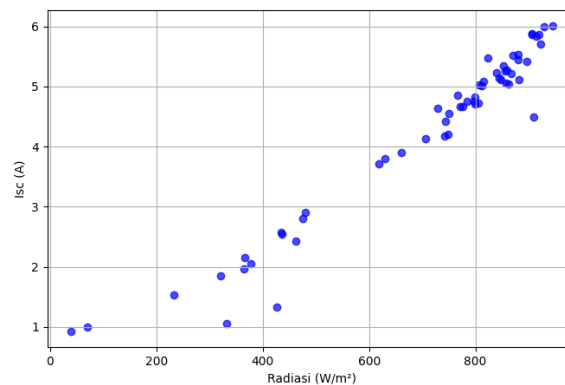


Figure 16. Relationship between solar radiation and short circuit current

Pearson correlation was used to see the strength of the relationship between radiation and short-circuit current in Figure 16. The second correlation value is 0.9742 (very close to 1). This data is strongly validated physically. The current I_{sc} is proven to be directly proportional to the radiation intensity ($I_{sc} \propto G$). At 13:20, the radiation value was at 910 W/m², but I_{sc} suddenly dropped to 4.49 A, this was due to partial shading of the solar panel surface at that minute.

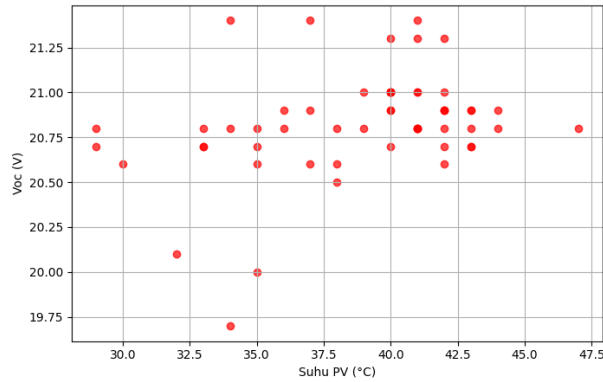


Figure 17. Relationship between PV temperature and Voc

Figure 17 is used to validate the relationship between temperature and Voc. From the graph, it can be seen that the relationship between PV temperature and Voc appears somewhat scattered. The dominant Voc value is stable in the short range of 20.5 V to 21.4 V. There is a low voltage outlier point at the bottom, namely 19.7 V at 15:50. This occurs because at that minute the solar radiation drops drastically to 40 W/m². In photovoltaic theory, when the radiation is very low, the Voc value will decrease logarithmically, ignoring the effect of temperature.

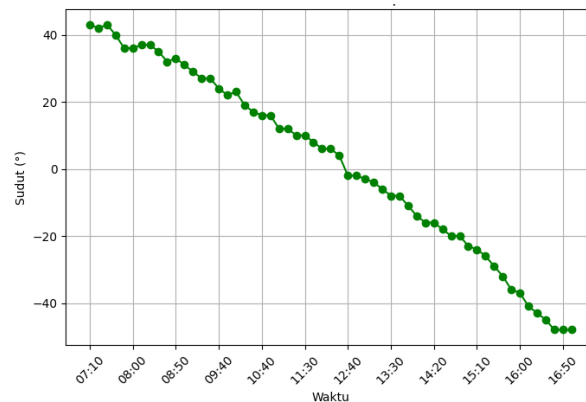


Figure 18. Solar Panel Angle Profile

Mechanical Validation of Movement (Solar Tracker Angle). Figure 18 shows a very smooth and monotonous decrease in angle, moving from +43° at 07:10 am (facing east) to -48° at 17:00 pm (facing west). This indicates that the solar tracker motor is functioning consistently and precisely. No extreme angular spikes or mechanical system jams were observed throughout the data collection.

4. Conclusion

In this study, a DAST system has been designed and tested with a novel combination of solar radiation measurements, solar panel temperature, and solar panel tilt, along with solar panel voltage and current. From the test, it was found that the movement of the tracking system was able to track sunlight based on fuzzy Mamdani control so that it could increase sunlight absorption during the experiment. The DAST system is capable of detecting the sun's movement through precise and consistent movements to maintain the solar radiation captured by the solar panels at optimum levels. Furthermore, the maintained solar radiation exposure is evident from the I_{sc} value, which forms a bell curve (rising from morning to midday and gradually decreasing again until evening) proportional to the solar radiation value.

The use of this tracking system can increase the average power generated by solar panels by

45.33% compared to fixed solar panels. Similarly, the solar panels using tracking can increase the energy generated by 0.29 kWh compared to fixed solar panels. This shows that adjusting the solar panel's position relative to sunlight increases its power output and efficiency [28], [29].

Suggested follow-up research plans are solar tracking systems focusing on the integration of AI and IoT for intelligent algorithms, structural optimization to reduce costs [30], [31]. In addition, the study focuses on physical validation, implementation of two-axis tracking, and local data-driven optimization to maximize energy efficiency. Further developments include hybrid system integration, cost-benefit analysis, and application to grid-connected PV systems [32].

Acknowledgment

The authors would like to express their gratitude to all parties, especially to the Department of Electrical Engineering, Pamulang University, for their support in providing facilities during this research.

References

- [1] M. Božíková *et al.*, “The effect of azimuth and tilt angle changes on the energy balance of photovoltaic system installed in the southern slovakia region,” *Applied Sciences (Switzerland)*, vol. 11, no. 19, Oct. 2021, doi: 10.3390/app11198998.
- [2] H. U. Manzoor, S. M. Aaqib, T. Manzoor, F. Azeem, M. W. Ashraf, and S. Manzoor, “Effect of Optimized Tilt Angle of PV Modules on Solar Irradiance for Residential and Commercial Buildings in Different Cities of Pakistan: Simulation-Based Study,” *Energy Sci. Eng.*, vol. 13, no. 4, pp. 1831–1845, Apr. 2025, doi: 10.1002/ese3.70004.
- [3] D. Muhammad, A. Hiendro, and Y. Yandri, “Determination Of Tilt And Azimuth Angles Of Solar Panels At Tanjungpura University Solar Power Plant Using Pvsyst 7.3 Software Simulation,” *Telecommunications, Computers, and Electricals Engineering Journal*, vol. 1, no. 3, p. 218, Feb. 2024, doi: 10.26418/telectrical.v1i3.72983.
- [4] M. Asloune, G. Notton, and C. Voyant, “Quality control of tilted solar irradiance: Asystematic and generalizable procedure,” *Renew. Energy*, vol. 259, Mar. 2026, doi: 10.1016/j.renene.2025.125090.
- [5] R. Melhem, Y. Shaker, F. M. A. Mazen, and A. Abou-Elnour, “Investigation of the Optimum Solar Insolation for PV Systems Considering the Effect of Tilt Angle and Ambient Temperature,” *Energies (Basel)*, vol. 18, no. 19, Oct. 2025, doi: 10.3390/en18195257.
- [6] H. M. Nahim, T. Ibrahim, J. Faraj, S. Ali, M. Khaled, and M. Darwiche, “Optimizing solar panel tilt angles for enhanced energy Production: Case studies in Lebanon,” *Case Studies in Thermal Engineering*, vol. 73, p. 106720, Sep. 2025, doi: 10.1016/j.csite.2025.106720.
- [7] M. S. Khan, M. A. M. Ramli, H. F. Sindi, T. Hidayat, and H. R. E. H. Bouchekara, “Estimation of Solar Radiation on a PV Panel Surface with an Optimal Tilt Angle Using Electric Charged Particles Optimization,” *Electronics (Switzerland)*, vol. 11, no. 13, Jul. 2022, doi: 10.3390/electronics11132056.
- [8] A. Imthiyas, S. Prakash, N. Vijay, A. Alwin Abraham, and B. Ganesh Kumar, “Increasing the efficiency of solar panel by solar tracking system,” in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing Ltd, Dec. 2020. doi: 10.1088/1757-899X/993/1/012124.
- [9] W. Sasmitaninghidayah, B. C. Pakartiluwih, I. Tazi, A. Abtokhi, M. Mutmainnah, and S. Suhaimi, “Development Of An Automatic Sun Tracking System On Solar Panels As Electric Power Supplier At Smart Garden,” *Journal of Renewable Energies*, vol. 28, no. 1, pp. 69–80, Jun. 2025, doi: 10.54966/jreen.v28i1.1287.

- [10] M. Hammas, H. Fituri, A. Shour, A. A. Khan, U. A. Khan, and S. Ahmed, “A Hybrid Dual-Axis Solar Tracking System: Combining Light-Sensing and Time-Based GPS for Optimal Energy Efficiency,” *Energies (Basel)*, vol. 18, no. 1, Jan. 2025, doi: 10.3390/en18010217.
- [11] P. Rai, D. Prasad, R. P. Singh, and R. Roy, “A self-powered hybrid dual-axis solar tracker with integrated PV-TEG model for improved grid injection and autonomous operation,” *Results in Engineering*, vol. 29, Mar. 2026, doi: 10.1016/j.rineng.2025.108480.
- [12] T. Zou *et al.*, “Research progress and engineering applications of technology-driven strategies for solar tracking systems,” Apr. 01, 2026, *Elsevier B.V.* doi: 10.1016/j.esd.2025.101901.
- [13] Z. Zhang *et al.*, “A novel solar tracking model integrated with bistable composite structures and bimetallic strips,” *Compos. Struct.*, vol. 248, Sep. 2020, doi: 10.1016/j.compstruct.2020.112506.
- [14] A. A. Abed, M. R. El-Marghany, W. M. El-Awady, and A. M. Hamed, “Recent advances in parabolic dish solar concentrators: Receiver design, heat loss reduction, and nanofluid optimization for enhanced efficiency and applications,” Aug. 15, 2024, *Elsevier B.V.* doi: 10.1016/j.solmat.2024.112930.
- [15] A. Bahrami, C. O. Okoye, H. H. Poursasl, and V. M. Khojastehnezhad, “Techno-economic comparison of fixed and tracking flat plate solar collectors in the northern hemisphere,” *J. Clean. Prod.*, vol. 378, Dec. 2022, doi: 10.1016/j.jclepro.2022.134523.
- [16] M. S. Azam *et al.*, “Performance enhancement of solar PV system introducing semi-continuous tracking algorithm based solar tracker,” *Energy*, vol. 289, Feb. 2024, doi: 10.1016/j.energy.2023.129989.
- [17] M. O. Okwu *et al.*, “Single-Axis Solar Tracking Systems: A Comprehensive Design and Performance Study,” in *Procedia Computer Science*, Elsevier B.V., 2025, pp. 2740–2752. doi: 10.1016/j.procs.2025.01.334.
- [18] R. Rotar, F. M. Petcuț, R. Susany, F. Oprițoiu, and M. Vlăduțiu, “Dependability Assessment of a Dual-Axis Solar Tracking Prototype Using a Maintenance-Oriented Metric System,” *Applied System Innovation*, vol. 7, no. 4, Aug. 2024, doi: 10.3390/asi7040067.
- [19] B. Zhu, L. Wang, J. Wu, H. Cui, and Y. Tian, “Optimal design of a novel dual-axis parallel solar tracker,” *Chinese Journal of Mechanical Engineering*, vol. 39, p. 100108, 2026, doi: 10.1016/j.cjme.2025.100108.
- [20] B. M. A. R. Mendis, J. C. Kurnia, M. M. Reddy, S. Roy, and S. M. Al-Ameri, “Dual-axis solar tracking system with real-time weather-responsive self-cleaning mechanism for photovoltaic panels,” *Renew. Energy*, vol. 259, Mar. 2026, doi: 10.1016/j.renene.2025.125084.
- [21] B. S. Aprilia, M. Z. Romdlony, J. Raharjo, and Y. G. Sidik, “Fuzzy based sensorless tracking controller on the dual-axis PV panel for optimizing the power production,” *JURNAL INFOTEL*, vol. 13, no. 4, pp. 230–238, Dec. 2021, doi: 10.20895/infotel.v13i4.738.
- [22] U. Mamodiya and N. Tiwari, “Dual-axis solar tracking system with different control strategies for improved energy efficiency,” *Computers and Electrical Engineering*, vol. 111, Oct. 2023, doi: 10.1016/j.compeleceng.2023.108920.
- [23] C. Jamroen, P. Komkum, S. Kohsri, W. Himananto, S. Panupintu, and S. Unkat, “A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation,” *Sustainable Energy Technologies and Assessments*, vol. 37, Feb. 2020, doi: 10.1016/j.seta.2019.100618.
- [24] P. Raheem, Fattah H. Hasan, Sameer Algburi, and Sarah B. Ezzat, “Investigating the Impact of Internal and External Factors on Solar Cell Performance to Enhance Energy Conversion Efficiency,” *NTU Journal of Renewable Energy*, vol. 8, no. 1, pp. 14–23, Jan. 2025, doi: 10.56286/x12hd434.
- [25] L. G. Hua *et al.*, “Comparative Analysis of Power Output, Fill Factor, and Efficiency at Fixed and Variable Tilt Angles for Polycrystalline and Monocrystalline Photovoltaic Panels—The Case of Sukkur IBA University,” *Energies (Basel)*, vol. 15, no. 11, Jun. 2022, doi: 10.3390/en15113917.
- [26] D. Atsu, I. Seres, and I. Farkas, “The state of solar PV and performance analysis of different PV technologies grid-connected installations in Hungary,” *Renewable and Sustainable Energy Reviews*, vol. 141, May 2021, doi: 10.1016/j.rser.2021.110808.

- [27] V. Muniyandi, V. K. Reddy Majji, M. Ravindra, R. Adireddy, and A. K. Balasubramanian, “Feature selection-based irradiance forecast for efficient operation of a stand-alone PV system,” *Green Energy and Intelligent Transportation*, vol. 5, no. 2, Apr. 2026, doi: 10.1016/j.geits.2025.100308.
- [28] B. Rinchi, R. Dababseh, M. Jubran, S. Al-Dahidi, M. E. B. Abdalla, and O. Ayadi, “Global prediction of optimal solar panel tilt angles via machine learning,” *Appl. Energy*, vol. 382, Mar. 2025, doi: 10.1016/j.apenergy.2025.125322.
- [29] H. Nadeem, R. J. Milcarek, C. A. Miller, and E. B. Stechel, “Impact of Panel Tilt Angle and Tracking Configuration on Solar PV and Energy Storage Capacity for a Carbon-Neutral Grid in Arizona,” *Energies (Basel)*, vol. 18, no. 18, Sep. 2025, doi: 10.3390/en18184974.
- [30] K. Kumba, P. Upender, P. Buduma, M. Sarkar, S. P. Simon, and V. Gundu, “Solar tracking systems: Advancements, challenges, and future directions: A review,” Dec. 01, 2024, *Elsevier Ltd.* doi: 10.1016/j.egyr.2024.09.038.
- [31] R. Sadeghi, M. Parenti, S. Memme, M. Fossa, and S. Morchio, “A Review and Comparative Analysis of Solar Tracking Systems,” May 01, 2025, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/en18102553.
- [32] N. Guler, Z. Ben Hazem, I. A. R. Moghrabi, and A. Gunes, “A fuzzy logic controlled solar tilt angle optimization for renewable energy applications,” *Franklin Open*, vol. 13, Dec. 2025, doi: 10.1016/j.fraope.2025.100420.