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Solar Panel Efficiency Improvement through Dual-Axis Solar Tracking with Fuzzy Logic and Water Treatment Techniques

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A B S T R A C T

Indonesia's heavy reliance on non-renewable energy sources, such as fossil fuels and other resources obtained from mining, poses sustainability challenges. Solar panels, which are environmentally friendly and renewable energy alternatives, are designed to convert solar energy into electricity, and they have shown room for improvement in their efficiency. One method to enhance its efficiency is the utilization of dual-axis solar tracking, employing linear actuators for control over both horizontal and vertical panel movements. In addition, solar panels frequently experience efficiency losses as a result of high working temperatures when exposed to sunlight. The use of water treatment techniques may help address this problem. In this research, the two-axis solar tracking approach with water treatment methods were combined to achieve greater efficiency and boost energy production. A notable increase in solar panel efficiency was seen subsequent to the design, implementation, and testing of the proposed system, resulting in a notable rise in power output. Combining the two-axis solar tracking approach with water treatment methods produced solar panels with a 7.46% efficiency and a 17.77% power increment. Dual-axis solar tracking and combined with water treatment could significantly increase solar panel efficiency, which will ultimately lead to environtmentally clean renewable energy production increment.

INTRODUCTION

Indonesia predominantly relies on non-renewable natural resources like fossil fuels and other resources obtained through mining for its electricity consumption [1]. At present, the availability of these resources is decreasing [2], resulting in increments in the prices of these non-renewable resources [3]. Additionally, their usage contributes to environmental pollution, which is not environmentally friendly [4]. Therefore, there is a need for new renewable energy sources.

Solar energy, alternatively referred to as solar power, is a renewable source of energy obtained from the sun [5], [6]. Due to its proximity to the equator, Indonesia receives ample sunlight, positioning it as an optimal region for harnessing solar energy [7]. In order to convert solar energy to electricity, a device is used which is solar panel.

Solar panel efficiency pertains to the capacity of a solar panel to transform sunlight into practical electrical energy [8]. While solar panels have made significant advancements in recent years, their efficiency is still not at its maximum potential [9].

In [10], the dual-axis solar tracking technique was utilized, employing a stepper motor and a linear actuator as the actuator components. To sense light, a photodiode controlled by an Arduino was employed. As a result, the efficiency of the solar panel experienced a notable improvement of 18%. On the other hand, in [11], utilization of an Arduino Mega 2560 microcontroller and a Linear Actuator motor was employed, resulting in 27.62% efficiency. In [12], the dual-axis solar tracking method was employed using an LDR sensor and a linear actuator to control the solar panel's movement. Additionally, a watering method was applied every day at 4 pm. The efficiency increased up to 43% over an 11-hour testing period. Based on the studies, the method used achieved the highest efficiency. In [13], a system was developed to enhance the efficiency of monocrystalline solar panels using water treatments. It has been demonstrated that water-based cooling is the most effective method, but the solar panels used are static. According to [14], fuzzy logic-based solar tracking can increase efficiency by 2.39%.

However, in this research, a combination of tracking and water treatment methods was designed, tested, and implemented. The tracking method used in this research was dual-axis tracking with fuzzy logic because it yields higher efficiency compared to single-axis tracking. On the other hand, fuzzy logic was added to increase efficiency even more, since prior research [15] has demonstrated that it increases efficiency more successfully than tracking methods without fuzzy logic.

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METHODS

The system comprised solar panels, four light sensors, two linear actuators, and a water treatment system. Each sensor was positioned in four directions: top, bottom, left, and right. The first linear actuator was horizontally adjusted to the solar panel based on the comparison of light intensity between the right and left sides. The second linear actuator was vertically adjusted to the solar panel based on the comparison of light intensity at the top and bottom. Lux data ranging from 1 to 100 was used for simplicity in calculations. The water treatment method involved the flow of water over the solar panel's surface when the temperature surpassed 65 °C.

Solar Panel

A solar panel is a device that transforms the energy of sunlight, which is composed of photons, into electrical energy [16]. According to the efficiency equation, a decrease in the current and voltage values will lead to a reduction in the efficiency of the solar panel. The comparison between current and voltage can be observed in Figure 1. The current measured at short circuit conditions is referred to as Isc, while the voltage measured at open circuit conditions is called Voc.

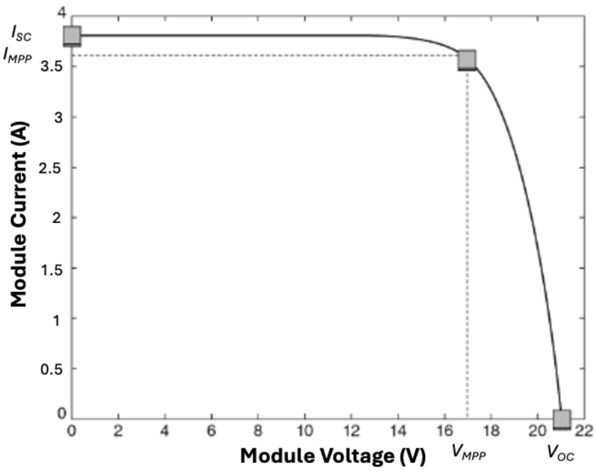

Figure 1. Graph of Current Against Voltage [17]

The solar panel used in this research was the GH solar Type GH 50M-18 Monocrystalline solar panel.

Light Intensity Sensor

Light Dependent Resistor (LDR) is a type of resistor that can detect light. Its resistance changes in response to the intensity of light it receives. The resistance of the solar panel decreases when subjected to higher light intensity, whereas it increases when exposed to lower light intensity. The LDR sensor offers the advantage of relying solely on the amount of light it receives for its operation [18].

Linear Actuator

A linear actuator is a type of actuator that facilitates motion along a straight or linear path [19]. This mechanism operates by extending and retracting a rod or cylinder to achieve movement as shown in Figure 2.

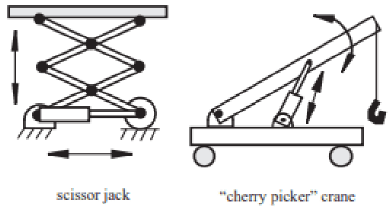

Figure 2. Example Movement of Actuator [19]

The linear motion produced by this device is caused by a screw, more commonly known as a lead screw [20]. This screw can rotate clockwise or counterclockwise, which causes its shaft to rotate. Essentially, it is a threaded rod that operates to raise and lower the screw while it is rotating. A 12V DC linear actuator with a rated power of 20W and a maximum power of 30W is utilized. This linear actuator has a length of 12 inches and a force of 1100 N.

The motor used can be either AC or DC, but the most commonly used is a 12V DC motor. The difference in speed and force is obtained by comparing the gear ratios within the gearbox system. In a linear actuator, speed and force are inversely proportional. If a greater force is desired, the speed needs to be reduced. This is because the constant in the linear actuator relates only to speed and force. The shaft will automatically stop when it reaches the end, thanks to limit switches or micro switches. These switches are located at the top and bottom of the shaft. When the switch is flicked, the power to the DC motor is cut off.

Temperature Sensor

A DS18B20 sensor was utilized as a temperature sensor. Its small size and compact surface have the advantage of providing fast output.

Fuzzy Logic

Fuzzy logic can also be referred to as vague logic. According to [21], in the realm of Boolean logic, the resulting values are limited to either 1 or 0. Fuzzy logic, often referred to as vague logic, aims to derive values that lie between 1 and 0. It is important to note that probability and fuzzy logic cannot be interpreted in the same manner since probability assesses the likelihood of an event transpiring, whereas fuzzy logic can generate values based on predictions. The fuzzy logic controller (FLC) diagram is structured into three sequential steps [22]: fuzzification, inference mechanism, and defuzzification.

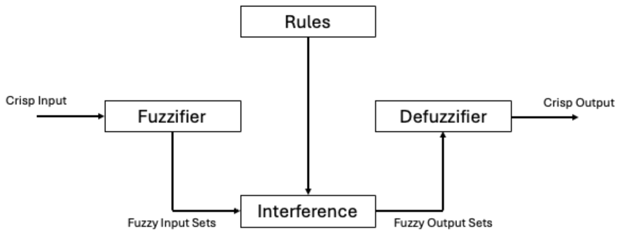

Figure 3. Scheme of FLC

According to Figure 3, the fuzzy logic system initiates with a crisp input, which represents a precise value obtained from a sensor or user. The fuzzification process is then employed to convert this crisp value into fuzzy input sets. These fuzzy input sets are subsequently processed in the inference mechanism stage, where rules or regulations specified in the rules table are applied to transform the fuzzy input sets into fuzzy output sets. The final step involves the defuzzification process, which converts the fuzzy output sets back into a crisp output. To provide a more comprehensive understanding, each process within the fuzzy logic design will be explained in detail individually [22].

The first step is fuzzification, where the input value is transformed into a fuzzy value. This transformation ensures compatibility with the subsequent inference mechanism process. The fuzzy value, also known as a membership function, varies for each input set, reflecting its distinct characteristics.

Following fuzzification is the inference mechanism, a more intricate stage. It takes the fuzzy value obtained from fuzzification as input and utilizes a rule table to generate a corresponding fuzzy output value.

The final process in the fuzzy method is defuzzification. This stage involves converting the output value obtained from the inference mechanism into a precise value. An equation is employed to calculate the fuzzy value and subsequently transform it into a precise value.

This value is a fuzzy decision, and the following is the equation for the fuzzy decision:

$$\text{Fuzzy decision} = \frac{\sum \mu(K_n) \times K_n}{\sum \mu K_n} \quad (1)$$

where μ is the crisp value obtained, and Kn is the value of the category in the output.

The defuzzification process has three working methods, which are Mamdani method, TSK method, and Tsukamoto method.

The Sugeno method has the best values Based on the accuracy, precision, and sensitivity. Since this research used a large amount of data, the Sugeno method was also suitable because it uses an average calculation in defuzzification.

Fuzzy Logic Modelling

The dual-axis solar panel design used the Fuzzy Logic Designer Toolbox available in MATLAB [23]. The Arduino Uno microcontroller executed the fuzzy logic processing, and its output was utilized to regulate the movement of the linear actuator. Figure 4 visualizes the fuzzy logic design, depicting the uniform membership functions associated with each input and output throughout the system.

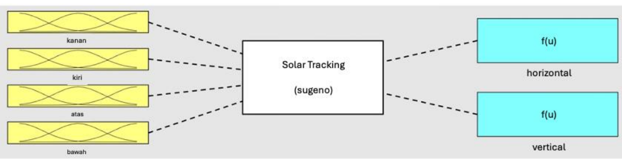

Figure 4. Input and Output Fuzzy

During the initial phase of the design process, the membership functions for both the input and output variables were established. The input variables were derived from the light sensor readings and were labeled as "*kanan*" (right), "*kiri*" (left), "*atas*" (up), and "*bawah*" (down). The membership functions for the light sensor input were divided into three fuzzy sets: "*gelap*" (dark), "*normal*" (normal), and "*terang*" (bright). Each membership function represented a specific range of data, as illustrated in Figure 5. These membership functions played a crucial role in capturing and representing the linguistic terms associated with the input variables, enabling the fuzzy logic system to make informed decisions based on the sensor readings.

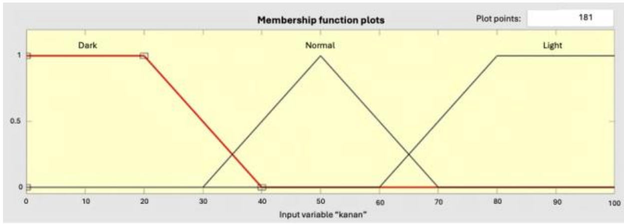

Figure 5. Right and Left Input Sensor

Figure 6 illustrates the output of the system, an essential component in determining the actuator's movement. The output variable was divided into three linguistic terms with their respective membership functions. The first linguistic term was "CW" (clockwise) with a membership value of 1, indicating a strong inclination toward clockwise movement. The second term was "OFF" with a membership value of 50, representing a neutral state or no movement. The third term was "CCW" (counterclockwise) with a membership value of 100, indicating a strong inclination toward counterclockwise movement. These membership functions played a crucial role in mapping the fuzzy output values to the appropriate actions of the actuator, providing precise control based on the system's inputs and internal rules.

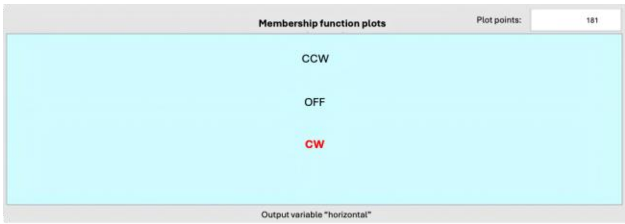

Figure 6. Output Variable.

Table 1 displays the rules pertaining to the horizontal conditions, while Table 2 illustrates the rules related to the vertical conditions.

Table 1. The Rules of Horizontal Conditions

		Left		
		Dark	**Normal**	**Bright**
Right	Dark	OFF	CCW	CCW
	Normal	CW	OFF	CCW
	Bright	CW	CW	OFF

Table 2. The Rules of Vertical Conditions

			Down	
		Dark	**Normal**	**Bright**
Up	Dark	OFF	CCW	CCW
	Normal	CW	OFF	CCW
	Bright	CW	CW	OFF

Validation of the fuzzy logic model was performed to check if the system used in MATLAB was accurate by comparing the final

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values obtained by MATLAB with manual calculations as shown in a previous study [22].

Testing Method

LDR sensors, DS18B20 sensors, relays, a 12V battery, Arduino Mega, a pump, and a BTS7960 Motor Driver were required to achieve the intended results in the efficiency of solar panels and the improvement of energy in the form of voltage (V), current (I), and power (W).

The solar panel movement occured in real-time, but data were collected every half an hour and during the water treatment process to monitor the hourly fluctuations in voltage and current. The voltage and current of the solar panel were obtained by connecting two multimeters to the solar panel and load. The load was used to measure the current from the solar panel. In this case, a 20-watt incandescent lamp was used as the load.

Figure 7 displays the data from each LDR sensor. The top, bottom, left, and right sensors were labeled with directions for easier interpretation and to identify which sensor malfunctioned in case of errors. The presence of the "50 OF" label on the right side signified that the solar panel was aligned perpendicular to the incoming light.

Figure 7. Data Collection from LDR Sensor

The top part represented the vertical movement, while the bottom part the horizontal movement. When the direction of light changed, the value of 50 and the label OF was modified according to the fuzzy logic calculations.

RESULTS AND DISCUSSION

System Design

The system comprised solar panels, four light sensors, two linear actuators, and a water treatment system. Each sensor was strategically positioned in four distinct directions: top, bottom, left, and right. The first linear actuator facilitated horizontal movement of the solar panel by assessing and comparing the light intensity on its right and left sides. Similarly, the second linear actuator enabled vertical movement of the solar panel by evaluating and comparing the light intensity on its top and bottom.

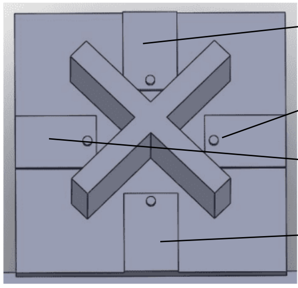

Figure 8. Sensor Placement Design

Figure 8 is a design for the placement of LDR sensors. The placement of LDR sensors was divided into four sections: top, bottom, left, and right. Each section of the sensor was equipped with a barrier.

Figure 9 shows an isometric view of the initial design of the tracking system, consisting of four LDR sensors positioned on the top of the panel to monitor the sun's location and two linear actuators responsible for system movement. The tracking system was 1300 mm x 720 mm in size. During operation, the actuators responded to the sensor input, with the first actuator tracking the south and north directions, while the second actuator tracked the east and west directions.

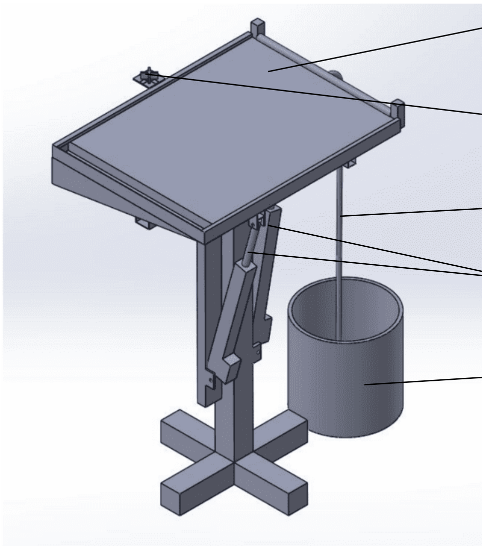

Figure 9. Isometric Design of the Proposed System

The solar tracking system operates through a meticulous process [22]. It begins with an LDR sensor measuring the incoming light intensity. If light intensity data is detected, the system proceeds to measure the solar panel temperature; if not, the LDR sensor undergoes a recheck. Once lux data is received, it enters the fuzzification process, where crisp values are transformed into fuzzy input set values.

Next, during the inference stage, the fuzzy input set values are compared against a predefined rule set, resulting in fuzzy output set values. These values are then converted into crisp output values through the defuzzification process. The crisp values from the defuzzification stage serve as inputs for the linear actuator, which adjusts its movement based on these values.

A 12V DC rechargeable sealed lead acid battery was used to power water pumps and linear actuators. The battery could be charged using a solar charge controller, which controlled the current and voltage entering the battery.

Fuzzy Logic System

The fuzzy logic system utilized for this research is shown in the flowchart in Figure 10.

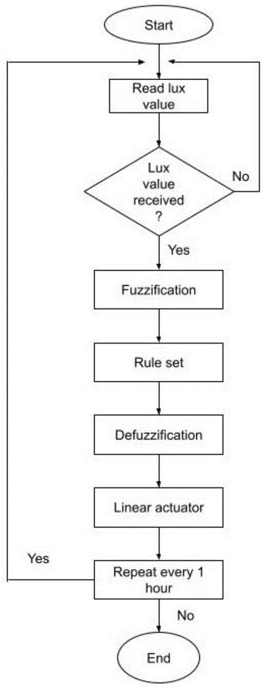

Figure 10. Flowchart of Fuzzy Logic

The solar tracking system's operation is a sequential process that functions as follows: Initially, the light sensor, known as a Light Dependent Resistor (LDR), evaluates the incoming light intensity. If the system detects light intensity data, it then measures the solar panel's temperature. Should light intensity not be detected, the system reevaluates the reading from the LDR sensor.

Next, the received lux data is subject to fuzzification, which converts the crisp values into fuzzy input sets. During the inference phase, these fuzzy inputs are compared using a predefined rule set, yielding fuzzy output sets. The defuzzification process follows, transforming these fuzzy outputs into precise, actionable output values.

These precise output values are then used to inform the linear actuator, which adjusts its movement accordingly. This cycle of operations is set to repeat on an hourly basis to ensure optimal performance.

The block diagram of the system is shown in Figure 11. The system was equipped with 4 sensors that detected in real-time at a specific frequency. The controller compared the values of each Light Dependent Resistor (LDR) and sent signals to the linear actuator to minimize the differences in values among each LDR.

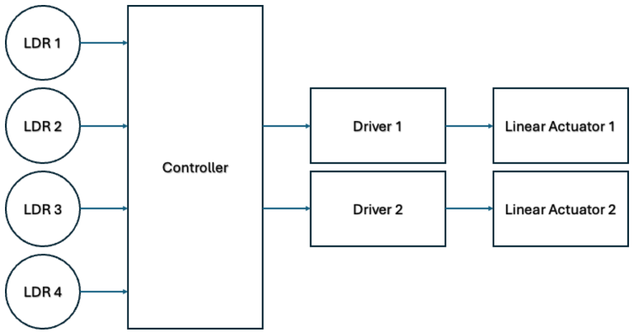

Figure 11. Block Diagram of the System

Water Treatment System

The main consideration for this research was to combine dual-axis tracking with the water treatment method. The water treatment system is shown in Figure 12.

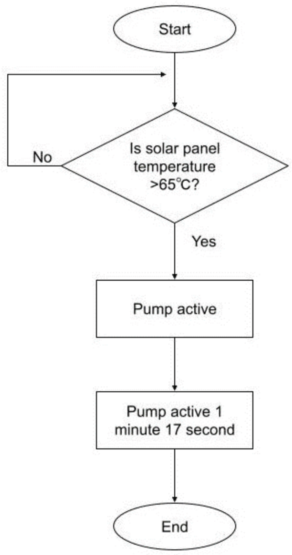

Figure 12. Flowchart of Water System

The water system designed to cool the solar panels operates through a series of carefully orchestrated steps. Initially, a sensor is activated to determine if the temperature of the solar panel exceeds the critical threshold of 65°C. If the temperature is below this threshold, the sensor remains vigilant, continuously monitoring the panel's temperature.

Once the temperature reaches or surpasses 65°C, a relay mechanism is triggered, which in turn activates the water pump. The pump's primary role is to circulate water across the surface of the solar panel. This cooling process is maintained for a specific duration, precisely 1 minute and 17 seconds, to manage the panel's temperature and ensure optimal functioning efficiently.

System Implementation

The results of the system design were then implemented concretely to obtain more valid testing results. The result of the solar tracking design is shown in Figure 13.

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Figure 13. Results of Solar Tracking Design

The design consisted of a framework to support the solar panel, linear actuator, limit switch, water pipes, cross-section, and LDR sensor. The framework held these components in place and ensured their proper function within the system.

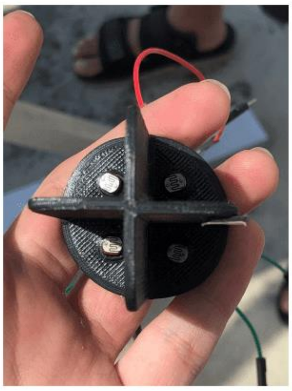

Figure 14. LDR Sensor Placement

Figure 14 shows the inside of the LDR sensor. There were 4 parts that functioned to reduce the incoming light on each LDR sensor. The sensor had poles and boxes on the limit switch. The poles and boxes followed the direction of movement of the linear actuator, so at the maximum and minimum distances of linear actuator movement, it stopped.

The components used were relays, pumps, and Arduino Uno. The process was carried out in the same way as [15]. The only difference was in the temperature sensor. In this research, a single DS18B20 sensor was used because the research [13] found that the temperature difference at the bottom point of the solar panel was not significantly different.

The watering process occured simultaneously for 1 minute and 17 seconds. The pump activated once the surface temperature of the solar panel had reached the designated threshold.

Fill Factor and Initial Efficiency Value

The values of V_{mp} (maximum power voltage), I_{mp} (maximum power current), I_{sc} (short circuit current), and V_{oc} (open circuit voltage) are available for observation, enabling the determination of the solar panel's fill factor and initial efficiency. The calculation for the initial fill factor value can be found in equation (2).

$$\text{Fill Factor} = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \tag{2}$$

V_{mp} = Voltage at maximum power
I_{mp} = Current at maximum power
V_{oc} = Maximum voltage of the solar panel at open circuit
I_{sc} =Maximum current of the solar panel at open circuit

Efficiency is defined as the ratio of the output energy from a solar panel to the input energy from the sun. The efficiency of a solar panel also depends on the spectrum and intensity of sunlight on the panel, which is why the careful use of each device and the use of multiple devices are necessary to achieve better efficiency. The efficiency of a solar panel can be defined as follows:

$$\text{Efficiency} = \frac{V_{oc}I_{sc}\,FF}{SI\ A} \tag{3}$$

By applying equations (2) and (3), the initial fill factor and efficiency values from datasheet can be calculated as follows:

$$\text{Fill Factor Fixed} = \frac{17.5V \times 2.86A}{21V \times 3.09A} = 0.77 \tag{4}$$

The value of 0.77 indicates how much sunlight can be absorbed by the solar panel under Standard Test Conditions (STC). Once the fill factor is determined, the efficiency can be calculated using (3).

$$\text{Efficiency} = \frac{21V \times 3.09A \times 0{,}77}{1000W/m^2 \times 0.67m \times 0.54m} \times 100\% = 13.8\% \tag{5}$$

The percentage value of 13.8% represents the conversion efficiency of solar energy into electrical energy under Standard Test Conditions (STC). STC is a standard utilized by solar panel manufacturers to assess the efficiency of solar panels. Within the context of STC, the solar panel temperature is set at 25°C, the solar radiation is 1000 W/m^2, and the air mass is 1.5.

Implementation and Results

Implementation of the proposed system also considered the previous study [22]. The research data were presented through two distinct scenarios to evaluate system performance. In the first scenario, titled "Tracking," the system employed solar tracking utilizing a dual-axis fuzzy logic method in conjunction with water treatments. This scenario was designed to assess the efficacy of actively adjusting the solar panel's position in relation to the sun's trajectory, thereby maximizing energy absorption, while also applying water treatments as a cooling mechanism.

The second scenario, referred to as "Fixed," did not incorporate the solar tracking feature. Instead, the system remained stationary, relying solely on water treatments for cooling. The purpose of this setup was to determine the effectiveness of water treatments in the absence of the enhanced exposure to sunlight that tracking provides. Through these two scenarios, the research aimed to contrast the benefits and limitations of each system configuration.

Table 3. Result of Fixed Scenario

Time	Volt	Ampere	Watt
09:00	18.03	1.21	21.81
09:30	18.21	1.29	23.49
10:00	18.49	1.32	24.4
10:30	18.92	1.32	25.16
11:00	20.15	1.44	29.01
11:07	21.06	1.51	31.8
11:30	20.64	1.45	29.92
12:00	19.25	1.33	25.60
12:30	18.42	1.25	23.02
13:00	18.21	1.21	22.03
13:30	18.01	1.19	21.43
14:00	17.53	1.15	20.15
14:30	17.02	1.1	18.72
15:00	16.73	1.03	17.23

Table 3 is the data from V (voltage), I (current), and calculated W (power) on solar panel with fixed scenarios. At 11:07, the water treatments started. When the water treatments occurred, the power output increased. From 09:30, there was an increase in power output, indicating that the sun was approaching a perpendicular position to the solar panel. As a result, there was a gradual increase in power output every hour until 11:30. After 11:30, there was a decrease in power output as the sun started to move away from the optimal position. A comparison between power output at 09:00 and that at 15:00 showed that the power output at 09:00 was higher than that at 15:00.

Table 4. Result of Tracking Scenario

Time	Volt	Ampere	Watt
09:00	20.06	1.43	28.68
09:30	20.27	1.46	29.59
10:00	20.47	1.47	30.09
10:30	20.79	1.46	30.35
11:00	20.91	1.49	31.15
11:04	21.33	1.57	33.48
11:30	20.72	1.49	30.83
12:00	20.56	1.48	30.42
12:30	20.12	1.45	29.12
13:00	20.67	1.47	30.38
13:30	20.19	1.44	29.06
14:00	20.43	1.47	30.09
14:30	20.21	1.45	20.30
15:00	20.54	1.48	30.39

Based on Table 4, the data collection process for the tracking position was the same as the fixed scenario, which involved collecting data every half an hour. This interval allowed us to observe the changes in power output that occured each hour. In the tracking process, during the hourly observation, the power obtained remained relatively consistent without significant variations. However, upon examination of data collected every half an hour, a slight decrease was observed. This decrease occured because the sun continued to move within each hour interval, while the solar panel adjusted its position every hour. Therefore, during these intervals, a slight decrease in power output was observed.

From 09:00 onwards, the difference in power generated between the fixed and tracking methods was observed. The tracking method achieved a higher power output because at 09:00 the solar panel was positioned perpendicular to the sun, maximizing power generation. In contrast, in the fixed method, the solar panel was already facing the sun but not in a perpendicular position, resulting in lower power output compared to the tracking scenario.

Until 11:00, both solar panels experienced an increase in power output. In the tracking method, the increase was not significant because the solar panel adjusted its position every hour. Ideally, the power output in the tracking method should experience a slight decrease every half an hour, as observed from 12:00 to 15:00. This was because the solar panel adjusted every hour while the sun continued to move based on time. As a result, there was a lower light intensity in the morning compared to the afternoon. The same was true of the fixed method, where an increase in power output was observed until 11:00. The fixed method achieved the highest power output at that time due to the solar panel's perpendicular position. After 11:00, the fixed solar panel started to experience a slight decrease in power output as the sun moved away from its optimal position. Power could still be generated, but not as much as in the tracking method.

At 11:04 and 11:07, the water treatment procedure took place due to the solar panel's surface temperature reaching the predetermined threshold.

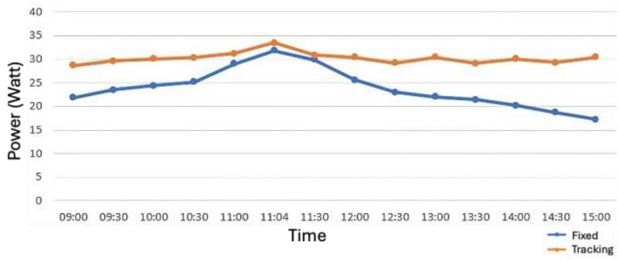

Figure 15. Comparison of the Results of the Fixed and Tracking Methods

From Figure 15, starting from 09:00, the difference in power generated by the fixed and tracking methods became noticeable. The tracking method produced more power because the solar panel was positioned perpendicular to the sun at 09:00, allowing it to capture maximum power. Until 11:00, both solar panels experienced an increase in power. However, the increase in the tracking method was not significant because the solar panel continued to move every hour. The tracking power should experience a slight decrease every half hour, starting from 12:00 to 15:00, as the solar panel moved while the sun continued its motion based on time. This was due to the lower light intensity in the morning compared to the afternoon when the solar panel was positioned almost perpendicular to the sun. After 11:00, the fixed solar panel gradually experienced a slight decrease in power because the sun started to move away and was behind it. Power could still be obtained, but it was not as much as the tracking

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method. At 11:04 and 11:07, the water treatment process began when the surface temperature of the solar panel reached the designated temperature.

Energy Increment Analysis

To calculate the efficiency of a solar panel, equation (3) can be employed. As for the energy improvement aspect, the power obtained needs to be converted into a watt-hours unit using equations (6) and (7).

$$E_n = 0.5(n + (n+1))(\frac{1}{3600}) \quad (6)$$

$$\sum_{n=1}^{n} E_n = E_1 + E_2 + \cdots + E_n - 1 + E_n \quad (7)$$

E_n = Energy to – (Watt hour)
n = power at the time (Watt)
$\sum_{n=1}^{n}$ = Total Energy (Watt-hour)

Table 5 lists the generated energy for each hour. Therefore, a graph could be created to show the energy power of the tracking and fixed systems for each hour.

Table 5. Output Power

Time	Fixed (Wh)	Tracking (Wh)
09:00	23.23	29.45
10:00	26.19	30.53
11:00	29.08	31.48
12:00	23.55	29.99
13:00	21.20	29.84
14:00	18.70	29.93
15:00	17.23	30.39

The total energy obtained from the solar tracking dual-axis system with fuzzy logic and water treatments was 211.6 Watt-hour. This accounted for the combined energy generated by the system.

By contrast, the total energy obtained from the fixed method without tracking or water treatments was 159.2 Watt-hour. Regarding the energy consumption of the linear actuators, a total of 23.3 Watt-hour was used. This value already included the total energy consumption of both linear actuators. The pump, however, consumed 0.4 Watt-hour of energy.

The energy increment can be defined using the following equation (8).

$$\text{Energy increment} = \frac{A-B-C-D}{B} \times 100\% \quad (8)$$

A = Total energy tracking
B = Total fixed energy
C = Total linear actuator energy
D = Total pump energy

Using equation (8), the energy increment of the solar panel was:

$$\text{Energy increment} = \frac{211.6-159.2-23.3-0.4-0.4}{1559.6} X100\% = 17.77\% \quad (9)$$

The value of 17.77% indicates that the system with solar tracking dual-axis fuzzy logic and water treatment method generates higher values of total energy. The total energy obtained after moving the linear actuator every hour and using the pump was still more than 17.77% higher. For comparison, according to [14], fuzzy logic-based solar tracking can increase its efficiency by 2.39%. However, to determine the remaining energy available, it is necessary to subtract the energy consumed by the linear actuator's movement per hour and the energy used by the pump during the water treatment process.

Unfortunately, the specific energy consumption values for the linear actuator and pump were not available in this research. In order to calculate the remaining energy, it might be necessary to observe the energy consumption rates of these devices per hour or per cycle. The total energy generated by the tracking method (211.6 Watt-hour) was then utilized to find the remaining energy as shown in equation (10).

$$\text{Remaining Energy} = 211.6 - 23.3 - 0.4 = 187.9 \text{ Wh} \quad (10)$$

Based on the calculation above, the remaining energy from the use of the system was 187.9 Watt-hour. This remaining energy could be used to recharge the battery that powered the linear actuator and pump.

In terms of energy increment, this research sets a new standard in the field of solar energy optimization. An energy increase of 17.77% is achieved by combining dual-axis solar tracking with fuzzy logic and water treatment methods. This substantially exceeds the increments reported in other recent studies. For example, [23] demonstrated the advantages of a dual-axis solar tracking system for hydroponic pumps. Also, in [24] evaluated the performance of a solar collector with tracking, neither study achieved the same level of improvement as this research. Similarly, the analysis on fixed and single-axis tracking solar panels by [25] highlight the benefits of tracking systems but fall short of the significant energy yield increase as shown in this research. The method on this research not only confirms the effectiveness of solar tracking as seen in [26], but also significantly advances it in terms of energy output.

Efficiency Analysis

Prior to evaluating the efficiency of the solar panel,the fill factor was computed using equations (2) and (3) for both fixed and tracking scenarios. The results of fill factor and efficiency values are shown in equations (11), (12), (13), and (14).

$$\text{Fill Factor of Fixed} = \frac{18.39V \times 1.24A}{21.06V \times 1.51A} = 0.71 \quad (11)$$

$$\text{Fill Factor of Tracking} = \frac{19.08V \times 1.28A}{21.33V \times 1.57A} = 0.73 \quad (12)$$

Once the fill factor had been determined for each method, the efficiency of the solar panel was calculated using the obtained results.

$$\text{Fixed Efficiency} = \frac{21.06V \times 1.51A \times 0.71}{953.26W/m^2 \times 0.64m \times 0.53m} \times 100\% = 7.04\% \quad (13)$$

$$\text{Tracking Efficiency } = \frac{21.33V \times 1.57A \times 0.73}{965.19W/m^2 \times 0.64m \times 0.53m} \times 100\% \quad (14)$$

Tracking Efficiency = = 7.46%

The solar panel using the tracking method produced higher efficiency. During the water treatment process, the tracking solar panel was more directly aligned with the sun compared to the fixed solar panel. The tracking system exhibited a higher level of efficiency as an outcome.

Furthermore, this research excels in the field of improving energy efficiency. The implementation of the proposed system resulted in a 7.46% increase in energy conversion efficiency, far exceeding the figures reported in similar studies. For comparison, a previous study [13] found that the efficiency of similar water treatment tehcnique was only 7.01 %, without the solar tracking system. While in [11] provided a comprehensive evaluation of photovoltaic systems and tracking approaches, and [27] discussed an optimized single-axis tracker, the level of efficiency enhancement achieved by the proposed system in this research was not comparable. The research [28] proposed single-axis tracker design, which, while innovative, did not achieve the efficiency levels this research demonstrated.

The solar panel using the dual-axis solar tracking with fuzzy logic obtains higher current and voltage because its surface is more perpendicular to the incoming sunlight. Both equations also have different solar radiation values since solar radiation changes with time. Solar panels that are oriented in a more perpendicular manner to the sun receive increased solar radiation, much like the relationship between current and voltage. In this research, the fixed method obtained maximum solar radiation of 953.26 W/m^2, while the tracking method obtained radiation of 965.19 W/m^2.

With the implementation of sophisticated tracking combining with water treatment technologies, this research contributes to the improvement of solar panel efficiency, providing a notable point of reference for ongoing developments in this dynamic area of research.

CONCLUSIONS

In this research, the implementation of a novel integration involving dual-axis solar tracking with fuzzy logic control and water treatment methods to enhance solar panel efficiency is explored. Employing a system utilizing LDR sensors, linear actuators, limit switches, a Motor Driver BTS7960, an Arduino Mega, a pump, and a 12V battery, a 17.77% increase in energy output and a 7.46% improvement in energy conversion efficiency is observed. These results underscore the potential of the proposed system to increase energy production, particularly by optimizing solar panel alignment with the sun's trajectory. The findings not only corroborate the anticipated benefits of precise solar tracking but also reveal the better improvement of combining it with water cooling treatments. WhSilahklaile the findings of this study are favorable, additional comparative studies with existing solar panel enhancements could solidify the proposed system's role in advancing solar energy technologies. In order to to fully assess the system's performance in variable climatic conditions it is necessary to extend field testing, which will be an avenue for future research.

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