International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 2, April 2025, pp. 1251~1261
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i2.pp1251-1261

Computer vision-based sun tracking control for optimizing photovoltaic power generation

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Article Info

Article history:

Received Jul 15, 2024
Revised Oct 4, 2024
Accepted Oct 23, 2024

Keywords:

Energy efficiency
Image processing
Photovoltaic
Renewable energy
Solar tracking systems

ABSTRACT

As global energy consumption rises and fossil fuel reserves dwindle, the transition to renewable energy sources becomes imperative. Solar photovoltaic (PV) technology, crucial in this shift, faces challenges in efficiency and cost. This study explores a motorized sun-tracking system employing image processing techniques to optimize solar panel orientation and maximize energy capture. Using an Arduino Mega 2560 microcontroller, L298N motor driver, Raspberry Pi 3 Model B, and webcam integration, the system dynamically adjusts solar panels based on real-time sun position detection. Experiments compare the performance of fixed and sun-tracking solar panels, revealing that sun-tracking panels consistently outperform fixed ones, particularly during low sun angles, resulting in up to 84.9% higher power output. These findings underscore the potential of sun-tracking technology to significantly enhance solar energy efficiency and support sustainable energy goals. Future research should focus on refining tracking algorithms and optimizing system design to further boost energy capture and reliability.

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1. INTRODUCTION

In today's global scenario, energy consumption has been steadily on the rise, spanning both residential and industrial sectors, while fossil fuel reserves, including oil, natural gas, and coal, are dwindling. The extraction and utilization of these limited resources not only add to environmental pollution, particularly air pollution, but also worsen the effects of climate change. As countries worldwide grapple with these challenges, many have implemented energy sector policies aimed at transitioning towards cleaner energy sources and achieving net zero greenhouse gas emissions [1]. The remarkable expansion of global photovoltaic (PV) capacity, surging to 591 GW in 2019, owes much to advancements in solar cell efficiency and cost reduction, rendering PV technology increasingly competitive in terms of levelized costs of electricity [2]. As PV systems approach cost parity with traditional energy sources, there is an urgent requirement for a detailed plan outlining essential paths for development to enable installations on a terawatt scale [1]. This roadmap must address key technical hurdles and highlight breakthroughs essential for steering future research endeavors and guiding industry investments [2].

Solar PV technology, a vital renewable energy source, faces challenges such as high costs, low efficiency, and intermittency in current systems compared to fossil fuels. Achieving optimal energy capture from the sun with PV systems is complex, influenced by factors like PV material, geographic location, ambient conditions, sun angle, and panel orientation. The various solar tracking systems based on their technologies and driving methods while shedding light on future trends in tracking system development [3]. Solar tracking systems can be divided into two main types including active and passive solar tracking systems. An active solar tracking system dynamically adjusts the orientation of solar panels to optimize their alignment with the sun's position throughout the day [3]–[6]. A passive solar tracking system utilizes fixed mechanisms or designs that respond passively to environmental conditions to adjust the orientation of solar panels [7], [8].

Single-axis solar tracking systems operate by moving along either the vertical or horizontal axis, with manual adjustments to the inclination angle at specific intervals and automatic east–west movement. While cost-effective, these systems exhibit lower efficiency compared to two-axis systems. The choice between vertical and horizontal movement depends on the solar trajectory and prevailing weather conditions. On the other hand, two-axis solar tracking systems dynamically adjust solar panel orientation along both horizontal and vertical axes to accurately follow the sun's trajectory throughout the day. By optimizing tilt and azimuth angles continuously, these systems maximize sunlight exposure, resulting in enhanced energy capture and efficiency. Particularly advantageous in locations with significant solar variability or during seasons with low sun angles, two-axis tracking systems ensure optimal energy production year-round.

The integration of light dependent resistors (LDRs) within solar tracking systems represents a notable advancement in PV technology. LDRs, also known as photoresistors, are semiconductor devices whose electrical resistance varies with incident light intensity. In solar tracking applications, LDRs serve as sensors to detect changes in ambient light levels, providing crucial feedback for adjusting the orientation of solar panels to optimize sunlight capture. This adaptive mechanism enables solar panels to dynamically align themselves with the sun's position throughout the day, maximizing energy conversion efficiency. By employing LDRs, solar tracking systems can autonomously adjust panel orientation, ensuring optimal exposure to sunlight and enhancing overall system performance [9]–[14]. This integration of LDR technology underscores the significance of sensor-based feedback mechanisms in advancing the efficacy and sustainability of solar energy harvesting systems. However, LDRs can degrade over time due to factors like exposure to ultraviolet (UV) light and environmental contaminants. This degradation can affect their sensitivity and accuracy, requiring regular calibration and potentially replacement [15], [16]. In addressing the challenges posed by uncertain lighting conditions in solar tracking systems utilizing LDRs, researchers have turned to UV sensors as a solution. UV sensors are integral components of environmental monitoring systems, tasked with gauging UV radiation levels in the atmosphere. This alternative approach can overcome the limitations associated with LDRs and enhance the accuracy of sun tracking mechanisms [17], [18]. Image processing techniques have been increasingly utilized in solar tracking systems to enhance accuracy and efficiency [18]–[21]. By analyzing images of the sky, horizon, and sun position, these systems can dynamically adjust solar panel orientation for optimal energy capture. This integration of image processing technology allows for real-time adaptation to changing environmental conditions, improving overall system performance. Many studies have incorporated global positioning system (GPS) and compass modules into solar tracking systems [22]–[25]. GPS provides precise geographical coordinates (latitude and longitude), which are crucial for accurately determining the sun's position at any given time relative to the solar panels' location. This enables the solar tracker to adjust the panels' angle, optimizing sun exposure and enhancing overall energy efficiency. Additionally, a compass module determines the exact orientation of the solar panel system in relation to the Earth's magnetic poles. This ensures that the panels are not only accurately positioned in terms of latitude and longitude but are also facing the optimal direction. This study proposes developing a motorized sun tracking system employing image processing techniques. It involves capturing sun images with a camera, processing them to identify the sun's position, and directing a motor to adjust the solar panel accordingly.

2. HARDWARE DESIGN AND SOFTWARE ALGORITHM

2.1. Hardware design

The hardware architecture for controlling monocrystalline silicon solar panels, each with a power rating of 20 W, is designed to optimize sunlight exposure through the implementation of an efficient solar tracking system. This system integrates several key components, including an Arduino Mega 2560 microcontroller, which facilitates precise control of direct current (DC) motors. The incorporation of an L298N motor driver circuit ensures effective motor operation. Additionally, a Raspberry Pi 3 Model B is utilized for the integration of a webcam and the processing of image signals. Together, these components form a comprehensive system aimed at enhancing solar energy capture by enabling intelligent tracking and positioning of the solar panels.

The Arduino Mega 2560 serves as the central control unit for the DC motors, managing the movements necessary to adjust the solar panels' tilt and azimuth angles accurately. This microcontroller communicates with the L298N motor driver circuit, which provides the requisite power and control signals to the DC motors, ensuring smooth and precise panel adjustments. Additionally, the Raspberry Pi 3 Model B plays a crucial role in the system by interfacing with a webcam. This webcam captures real-time images of the solar panels' position, providing essential visual data. The Raspberry Pi processes these images using sophisticated algorithms to ascertain the sun's exact location relative to the panels, thereby enabling the system to make informed adjustments for optimal solar tracking.

The physical setup includes a specialized solar panel tracker mechanism equipped with DC motors, as illustrated in Figure 1. This mechanism facilitates the continuous and precise movement of the solar panels, enabling them to follow the sun's path throughout the day. The motor control circuitry configuration, depicted in Figure 2, details the interconnections and interactions between the Arduino Mega 2560, the L298N motor driver, and the DC motors, ensuring seamless operation.

Figure 1. Single pole structure used for installing solar panels

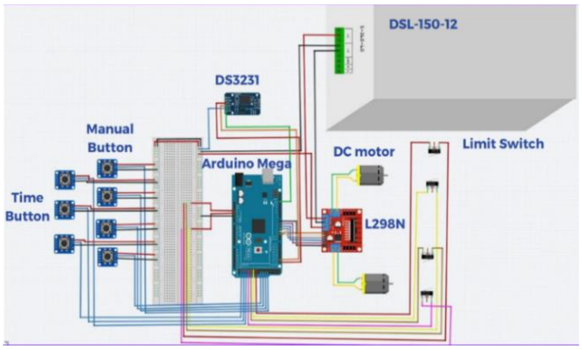

Figure 2. Circuit diagram of the solar panel tracking system

2.2. Sun detection with image processing

This part describes the development of a sun position detection system where MATLAB was employed as the primary tool in the algorithm designed to detect the sun within sky images. A total of 130 sky images taken from 6:00 AM to 6:00 PM were used to ensure the system's accuracy in sun detection. The workflow consists of the following steps:

Step 1: Image acquisition and processing

The initial step involves importing the sky image, as illustrated in Figure 3(a). The image is initially in red, green, and blue (RGB) color space, which is not optimal for detecting the sun due to complex variations in color and intensity. To enhance the detection process, the image is converted from the RGB color space to the CIELAB color space, as defined by the International Commission on Illumination (CIE) [26]. The CIELAB color space is a color-opponent space with three components: lightness (L), green-red (a), and blue-yellow (b), and is widely recognized for its perceptual uniformity in color representation. This conversion, as shown in Figure 3(b), allows for a more accurate analysis of color and brightness. In this research, only the lightness component (L) is used, as it offers a clearer representation of brightness variations, which is essential for accurately detecting the sun.

Step 2: Luminance threshold calculation

In this step, a threshold value is determined to convert the image into a binary format (black and white). This involves calculating the mean (μ) and standard deviation (σ) of the lightness (L) values in the image. The brightness level expected to correspond to the sun (B) is calculated in (1).

$$B = \mu + \sigma A \quad (1)$$

B is the threshold value expected to correspond to the sun's brightness and *A* is a constant.

Step 3: Binary image creation

Using the calculated threshold, the lightness component of the image is converted to a binary format. In the resulting binary image, areas with brightness values below the threshold are set to black, and areas with brightness values above the threshold are set to white. This transformation isolates the bright regions, which include the sun, from the darker background, as shown in Figure 3(c). This step is crucial for distinguishing the sun from other elements in the sky, such as clouds or the sky itself.

Step 4: Edge refinement

To enhance the accuracy of sun detection, the edges of the detected bright region are refined. This involves morphological operations such as erosion and dilation on the binary image. Erosion removes small white noise, while dilation restores the eroded parts of the sun, smoothing the edges and making the detected region more consistent with the actual shape of the sun. This refinement process ensures that the detected region is clean and accurately represents the sun's position.

Step 5: Region analysis and sun identification

In the final step, the system analyzes the binary image to identify and count the regions likely to be the sun. The size of each bright region is calculated to determine their centroids. The region that closely matches the median size of the sun, based on prior data from the photographs used in this research, is selected. The centroid of this selected region is then used to draw a circle, indicating the detected position of the sun, as shown in Figure 3(d).

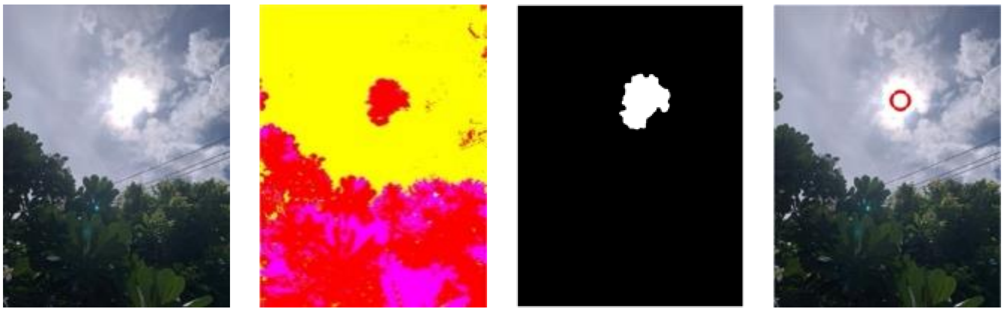
(a) (b) (c) (d)

Figure 3. Image processing steps in sun detection: (a) original image, (b) image in CIELAB, (c) binary image, and (d) sun position detection

The evaluation of the sun position detection system utilized a dataset comprising 130 images, capturing diverse sun positions throughout the day. The images were segmented into four distinct time intervals as presented in Table 1 to account for the sun's trajectory and corresponding changes in illumination throughout the day. Additionally, the dataset was categorized based on cloud coverage and other obstructive factors, enabling an analysis of sun luminosity relative to the transparency of these obstructions. Table 2 presents the categorization schema and corresponding image counts, distinguishing between clear sky conditions, partially cloudy conditions, overcast conditions, and other obstructions. This system aims to provide accurate and reliable sun detection in various sky conditions and times of the day, enhancing the potential applications in solar energy, climate studies, and environmental monitoring.

Table 1. Time intervals of the photographs used in experiment

Time interval	Number of images
6:01 AM to 9:00 AM	19
9.01 AM to 12.00 PM	21
12.01 PM to 3.00 PM	26
3.01 PM to 6.00 PM	64

Table 2. Cloud or obstruction types affecting sun visibility

Sky condition	Description	Number of images
Clear sky	Sun fully visible with little to no cloud cover	29
Partially cloudy	Sun partially obscured by clouds	38
Overcast	Sun completely obscured by clouds	50
Other obstructions	Sun partially obscured by objects like trees or buildings	13

2.3. Concept of solar panel movement control

To control the movement of solar panels, two DC motors are employed to manage the rotational axis and tilt axis. The objective is to align the sun's position in the captured image, determined from a webcam image, precisely at the center of the image frame. The sequential steps involved are as follows:

Step 1: Calculating the distance between the sun's position and the center of the frame

In this initial step, previously explained principles of sun image detection are employed to determine the pixel position of the sun within the image. Subsequently, the distance between the center of the frame and the detected pixel coordinates of the sun's position along the X and Y axes is calculated, as shown in Figure 4. This calculation is crucial as it forms the basis for the subsequent motor control adjustments.

Step 2: Motor rotation control

To achieve precise control of the solar panel's movement, a two-axis DC motor control system is implemented to position the sun at the center of the image. This control mechanism is based on proportional control technique, detailed in the block diagram in Figure 5. The motor operation time (T) required for each axis is calculated, with adjustments made to the X-axis position first, followed by the Y-axis position. The time T can be determined using (2):

$$T = K_p D_{x,y} \tag{2}$$

where T represents the motor movement time (in seconds), $D_{x,y}$ denotes the distance between the center of the frame and the sun's position in each axis (in pixels), and K_p is the proportional gain constant.

The proportional control method guarantees that motor movement corresponds directly to the detected positional error, facilitating precise adjustments. The control sequence concludes when the sun's position is centered within a specified rectangular area, as shown in Figure 6, ensuring optimal alignment for maximum solar energy capture. This precise alignment minimizes energy loss due to misalignment and improves overall system efficiency. By employing this method, the system achieves a balance between responsiveness and stability, enhancing its ability to adapt to changing solar angles throughout the day.

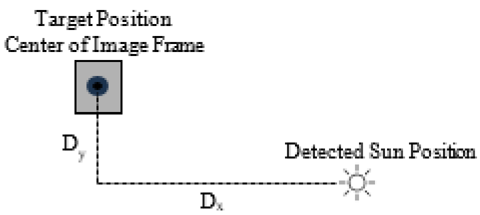

Figure 4. Distance utilized for motor control

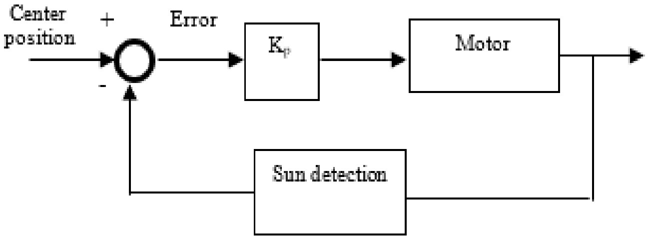

Figure 5. Block diagram of motor rotation control

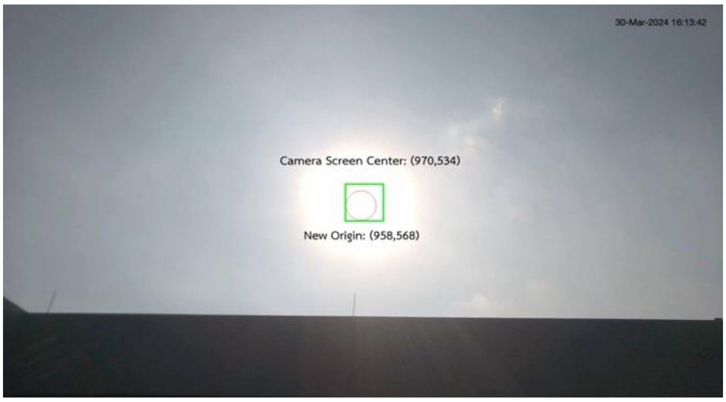

Figure 6. Sun position centering within specified rectangular area using proportional control method

2.4. Experimental design for comparing power output from fixed solar panels and sun-tracking solar panels

This section details the experimental methodology devised to rigorously assess the electricity generation efficiency of solar panels equipped with and without sun-tracking capabilities. The solar panels utilized in this investigation are monocrystalline silicon solar cells, each rated at 20 W, chosen for their common use and reliable performance in solar energy applications. The experiment comprises two distinct setups: a fixed solar panel and a sun-tracking solar panel. The fixed solar panel is strategically oriented in a southward direction with a tilt angle of 15° from the horizontal plane. This orientation is carefully selected based on site-specific considerations to optimize electricity generation, as depicted in Figure 7. In contrast, the sun-tracking solar panel incorporates a single-pole tracking mechanism and is supplemented with a webcam positioned above to monitor solar movement throughout the day, as illustrated in Figure 7. This dynamic tracking mechanism allows the solar panel to continuously adjust its orientation to face the sun, maximizing incident solar radiation and thereby potentially enhancing energy capture efficiency. The measurement of power output is conducted meticulously by recording the open-circuit voltage and short-circuit current at hourly intervals from 8:00 AM to 4:00 PM over a period of 10 consecutive days. The main goal of this study is to compare the power output of fixed and sun-tracking solar panels. Through a systematic evaluation of their performance under real-world conditions, the research seeks to determine how effective sun-tracking technology is in improving solar energy capture efficiency and overall electrical output. This comparative analysis offers valuable insights into the practical advantages and limitations of sun-tracking systems in optimizing solar panel performance across different environmental conditions and geographic locations.

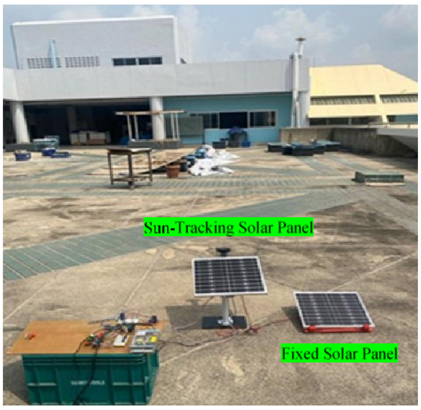

Figure 7. Experiment installation

3. EXPERIMENTAL RESULTS

This section reports the findings from the experimentation on the development of a sun-tracking system for solar panels, as outlined in the preceding sections. The results are divided into two parts: the accuracy of sun position detection and the comparative analysis of electrical power output from solar panels. The first part focuses on evaluating how precisely the system can detect and align with the sun's position under varying environmental conditions. The second part highlights the performance difference between sun-tracking and fixed solar panels, emphasizing the potential for increased energy efficiency. Together, these findings provide insights into the effectiveness of the proposed system and its implications for enhancing solar energy utilization.

3.1. Sun position detection results

The sun position detection experiment is subdivided into two aspects: the effectiveness during different time intervals and the impact of cloud cover and other obstructions. The evaluation of the sun position detection system during specific time intervals involves assessing its capability based on the number of accurately detected sun positions compared to the total number of images captured during each period, as shown in Table 3 and Figure 8. The example illustrates sun detection during different time intervals: 6:00-8:59 AM, 9:00-11:59 AM, 12:00-2:59 PM, and 3:00-6:00 PM, showing how the system tracks the sun's position throughout the day as shown in Figures 8(a)-(d). The sun position detection system demonstrates high accuracy during the periods from 6:01 AM to 12:00 PM when the sun is lower in the sky and the illumination is more uniform, enhancing image clarity. During these times, the system successfully detected 16 out of 19 images between 6:01 AM and 9:00 AM, and 24 out of 26 images between 12:01 PM and 3:00 PM. However, in the late afternoon period from 3:01 PM to 6:00 PM, the system's performance declines as the sun approaches the horizon, causing increased scattering of light and reduced image clarity. Consequently, during this period, the system detected 44 out of 64 images, reflecting a lower accuracy rate due to challenging lighting conditions and potential obstructions such as clouds and buildings. The sun position detection system effectively identifies the sun's location during the morning and midday hours when solar angles are optimal, enabling precise tracking. Despite facing challenges in the late afternoon, such as obstructions from tall buildings and trees that hinder direct sun visibility, the system maintains robust performance under favorable conditions, enhancing its utility in solar tracking applications. As a result of these obstacles, the system detects fewer images in the late afternoon, leading to lower accuracy rates compared to the morning and midday periods when sunlight is more uniformly distributed and obstructions are minimal.

Table 3. Time intervals and sun position detection accuracy

Time interval	Number of images	Detected sun position images	Accuracy (%)
6:01 AM to 9:00 AM	19	16	84.21
9.01 AM to 12.00 PM	21	18	85.70
12.01 PM to 3.00 PM	26	24	92.31
3.01 PM to 6.00 PM	64	44	68.75


(a) (b) (c) (d)

Figure 8. Example of sun detection in each time interval: (a) 6:00-8.59 AM, (b) 9:00-11.59 AM, (c) 12:00-2.59 PM, and (d) 3:00-6.00 PM

The experiment on the sun position detection system, considering occlusions by clouds or other objects, evaluates the system's ability by examining the number of sky images where the sun's position is accurately detected compared to the total number of images for each occlusion pattern. The experimental results are shown in Table 4 and Figure 9. Figure 9(a) to (d) illustrates examples of sun detection under varying sky conditions and obstructions: clear sky, partially cloudy, mostly cloudy, and other obstructions, demonstrating the system's adaptability to different environmental factors.

Table 4. Experimental results for sun detection due to sky conditions

Sky Condition	Number of Image	Detected Sun Position Images	Accuracy (%)
Clear sky	29	24	82.76
Partially cloudy	38	30	78.95
Mostly cloudy	50	41	82.00
Other obstructions	13	6	46.15

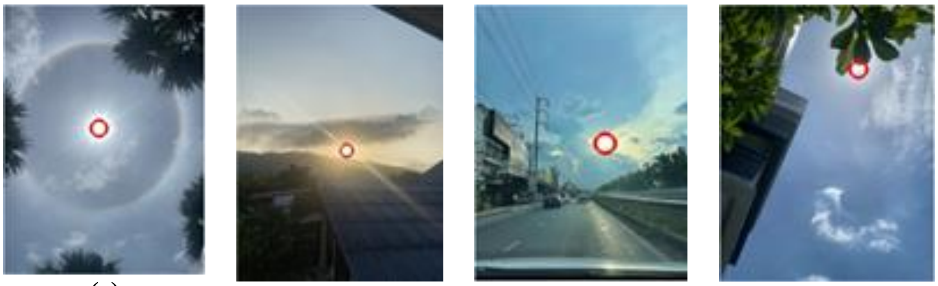
(a) (b) (c) (d)

Figure 9. Examples of sun detection under different sky conditions and obstructions: (a) clear sky, (b) partially cloudy, (c) mostly cloudy, and (d) other obstructions

The system demonstrates high accuracy under clear sky conditions, successfully detecting the sun in 24 out of 29 images due to the absence of clouds enabling precise image analysis. Under partially cloudy conditions, the system's accuracy decreases, detecting the sun in 30 out of 38 images. Clouds partially obscure the sun, causing light dispersion, which results in the system's sun position identification deviating from its actual position. Under mostly cloudy conditions, the system maintains accuracy similar to that in partially cloudy conditions, detecting the sun in 41 out of 50 images. The sun is completely obscured, resulting in a calculated sun area smaller than the average used in this research, leading to undetectable conditions. When there are obstructions like trees or buildings, the accuracy is the lowest. Obstacles reduce the sun's area within the sky images significantly below the set threshold, resulting in the system detecting the sun in only 6 out of 13 images. These results underscore the varying levels of effectiveness of the sun position detection system under different sky conditions, highlighting its robustness in accurately detecting the sun's position in clear skies and mostly cloudy conditions, while also pointing out significant challenges when dealing with obstructions such as trees or buildings, which severely reduce the system's ability to detect the sun within sky images.

3.2. Comparison of solar panel performance throughout the day

This study examines the electricity generation capabilities of fixed and sun-tracking solar panels installed on the rooftop of a seven-story building. Measurements were taken hourly from 8:00 AM to 4:00 PM over a period of 10 days. The experiment was conducted in diverse weather conditions, including clear skies, partial cloud cover, and mostly cloudy conditions. Results detailing the solar panel outputs are presented in Table 5 and Figure 10. The presented data compares the power output from fixed solar panels and sun-tracking solar panels at various times throughout the day, illustrating clear differences in their performance. Measurements include open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), and the resultant power output for each panel type. At each recorded time interval, the sun-tracking panels consistently produce more power than the fixed panels. For instance, at 8:00 AM, the fixed panel generates 11.61 W, whereas the sun-tracking panel generates 18.74 W, yielding a substantial improvement of 61.41%. This trend of enhanced performance for sun-tracking panels persists throughout the day with varying degrees of improvement. The most significant improvement is noted at 4:00 PM, where the sun-tracking panel achieves an 84.9% increase in power output compared to the fixed panel.

Table 5. Result of solar panel performance throughout the day

Time	Fixed Panel			Sun Tracking Panel			Improvement (%)
	V_{OC} (V)	I_{SC} (A)	Power (W)	V_{OC} (V)	I_{SC} (A)	Power (W)	
8:00 AM	22.77±0.27	0.51±0.07	11.61	23.13±0.25	0.81±0.11	18.74	61.41
9:00 AM	22.66±0.24	0.63±0.09	14.28	22.82±0.24	0.9±0.08	20.54	43.84
10:00 AM	22.56±0.20	0.83±0.14	18.72	22.75±0.14	0.97±0.16	22.07	17.9
11:00 AM	22.19±0.36	0.89±0.22	19.75	22.50±0.31	0.96±0.22	21.6	9.37
12:00 PM	22.62±0.30	1.01±0.21	22.85	22.77±0.29	1.02±0.20	23.22	1.62
1:00 PM	22.45±0.38	0.98±0.14	22	22.68±0.34	1.03±0.12	23.36	6.18
2:00 PM	22.43±0.27	0.74±0.21	16.6	22.66±0.31	0.88±0.26	19.94	20.12
3:00 PM	22.27±0.31	0.61±0.18	13.58	22.53±0.29	0.79±0.25	17.8	31.08
4:00 PM	22.19±0.34	0.37±0.16	8.21	22.65±0.22	0.67±0.21	15.18	84.90

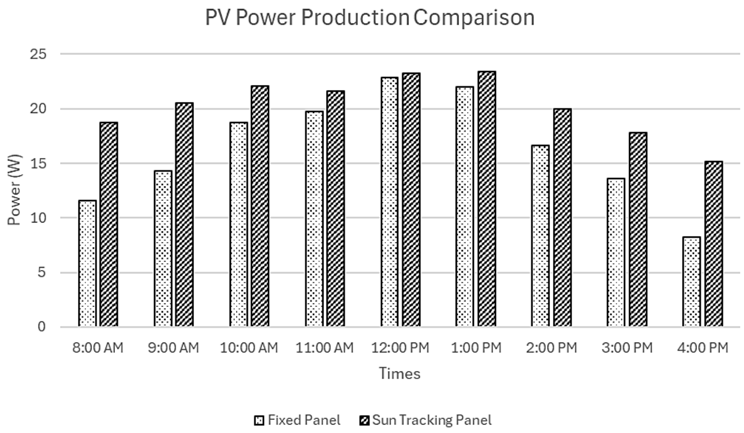

Figure 10. The electrical power generated by the solar cell throughout the day

These findings underscore the efficiency advantages of employing sun-tracking solar panels, particularly during the early morning and late afternoon when the sun's angle is lower in the sky. While the fixed panels demonstrate a relatively stable increase in power output during midday when the sun is at its peak, the sun-tracking panels still exhibit superior performance, though with smaller percentage improvements. For instance, at 12:00 PM, the improvement is only 1.62%, but as the sun moves away from its zenith, the sun-tracking panels continue to maintain higher power output levels. This capability to capture more solar energy throughout the day highlights the potential of sun-tracking panels to significantly enhance the overall efficiency and reliability of solar power systems. Such improvements in energy capture can be particularly beneficial in optimizing the performance of solar installations, thereby contributing to more effective and sustainable energy.

4. DISCUSSION

The experimental findings clearly demonstrate the effectiveness of sun-tracking solar panels in enhancing energy capture efficiency relative to fixed panels under diverse environmental conditions and throughout various times of the day. Over a ten-day period from 8:00 AM to 4:00 PM, sun-tracking panels consistently surpassed their fixed counterparts in power output. For instance, at the outset of the day (8:00 AM), sun-tracking panels averaged 18.74 W, representing a notable 61.41% increase compared to 11.61 W generated by fixed panels. This performance advantage persisted throughout the day, peaking at 4:00 PM when sun-tracking panels exhibited an 84.9% higher power output than fixed panels. These findings underscore the capacity of sun-tracking systems to optimize solar panel alignment with the sun's position, thereby maximizing incident radiation and overall energy production.

Furthermore, the comparative analysis underscored the adaptability of sun-tracking technology to varying solar angles and environmental conditions. While fixed panels demonstrated relatively stable performance during midday, when the sun was at its zenith, sun-tracking panels maintained superior energy capture capabilities even during low sun angle periods like early morning and late afternoon. This adaptability is critical for maintaining solar panel efficiency throughout the day, ensuring consistent and reliable energy generation amidst changing sunlight conditions. The study's results highlight the practical benefits of integrating sun-tracking mechanisms into solar energy systems, which contribute to increased energy yield and enhanced economic viability over the long term. Additionally, recent research has emphasized the importance of advanced technologies, such as artificial intelligence and deep learning, in optimizing solar tracking systems and improving energy system efficiency, as demonstrated in studies [27]–[29].

5. CONCLUSION

This study provides empirical evidence supporting the advantages of sun-tracking solar panels in enhancing energy capture efficiency compared to fixed panels. By dynamically adjusting panel orientation to track the sun's trajectory throughout the day, sun-tracking systems consistently optimize solar radiation absorption, resulting in higher power output across varying environmental contexts. The findings emphasize significant improvements in energy generation from sun-tracking panels, particularly during periods of low sun angle where fixed panels typically exhibit diminished performance. This capability underscores the potential of sun-tracking technology to play a pivotal role in advancing the efficiency and sustainability of solar energy systems, offering a viable pathway toward achieving global renewable energy objectives.

Future work in this research area should focus on several key aspects. First, refining the sun-tracking algorithms to improve their accuracy and responsiveness under rapidly changing weather conditions is crucial. Enhanced algorithms can further boost the efficiency and reliability of sun-tracking systems, ensuring optimal performance across all environmental scenarios. Additionally, integrating advanced sensors and real-time data processing capabilities can enable more precise adjustments, thereby maximizing energy capture. Moreover, the incorporation of artificial intelligence (AI) in solar tracking control presents a promising avenue for future development. AI-driven models, such as machine learning and deep learning algorithms, can analyze large datasets from environmental sensors, predict solar trajectories, and dynamically adjust the orientation of solar panels with greater precision. Recent studies have shown that AI can significantly enhance the adaptability and efficiency of solar tracking systems, particularly under unpredictable weather conditions and varying geographic locations. By leveraging AI, future sun-tracking systems could achieve unprecedented levels of optimization, further advancing the role of solar energy in global renewable energy strategies.

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