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Comparison of the Efficiency of Solar PV Fixed, Single-Axis, and Dual-Axis Solar Trackers: A Review

Mas Efendi[1*], Rahmat Imam Mainil[1], Azridjal Aziz[1]
[1] *Department of Mechanical Engineering, Universitas Riau, Riau, 28293, Indonesia.*
* Corresponding Author. E-mail : masefendi318@gmail.com

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Abstract

The global energy shortage, especially in developing countries, drives the search for alternative energy sources such as solar power, which is one of the cleanest energy sources. This research discusses the comparison of efficiency between solar PV fixed, single-axis solar trackers, and dual-axis solar trackers. The method used is a survey of the literature of multiple studies that only analyzes the efficiency of solar PV using different tracking devices. The efficiency data is normalized based on location factors and light intensity for a fair comparison. The results show that fixed solar panels are stationary and simple, serving as a baseline with 100 % efficiency. Single-axis panels track the sun horizontally, boosting efficiency by 25.6 % but with moderate complexity due to motors and controls. Dual-axis panels track the sun both horizontally and vertically, increasing efficiency by up to 50 % but with the highest complexity due to more moving parts and dual-axis control systems.

Keywords: solar PV; solar tracker; efficiency.

1. Introduction

The global energy constraint, particularly in developing nations, encourages researchers to explore alternative energy sources that can substitute conventional fossil fuels [1], [2]. Alternative energy sources include solar, nuclear, and wind energy [3]. Solar energy is produced by harnessing solar radiation and is one of the cleanest energy sources with the least causing pollution impact on the environment. The energy received by the Earth from the sun is estimated to be around 1.8×10^{11} MW [4]. Given its equatorial location, Indonesia has solar energy sources with an average daily solar radiation intensity of roughly 4.8 kWh/m^2 across the whole country [3]. With the use of photovoltaic (PV) systems and PV panels, solar energy has the potential to significantly contribute to the world's energy demands [5]. However, the energy efficiency generated by PV panels is greatly influenced by weather conditions such as temperature, wind speed, ambient air humidity, and solar radiation levels. To achieve optimal efficiency, PV panels need to receive sunlight perpendicularly during operation, which can be accomplished using a solar tracker system that follows the sun's movement throughout the day [6]. Extensive research has been accomplished to improve the performance of PV panels through the installation of a solar tracker system [7].

Due to the high costs and challenges associated with the procurement of solar panels, it is crucial to utilize this technology as optimally as possible to achieve high efficiency. This can be done through the development of advanced solar tracker systems, precise tilt angle adjustments, and strategic location selection. These efforts will ensure that each panel operates at maximum capacity, thereby optimizing the investment made in the procurement of solar panels [8].

In recent years, researchers have developed various designs of solar tracker systems to maximize energy production from PV panels [9]. Numerous investigations have been carried out to enhance this solar tracker systems' performance using effective mechanical actuators and ideal control systems. Three types of solar tracker systems-fixed, single-axis, and dual-axis that are used on PV panels to improve electrical energy efficiency will be reviewed in this paper. The study's main objective is to compare the energy efficiency that each kind of solar tracker produces. Economic factors, like installation and maintenance costs, are not covered in this study; instead, the primary emphasis is on the PV panels' pure energy efficiency.

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1.1. Solar Photovoltaic (PV)

Solar PV is a solar cell technology that uses semiconductor materials (silicon (Si), gemanium (Ge), zinc oxide (ZnO), and cadmium telluride (CdTe)) to convert sunlight into electrical energy. This technology consists of two main components: electrodes and semiconductors. The surface of the electrodes is responsible for capturing sunlight, which is then converted into electricity by the semiconductors. The semiconductor material used must be able to effectively absorb sunlight [10].

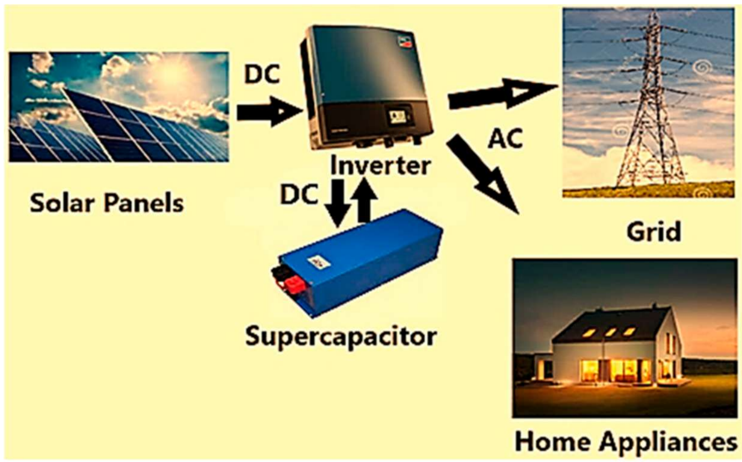

Figure 1. Illustration of solar power plant [10]

Figure 1 shows that the installation of solar panels is relatively easy to do. The most important thing is to ensure that the panels receive optimal sunlight exposure.

2. Methodology

Based on earlier research, this study intends to evaluate journals and compare the efficiency of fixed solar panels, solar panels with a single-axis tracking system, and solar panels with a dual-axis tracking system. The methodology undertaken includes the following steps: identification and collection of literature, classification and analysis of literature, data processing and comparison and discussion of results.

2.1. Identification and Collection of Literature

The criteria for selecting journals in this research include a focus on studies discussing the efficiency of fixed solar panels, single-axis, and dual-axis, with sources taken from reputable journals, conference proceedings, or technical reports within the last 10 years to ensure relevance to current technological developments. Databases like Scopus, IEEE Xplore, ScienceDirect, and Google Scholar were used to search the literature using keywords like "fixed solar panel efficiency," "single-axis solar tracker efficiency," and "dual-axis solar tracker efficiency".

2.2. Classification and Analysis of Literature

In the study classification process, journals are grouped based on the type of solar panel system being researched; fixed, single-axis, and dual-axis, as well as the research methods used, such as experimental, simulation, or a combination of both. Important data extracted includes the reported energy efficiency (%), geographical location or environmental conditions where the experiments were conducted. The technology used is also included (such as the type of tracker, sensors, or tracking algorithms), as well as information on implementation costs and system complexity if available.

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2.3. Data Processing and Comparison

The efficiency data from various studies are normalized based on location factors, sunlight intensity, and measurement duration to allow fair comparisons. Subsequently, the average efficiency is calculated for each type of solar panel system, namely fixed, single-axis, and dual-axis. Comparative analysis is conducted to evaluate the efficiency improvements of solar panels with single-axis and dual-axis systems compared to fixed panels, while also identifying factors that influence efficiency differences, such as sensor technology, tracking algorithms, and weather conditions.

2.4. Discussion of Results

Qualitative analysis was conducted by discussing the benefits and drawbacks of each type of solar panels system (fixed, single-axis, and dual-axis) based on previous research findings, while quantitative analysis was carried out by compiling tables or graphs to compare the efficiency of the three types of systems in detail.

3. Results and Discussion

3.1. Fixed PV Panel

A fixed solar panel system is permanently installed and does not have a mechanism for tracking the sun's movement. This type of panel is installed at a specific angle optimized based on the geographical location to receive as much sunlight as possible throughout the day, as shown in Figure 2 [11], [12]. Fixed solar panels have various advantages that make them a viable alternative in solar energy applications. With lower installation and maintenance costs, these panels become the right solution for users who prioritize cost efficiency. Its simple design without moving components enhances durability and simplifies the maintenance process, allowing the panel to operate stably in the long term. Although fixed solar panels cannot optimize energy absorption as well as solar trackers, this technology can still effectively absorb sunlight through optimal angle adjustments, especially in locations with stable sunlight intensity throughout the year [13].

Figure 2. Fixed PV panels [14]

Despite simpler and requiring less maintenance compared to solar tracker systems, fixed solar panels have limitations because they cannot capture sunlight maximally throughout the day. Due to the changing position of the sun throughout the day and year, fixed solar panels are often less efficient in capturing solar energy compared to panels equipped with solar trackers, which can adapt to the direction of sunlight. Fixed panels, on the other hand, seem to be popular because to their inexpensive installation costs, simple construction, and excellent stability.

A series of studies on fixed solar panels have explored various aspects, including the optimization of installation angles, materials, and performance comparisons with other technologies [15]. Examining the impact

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of optimal installation angles corresponds to variations in geographic latitude, which can significantly increase the efficiency of solar panels through periodic adjustments throughout the year [16]. In the comparison of semiconductor materials, it can be found that monocrystalline silicon offers higher efficiency than polycrystalline, although the latter is more economical. A study compared fixed solar panels and solar trackers, showing that solar trackers can increase efficiency by up to 57.4 %, although fixed panels remain a more practical choice in areas with inconsistent sunlight intensity [17].

3.2. Solar Tracking System

The solar tracker system is specifically designed to keep PV panels perpendicular to the direction of solar radiation [18] - [20]. To achieve the optimal angle of incidence and maximize the electricity production from the PV panels, the solar tracker system must be positioned correctly [21] - [23]. The ideal location for the solar tracker system depends on several crucial factors, including sun irradiation, azimuth angle, elevation angle, inclination angle, declination angle, and zenith angle. The elevation angle and the azimuth angle are the two most important of these angles for figuring out where the sun is [11], [24].

Solar irradiation can be determined through the measurement of power from a light source or luminous flux [25]. The declination angle is strongly related to the elevation angle (α_s) and zenith angle (θ_z). The angle between the Earth's equatorial plane and the line that connects the Earth's and the sun's centers is known as the declination angle (δ). On the other hand, the angle created between the horizon and solar radiation is known as the elevation angle. The angle that quantifies the sun's beams' clockwise departure toward the north is known as the solar azimuth angle (γ_s) [19], [26], [27]. The surface azimuth angle (γ), conversely, indicates how far the surface deviates from its vertical position in relation to the meridian. The angle between the surface and the sky is known as the inclination angle (β), and it is positive for surfaces that face the equator. A graphic displaying those sun angles can be found in Figure 3 [19], [26].

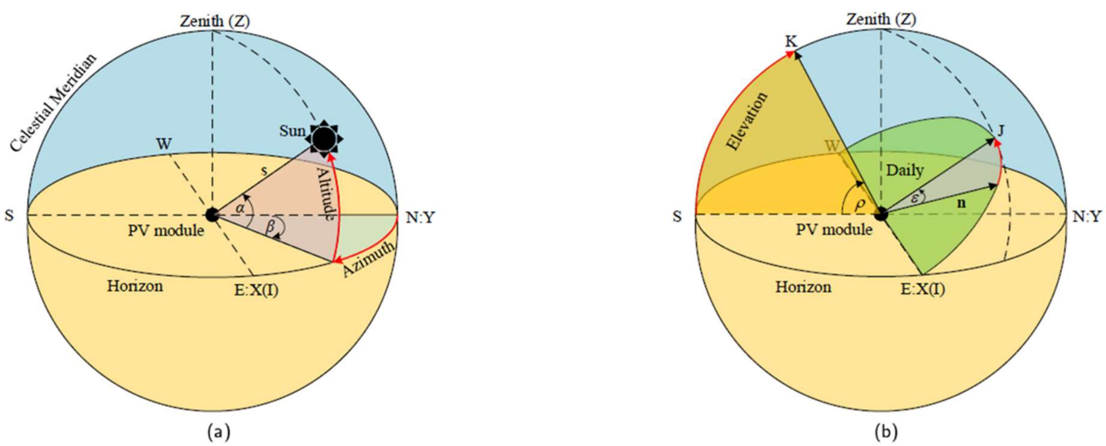

Figure 3. Representation of system solar angles (a) sun position horizontal coordinate system and (b) tracking system pseudo-azimuthal [28]

3.2.1 PV Panel with Solar Tracker Single-Axis

PV panel with solar tracker single-axis aims to dynamically increase energy efficiency by aligning solar panels with the direction of sunlight through a single-axis tracker mechanism [17], [29], [30].

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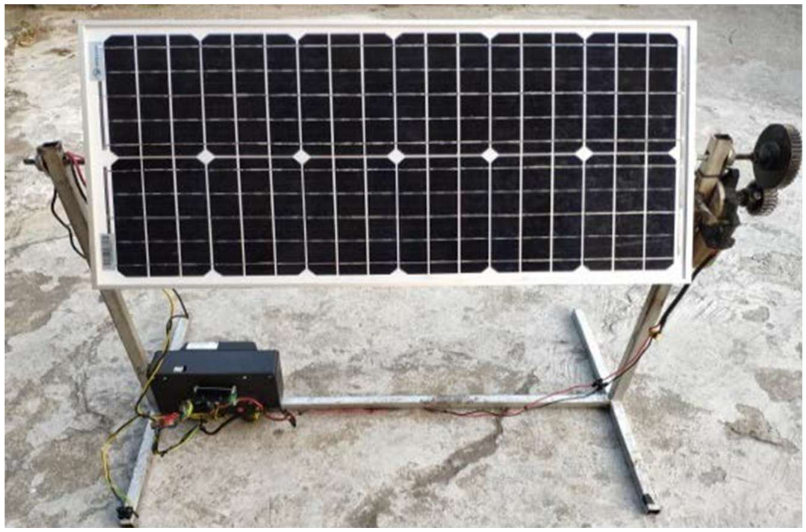

Figure 4. PV panel with solar tracker single-axis [11]

Figure 4. shows a single-axis solar tracker, a system mechanism that functions to follow the movement of the sun along one axis, which is generally applied in tropical regions, as the position of the sun is relatively stable throughout the year [31], [32]. This system uses a single linear actuator equipped with a motor to move the solar panels to always align with the movement of the sun [32].

Research conducted by Manu et al. [33] presents an in-depth analysis of the design, development, and implementation of a single-axis solar tracker system aimed at optimizing solar energy utilization. By using the Arduino atmega328p and light dependent resistors (LDR), this system dynamically aligns the solar panels with the direction of sunlight, which has the potential to increase energy output efficiency. The average increase in radiation achieved in this study is 29.9%. In another study, the single-axis solar tracker system successfully significantly improved the energy production efficiency of photovoltaic panels, with an increase of 72.45% compared to fixed panels [34]. In another study, it was shown that a single-axis solar tracker significantly improves the efficiency of grid-connected photovoltaic (PV) systems in Central Vietnam. A 250 W PV system with a solar tracker produced a maximum energy output of 1732 Wh on sunny days, with an overall efficiency increase of up to 30.3%, while the energy consumption for the controller and linear actuator was only 35 Wh [35]. It can be seen in Table 1 that the efficiency of solar PV using a single-axis solar tracker has improved in several studies [36], [37].

Tabel 1. The efficiency of solar PV using a single-axis solar tracker.

Author	PV panel	Microcontroller	Sensor	Actuator	Efficiency
Ngo et al., 2020 [35]	Monocrystalline silicon	WST03-5	Sensor cahaya	HF-TGA-A 450-12-4	30.30 %
Nahar et al., 2021 [34]	PV panel	PIC16F877A.	2 × LDR	Stepper motor	22.45 %
Manu et al., 2024 [33]	PV Panel	ATmega328	2 × LDR	Servo motor	29.90 %
Hamad et al., 2020 [30]	PV panel	Arduino mega 2560	2 × LDR	Servo motor	20 %
Qader et al., 2023 [36]	150wp	Arduino UNO	2 × LDR	Actuator linier	29.3 %
Rinaldi et al., 2020 [37]	100wp	Nodemcu	Desired panel angle control by mobile	Servo motor	25 %

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3.2.2 PV panel with Solar Tracker Dual-Axis

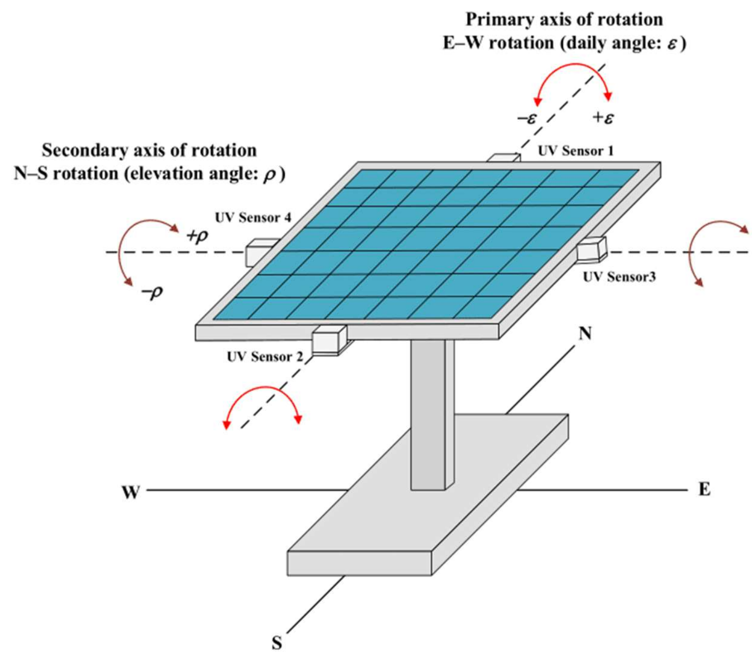

Figure 4. PV panel with solar tracker dual-axis [38]

The dual-axis solar tracker system has been designed for boosting the efficiency of solar panels by adjusting its angle in accordance with the daily and annual movement of the sun [15], [28], [39]. With two degrees of freedom, namely the elevation and azimuth axes, this system generally uses components such as Light Dependent Resistor (LDR), stepper motors or servos, and microcontrollers [29], [30], [40]. Experimental results show that the dual-axis solar tracker system can increase the energy efficiency of PV panels by up to 44.89 % compared to fixed PV systems [28]. Another study concluded that the dual-axis solar tracker is a solution to enhance solar energy production [26], [41]-[43]. Its user-friendly design allows for easy assembly and maintenance [44] - [49]. In Table 2, it shows the increase in solar PV efficiency using a dual-axis solar tracker from several studies that have been conducted.

Table 2. Efficiency solar PV using solar tracker dual-axis

Author	PV Panel	Microcontroller	Sensor	Actuator	Efficiency
Jamroen et al., 2020 [28]	20wp	Arduino uno	4 x LDR	2 × Motor DC Gear	44. 89 %
Fathi et al., 2022 [44]	80wp	L293D	4 x LDR	2 × DC gear head actuators	34.7 %
Shang and Shen, 2023 [26]	Polysilicon	STC89C52	Photoresistor	2 × Motor Stepping	24.60 %
Zhu et al., 2020 [15]	PV Panel	-	4 × LDR	2 × Actuator servo	96 %
Mamodiya and Kishor, 2024 [48]	335w	-	-	2 × Motor DC	45-48 %
Ghassoul, 2021 [49]	PV Panel	AA5880 integrated circuit	2 × LDR	3 × Servo Motor	69 %

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4. Conclusion

After conducting a qualitative analysis of each solar PV panel system (fixed, single-axis, and dual-axis) based on previous research findings: fixed solar panels are installed stationary without a mechanism to follow the movement of the sun, making them the simplest system because they do not require adjustments, with a baseline efficiency of 100 % as a reference. Single-axis panels move on one axis (usually from east to west) to follow the sun's movement throughout the day. Its increasing average energy efficiency is by 25.6 % compared to fixed panels. Although they require motors and control systems, it makes their complexity moderate. Meanwhile, dual-axis panels move on two axes to fully track the sun, both horizontally (east-west) and vertically (north-south), achieving up to 50 % higher efficiency compared to fixed panels. However, with the most complex design, they require motors and control systems for two axes and more moving parts.

5. Acknowledgments

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