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Technologies of Solar Tracking Systems for PV Panels

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ABSTRACT

Solar energy is a sustainable energy resource worldwide, but the amount of energy captured by solar panels is usually minimal because the panels are installed at a specific angle of inclination to capture the highest level of sun radiation during the day. The best performance of photovoltaic systems can be achieved if the panel remains perpendicular to the direction of the sun's radiation. To obtain the maximum output power of the panels, scientists have found that this is achieved by making them as perpendicular to the solar radiation falling on them as possible and this is done by solar trackers known as "solar trackers", which track The Sun's rays throughout the day. This study aims to discover the best orientation of photovoltaic panels by analyzing several sun tracking technologies. Several types of solar tracking technology are discussed, such as the degrees of motion of single- axis and dual-axis solar tracking systems, active and passive solar tracking, open/ closed loop are also discussed. This study included a summary of the performance of tracking technologies and the benefits and disadvantages of existing solar tracking systems. The results indicate that dual-axis solar tracking systems significantly enhance the energy efficiency and overall performance of photovoltaic systems, making them a viable solution for optimizing the use of solar energy.

1. Introduction

Growing environmental concerns and the depletion of traditional fossil fuel supplies have led to a major growth in the demand for clean and sustainable energy worldwide in recent decades [1], [2]. Solar energy has gained great attention among other renewable energy sources due to its abundance and

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sustainability [3]. Photovoltaic solar panels are used to convert solar radiation into electrical energy, which consist mainly of semiconductors, they have become one of the most widely adopted and widespread renewable energy technologies [4]. However, the angle between the panels and the solar radiation has a significant impact on the system's performance [5]. The maximum amount of energy is generated when the panels are perpendicular to the solar radiation [6]. In traditional fixed photovoltaic systems, the installation site's latitude and geographic location determine the PV panel's tilt angle [7]. Although this configuration provides a reasonable compromise for energy production, fixed PV systems cannot maintain the optimal orientation relative to the sun during the day and in various seasons [8]. For this reason, a large amount of solar energy is not collected, which reduces the efficiency of the system [8], [9]. To get around this restriction, solar tracking systems have been created that continuously modify the orientation of photovoltaic panels to keep them in line with the sun's position [10]. By maintaining the PV modules perpendicular to solar radiation during daylight hours, by greatly increasing the quantity of solar energy gathered, solar trackers can enhance the electrical energy produced by photovoltaic systems. An ideal solar tracking system allows the photovoltaic panel to track the sun throughout the day by adjusting for changes in the solar azimuth and altitude angles [11]. These tracking angles depend on the geographical latitude and atmospheric conditions of the installation site [11], [12]. Researchers have proposed, over the past decades, many studies that have investigated mechanical driving mechanisms, control algorithms and sensor technologies in order to improve and increase the production and reliability of solar energy systems [13].

This paper presents a review and study of various solar tracking technologies used in the generation of energy from photovoltaic systems. The paper is structured as follows: Section I, introduction. Section II, presents the review methodology for solar tracking systems. The third section explains the basics of solar tracking. The fourth section reviews the various classifications and operational systems of solar tracking systems. Finally, the fifth section explains the advantages and limitations of solar tracking systems.

2. Methodology of the Review

This review study was conducted through the collection of literature and analysis of articles and scientific research on solar tracking systems published in scientific data bases including Scopus, Google Scholar, Science Direct, IEEE Xplore and Web of Science. The literature search focused on publications between 2020 and 2026 and then the studies were collected, classified and analyzed based on tracking technologies and compared between them to identify the advantages and disadvantages of each of them.

Table 1: Summary of previous studies on solar tracking systems

Author	Year	Tracker Type	Axis	Method	Energy Improvement
Amelia et al. [14]	2020	Review	Single-axis & Dual-axis	Comparative study	15–45%
Mousazadeh et al. [12]	2020	Active tracker	Dual axis	Sensor control	35–40%
Abdallah et al. [15]	2021	PLC tracker	Dual axis	Closed-loop	34%
Zhao et al. [16]	2021	Active tracker	Dual axis	Sensor-based	38%
Park & Kim [17]	2021	Tracking PV	Single axis	Algorithm control	22%
Huang et al. [8]	2021	Intelligent tracker	Single axis	Microcontroller	25%

Author	Year	Tracker Type	Axis	Method	Energy Improvement
Hafez et al. [10]	2022	Review	Single & Dual-axis	Comparative analysis	15–40%
Li et al. [13]	2022	Active tracker	Single axis	Control system	20–28%
Chen et al. [18]	2022	Hybrid tracker	Dual axis	Sensor + algorithm	32%
Rahman & Islam [19]	2022	Optimization tracker	Dual axis	Optimization model	30%
Ahmed & Khan [20]	2023	Active tracker	Dual axis	Motor control	40%
Silva & Fernandes [21]	2023	Smart tracker	Dual axis	Machine learning	42%
Kumar et al. [22]	2024	Active tracker	Single axis	Control algorithm	24%
Wang & Liu [23]	2024	AI tracker	Dual axis	Artificial intelligence	43%
Sadeghi et al. [24]	2025	Review	Single-axis & Dual-axis	Comparative analysis	Up to 46%
Oduah& Abdulkadir. [25]	2026	Smart tracker	Dual axis	Adaptive AI-based control system	Up to 48%

3. Solar Tracking Fundamentals

Solar tracking systems rely on determining and tracking the sun's location in the sky. There is many important information that must be known to understand the movement of the sun radiation and design effective tracking systems [26].

Latitude: The sun's apparent motion is greatly influenced by latitude, which is the position of a place on Earth with respect to the equator [27].

Angle of Incidence: The angle between the sun radiation and the vertical line on top of the solar panels, the design goal is that this angle is closer to zero by making the panels at a 90-degree angle with the solar radiation to minimize reflection and get maximum energy [28].

Solar Altitude Angle: It is the angle between the sun radiation and the local horizon and is variable throughout the day and seasons [29].

Solar Azimuth Angle: It describes the direction of the sun along a true horizontal plane, such as the direction of the south, to ensure that the solar radiation is perpendicular to the panels for the longest period [28].

3.1. Solar Geometry Fundamentals

Solar tracking relies on understanding the apparent motion of the sun radiation. Several geometric parameters are used to describe the sun's position, including solar declination, solar hour angle, altitude angle, and azimuth angle [27]. The sun's angular position with respect to the equatorial plane of Earth is described by the solar declination angle.

It changes all year round and may be calculated with the formula below:

$$\delta = 23.45° \sin(360(284+n)/365) \quad (1)$$

The sun's angular displacement from local solar noon is represented by the solar hour angle, which may be computed as follows:

$$H = 15° (t - 12) \quad (2)$$

Accurate calculation of these parameters enables algorithm-based solar trackers to specify the location of the sun radiation without using optical sensors [28].

4 (Classification of solar tracker methodology):

4.1. Based on number of axis.

4.1.1. Single-Axis Trackers

Single-axis solar trackers rotate around a single axis, allowing photovoltaic panels to track the sun's apparent movement, either eastward to westward or along a tilted rotational axis [29]. These tracking systems are widely used in large-scale photovoltaic power plants because of their relatively simple mechanical structure, high reliability, and lower installation and expenses of upkeep in comparison to dual-axis tracking systems [30], [31]. In a typical configuration, throughout the day, the tracker rotates to keep the photovoltaic modules oriented towards solar radiation. The device captures more solar energy by changing the angle between the surface of the photovoltaic panel and the incoming sunlight [32].

Figure 1: Single- axis solar tracker

Single-axis solar trackers can boost photovoltaic systems' yearly energy production, according to many studies by approximately 15–30% compared with fixed-tilt PV installations, depending on geographical location, climate conditions, and system design [32], [33]

4.1.2. Dual-Axis Trackers

Dual-axis solar trackers rotate along two perpendicular axes, allowing photovoltaic panels to follow the sun's daily and seasonal motions [34]. These trackers continuously adjust the orientation of the PV module to maintain it nearly perpendicular to incoming solar radiation all day long. Thus, the capture of solar energy is enhanced by reducing the angle of incidence between the sun's rays and the panel surface as much as possible [36]. Comparing with single-axis tracking systems, dual-axis trackers provide the highest energy yield among solar tracking technologies because they can compensate for variations in both solar altitude and solar azimuth angles [37]. Dual-axis solar trackers can boost photovoltaic systems' yearly energy production, according to several studies by approximately 30–45% compared with fixed photovoltaic installations, depending on geographical location and climatic conditions [38]. Due to their high energy efficiency, dual-axis trackers are commonly used in applications where maximum energy production is required, such as research facilities, concentrated photovoltaic systems, and high-efficiency solar power plants [39].

Figure 2: Dual -Axis solar tracker

Table 2: Advantages and Disadvantages of Solar tracking systems that are fixed, single-axis, and dual-axis

Technology	Advantages	Disadvantages
Fixed solar panels	Lower cost, maintenance and complexity than solar tracking panels [8]	Less efficient in energy production because it does not follow the solar radiation [9]
Single Axis Tracker	Longer lifespan compared to dual-axis trackers [31] - High reliability and simpler mechanical structure [31] - Lower cost compared to dual-axis trackers [30] - Increases energy production by ~15–30% compared to fixed systems [32], [33]	The closer to the north, the less useful the uniaxial controllers are due to the high differences in the solar angle between summer and winter.[32] - More expensive than Fixed solar panels [30]
Dual-axis trackers	-Continuously track the sun throughout the day and seasons [34] - Maximum energy yield among tracking systems [36] - Increase annual energy production by ~30–45% [37] - Suitable for complex terrains and high-efficiency applications [38]	-Higher mechanical and control complexity [37] - More prone to failure due to complexity [37] - Higher cost compared to other systems [38]

4.2. Based on drives

4.2.1. Active solar tracking

Photovoltaic panels are dynamically oriented towards the sun using actuators [39]. As seen in Figure 3, photodetectors or light sensors gather the sun position data in real time. An analog-to-digital interface then transforms the data into digital signals. A control unit or microcontroller, such an Arduino or programmable logic controller (PLC), processes these signals and then instructs a motor driver to activate an electric linear actuator or DC motor [39], [40]. The PV tracking system's orientation is modified by this controlled actuation, allowing the solar panel to continuously follow the sun's movement and maximize solar radiation capture throughout the day [40]. Such systems typically rely on light-dependent resistors (LDRs), photodiodes, or other optical sensors to detect differences in solar intensity and determine the optimal panel orientation [41].

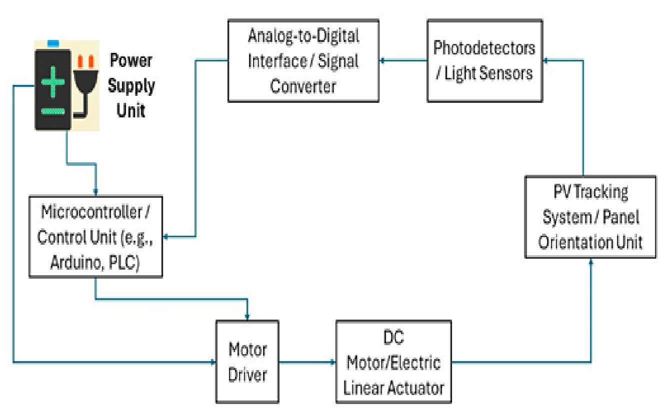

Figure 3: Scheme shows the work of the Active solar tracking

4.2.2. Passive tracking system

In its work, it relies on physical mechanisms such as thermal expansion, deformation of materials or displacement of liquids to adjust the perpendicular of the panels to solar radiation, so it does not need sensors or external energy sources [42]. It is simple, energy-saving and less maintenance compared to active trackers [43] However, they offer lower tracking accuracy and a slower response than sensor-based tracking devices [44]. Despite these limitations, they remain suitable for small off-grid PV installations because they are simple and less expensive [45].

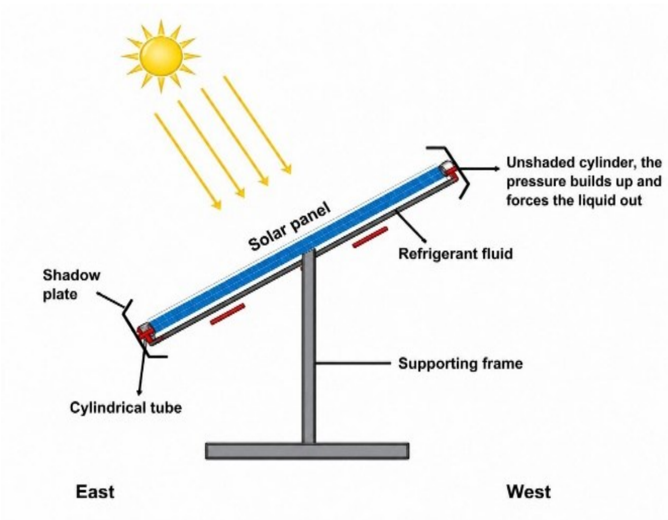

Figure 4: Scheme shows the work of the Passive solar tracking

4.2.3. Semi-Passive

Semi-passive tracking systems combine a specific number of active components with passive mechanical or thermal mechanisms in order to improve the efficiency of solar tracking [46]. Therefore, this system provides a balance between the cost of the system on the one hand and the efficiency and accuracy of solar tracking on the other hand, which makes it suitable for medium-sized photovoltaic applications [47].

4.2.4. Manual Solar Tracking Systems

Manual tracking systems, in contrast to automated tracking systems, depend on human interaction to move solar panels at regular intervals—typically twice or thrice a day [48]. They are simple, inexpensive and do not require sensors, motors or microcontrollers [49]. These systems are better than stationary systems, but they are less accurate and efficient than other automated tracking systems, they are used in small photovoltaic projects and are often used in rural areas and areas that are off-grid [50].

4.3. Based on Control Systems

4.3.1. closed-loop sun tracking system

A closed-loop sun tracking system is considered one of the most effective methods for improving the performance of photovoltaic (PV) systems by continuously aligning the solar panels with the sun's position. The system is categorized as a closed-loop system when sensors are used to detect the position of the sun and provide feedback to the control unit, no matter what kind of driving mechanism is employed to move the tracker, whether it is a predetermined procedure based on a passive system. In such systems, the signals from the sensors are sent to a comparator or microprocessor that analyzes the difference between the measured and desired positions. The controller then determines the error and generates appropriate actuation signals to the motors in order to correct the panel orientation and maintain optimal alignment with solar radiation [51], [52].

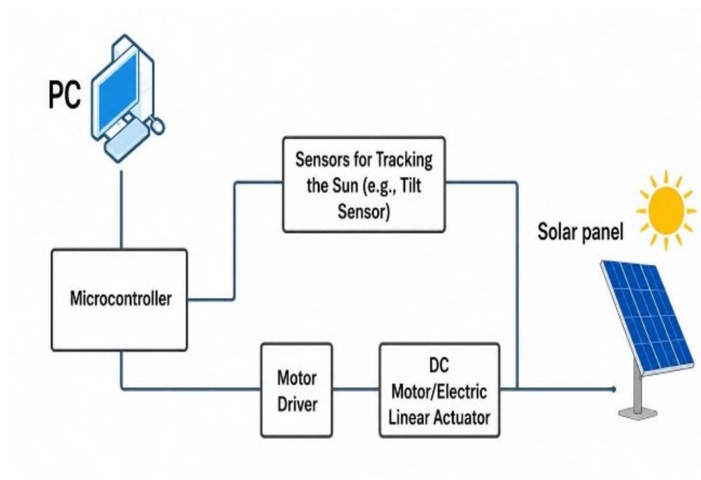

Figure 5: Block diagram of a closed loop tracking system

4.3.2. Open loop tracking system

It is one of the control systems whose principle of operation depends on sending driving signals to the engine based on the input data and the operating algorithm only, i.e. the control unit does not monitor the system or evaluate the output to verify the data, but relies on pre-calculations of the site and movement of the sun [53]. In general, open-loop systems are simpler to implement and less expensive than closed-loop systems, but they cannot correct errors caused by environmental factors or system disruptions due to the lack of a feedback mechanism in them [54].

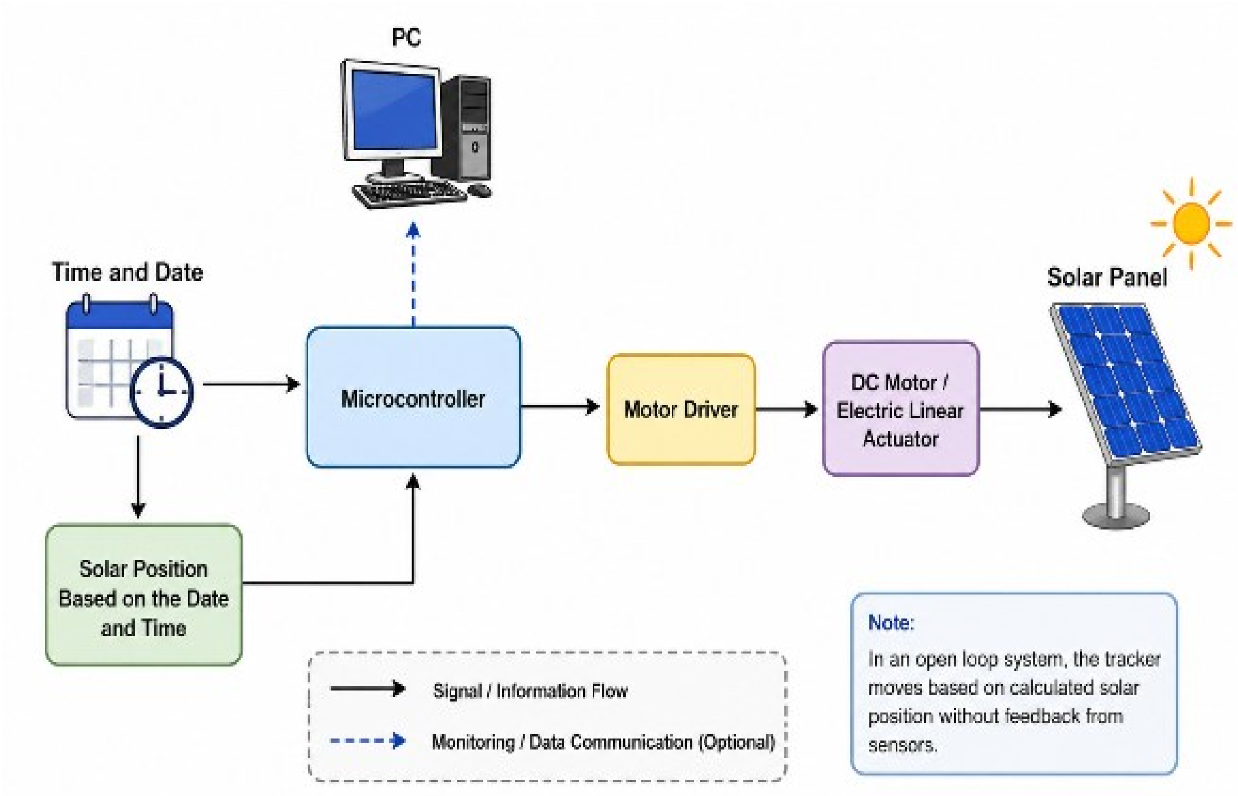

Figure 6: Block diagram of a open loop tracking system

Table 3: Comparison of Different Solar Tracking Systems

Tracker Type	Axis	Control	Energy Gain	Cost	Complexity
Fixed PV	None	None	Base value [8], [9]	Low [8]	Very Low [8]
Single Axis Tracker	1	Open/ Closed Loop [53], [51]	15–30% [32]	Medium [30]	Medium [30]
Dual Axis Tracker	2	Closed Loop [51]	30–45% [37], [38]	High [38]	High [38]
Passive Tracker	1	Passive	10–20% [42]	Low [43]	Low [43]
Active Tracker	1–2	Sensor Based [41]	25–40% [41], [57]	Medium [39]	Medium [39]
Semi-Passive Tracker	1	Hybrid [46]	20–30% [47]	Medium [47]	Medium [47]
Manual Tracker	1–2	Human [50]	10–15% [50]	Very Low [50]	Very Low [50]

5. Advantages and Limitations of Solar Tracking Systems Advantages

5.1. Advantages

- Get the maximum amount of captured solar energy by adjusting the direction of the panels to follow the movement of the sun throughout the day [54].
- Improved photovoltaic efficiency because the panels stay close to the optimal angle of solar radiation throughout the day [55].
- Achieve the best use of solar radiation, which increases the energy generated during the day [56].
- Solar trackers increase the total generated energy by 15-40% depending on the type of tracker compared to stationary systems [57].
- Suitable for photovoltaic power plants where increased power output is necessary [58].

5.2. Limitations

- Their cost is high compared to stationary systems due to additional components such as sensors, controllers and tracking structures [59].
- More complicated because it contains moving parts such as gears and actuators [60].
- Require regular maintenance to ensure continuous operation and reduce wear of moving mechanical components [61].
- It is more affected by harsh environmental conditions such as storms and dust, so it is more prone to malfunctions than stationary systems [62].
- Consumes extra energy to power the engines and tracking devices [63].

6. Conclusion

In conclusion, this review has shown that solar tracking systems are of utmost importance for the performance and optimization of a photovoltaic (PV) system by keeping an optimum alignment with solar radiation during day. The comparative analysis conducted in this study indicates that the energy gain of tracking systems varies significantly depending on the type of tracker and control strategy employed.

Specifically, dual-axis tracking systems exhibit the highest performance improvement, achieving energy gains of approximately 30–45%, and up to 48% in advanced intelligent systems, compared to fixed PV installations. However, this increased efficiency is accompanied by higher capital costs, greater mechanical complexity, and increased maintenance requirements. On the other hand, single-axis tracking systems provide a balanced solution, with energy gains ranging from 15–30%, while maintaining moderate cost and system complexity, making them particularly suitable for large-scale photovoltaic power plants.

In addition, passive and manual tracking systems although less efficient (10–20% and 10–15%, respectively), are still considered for small-scale and off-grid applications due to their simplicity, low cost, and lower requirements of maintenance. The paper also shows that active tracking systems could yield 25–40% improvement in performance depending on the control mechanism and environmental conditions.

Most importantly, the results underscore that the choice of a proper solar tracking system should be made not only based on energetic efficiency but also upon financial feasibility, operational reliability as well as environmental parameters and scale of use. In this regard, single-axis and hybrid tracking systems have a good balance between cost and performance.

Lastly, recent developments in smart control approaches (i.e., artificial intelligence and adaptive control systems) have demonstrated significant potential in further improving tracking accuracy with considerable energy savings, as well as an improvement in system reliability. Hence, future research focus should be on designing smart hybrid low-cost solar tracking systems that can work effectively in the demanding environment to pave way for the large-scale implementation of solar energy as a sustainable reliable source of energy.

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Conflicts of Interest

The authors declare no conflict of interest.

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