

"Optimizing Solar Energy Capture: A Comprehensive Review Of Solar Tracking Technologies"

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Renewable energy sources coming from solar energy is largely available in nature. The big problem with the sun system is that hardly any amount of sun's energy is utilized by photovoltaic (PV) systems. PV systems are fine only if the panels can be kept perpendicular to the direction of the radiations of the sun. Such a system should, therefore, essentially lead to keeping the PV panel in an optimal position such that at all times it is perpendicular to the sun radiation. This research aims at reviewing several solar tracking methods to attempt to identify the optimal PV panel orientation. The numerous technologies found in the solar tracking system have been studied based on research, such as a passive solar tracker, an active solar tracker, and degrees of movement of the solar tracking system, which includes both single and double axes. Tracking performance, benefits, and drawbacks of the existing solar tracking systems are also provided by this study. Limits of the solar tracking devices are also pinpointed as improvement areas for the near future. In addition, the latest development of a solar tracking system with artificial intelligence and machine learning, which is also focused in this research, is considered. The most successful sun tracking technique discovered during this research is an energetic solar monitor with multiple axis rotation.

Keywords: Solar Tracking, Photovoltaic Systems, Active Solar Tracker, Dual-Axis Rotation, Artificial Intelligence, Energy Efficiency

Introduction

The development and use of sources of renewable energy is aided by the population growth and ever-increasing demand for power brought on by industrial advancement. Because solar energy has so much potential, it is seen to be the most promising energy source. The amount of solar energy that the world receives is around 1.8×10^{11} MW, which is millions of times more than the total amount of currently used commercial energy on the planet [1]. Hence, solar power is a rapidly growing energy source for beneficial effects on sustainability. The increasing electricity costs and the decreasing efficiency of solar cell have inspired researchers over last two decades to design and implement new set ups to utilize solar energy, aiming to increase efficiency and make the technology competitive with fossil fuels. Many researches are conducted on Photovoltaic (PV) systems and it is mostly based on the operating and controlling of these systems [2-5]. The efficiency of PV systems is directly proportional to the intensity of sunshine and is significantly impacted by shade and loading. Keeping a PV system directly facing the sun is a simple and effective approach for reducing power loss and increasing efficiency [6]. To maximize solar energy collection, seasonal and daily tracking of the Sun can assist to keep solar collectors such as photovoltaic panels (PVs), parabolic reflectors, flat plate collectors, and so on perpendicular to sunlight. There are two types of solar tracking systems: single-axis (SAST) and dual-axis (DAST). Dual axis tracking systems position the panels to face the sun and follow its elevation and azimuth angles. Various dual axis solar tracking systems have been developed with arrangements like clutches, racks-pinion, or belt arrangements with motors, actuators and automation electronics [7, 8]. This approach is able to align with the Sun's position on two different axes for uninterrupted collection of solar energy. However, this multi-directional tracking is costly, complex, and requires constant maintenance leading to unwanted breakdowns. Passive solar tracking systems are a step towards a low-cost approach for solar tracking mechanisms. The planet has a vast amount of solar energy accessible, thus designing solar energy monitoring systems as economically as possible will increase the efficiency of solar energy use.

The main types of solar tracking systems are discussed in this study along with their advantages and working principles. Through a comparison analysis, the main objective is to investigate the different kinds of trackers that offer advantages like improved productivity, tracking accuracy, simplicity of installation, and cost efficiency. Additionally, it draws attention to the trends in the creation of solar trackers that work and have larger solar energy gathering capacity. The paper also covers a substantial overview of the literature on the optimization of solar tracking systems in conjunction with AI and machine learning technologies.

In a nutshell, the various solar tracking systems with recent advancement and developments in last decade have been reviewed.

1.1 Importance of Solar tracking system over fixed panels

The sun is a boundless source of power found on earth. Above 5000 trillion kWh of solar energy reaches the earth annually. Harnessing the sun's energy involves its conversion into usable forms of energy. It is renewable and friendly to the environment. However, the amount of energy received from a solar energy source depends on its orientation relative to the

collecting devices. When the sun is growing in angle, less energy is received, and, when the sun is below the horizon, it will be zero. Thus mounting of solar panel structures on the roof of buildings is not optimum. Such mounting structures are fixed for the lifetime of panels and this technique reduces the total collection considerably; tracking of angle of sun concerning the earth's surface is quite essential hence the focus shifted towards a tracking device. In 1962 Finster designed the first mechanical solar tracker [9]. In the following year, Saavedra designed a device to align Eppley pyrliometer with an autonomous electronic control system [10]. While the fixed photovoltaic panels have several drawbacks, Anusha and Chandra Reddy suggest the concept of designing a cost-effective, high performance, single axis solar tracker using a processor carrying an ARM real time clock. During six days, the experiment was done utilizing a tracking and a fixed system. Results: The capture of solar power between 9:00 am and 6:00 pm improved by around 40% of the solar tracking system [11]. A Comparison of Tracking Systems for Single- and Dual-Axis Permanent Mounts with Static Panels Deepthi S. et al. (2013):. Work was done between 8 a.m. From 12 p.m. until 6 p.m., the data on the fixed panel, single axis tracker, and dual axis tracker were recorded hourly. According to the same data, the dual axis tracking system's efficiency is 81.68% when compared to a fixed panel, whereas the single axis tracking system's efficiency is 32.17% [12]. R. Monika Gajadharane et al. developed and built the mechanical solar tracking system that supports the solar panels. To provide a proper electrical supply to the motor, the rotating mechanism of the motor is run for one minute each hour. Panels were connected to the 12 V battery load and the voltage and current for tracking as well as static panels was recorded every 30 minutes. The acquired results are represented in Fig 1. Based on the studies, a tracking system is efficient by 28.4% as compared to a static system [13]. As much as 40% more energy can be absorbed by a solar tracker device which in turn reduces the area of the solar field and helps reduce the cost incurred to produce electricity [14].

This technique was applied by Amit Chakraborty Chhoton and Narayan Ranjan Chakraborty to evaluate the performance of a dual-axis solar tracking system. The results were compared to fixed and single axis tracking systems, and it was determined that dual-axis solar tracking systems could generate 10.53 watts more electricity than fixed or single-axis systems [15]. With most current studies, dual-axis tracking systems with two degrees of freedom, which use azimuth and zenith tracking is the better option. This means that the solar panels will be oriented and placed in an optimum way to get the highest solar energy irradiation given by their special features. [16, 17]. Static ones, on the other hand, may be susceptible to larger energy yield gains compared to interruptions in environment adaptation from dual-axis tracking systems. Some solar sun tracking devices have been implemented in commercial applications. There are quite a few available systems. Unfortunately, though, the average person cannot put them on their homes because of their exorbitant cost. Consequently, a solar sun tracking device at a low cost should be developed in such a way that people dwelling in rooftops could exploit the captured energy from the sun to charge their batteries. This energy may be used as an auxiliary source of power with storage in batteries. This could be carried out especially where the power supply is unstable.

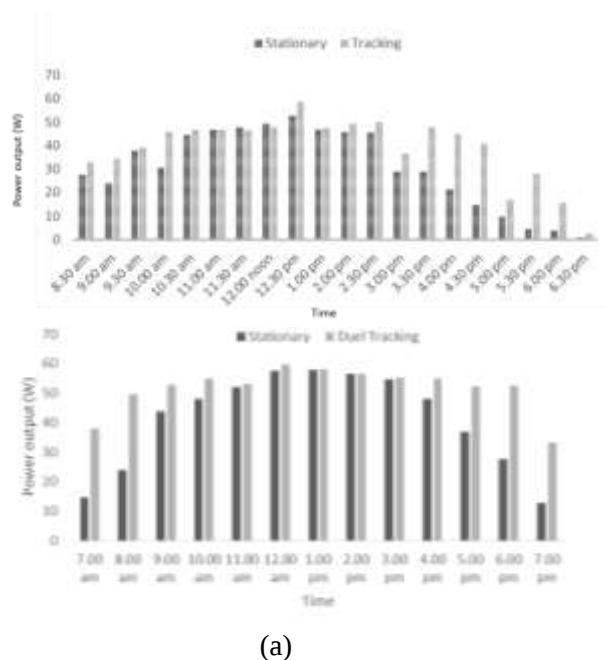


Fig 1 Power output of Stationary solar panel and Tracking system [12, 13]

2.0 Fundamentals of Sun Tracking System

Most PV solar energy systems come with fixed installation choices. However, more energy may be produced with the same amount of PV panels and inverters. Tracker systems provide an alternative to normal installation with a varied variation. The necessary equipment is mechanical construction (moving components) and software. Figure 2 depicts several types of solar tracking systems based on degree of freedom, drives, control techniques, and tracking strategies [18]. Stationary Solar Systems: Fixed at specified angles that remain constant unless modified manually. Economically affordable and simple to install. Tracking systems cost more to install and to maintain over time as compared to the non-tracking system when the considerations regarding design are kept in view. The benefit of a tracking system is that it can produce more energy in the same space.

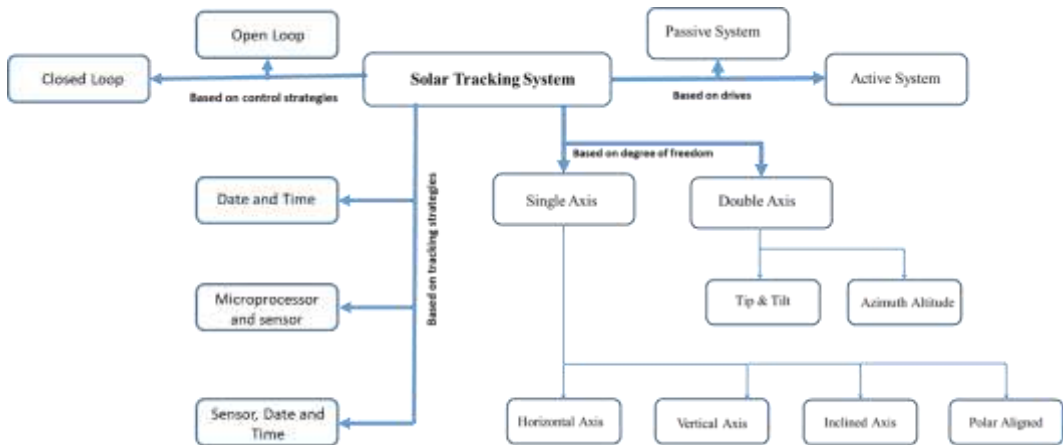


Figure 2: Types of solar tracking system

There are two common solar tracking systems: single-axis and dual-axis systems. Single-axis solar tracking systems are mainly employed in many applications due to their simplicity and manufacturability. The position of the sun is changeable during a day and every day of the year with respect to latitude, zenith, and longitude angles, which are directly associated with the output power of solar panels and energy utilization.

The single-axis solar tracking systems can be grouped as horizontal, vertical and inclined types according to their rotation mechanisms. Horizontal rotation axis mechanisms are constructed to rotate around the earth or post all day and every day, respectively. The azimuth angle is the solar position parameter on the earth's surface, which can vary from 0° to 360° with respect to the due south direction. Vertical rotation axis mechanisms are constructed to rotate around the earth according to the valid inclination angle of the site, which can vary from 180° to 540° with respect to the due south direction. Dual axis system involves two perpendicular axes of rotation. It requires a complicated control system however it is more efficient than single-axis tracking systems [19].

Based on drives sun tracking mechanisms available in the market: passive and active. Passive tracking systems are economical, simple, and robust with few moving parts. They have very low maintenance costs. In these systems, sun trackers are designed using thermal expansion principles of materials that cause the panel to rotate. When one side of the tracker heats up, the gas expands causing the panels to tilt towards Sun. A disadvantage of this system is, it does not perform well in critical environments. Active tracking systems are dominated in the market as they are more complicated and expensive than passive systems, with higher energy generation [20]. An additional supply of energy is needed for these systems to move. Active systems use external energy sources such as electric motors to move the mechanism according to the sun's position. It is highly accurate tracking system and adjusts dynamically throughout the day. Also it can respond to sudden changes in sunlight due to clouds. Table 1 summarizes the working principle, advantages and limitations of solar tracking system based on control strategies and tracking strategies [21].

Solar Tracking system	Working principle	Advantage	Limitation
Based on control strategies	• Open loop system does not rely on preprogramed algorithm or mathematical models to follow the sun's predicted path.	Simple and robust	Does not adjust for unexpected obstructions like clouds
	• Closed loop systems use feedback from sensors to constantly adjust the position of the solar panels in real time.	Can correct deviations due to wind, obstacles or sensor errors	More complex and requires regular calibration
Based on tracking strategies	• Date and time- utilizes algorithm to calculate the Sun's position throughout the day.	High accuracy as it relies on precise solar position data	Needs regular calibration to maintain accuracy over the time
	• Microprocessor- uses sensors to detect sunlight intensity and transmitted to the microprocessor.	Dynamic adjustment ensures panels are always optimally aligned, even with changing weather	Sensors can be affected by environmental factors such as dirt, dust or shading that reduces efficiency
	• Sensor, Date and Time- Combines both Microprocessor and sensor based tracking strategies to achieve optimal performance.	Offers the highest accuracy and efficiency by leveraging the strengths of both methods	More complex and expensive due to the combination of both control systems hence high maintenance requirements.

Table 1 Working principle, advantages and limitations of solar tracking system

3.0 Overall insights on Solar Tracking systems [21]

- **Efficiency Vs Cost:** Dual-axis and combination of sensor, date and time systems offer the highest efficiency but come with increased complexity and costs, making them suitable for high-value projects like concentrated solar power (CSP) plants.

On the other hand, single-axis and open-loop trackers provide a good balance for large-scale photovoltaic (PV) farms where cost-efficiency is vital.

- **Maintenance Considerations:** Systems like passive and time-based trackers offer lower maintenance needs, which are ideal for installations in remote or harsh environments. In contrast, active and sensor-based systems require more upkeep but provide dynamic performance and adaptability.
- **Adaptability:** Sensor-based and closed-loop systems excel in environments with variable weather due to their real-time adjustments, while the time-based trackers are better suited for predictable, sunny locations.
- **Scalability:** Single-axis and time-based systems are often the preferred choice for large solar farms due to their relatively simple design, lower costs, and scalability. In contrast, dual-axis and hybrid systems, despite their higher efficiency, are usually reserved for smaller-scale, high-efficiency setups due to their higher costs and maintenance needs.

4. Current challenges in Solar tracking system

Although somewhat very vital in optimizing the photovoltaic solar panel's efficiencies due to alignment of the panels with the position of the sun throughout the day, the static alignment of fixed installations cannot match this dynamic alignment in capturing energy. This, therefore, makes much hope in the technology application of solar tracking for the improvement of generation solar power. However, notwithstanding all these advantages offered by the solar tracking systems, they face several challenges which undermine their adoption and efficiency [9, 14]. These range from technical and operational challenges to economic and environmental ones. Understanding these challenges is very important for development improvements in design, performance, and cost-effectiveness of solar tracking technologies. Current challenges and limitations are explained as follows:

- i. **High Initial Costs:** Solar tracking systems are much more costlier than fixed solar panel setups due to its complex mechanical and electronic component. The increased initial investment can be a deterrant especially for smaller installations or regions with limited financial resources.
- ii. **Maintaining Reliability Challenges.** Mechanical systems, for example, solar trackers with moving parts could be prone to wear and tear. Maintaining a solar tracker will be significantly higher compared to fixed systems as maintenance is required for most of its components like the motors, gears, and sensors, bringing costs in order to run.
- iii. **Tracker's Energy Consumption:** Trackers also consume energy for motor and sensor operation. This in-body energy consumption slightly reduces the net gain achieved from the system, which at low sunlight levels could lower the overall efficiency of the entire system.
- iv. **Difficulty in Installation and Alignment:** Trackers are installed in precise alignment and calibration, more so than a fixed solar panel. This lack of proper installation will lead to

underperformance, giving less effectiveness to the system.

v. Environmental Sensitivity: Tracking mechanisms are sensitive to the environment in terms of wind, dust, and extreme temperatures. High winds can break tracking mechanisms, and dust particles and debris will hit sensors, which means a lower tracking accuracy.

vi. Area Requirements: Single-axis and dual-axis trackers will demand more space than a fixed installation of solar panels since the area available on properties with land constraints is limited by the amount of movement range.

vii. Grid Integration: The fact that the nature of solar energy is variable will make it unstable at the grid level, particularly when a tracker is applied; in this case, the variations in gradients enhance the fluctuations because of an abrupt change in the intensity of the solar irradiation.

viii. Not Suitable for Places with Little Sunlight: The locations where clouds are found continuously or even more by overcast conditions do not gain significantly by making use of these tracking devices. For that matter, the expense is even higher as compared to stationary solar panels.

ix. Dependence on fancy control systems and software: Tracking requires high-end control systems and software packages, which may be prone to system crashes, poor calibration, or faulty sensors that can make the tracker less effective.

x. Expensive repair and replacement: If a tracker breaks down, it can be a very costly affair to repair or replace some parts, and very often requires people with specialized knowledge. Such challenges will continue to demand the availability of technological breakthrough, innovative design approaches, and rugged, cost-effective components for making solar tracking technology more feasible.

5. Recent Technological Advancement

In order to resolve the challenge of supply variability and uncertainty associated with solar energy, artificial intelligence has been increasingly involved for the management, control and forecasts of energy production and electricity prices in solar process plants. Until 2020, forecasting was the main domain of AI in solar energy plants; however, in the last 5 years, other applications, for instance, design optimizations or correlations between the weather, energy production, and energy price, have been appearing more often [22, 23, 24]. With the growing capacities of solar energy plants, research on use of artificial intelligence technologies for solar plants management has significantly increased. The integration of Artificial Intelligence (AI) and Machine Learning (ML) with solar tracking systems significantly enhances the efficiency and reliability of solar power generation. The solar tracking system is designed to move the position of the solar panels to track the path of the sun at its most favorable position to catch as much sunlight as possible during the day.

5.1. Artificial Intelligence and Machine Learning Integration

AI and ML play a very crucial role in the optimisation of solar tracking systems by enhancing the accuracy of positioning for the sun. Most conventional solar trackers typically follow a predefined track, based on known sun paths that are followed under normal conditions, whereas AI and ML change and update themselves as the input to the models depends on real-time inputs, season, and weather patterns. Contrasted to the rigid patterns that are normally adopted in ML models, these track with a continually changing pattern based on inputs such as sunlight intensity, temperature, and weather forecasts. The advantage of this setup is real-time adjustments that improve the capture of sunlight [25]. The three key constituents of an AI/ML-enhanced solar tracker are sensors, AI algorithms, and ML models. Sensors take in data on intensity, temperature, wind speed, and panel orientation. AI algorithms make use of this data to predict the weather and self-adjust the panel placement. Through historical data learnt from models, such as regression models, neural networks, or deep learning, it optimizes the tracking algorithms. Therefore, it optimizes the system to make improvements in its performance [26]. Integration techniques of AI/ML are: collection and analysis of data, predictive modeling, and AI-based control systems. The data obtained through the sensors is processed with the help of AI techniques, by which they can predict a pattern of solar and accordingly adjust these in turn [27, 28]. The ML-based models predict the optimal orientation and angle based on the time of the day, season, and weather conditions. AI-driven systems regulate the motors of a solar tracker based on the output to maximize the sunlight faced by the panels.

The advantages of integration into solar tracking systems are significant with AI and ML. These types of technologies improve efficiency by optimizing the angle at which the sun's rays will be trapped by solar panels, therefore raising the general energy output by up to 20-30% from fixed systems [29,33]. Adaptive performance is another aspect as AI systems can respond based on certain unforeseen weather changes, such as cloud cover, and adjust trackers to prevent energy losses. In addition, the AI-based monitoring predicts the time and need for maintenance, reduces downtime, and cuts down the operational costs by increasing the long-life operation of equipment. AI models are also known to help in the prediction of energy output for the proper management of grids and better distribution of energy [30].

Applications of AI-driven solar tracking have already been seen in all kinds of applications. In big solar farms, AI-tracking systems are being installed to optimize thousands of units toward the maximum energy harvest. In smaller setups involving residential and commercial applications, AI is also applied to ensure panels are always pointed in the most efficient directions. However, the path remains long: ensuring sensor data quality, managing the significant upfront investment in AI and ML technologies, and preserving and updating AI models in ways that ensure their effectiveness over time [31].

The prospects for AI and ML for the future look good, and may even be integrated into the Internet of Things (IoT) systems. This combination could lead to more sophisticated, interconnected systems that optimise energy production on a larger scale [32]. Continued research aims to develop advanced AI algorithms capable of accounting for more complex weather patterns and environmental factors, further enhancing the effectiveness of solar tracking

systems.

6. Conclusion

Modern solar tracking technologies, in terms of control strategies, drive systems, and degrees of freedom. It can be emphasized that the various classifications of solar trackers are subdivided into only two categories: single-axis and dual-axis systems. The three single-axis configurations include the vertical axis, horizontal axis, and inclined axis. Meanwhile, there are only two categories for dual-axis systems-azimuth-altitude trackers, and tip-and-tilt trackers.

An analysis of the results points to the fact that the benefits of energy efficiency in a solar tracking system are very much influenced by the type of tracking equipment employed. While single-axis trackers can enhance the efficiency of PV systems by as much as 12-25%, dual-axis trackers boost it by 30-45%. Utilizing AI and ML in sun tracking was also considered, and these two disciplines have good future prospects for optimizing performance as well as raising total system efficiency.

It discussed problems associated with the present solar tracking systems and recommended that performance could be significantly enhanced by incorporating advanced AI and ML techniques. The review concluded that the energy efficiency of the solar tracking systems is greater than that of the fixed PV system by a large margin, with highest efficiency gains offered by dual axis trackers. Active dual-axis trackers should thus be considered to garner maximum benefits.

One of the biggest leaps solar technology can make in the near future is an AI and machine learning integration into the sun tracking systems, enabling super efficiency improvements with real-time data coupled with predictive analytics, making solar power a reliable and scalable source of energy. Although this integration of the technologies promises much in the quest for meeting global energy consumption sustainably, increased energy costs with AI-based tracking systems raise concerns as to their overall cost effectiveness.

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