

## Review

# A Review and Comparative Analysis of Solar Tracking Systems

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**Abstract:** This review provides a comprehensive and multidisciplinary overview of recent advancements in solar tracking systems (STSs) aimed at improving the efficiency and adaptability of photovoltaic (PV) technologies. The study systematically classifies solar trackers based on tracking axes (fixed, single-axis, and dual-axis), drive mechanisms (active, passive, semi-passive, manual, and chronological), and control strategies (open-loop, closed-loop, hybrid, and AI-based). Fixed-tilt PV systems serve as a baseline, with single-axis trackers achieving 20–35% higher energy yield, and dual-axis trackers offering energy gains ranging from 30% to 45% depending on geographic and climatic conditions. In particular, dual-axis systems outperform others in high-latitude and equatorial regions due to their ability to follow both azimuth and elevation angles throughout the year. Sensor technologies such as LDRs, UV sensors, and fiber-optic sensors are compared in terms of precision and environmental adaptability, while microcontroller platforms—including Arduino, ATmega, and PLC-based controllers—are evaluated for their scalability and application scope. Intelligent tracking systems, especially those leveraging machine learning and predictive analytics, demonstrate additional energy gains up to 7.83% under cloudy conditions compared to conventional algorithms. The review also emphasizes adaptive tracking strategies for backtracking, high-latitude conditions, and cloudy weather, alongside emerging applications in agrivoltaics, where solar tracking not only enhances energy capture but also improves shading control, crop productivity, and rainwater distribution. The findings underscore the importance of selecting appropriate tracking strategies based on site-specific factors, economic constraints, and climatic conditions, while highlighting the central role of solar tracking technologies in achieving greater solar penetration and supporting global sustainability goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

**Keywords:** solar tracking system; control strategies; optical cameras; agrivoltaics



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## 1. Introduction

The growing energy demand, driven by industrial expansion and population growth, has doubled in the last decade, placing immense pressure on existing resources and accelerating the transition to renewable energy [1]. While fossil fuels are depleting and harming the environment, solar PV have emerged as a reliable and clean alternative, capable of supporting diverse applications, including large-scale power generation, water desalination, and transportation [2]. However, maximizing PV efficiency remains a challenge, particularly in the face of climate variations. Some models suggest that global warming could reduce energy consumption in certain regions, raising questions about its economic impact and the effectiveness of current energy policies [3]. Given these dynamics, further

advancements in solar tracking and PV optimization are essential to harness solar energy more efficiently and ensure a sustainable energy future. However, harnessing this large amount of power is challenging due to sunlight being an intermittent power source and due to power losses in current solar panels. Conventional fixed solar panels have lower power conversion efficiency due to unfavorable orientation toward solar radiation.

### *1.1. Challenges in Implementing Solar Energy*

The fixed PV panels are widely used in both residential and commercial settings due to their lower installation and maintenance costs. However, they have intrinsic limitations, as they cannot adjust to the sun's movement across the sky, resulting in suboptimal solar energy capture. Solar tracking systems (STSs) address this inefficiency by dynamically adjusting the panel orientation to follow the sun, thereby enhancing energy yield [4]. Despite challenges like cost and maintenance, advancements in intelligent tracking methods offer promising solutions for improved performance and broader adoption [5]. For counteracting global warming, it is imperative to pass from fossil fuel dependency toward sustainable and alternative forms of renewable power sources [6]. For maximizing solar power harnessing [7], different strategies have been proposed, for example, improving materials of PV systems [8] and cooling systems, and algorithms for maximum power point tracking [9,10]. However, among all other strategies, utilizing the STSs, which dynamically change the direction of PV panels in relation to solar radiation to provide an ideal position, is among the best ways of improving efficiency [10,11].

### *1.2. Solar Tracking Systems (STSs) as a Solution*

STSs are electromechanical devices designed to optimize solar energy collection by following the sun's apparent trajectory [11]. These systems improve efficiency while reducing complexity and maintenance, making them crucial for the future of solar energy. Advancing solar tracking technology will be key to meeting renewable energy goals for the next decades [12]. Studies show that STSs can increase energy capture by 12–20% compared to fixed PV systems [13], with dual-axis trackers achieving efficiencies as high as 90% [14]. Also, computers make it more efficient for tracking systems [15]. STSs are categorized based on tracking axes, control methodology, and tracking strategy [14]. Single-axis tracking PV systems enhance energy capture by dynamically adjusting panel orientation to follow the sun's trajectory. Optimization strategies, such as the YAREA metric, provide a comprehensive approach to balancing energy yield and land-use efficiency in large-scale PV installations. YAREA, or Area-Specific Energy Yield, is defined as the ratio of the annual energy output of a PV system to the total active module area, expressed in (kWh/m<sup>2</sup>/year). This performance metric serves as a valuable indicator for evaluating the energy generation density and economic viability of different tracking configurations. By integrating historical solar irradiation data, this method refines decision-making in PV plant design, optimizing both technical and economic performance. Studies have demonstrated that incorporating YAREA into system planning significantly improves energy production per unit area, offering a cost-effective solution for maximizing investment potential in solar energy deployment [16]. In Nigeria, incorporating two-axis tracking in solar PV systems significantly enhances energy generation potential. A study determined that peak energy generation levels are achieved with this tracking mechanism, optimizing solar energy capture. The results indicate that two-axis tracking offers substantial improvements over fixed PV systems, making it a viable solution for maximizing solar energy efficiency in the region [17].

### *1.3. Control Mechanisms and Sensor Integration in STSs*

STSs employ passive and active control mechanisms to adjust PV panel orientation.

Passive solar trackers utilize thermal expansion of fluids to induce movement; it is simple but less precise [18]. Active trackers [19] use motors and control systems to optimize panel orientation, significantly improving energy capture. The intelligent sun tracking system proposed in [20] integrates a dual-axis tracker with maximum power point tracking (MPPT), using a Field-Programmable Gate Array (FPGA)-based controller to enhance energy output. The system employs particle swarm optimization (PSO) for precise positioning and Fuzzy Logic for MPPT adjustment, ensuring rapid and stable tracking. Additionally, features such as automatic homing, delay functions to reduce motor power consumption, and the flexibility to switch between single-axis, dual-axis, and fixed modes enhance adaptability and efficiency [20], which lead to an increase in energy efficiency of up to 25% for single-axis and up to 45% gain for dual-axis [21]. Sensor-based tracking strategies have advanced significantly, integrating light-dependent resistors (LDRs), cameras, GPS modules, accelerometers, and gyroscopes to optimize solar panel orientation [22,23]. LDR-based systems measure light intensity differences to adjust PV angles [24], while hybrid models combine real-time sensor data with astronomical algorithms for greater precision [25]. Additionally, modern STSs incorporate microcontrollers, PID controllers, and real-time computing techniques to further enhance efficiency [26].

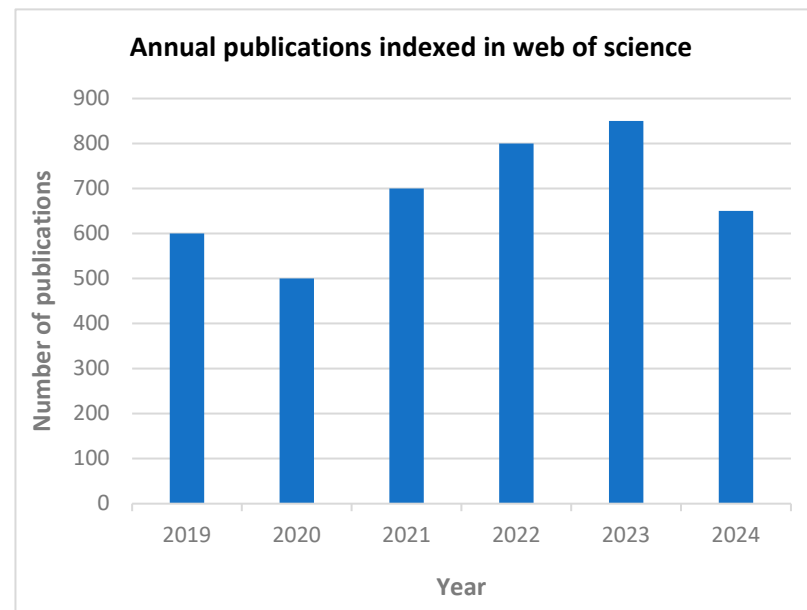
#### 1.4. Research Scope and Contribution

This paper provides a comprehensive review of solar tracking technologies, focusing on their classification, control methodologies, and sensor integration. Although primarily emphasizing PV systems, the study acknowledges existing tracking applications in concentrated solar power (CSP) systems, particularly parabolic trough collectors (PTCs). However, an extensive review of solar trackers specifically designed for CSP systems, including dual-axis trackers for PTC and associated control strategies such as dual-feedback and closed-loop algorithms, is intentionally beyond the scope of this study. In addition to reviewing conventional mechanical types and control systems, the study incorporates recent developments in intelligent tracking—particularly the integration of artificial intelligence (AI) techniques, such as machine learning and deep learning. It also highlights the role of solar trackers in agrivoltaic systems, a growing application area often overlooked in previous reviews. By combining mechanical classifications with advanced control strategies and cross-sectoral applications, this review offers an updated and multidisciplinary perspective. The study aims to bridge existing knowledge gaps by comparing technical approaches, energy performance, and contextual suitability of different tracking systems to support both research and real-world deployment.

##### 1.4.1. Annual Submission of Publications on STSs

In this study, a systematic literature review was conducted using the Web of Science Core Collection database to analyze research trends in solar tracking systems over the past five years (2019–2025). The search strategy followed the TAT (Title, Abstract, and Topic) approach, incorporating keywords such as “solar tracking system”, “single-axis tracking”, and “dual-axis tracking”. The search results were filtered to ensure relevance, focusing specifically on active tracking systems and their applications in solar energy production. The dataset comprises 4297 scientific records distributed across publication years from 2019 to 2024. Figure 1 presents the total number of articles published each year along with their respective percentages of the total research output and visually represents the temporal evolution of research output in solar tracking systems within the considered timespan. The vertical axis corresponds to the number of published articles, while the horizontal axis denotes the publication years. The trend clearly illustrates an upward trajectory, with the most significant increase occurring between 2019 and 2022. The

sustained publication volume in 2023 and 2024 further reinforces the field's importance in contemporary renewable energy research.



**Figure 1.** Annual publications indexed in Web of Science Core Collection related to solar tracking systems, covering the period 2019–2025.

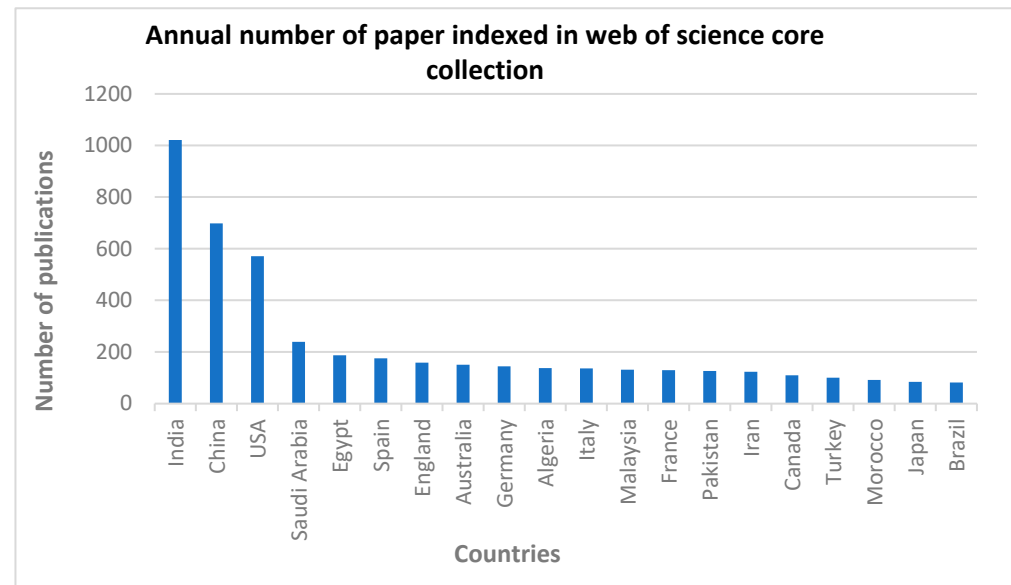
The distribution of publications over the last five years reveals a significant increase in research activity, particularly from 2020 onward. The highest number of articles was published in 2022 (18.22%), indicating a peak in research interest and scientific contributions related to solar tracking technology. This trend suggests a growing emphasis on improving tracking mechanisms, sensor integration, and automation techniques to enhance solar energy efficiency. The data for 2024 (16.45%) and 2023 (16.08%) show a sustained research focus, highlighting the continuing evolution of tracking technologies. The slight decline in 2023 compared to 2022 may indicate a phase of refinement, where existing models and control strategies are being validated rather than entirely new approaches being introduced. Despite this, the steady number of publications suggests that researchers are actively working on optimization and real-world applications of single-axis and dual-axis tracking systems.

In 2021 and 2020, research activity accounted for 17.31% and 15.50%, respectively. This period marks a transition where solar tracking research gained momentum, possibly due to increasing investments in renewable energy, advancements in microcontroller-based automation, and improvements in sensor accuracy. The relatively high research output in 2019 (16.43%) suggests that interest in solar tracking systems was already well-established before experiencing an upward trend in the following years.

This temporal analysis provides critical insights into the development of solar tracking technologies and highlights the research community's growing interest in optimizing solar energy efficiency. The steady increase in publications indicates that as the demand for renewable energy solutions rises, further advancements in sensor technology, automation, and tracking algorithms will continue to drive innovation in this field. Building on this initial analysis, the next sections will delve into regional contributions, journal distributions, and institutional research trends to provide a more comprehensive view of the global research landscape in solar tracking systems.

#### 1.4.2. Geographical Distribution of Research Contributions

The dataset also presents an analysis of research contributions across different countries and regions, illustrating the global impact of solar tracking system research. As shown in Figure 2, India leads with the highest number of research articles, contributing 1021 records (23.76%), highlighting its strong focus on solar energy advancements and tracking system innovations. This significant contribution aligns with India's increasing investments in renewable energy infrastructure and government-led solar initiatives.

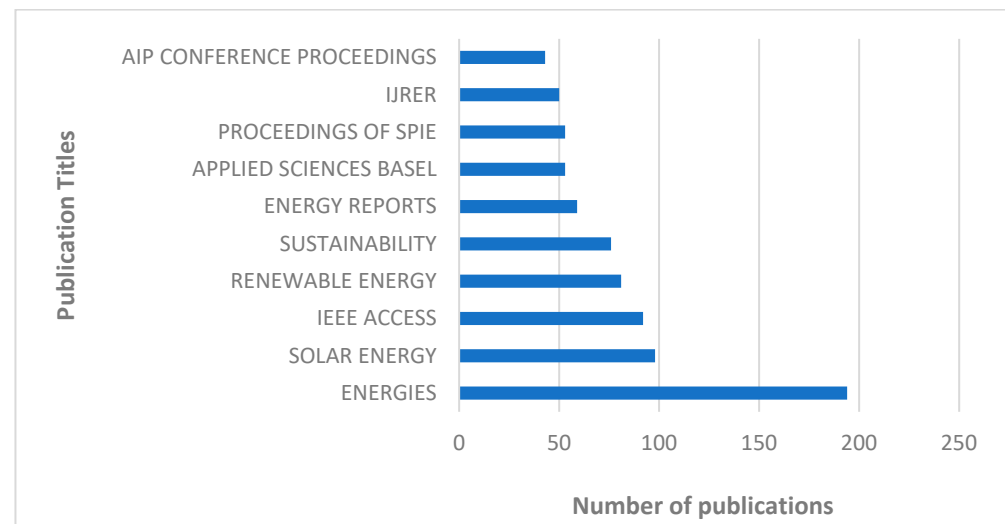


**Figure 2.** Distribution of research contributions across different countries and regions, based on publications indexed in Web of Science Core Collection for the period 2019–2025.

The People's Republic of China follows with 698 articles (16.24%), reinforcing its pivotal role in solar technology advancements. China's extensive solar industry and its commitment to large-scale solar farms and PV efficiency improvements likely contribute to its substantial research output. The United States (USA) ranks third, accounting for 571 publications (13.29%), indicating its continued leadership in solar research, automation, and sensor-based tracking systems. Countries worldwide are actively contributing to solar tracking system research. In the Middle East, Saudi Arabia and Egypt are making significant strides as they invest in solar energy to reduce fossil fuel dependency. In Europe, nations like Spain, the UK, Germany, Italy, and France are key players, reflecting their strong focus on solar innovation. Australia, Malaysia, Algeria, and Pakistan are also engaged, showing a growing global interest in sustainable energy. Other countries like Iran, Canada, Turkey, Morocco, Japan, and Brazil further highlight the worldwide commitment to solar tracking advancements. This global participation underscores the recognition of solar energy's potential, with continued research likely driving future innovations through international collaboration.

#### 1.4.3. Publication Titles Distribution

The dataset highlights the distribution of research publications across various scientific journals and conference proceedings, as shown in Figure 3. The journal *Energies* leads with 194 publications (4.52%), reflecting its strong focus on solar tracking and renewable energy technologies.

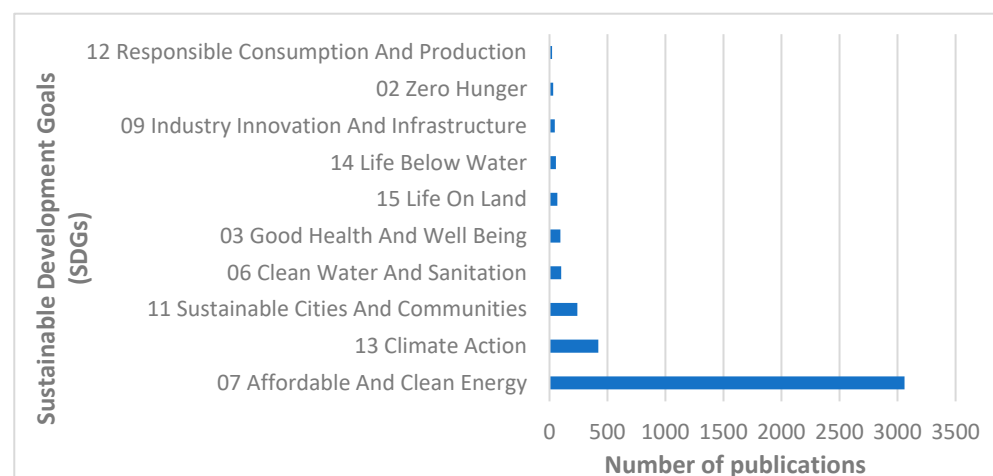


**Figure 3.** Distribution of research publications across scientific journals and conference proceedings, indexed in Web of Science Core Collection from 2019 to 2025.

Other significant journals include *Solar Energy* (2.28%), *IEEE Access* (2.14%), *Renewable Energy* (1.89%), and *Sustainability* (1.77%), emphasizing research on solar PV efficiency, automation, and sustainability. Additionally, *Energy Reports* (1.37%), *Applied Sciences Basel* (1.23%), and *Proceedings of SPIE* (1.23%) contribute to advancements in solar technology and applied sciences. Further, *International Journal of Renewable Energy Research* (1.16%) and *AIP Conference Proceedings* (1.00%) underscore the role of academic conferences and technical symposia in shaping solar tracking discussions. The diverse range of publication venues highlights a multidisciplinary approach, spanning engineering, sustainability, and applied physics, reinforcing the significance of solar tracking research in energy optimization and automation.

#### 1.4.4. Alignment with Sustainable Development Goals (SDGs)

The dataset highlights the strong alignment of solar tracking research with global sustainability efforts (Figure 4). SDG 07—Affordable and Clean Energy dominates with 3060 records (71.21%), emphasizing the critical role of solar tracking in renewable energy advancements. SDG 13—Climate Action follows at 9.82%, showcasing its impact on reducing carbon emissions and enhancing sustainability.

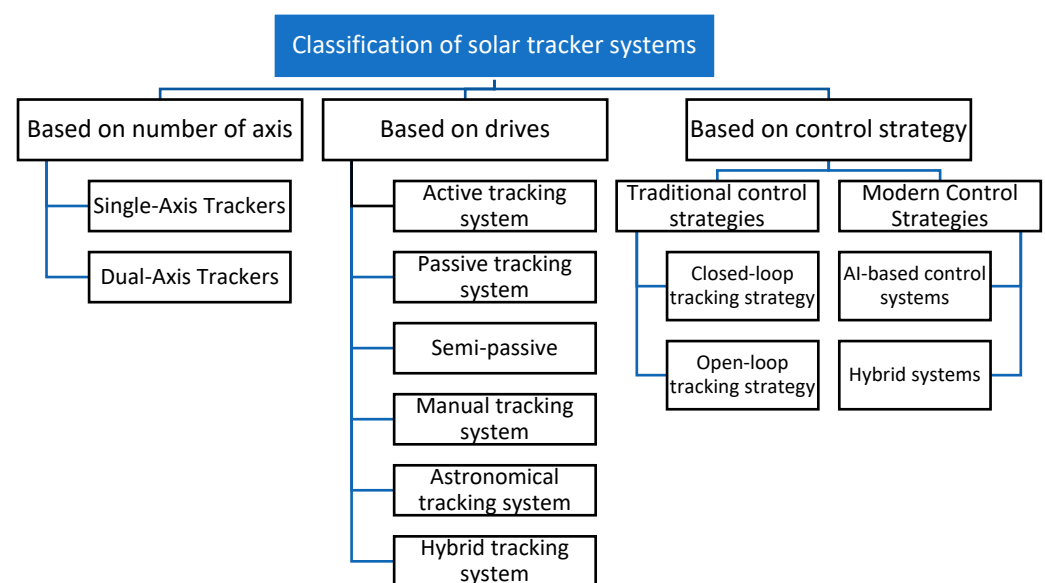


**Figure 4.** Research publications mapped to Sustainable Development Goals (SDGs), based on indexed records in Web of Science Core Collection from 2019 to 2025.

SDG 11—Sustainable Cities and Communities (5.61%) reflects solar integration into urban infrastructure, while SDG 06—Clean Water and Sanitation (2.37%), SDG 03—Good Health and Well-Being (2.19%), and SDG 15—Life on Land (1.58%) indicate broader environmental benefits. Other SDGs, including SDG 14, SDG 09, SDG 02, and SDG 12, contribute marginally, highlighting diverse applications of solar energy. The strong emphasis on SDG 07 and SDG 13 underscores solar tracking's role in energy sustainability and climate resilience, with additional SDG contributions reflecting its wider interdisciplinary impact.

## 2. Classification of Solar Trackers

Solar tracking systems can be categorized based on various criteria, including the type of control system, the drives employed, the tracking strategy implemented, or the degree of freedom in movement exhibited by the system. Figure 5 depicts all types of solar trackers reviewed in this study.



**Figure 5.** Overview of the types of solar tracking systems reviewed in this study.

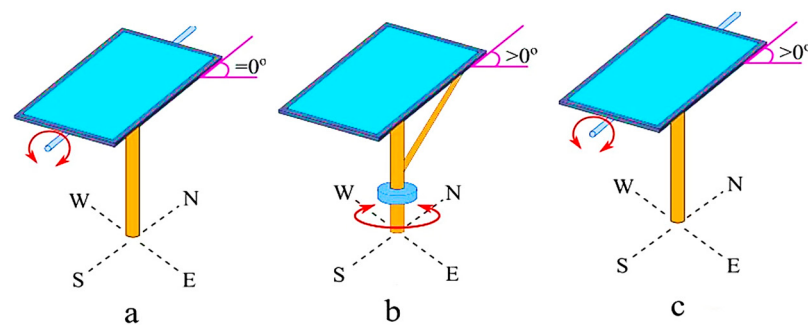
### 2.1. On the Basis of Number of Axes

STs are crucial for maximizing energy capture in PV applications, optimizing the alignment of PV panels with the sun's path. These systems play a vital role in diverse applications, from small-scale rooftop installations [27] and PV greenhouses [28] to large-scale PV power plants [29] and hydro PV-pumped storage systems [30]. STs enhance energy production by continuously adjusting the panel orientation to maintain a perpendicular relationship with the incident solar radiation. A fundamental classification of STs is based on their degrees of freedom, categorizing them into single-axis tracking (SAT) [31] and dual-axis tracking (DAT) [32]. The number of axes of movement dictates the system's complexity and its ability to precisely follow the sun's trajectory.

#### 2.1.1. Single-Axis Trackers (SATs)

SATs rotate around a single axis, aiming to maintain perpendicularity with the incoming solar radiation [33]. The SAST system generates 34.6% more energy than the fixed-tilt photovoltaic (FTPV) system, with an energy consumption of about 7.8% of its total generated energy, and its electrical control system consumes approximately 3.9% of the total energy production [34]. Several variations exist within SATs, each with distinct characteristics: Horizontal single-axis tracker (HSAT): The axis of rotation is horizontal to the ground [35]. Vertical single-axis trackers (VSAT) can collect up to 96% of the annual

solar radiation captured by dual-axis systems, with simpler mechanics. Their optimal tilt angle aligns closely with site latitude, offering 28% more energy than fixed panels in high-irradiance regions and 16% in low-irradiance areas, making them an effective option for non-concentrating PV systems [36]. A north–south orientation of the horizontal axis is generally preferred over an east–west alignment. Vertical Single-Axis Tracker (VSAT): The axis of rotation is vertical to the ground, typically aligned east–west. These are also referred to as V-axis trackers. Tilted single-axis tracker: The rotation axis is tilted at an angle between horizontal and vertical. Polar-Aligned Single-Axis Tracker (PSAT): A specific type of tilted single-axis tracker where the tilted axis is aligned parallel to the Earth’s polar axis, effectively pointing towards the polar star. Figure 6 illustrates different configurations of single-axis trackers: (a) shows the horizontal single-axis tracker (HSAT), (b) presents the VSAT, and (c) depicts the Polar-Aligned Single-Axis Tracker (PSAT).



**Figure 6.** Configurations of single-axis trackers: (a) HSAT, (b) VSAT, and (c) PSAT.

Another type of single-axis tracking system is the TR-axis tracking system which is a tracking structure that provides a tracking trajectory as close as possible to the sun’s movement. The TR-axis tracking structure was developed to achieve this goal [37]. SATs offer a balance between cost-effectiveness and performance, being less complex than DATs [38] and increasing power output by approximately 20% compared to fixed systems [16]. A simple SAT system can achieve the majority of the energy production of a continuous tracking system [39]. However, SATs are limited in their ability to track the sun’s annual movement, and their efficiency can be significantly reduced during cloudy conditions due to their single degree of freedom. Numerous studies have compared different single-axis configurations [40]. A study on surfaces with different latitudes from 3.53 to 67.82 and different longitudes as well reveals interesting results on optimal choice on inclined EW (IEW) axis tracking and NS axis tracking. This study illustrates that IEW-axis tracking is optimal for latitudes between 3 and 26 degrees, while V-axis tracking is superior for latitudes higher than 57° [41]. Global comparisons have also been conducted among single-axis, dual-axis, and fixed tracking systems in countries located near the equator. Dual-axis trackers yield the highest energy gains (12.52–29.58%) over fixed panels, but single-axis options like EW, IEWO, and VO offer competitive performance at lower costs. Economically, EW is the best choice, though IEWO becomes preferable as PV costs rise. These findings guide optimal solar tracker selection in low-latitude countries [42], and comparisons of optical performance between ISN-axis tracked, fixed and dual-axis tracked solar panels despite ISN single-axis trackers collecting up to 97% of the energy of dual-axis trackers. Adjusting the tilt four times a year makes them nearly as effective. They produce 30% more energy than fixed panels in sunny areas and 20% more in less sunny places, making them a good choice for high-sun regions [43]. The performance of different single-axis tracking systems has been extensively studied [16,39,44–49]. Li et al. [44] investigated the performance of a multi-position inclined north–south axis (INSA) sun-tracked V-trough system (MP-VPV) using advanced modeling techniques including vector algebra and 3D

radiation transfer. Their study demonstrated that the annual power output of MP-VPV systems is highly sensitive to the geometry of the V-trough and the wall reflectivity ( $\rho$ ). Optimal performance was achieved with  $\theta_a$  values of approximately  $21^\circ$ ,  $13.5^\circ$ , and  $10^\circ$  for 3P-, 5P-, and 7P-configurations, respectively, and opening angles ( $\varphi$ ) of  $30^\circ$  for  $k = 1$  and  $21^\circ$  for  $k = 2$  when  $\rho > 0.8$ . Results showed that these systems outperform comparable fixed south-facing PV systems, especially in regions with abundant solar resources like Beijing and Lhasa, providing power gains exceeding the geometric concentration ratios. Notably, the optimal tilting strategy (3T-MP-VPV), which adjusts the tilt angle four times per year, increased annual power output by 5–7% over the fixed-tilt strategy (1T-MP-VPV). These findings highlight the effectiveness of MP-VPV systems in maximizing energy yield through precise geometric and seasonal adjustments.

In a comparative study, Huang et al. [45] evaluated the performance of a 1-axis, 3-position (1A-3P) sun-tracking PV system against a fixed PV setup using two identical standalone solar-powered LED systems. Field tests revealed that the 1A-3P tracker increased daily energy generation by 35.6–35.8% under clear and partly cloudy conditions. Over a 13-month period in Taipei, the 1A-3P system achieved a 23.6% increase in total energy generation compared to the fixed PV, with expected gains exceeding 37.5% in areas with higher solar resources. The system's simplicity—utilizing a DC motor, timer-based control, and microcontroller—enabled low-cost, low-energy tracking, making it particularly suitable for building-integrated PV applications. Notably, it withstood a typhoon event with 50 m/s winds without operational failure, underscoring its durability. Despite its simplicity, the 1A-3P system's performance closely matched that of continuous dual-axis trackers, offering a cost-effective and reliable alternative for long-term solar deployment.

Alshaabani [46] introduced a simplified and cost-effective single-axis solar tracking system utilizing an analog sun sensor composed of four strategically placed photodiodes. This configuration enabled real-time tracking of the sun's movement from east to west, optimizing panel orientation throughout the day. Experimental validation, combined with MATLAB Simulink modeling, demonstrated that the proposed design increased energy output by approximately 20% compared to fixed PV systems. The system was further tested under seasonal variations, with winter and summer trials showing 21% and 18% average monthly efficiency gains, respectively. Peak generation improvements of up to 52% were observed during sunrise and sunset intervals. Despite minor limitations like spacing in dense installations and reduced performance during low solar angles, the system offers strong advantages in simplicity, scalability, and cost—particularly for applications in high-irradiance regions like Saudi Arabia. These findings position the tracker as a practical alternative to more complex dual-axis systems, offering a balance between performance and affordability.

Barbón et al. [48] proposed a comprehensive optimization methodology for large-scale PV plants using horizontal single-axis solar trackers, integrating factors such as inter-row spacing, operating modes, mounting system configurations, and irregular land shapes. A packing algorithm was implemented to maximize energy capture and land usage efficiency, while a levelized cost of energy (LCOE) assessment evaluated economic viability. Applied to the Granjera PV power plant in Zaragoza, Spain, the optimized layouts yielded substantial performance gains: energy output increased by 43.21% with the proposed 1 V configuration and by 91.18% with the 2 V configuration, compared to the current layout. Despite the higher initial investment costs (43.42% and 74.83%, respectively), the 2 V configuration offered superior LCOE performance, achieving an LCOE efficiency ratio of 1.09. The study demonstrated that, through effective spatial design and system sizing, single-axis tracking can approach the output of more complex systems with a competitive

cost–performance balance—especially when leveraging advanced layout algorithms for irregular terrain.

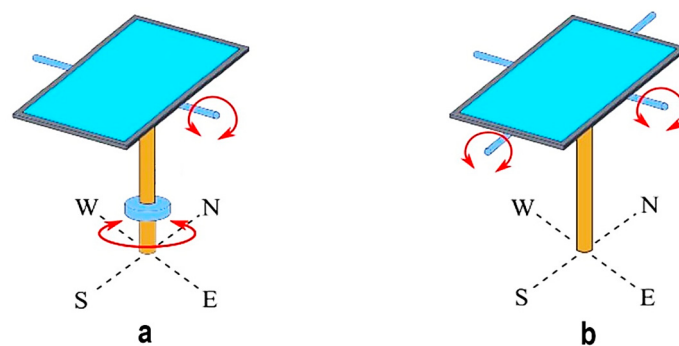
Wang et al. [49] introduced the bifacial companion method to enhance power output of tilted bifacial modules on horizontal single-axis trackers, by adding solar reflectors behind the modules to redirect sunlight to their rear side. Two types of reflectors—fixed and tracking—were evaluated through theoretical modeling and field experiments. Simulations showed this method is most effective at mid-to-high latitudes, where annual power generation gains can reach 30% (tracking reflector) and 17% (fixed reflector) at 37.5° latitude. Experimental testing in Weihai (37.53° N) confirmed theoretical trends, with maximum daily power gains of 18.1% (30° tilt), 13% (20° tilt), and 8.2% (10° tilt) in August 2021, and slightly lower gains in September. A module tilt angle near the optimal for a given latitude significantly improved performance. The economic evaluation showed that the bifacial companion's LCOE (0.0038–0.0054 USD/kWh) was substantially lower than traditional single-axis tracker systems (~0.05 USD/kWh), confirming its technical and cost viability for improving bifacial PV systems in suitable regions.

### 2.1.2. Dual-Axis Trackers (DATs)

DATs incorporate two axes of rotation, providing superior tracking accuracy and maximizing solar energy capture throughout the day and year [17,31,32,50–52]. A recent study presented a detailed design and experimental evaluation of a dual-axis tracking system that uses an open-loop control approach based on photo sensors to follow the sun's azimuth and zenith angles with high precision [50]. The tracking system was developed as a fully integrated electromechanical solution and tested under real-world conditions. Comparative results demonstrated that the proposed dual-axis tracker generated over 27% more electricity than a fixed PV system. The measured and calculated solar angles showed close alignment—within 3.6% for azimuth tracking—validating the accuracy and robustness of the control mechanism. Despite slight morning deviations caused by sensor shading, the system maintained less than 1° tracking error during peak sunlight hours, confirming its potential scalability for larger PV installations. A complementary innovation in dual-axis tracking is introduced by a sensorless yet high-precision closed-loop system that integrates maximum power point tracking (MPPT) directly into the control logic of the solar tracker [51]. Unlike conventional sensorless trackers, which operate open-loop using predefined solar paths, the proposed method dynamically adjusts the azimuth and altitude angles by continuously maximizing the PV module's output power. The MPPT unit uses real-time electrical data to determine the optimal orientation, achieving a minimal tracking error of just 0.11°. Experimental validation demonstrated seasonal energy efficiency improvements ranging from 28.8% in winter to 43.6% in summer compared to fixed systems, with cost recovery of additional tracking components occurring within approximately 4.3 years. This approach combines the cost-effectiveness of sensorless trackers with the accuracy of sensor-based systems, offering a hybrid solution that eliminates the typical limitations of both. A study analyzed the performance of two double-axis solar tracking PV systems over one year, showing that the tracking system generated 30.79% more electricity than a fixed-tilt system, with an annual yield of 15.07 MWh and an energy-to-power ratio of 1908 kWh/kWp. The measured and simulated energy values differed by less than 5%, confirming the system's reliability and accuracy [52]. Several studies have compared dual-axis tracking systems with fixed-tilt PV systems, highlighting the significant performance advantages of sun-tracking technology. Eke et al. [52] analyzed the annual electricity yield of both systems, reporting a 30.79% increase in energy production for a dual-axis tracker compared to a fixed latitude-tilt PV system. Their study, conducted in Mugla, Turkey, demonstrated that the dual-axis system generated 15.98 MWh annually,

outperforming the 11.53 MWh yield of the fixed-tilt system. Such findings reinforce the efficiency benefits of dual-axis tracking, particularly for maximizing energy capture in varying solar conditions [52]. A dual-axis solar tracking system designed for small and medium-sized applications showed a 24.6% increase in energy yield compared to a fixed panel tilted at  $30^\circ$  in Shanghai, China [53]. The system uses a simple electromechanical setup with step motor-driven gears and a photoelectric tracking method, ensuring ease of installation and operation. While effective for small-scale solar panels, its design and energy consumption make it less suitable for large photovoltaic systems [53]. However, this performance advantage comes at the cost of increased complexity and expense compared to SATs [54]. DATs are particularly crucial for concentrated solar power (CSP) applications, especially solar dish and solar tower systems, where the long distances between heliostat reflectors and the receiver demand high tracking accuracy to minimize angle errors [55]. The choice between SAT and DAT systems depends on the specific application requirements, considering factors like cost, complexity, energy gain, and choosing a control algorithm [56]. While SATs offer a cost-effective solution for many applications, DATs provide superior performance for applications demanding maximum energy capture and precise tracking, such as CSP systems [55].

To further illustrate the variations in DATs, Figure 7 presents two commonly applied configurations. Figure 7a shows a pseudo-azimuthal DAT, in which the PV panel rotates about a horizontal east–west axis and a vertical north–south axis, enabling precise adjustment to both solar azimuth and altitude. In contrast, Figure 7b depicts a pseudo-equatorial DAT, where the panel is fixed in azimuth orientation and rotates along the solar altitude and east–west direction, mimicking the Earth’s rotation. These configurations exemplify how mechanical design influences tracking accuracy and system application, especially in locations requiring high-precision solar alignment throughout the day.



**Figure 7.** Configurations of dual-axis solar tracking systems: (a) pseudo-azimuthal DAST with azimuth and altitude rotation; (b) pseudo-equatorial DAST with east–west and solar altitude tracking.

Jhee Phong Lee et al. [57] conducted a comprehensive study comparing the performance of a dual-axis solar tracker (DAST) and a Static Solar System (SSS) in Malaysia, with a focus on their correlation with the clearness index. Their findings revealed that DAST provided significant performance advantages during morning and evening hours, owing to its ability to continuously align with the sun’s position, unlike static systems. To strengthen statistical clarity, the clearness index was segmented into three time intervals—morning (0700–1100), midday (1101–1500), and evening (1501–1900)—to more accurately evaluate energy gain and efficiency. This segmentation improved correlation accuracy and reduced the standard deviation of the data; for instance, the standard deviations for energy gain across the three segments were  $0.0113 \text{ kWh/m}^2$  (morning),  $0.0133 \text{ kWh/m}^2$  (midday), and  $0.0109 \text{ kWh/m}^2$  (evening). Experimental results demonstrated that DAST yielded energy efficiency gains ranging from 24.91% on overcast days to 82.12% on clear days. These

gains were further validated against an HDKR anisotropic radiation model, confirming high agreement in trend lines across seven Malaysian cities. A case study of a 1 MW PV solar farm in Langkawi using Malaysia's feed-in tariff (FIT) scheme projected an additional annual profit of USD 219,499 due to DAST's enhanced performance, thus establishing both the technical and economic viability of dual-axis systems in equatorial regions.

Yilmaz et al. [58] conducted a comprehensive study comparing a dual-axis solar tracking system with a fixed-tilt PV system to assess efficiency gains. The research combined theoretical calculations and experimental validation using a 4.6 kW PV system, demonstrating a strong correlation between simulated and real-world data. Results confirmed that the dual-axis tracking system significantly outperforms fixed systems, optimizing solar radiation capture and improving overall energy yield.

Research comparing single-axis and dual-axis tracking systems has demonstrated the higher energy yield of dual-axis trackers. Vokas et al. [59] analyzed over 40 single-axis and 80 dual-axis PV plants across Greece, comparing real measured data with theoretical simulations. Their findings revealed that real-world energy production exceeded simulated estimates, with dual-axis trackers generating 8.47% more energy than single-axis systems based on actual measurements. This study highlights the limitations of simulation models and reinforces the practical advantages of dual-axis tracking for maximizing solar energy capture [59].

A study by Mamodiya and Tiwari [19] examined various strategies to enhance the energy efficiency of dual-axis tracking systems. They developed a SIMULINK-based dual-axis solar tracking system, integrating both electrical and mechanical components. Their simulation and experimental results in Jaipur, India, demonstrated that dual-axis tracking significantly improves current output compared to fixed PV systems. Additionally, they analyzed the impact of wind pressure on tracker stability, emphasizing the need for optimized structural designs. Their findings suggest that integrating real-time sun tracking, automation, and fault diagnosis can further enhance system efficiency and reliability, reducing overall solar electricity costs [60].

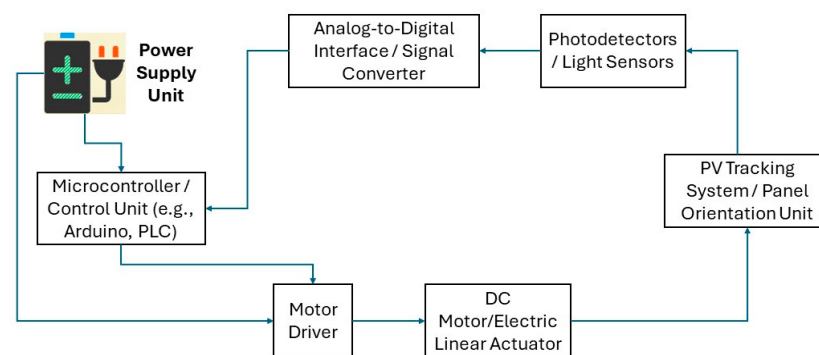
## 2.2. On the Basis of Driving System

Solar tracking systems are classified based on their drive mechanisms into five main types: active tracking, passive tracking, semi-passive tracking, manual tracking, and astronomical tracking [61]. Each type has distinct operational principles, advantages, and limitations, making them suitable for different applications. The active tracking system is the most widely used and extensively studied, as it relies on control circuits and sensors to optimize solar tracking [9,11,14–17,20,24,32,35,36,39,40,43–47,49,50,52,53]; astronomical tracking [62,63], on the other hand, relies on pre-determined solar position data, making it more energy-efficient as it eliminates unnecessary power losses due to continuous calibration. Meanwhile, passive [18,19], semi-passive [64], and manual tracking systems [65] emphasize simplicity, reduced component usage, and cost-effectiveness.

### 2.2.1. Active Solar Tracking Systems

Active solar trackers utilize sensors to determine the sun's position and actuate motors to adjust the system's orientation accordingly [66,67]. These systems can be categorized into several subtypes based on control methodologies such as microprocessor-based, electric-optical sensor-based, astronomical tracking system. Microprocessor-based tracking systems rely on photoresistors or light-dependent resistors (LDRs) to compare solar intensity at different positions [68]. Ghassoul [69] introduced a novel active solar tracking system that enhances energy extraction efficiency while reducing unnecessary motor movement and power consumption. Unlike conventional continuous tracking or pre-programmed systems,

which can be inefficient, this design utilizes a microcontroller-based control mechanism integrating a light-to-frequency (LTF) converter and LDR sensors. The PILOT system continuously tracks the sun, while the PANEL system only moves when it ensures higher energy output, preventing unnecessary repositioning. This method achieved a 40% increase in energy extraction compared to fixed panels, with 20% energy savings over continuously rotating panels. Additionally, the system operates with minimal movement, requiring only a few adjustments during peak hours, making it highly scalable for controlling multiple panels with a single low-power PILOT unit. These findings demonstrate a significant advancement in active solar tracking, optimizing both efficiency and energy management [69]. An active solar tracking system typically involves a structured integration of sensors, control units, and actuators to dynamically orient PV panels towards the sun. As shown in Figure 8, photodetectors or light sensors capture real-time solar position data, which are converted into digital signals via an analog-to-digital interface. These signals are processed by a microcontroller or control unit (such as an Arduino or PLC), which subsequently directs the motor driver to actuate a DC motor or electric linear actuator. This controlled actuation adjusts the PV tracking system's orientation, maximizing sunlight capture throughout the day. This systematic approach ensures high tracking accuracy and efficient energy utilization in active solar tracking applications.



**Figure 8.** Block diagram of an active solar tracking system.

A study by Ponce-Jara et al. [47] analyzed active single-axis solar tracking systems in an equatorial region, comparing an LDR-based system and an astronomical programming-based tracker against a fixed PV system. The results showed energy gains of 37% and 31.88%, respectively, over the static system, with net increases of 24.2% and 25.4% after accounting for losses. The LDR-based tracker required continuous power consumption, whereas the astronomical programming system operated intermittently, activating the stepper motor for two minutes per hour. Given its higher energy efficiency and lower operational complexity, the astronomical programming-based tracker was identified as the more suitable option for equatorial regions, where consistent solar radiation allows for efficient periodic adjustments. The study also suggested that reducing tracking intervals from 1 h to 15 or 30 min could further enhance solar energy capture and overall system performance [47].

Also, a study by Das et al. [70] developed and tested a smart dual-axis solar tracker using the ATMEGA-8L microcontroller, demonstrating a 19.73% increase in energy generation compared to a fixed PV system. The tracker effectively follows solar intensity regardless of motor speed, utilizing a low-speed servomotor to optimize tracking accuracy. While the system has higher initial costs, it benefits from low maintenance and no fuel expenses, making it a sustainable and cost-effective option for improving solar energy utilization.

A study conducted by Kabir et al. [71] examined the performance of fixed, single-axis, and dual-axis solar tracking systems controlled by an Arduino UNO. The tracking

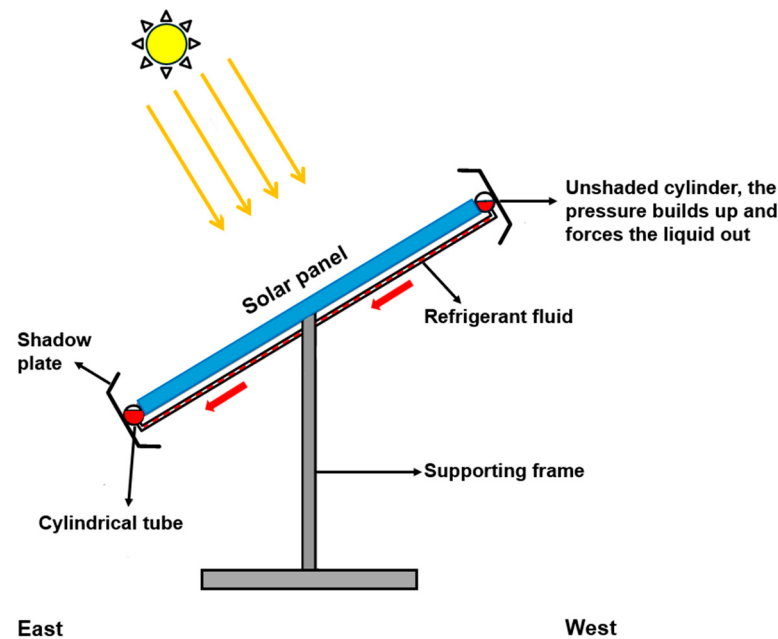
mechanism utilized four LDR sensors and two servo motors to optimize panel positioning based on real-time solar detection. Experimental results demonstrated that dual-axis tracking significantly improved energy efficiency, achieving up to 35.5% higher power output, while the single-axis system reached 33.23% compared to a fixed panel. These findings reinforce the effectiveness of active tracking systems, particularly dual-axis configurations, in maximizing solar radiation capture and overall energy generation.

### 2.2.2. Passive Solar Tracking Systems

Unlike active systems, passive solar trackers operate without electromechanical components, relying instead on thermal expansion principles to facilitate movement [18]. Passive solar trackers operate by using solar heat to create an imbalance, causing movement in the system [72]. They rely on thermal expansion, often using low-boiling-point compressed gas fluids or shape memory alloys. While they are less complex than active trackers, they lack the precision needed for concentrated solar power (CSP) systems. However, they are suitable for flat PV panels where high accuracy is not essential. One limitation of passive trackers is their reduced efficiency in low-temperature environments [72]. Poulek [73] tested a low-cost single-axis passive solar tracker using shape memory alloy (SMA) actuators, which deform at low temperatures and return to shape when heated, generating movement. The study found that SMA actuators function as heat engines with 2% efficiency, outperforming bimetallic alternatives, making them a cost-effective solution for passive PV tracking [73]. Passive solar tracking systems operate without electronic sensors or external power sources, relying instead on thermal expansion, fluid dynamics, or material properties to adjust the solar panel's position in response to sunlight. These systems use mechanical or chemical reactions to track the sun, making them energy-efficient and low-maintenance alternatives to active trackers. While passive trackers typically exhibit slower response times and lower precision compared to microprocessor-controlled systems, they remain a viable option for reducing energy consumption and operational costs in off-grid and remote applications. Also, in this type of tracking system, there is not any mechanical part to orient the panel toward the sun [74].

Low-concentration ratio solar concentration systems, such as CPCs (Compound Parabolic Concentrators), can also be considered passive tracking systems. These are fixed non-imaging concentrators that, due to the appropriately designed parabolic shape of their reflectors, can intercept and redirect solar radiation onto the absorber surface over a wide range of solar incidence angles on the collector. Another reason for their success is their ability to partially concentrate diffuse radiation [75].

Figure 9 illustrates the mechanism of a passive solar tracking system, utilizing thermal expansion to facilitate panel orientation. As the sun rises in the east, solar heat increases pressure within the unshaded west-side cylinder, forcing refrigerant fluid into the shaded east-side cylinder through a connecting tube. This fluid transfer causes the solar panel to rotate eastward, automatically aligning it with the sun's trajectory. Aluminum shadow plates regulate the heating of the fluid; when one cylinder receives more sunlight, its vapor pressure rises, pushing fluid toward the cooler, shaded cylinder. The shifting fluid weight continuously adjusts the panel orientation at approximately 15 degrees per hour until both cylinders achieve equal shading. At sunset, the panel faces west, remaining stationary overnight until reactivated by the morning sun, repeating the daily tracking cycle.



**Figure 9.** Schematic of a passive solar tracking mechanism using thermal expansion, refrigerant fluid transfer, and shadow plates to achieve continuous solar alignment.

### 2.2.3. Semi-Passive

Semi-passive solar tracking systems combine passive thermal or mechanical mechanisms with minimal active components to improve tracking efficiency while keeping energy consumption low [76]. These systems offer a balance between cost, energy efficiency, and precision, making them suitable for medium-scale PV applications where full active tracking may be too expensive or energy-intensive. Semi-passive tracking systems can also be integrated into solar tracking concentrators (STCs), which focus solar thermal energy onto a small receiver area. León et al. (2014) [76] proposed a semi-passive solar tracking concentrator (SPSTC) designed to minimize mechanical effort and solar ray deflection. The system includes a micro-heliostat array, a spot Fresnel lens, and a receiver, optimizing tilt for maximum lens efficiency while accounting for blocking and shading effects. This approach reduces tracking movement while maintaining effective solar concentration, making it a practical compromise between passive and active tracking [64].

### 2.2.4. Manual Solar Tracking Systems

Manual solar tracking relies on human intervention to adjust the position of solar panels at regular intervals, typically once or twice a day. Unlike automated systems, manual trackers do not require motors, sensors, or microcontrollers, making them a low-cost and simple alternative. While they improve energy capture compared to fixed panels, their effectiveness depends on the frequency and accuracy of adjustments. This method is often used in small-scale or off-grid applications where automation is impractical or too costly. Asfaw [77] developed and tested a dual-axis manual tracking system capable of seasonal sun tracking and daily adjustments up to  $75^\circ$  of the hour angle. The system, which secures a parabolic dish with a bolt and nut mechanism, adjusts every 10 min to align with the sun's path. Experimental results showed a strong correlation ( $r = 0.726$  to  $0.766$ ) between solar radiation and receiver surface temperature, confirming the effectiveness of manual tracking in maintaining solar alignment despite discrete temperature variations across the receiver.

Mwithiga and Kigo [78] investigated a manually adjustable solar dryer designed to track the sun in  $15^\circ$  increments throughout the day, evaluating its effect on thermal distri-

bution and drying efficiency for parchment coffee. The study tested four manual tracking strategies (T1, T3, T5, and T9), representing one to nine daily position changes, under both loaded and no-load conditions. Results showed that the maximum plenum temperature reached 70.4 °C, and temperature differentials ( $\Delta T$ ) between the dryer and ambient air exhibited a linear relationship with the number of manual adjustments ( $R^2 = 0.9757\text{--}0.9982$ ). Under the most frequent adjustment condition (T9), the moisture content of coffee beans decreased from 54.8% to below 13% (w.b.) within 2 days, significantly faster than traditional sun drying (5–7 days). However, despite higher internal temperatures and faster drying rates, the reduction in drying time across different manual tracking frequencies was marginal, suggesting limited practical advantage when labor and complexity are considered. The study concluded that while manual tracking can improve drying performance, its cost–benefit ratio is more justified in drying high-moisture, high-value crops, particularly in regions with high solar insolation.

#### 2.2.5. Astronomical Solar Tracking Systems

Astronomical trackers rely on predefined sun position algorithms, similar to date–time algorithm-based active trackers [64]. Unlike active trackers that rely on real-time sensor feedback, astronomical trackers eliminate energy consumption associated with calibration and are considered highly energy efficient [65]. However, they lack adaptability to sudden weather changes and require precise geographical calibration to function optimally. Flores-Hernández et al. [77] developed a novel astronomical tracking strategy aimed at optimizing solar tracking efficiency while reducing energy consumption and mechanical wear. By integrating a real-time decision-making algorithm, the proposed system decreased tracking energy consumption by 14.18% without compromising energy generation. Experimental results further demonstrated a 53.33% reduction in movement frequency and a 60.77% reduction in operation time, significantly extending the tracker’s lifetime by 6.8 times. This research highlights the potential of optimized astronomical tracking to enhance the profitability, durability, and environmental sustainability of solar tracking systems.

Roong and Chong [79] developed a laboratory-scale single-axis solar tracking system employing the astronomical tracking method, which uses the Earth’s rotation angle (15° per hour) as the basis for panel orientation. Designed for scalability and workspace evaluation, the system was experimentally validated at Universiti Teknikal Malaysia Melaka (UTeM), focusing on optimal angular rotation intervals. Their comparative study of rotation angles—10°, 15°, and 20° per hour and 7.5° every 30 min—revealed that a fixed 15° per hour movement yielded the highest performance ratio of 0.83, with up to 25% energy savings under sunny conditions, making it the most efficient and energy-conscious setting. Although more frequent tracking (e.g., every 30 min) marginally increased energy capture (by 4.6%), it also led to a 42% increase in power consumption, rendering it inefficient for low-power applications. The system integrated DC geared motors, a microcontroller-based control unit, and encoder feedback, with energy output monitored via a DC power meter and logged at one-minute intervals. The study supports the application of astronomical tracking methods in environments with high solar availability, such as Malaysia, where the average irradiance exceeds 600 W/m<sup>2</sup>, and reinforces the advantage of pre-programmed sun path-based tracking for reliable and low-energy-consumption systems.

#### 2.3. On the Basis of Control Systems

Solar tracking systems can be categorized based on the control strategies employed, primarily classified into traditional and modern control methods (Figure 5). Traditional strategies include open-loop and closed-loop systems [80]. Open-loop systems operate using pre-programmed astronomical data to guide panel positioning without real-time

sensor feedback, making them simpler and more cost-effective but less adaptive to changing conditions. In contrast, closed-loop systems rely on continuous feedback from sensors (e.g., photodiodes, LDRs, or pyranometers) to dynamically adjust the solar panels, offering higher precision but typically requiring more maintenance and energy consumption.

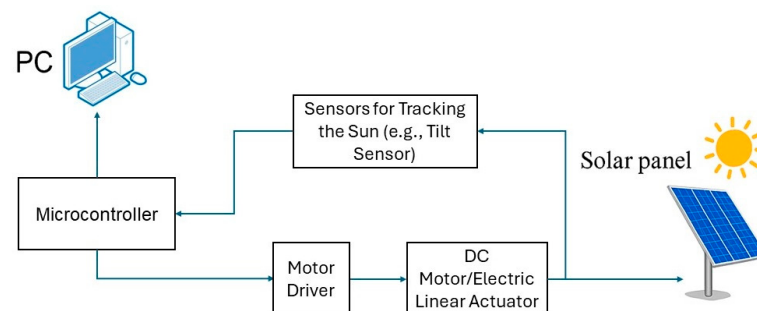
In response to recent technological advancements, modern control strategies have emerged, including hybrid and AI-based systems. Hybrid control strategies integrate open-loop and closed-loop methodologies, balancing simplicity and accuracy through combined use of astronomical algorithms and real-time sensor adjustments. AI-based control systems leverage advanced data-driven methods—such as machine learning and deep learning—to optimize tracker performance. These intelligent approaches predict and adapt to environmental changes, substantially improving energy efficiency, reducing unnecessary actuation, and enhancing the economic viability of solar tracking solutions.

### 2.3.1. Traditional Control Strategies

#### Closed-Loop

Closed-loop tracking systems rely on real-time data from sensors to detect the sun's position and adjust the tracker accordingly [80]. These systems function within a feedback control loop, where sensory data are continuously analyzed to minimize tracking errors [81]. Lee et al. [81] classified solar tracking systems into closed-loop and open-loop control methods, highlighting their role in optimizing solar thermal and PV applications. Closed-loop systems, relying on real-time sensor feedback, ensure higher accuracy but require more energy and maintenance, while open-loop systems, based on predefined algorithms, offer simplicity and efficiency but lack adaptability to weather changes. The study systematically analyzed the performance, benefits, and limitations of these methods, confirming their importance in high-performance solar applications [81]. Most sensor-based solar tracking systems operate on a closed-loop control strategy, where real-time feedback from sun position sensors continuously adjusts panel orientation to maximize solar capture. These systems rely on various sun position sensors, such as LDRs, photodiodes, and pyranometers, to detect sunlight intensity and dynamically correct misalignments.

Figure 10 illustrates a typical closed-loop solar tracking system, where sensors are used to ensure precise solar alignment. The system consists of a microcontroller interfaced with sun-tracking sensors, such as a tilt sensor, to determine the orientation of the solar panel. Based on sensor output signals, the microcontroller compares and computes the necessary adjustments and directs motor drivers to actuate the DC motor or electric linear actuator, reorienting the panel accordingly. The continuous feedback mechanism allows the system to adapt dynamically to changing solar panel orientation based on the environmental conditions. Integration with a PC enables monitoring, data logging, or advanced control logic, enhancing accuracy and operational flexibility.



**Figure 10.** Block diagram of a closed-loop solar tracking system using feedback to optimize PV panel orientation.

Salgado-Conrado [82] provided a comprehensive overview of sun position sensor prototypes, analyzing their geometrical designs, working principles, and performance limitations in solar technologies. The study highlighted that the most effective sensor configurations integrate the best characteristics of existing designs, optimizing cost-effectiveness, weight, accuracy, field of view (FOV), and data transmission. Despite advancements, key challenges remain, including limited geometric flexibility, control algorithm adaptability, temperature sensitivity, and auto-calibration constraints. Future research should focus on improving sensor design, enhancing data transmission efficiency, and refining calibration techniques to overcome these barriers and expanding sensor-based solar tracking applications.

Oliveira et al. [83] introduced a closed-loop solar tracking system utilizing a novel solar position sensor with a multifiber optical cable, designed to enhance precision and efficiency in concentrator photovoltaic (CPV) applications. This low-cost sensor provides real-time feedback, achieving a  $2.6 \times 10^{-3}$ -degree resolution within a  $\pm 0.1^\circ$  field of view, ensuring optimal panel orientation. The study highlights the importance of calibration and suggests AI-based control for further accuracy, reinforcing the practical value of closed-loop tracking in high-precision solar systems.

Shao et al. [84] explored closed-loop and open-loop solar tracking methods for solar remote-sensing instruments (SRSIs) in space missions. The primary closed-loop method utilized guide mirror offset angles to track sunlight, achieving high tracking precision of  $0.0121^\circ$  in azimuth and  $0.0037^\circ$  in pitch. The alternative open-loop method, based on precomputed sunlight angles, had lower precision ( $0.0992^\circ$  and  $0.0960^\circ$ , respectively). The study emphasized the importance of recalibration to counteract mechanical vibrations during launch, ensuring reliable solar tracking across different orbital inclinations. These findings highlight the superiority of closed-loop tracking for high-precision space applications, where real-time feedback is crucial for accurate sunlight capture.

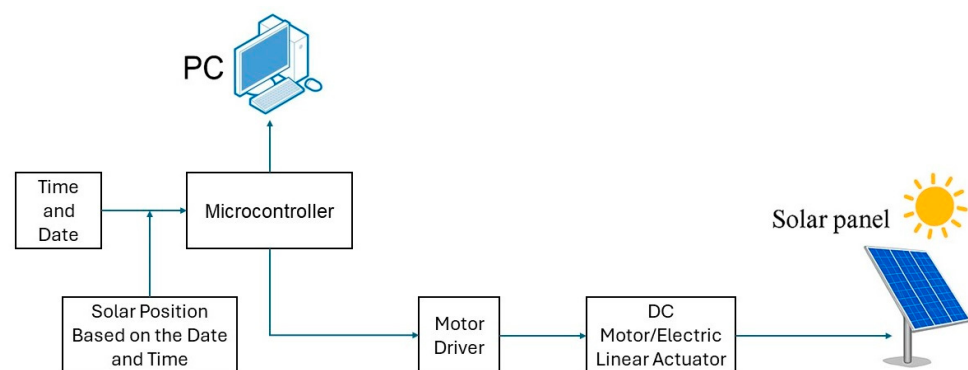
Recent comparative studies have reinforced the efficiency advantage of closed-loop tracking systems over open-loop alternatives. Melo et al. [85] developed two independent solar tracking systems—one open-loop and one closed-loop—each incorporating a dedicated control system. The closed-loop tracker used a control system driven by light-dependent resistors (LDRs) to dynamically adjust panel orientation based on real-time light intensity differences, while the open-loop tracker employed a control algorithm based on solar position geometry. Both systems were tested experimentally in Rio das Ostras, Brazil, under various sky conditions. Results showed the closed-loop system achieved a 33.0% increase in energy generation over a latitude-tilted fixed panel, slightly outperforming the open-loop system, which reached a 28.5% gain. The control architecture of the closed-loop setup allowed for superior responsiveness to sky variability, especially on partially cloudy days. The study highlights the significance of using real-time feedback and responsive control systems in closed-loop designs to maximize solar energy capture in dynamic environments.

### Open-Loop

Open-loop solar trackers work without using sensors, instead relying on pre-programmed data about the sun's position at different times of the day. A controller moves the solar panel according to these data, making the system simple and low-cost compared to closed-loop trackers. However, these trackers need careful calibration, and their accuracy can be affected by weather conditions or mechanical misalignment. The main challenge is creating an accurate algorithm that keeps the panel properly aligned with the sun throughout the day to avoid energy losses. Chen et al. [86] present a general solar tracking formula for heliostats with arbitrary orientations and target locations. This comprehensive solution encompasses existing tracking methods, such as azimuth-elevation

and spinning-elevation tracking, as special cases. By offering a flexible approach, the formula enables adaptable heliostat design, optimizing performance for various solar engineering applications [86]. The control unit, which may be a microcontroller, Arduino, or PLC, executes an algorithm that determines the necessary actuator movements to maintain the solar collector's alignment with the sun [87]. Open-loop solar tracking systems typically use astronomical algorithms to calculate the sun's zenith and azimuth angles throughout the day. Fuentes-Morales et al. [87] introduces a method based on the Solar Position Algorithm (SPA), which determines these angles using location and time and then converts them into commands for actuators through a computer, Arduino, microcontroller, or PLC. This approach allows CSP and CPV systems to align with the solar vector automatically, eliminating the need for real-time corrections. While cost-effective and easy to implement, open-loop trackers still require precise calibration to minimize tracking errors due to mechanical misalignment or external conditions.

Figure 11 illustrates the block diagram of the open-loop solar tracking system, where panel movement is based only on calculated solar positions without any sensor feedback. The microcontroller uses date and time inputs to compute the sun's coordinates, sending control signals to a motor driver and actuator to reposition the panel. Unlike closed-loop systems, this setup lacks real-time feedback, making accurate calibration essential for maintaining alignment. A PC interface supports control and monitoring functions.



**Figure 11.** Block diagram of an open-loop solar tracking system utilizing pre-programmed solar position data to orient the panel without real-time sensor feedback.

A novel one-axis general sun-tracking formula has been integrated into an open-loop tracking system, enhancing both accuracy and cost efficiency [88]. Unlike traditional open-loop methods, which rely on fixed astronomical data, this method introduces a correction mechanism that compensates for installation defects by analyzing solar images captured with a CCD camera. The system identifies and adjusts misalignment angles by simply modifying parameters in the tracking algorithm, achieving an impressive tracking accuracy of  $0.171^\circ$ , which is better than the encoder resolution limit of  $0.237^\circ$ . This approach demonstrates how calibration enhancements can significantly improve the reliability of open-loop sun-tracking systems.

Ahmad et al. [89] introduced an open-loop solar tracking system that integrates a PLC to precisely maneuver a two-axis photovoltaic solar module based on  $10^\circ$  altitude and  $1^\circ$  azimuth angle adjustments. Unlike conventional open-loop trackers, this system was evaluated under three different weather conditions—sunny, cloudy, and overcast days in the Malaysian tropical climate—confirming its effectiveness even in non-ideal weather. The study further analyzed power consumption, showing that tracking motors and the controller used only 5.89% of total generated power, demonstrating high efficiency. The findings suggest that even in less favorable weather, open-loop tracking remains viable,

and further improvements could be achieved by incorporating higher-output solar panels and lower-power controllers.

Sidek et al. [90] introduced an automated open-loop dual-axis solar tracking system that uses a Microcontroller Unit (MCU), GPS, and an encoder to improve positioning accuracy. Unlike conventional open-loop trackers, this system automatically adjusts its position based on the sun path trajectory algorithm, achieving an accuracy of  $\pm 0.5^\circ$ . The embedded PID control system further enhances elevation and azimuth tracking with minimal energy consumption. Performance tests showed 26.9% higher energy generation than fixed-tilted PV systems on clear days and 12.8% higher on overcast days. The tracker's low power consumption and automatic adaptability make it suitable for mobile solar tracking applications.

Alexandru [91] developed an advanced open-loop dual-axis equatorial tracking system designed to maximize photovoltaic energy output through precise mechanical modeling and optimized motor control. The control strategy was based on inputting predefined solar trajectories—daily and seasonal angles—into the system, eliminating the need for real-time feedback sensors. A multibody system (MBS) model of the tracker was created using ADAMS software and coupled with a DC motor control system modeled in MATLAB/Simulink, forming a fully integrated mechatronic prototype. Controller tuning was optimized via design of experiments (DOE) and response surface methodology, minimizing tracking error through regression analysis. The step-by-step tracking algorithm, implemented to minimize motor energy consumption, achieved a daily energy gain of approximately 49.2% compared to a fixed-tilt module, while maintaining a very low power usage of only 13 Wh/day for actuation. The system proved robust under simulated wind gusts of up to 30 m/s, and the root mean square tracking error remained below  $10^{-3}$ , indicating high precision. Experimental validation further confirmed the mechanical stability and energetic viability of the open-loop tracking system, especially under controlled environmental disturbances, making it a viable low-complexity alternative to sensor-based systems.

### 2.3.2. Modern Control Strategies

#### Hybrid Solar Tracking Systems

Hybrid solar tracking systems combine two or more tracking mechanisms to optimize energy capture while balancing efficiency, cost, and energy consumption. Ferdaus et al. designed a hybrid dual-axis solar tracker that improves power efficiency while reducing motor consumption. It achieved 25.62% more power than static panels with 44.44% less motor power use than continuous trackers, sacrificing only 4.2% power gain. By adjusting daily with one motor and seasonally with another, it optimizes energy use, making it ideal for large-scale applications like heliostat power plants and solar thermal systems [92]. A two-axis hybrid solar tracking system has been studied to optimize solar panel blinds (SPBs) for urban energy applications [93]. Using altitude and azimuth calculations, the system enables indirect tracking, with panel slope freely adjusting from  $0^\circ$  to  $90^\circ$ , while azimuth is limited to  $-9^\circ$  to  $+9^\circ$  due to vertical axis constraints. The findings suggest adaptability across different locations and highlight SPB integration as a sustainable solution for reducing urban carbon emissions. A hybrid solar lighting/thermal system integrating a dual-axis tracking mechanism with a parabolic dish collector has been developed to enhance energy efficiency in CSP applications [94]. The system transmits sunlight via fiber optics for indoor PV electricity generation or daylighting, while the collected heat is used for water heating. Al-Amayreh and Alahmer [94] implemented an LDR-based dual-axis tracking system using DC motors and linear actuators to optimize solar intensity, achieving a 32.2% increase in thermal efficiency compared to a single-axis tracker. However, this

improvement comes with a 64.7% rise in average system costs. These findings demonstrate the potential of hybrid tracking for multi-functional solar applications, optimizing both electrical and thermal energy use in buildings.

#### AI-Based Control Systems

AI-based control systems represent the latest advancement in solar tracking, employing advanced data-driven techniques such as machine learning (ML) and deep learning (DL) to optimize solar panel orientation dynamically. Unlike traditional systems, AI-driven trackers continuously learn from historical and real-time environmental data—such as solar irradiance, temperature, humidity, wind speed, and cloud cover—to predict and adapt to changing conditions proactively. Recent studies demonstrate the practical benefits of these methods. For example, Phiri et al. [95] reviewed DL-based solar tracking models, highlighting their superior performance in predicting irradiance patterns and optimizing panel angles, but also noting the increased computational and energy overheads associated with these techniques. Similarly, Araújo et al. [96] implemented an AI-based tracking algorithm in a commercial solar plant, achieving energy gains of up to 7.83% under cloudy conditions and significantly reducing operational costs by minimizing unnecessary tracker movements. Moreover, intelligent tracking strategies employing AI-driven predictive analytics have demonstrated substantial potential to improve energy yield and economic efficiency, making them particularly valuable for large-scale installations and applications like agrivoltaics, where balancing crop productivity and solar energy production is crucial [97–99]. Table 1 depicts the efficiency improvement, complexity, maintenance, and weather adaptability for various solar tracking types.

**Table 1.** Performance characteristics of different solar tracking types, including complexity, maintenance effort, and weather adaptability.

| Tracking Type              | Complexity | Maintenance | Weather Adaptability |
|----------------------------|------------|-------------|----------------------|
| Active Tracking [20]       | High       | High        | Moderate             |
| Passive Tracking [18]      | Low        | Low         | Poor                 |
| Semi-Passive Tracking [76] | Medium     | Medium      | Moderate             |
| Astronomical Tracking [64] | Medium     | Low         | Low                  |
| Manual Tracking [100]      | Very Low   | Very High   | N/A                  |
| Hybrid Tracking [94]       | High       | Medium      | High                 |

Solar tracker drive systems play a crucial role in optimizing energy capture, each exhibiting unique strengths and limitations. Active tracking systems offer the highest precision but demand significant computational resources and can be less effective under cloudy conditions. Passive tracking systems provide a cost-effective alternative but exhibit lower efficiency and slower response times. Astronomical tracking enhances energy savings by eliminating unnecessary power consumption but requires accurate astronomical data updates. Hybrid tracking solutions represent a promising approach, combining multiple methodologies to optimize performance across various environmental conditions. To further contextualize these technologies, Table 2 summarizes several real-world implementations of solar tracking systems across different regions, detailing their type (single- or dual-axis), operational mode (active, passive), control approach, and specific applications. This overview aids in understanding how various tracking configurations are selected based on local environmental, economic, and technological constraints.

**Table 2.** Overview of solar tracking systems by location, type, mode, control, and application.

| Ref. | Author                 | Country or Location             | Solar Tracking Method (Single or Dual) | Solar Tracking Mode (Active, Passive) | Control Type                      | Application                                        |
|------|------------------------|---------------------------------|----------------------------------------|---------------------------------------|-----------------------------------|----------------------------------------------------|
| [17] | Njoku, H. O.           | Nigeria                         | Dual                                   | Active                                | Closed-loop                       | General PV tracking                                |
| [43] | Li, Z. et al.          | China                           | Single                                 | Semi-passive                          | Open-loop                         | Optical performance comparison                     |
| [44] | Li et al.              | China (Beijing, Lhasa)          | Single                                 | Active                                | Open-loop                         | V-trough PV systems                                |
| [45] | Huang et al.           | Taipei                          | Single                                 | Active                                | Likely Closed-loop                | Building-integrated PV systems                     |
| [46] | Alshaabani             | Saudi Arabia                    | Single                                 | Active                                | Closed-loop                       | PV panels                                          |
| [47] | Ponce-Jara et al.      | Equatorial region               | Single                                 | Active                                | Mixed (LDR/Astronomical)          | PV tracking                                        |
| [48] | Barbón et al.          | Spain (Zaragoza)                | Single                                 | Active                                | Hybrid                            | Utility-scale PV plants (optimization via packing) |
| [49] | Wang et al.            | China (Weihai)                  | Single                                 | Active                                | Hybrid                            | Bifacial PV systems (bifacial companion method)    |
| [50] | Seme et al.            | Slovenia                        | Dual                                   | Active                                | Open-loop                         | General PV tracking                                |
| [51] | Fathabadi              | Iran                            | Dual                                   | Active                                | Closed-loop (sensorless via MPPT) | PV tracking                                        |
| [52] | Eke et al.             | Turkey (Mugla)                  | Dual                                   | Active                                | Closed-loop                       | PV tracking                                        |
| [53] | Shang, Het al          | China (Shanghai)                | Dual                                   | Active                                | Closed-loop                       | PV tracking                                        |
| [66] | Hussain, S. N. et al.  | Across the UK                   | (Generally, typically Single)          | Active                                | Sensor-based (Closed-loop)        | PV tracking                                        |
| [68] | Bentaher, H et al.     | Sfax region, Tunisia            | Single                                 | Active                                | Sensor-based (Closed-loop)        | PV tracking                                        |
| [69] | Ghassoul et al.        | Bahrain                         | Single                                 | Active                                | Sensor-based (Closed-loop)        | PV tracking                                        |
| [70] | Das et al.             | India (Jaipur)                  | Dual                                   | Active                                | Sensor-based                      | PV tracking                                        |
| [71] | Kabir et al.           | Malaysia                        | Single/Dual                            | Active                                | Sensor-based (Closed-loop)        | Sensor-based (Closed-loop)                         |
| [92] | Ferdaus et al.         | Dhaka, Bangladesh               | Dual                                   | Active                                | Hybrid                            | Heliostat power plants; solar thermal systems      |
| [93] | Hong et al.            | Seoul, South Korea              | Dual                                   | Active                                | Hybrid                            | Urban PV applications (SPB)                        |
| [94] | Al-Amayreh and Alahmer | Jordan                          | Dual                                   | Active                                | Hybrid                            | Solar lighting/thermal (CSP)                       |
| [89] | Ahmad et al.           | Malaysia                        | Single                                 | Active                                | Open-loop                         | PV tracking                                        |
| [90] | Sidek et al.           | Serdang, Malaysia               | Dual                                   | Active                                | Open-loop                         | Mobile solar tracking                              |
| [96] | Araújo et al.          | N/A (Commercial plant; Brazil?) | Single                                 | Active                                | AI-based                          | Commercial PV plant                                |

Future advancements in machine learning, IoT-based monitoring, and intelligent materials could further refine solar tracker efficiency, making them more adaptable to diverse

climate conditions. Additionally, integrating navigation sensors like GPS, accelerometers, and gyroscopes will enhance tracking precision and system robustness.

### Summary of Section 2

Section 2 provides an extensive classification of solar tracking systems based on tracking axes, driving mechanisms, and control strategies. Single-axis trackers (SATs) have been shown to increase energy output by 20% to 34.6% compared to fixed-tilt systems [16,34,39], with enhanced designs such as multi-position V-trough systems [44], timer-based three-position trackers [45], and bifacial modules with reflectors [49] offering gains of up to 91.18% in optimized layouts [48]. These configurations demonstrate scalability, particularly in large PV plants and high-irradiance regions. Dual-axis trackers (DATs) further improve energy capture, with studies reporting seasonal gains of 28.8% to 43.6% [51] and annual increases exceeding 30% over fixed systems [52,53,59]. Innovations such as MPPT-integrated control [51] and low-cost photo sensor-based systems [50] highlight the potential of DATs in both small- and large-scale applications. From the perspective of driving mechanisms, active tracking systems dominate, primarily utilizing sensor-based real-time positioning for maximum solar capture. Sensor comparison reveals that light-dependent resistors (LDRs), as used in [47,69,71], provide cost-effective, responsive tracking suitable for residential and equatorial applications. More advanced sensor technologies, such as the multifiber optical sensor implemented by Oliveira et al. [83], offer high tracking precision ( $\pm 0.1^\circ$  field of view), making them well-suited for CPV and high-performance systems. Meanwhile, sensorless configurations integrated with MPPT, such as the system in [51], achieve  $0.11^\circ$  tracking error while reducing complexity and enabling broader scalability. Passive and semi-passive systems [64,72,73] are recognized for low energy consumption and operational simplicity, although they typically exhibit lower precision. Manual [77] and astronomical trackers [62,63,77] present viable alternatives in off-grid and low-cost settings. Control systems were classified into open-loop, closed-loop, hybrid, and AI-enhanced strategies. Open-loop trackers use astronomical data to offer simplicity and energy efficiency [87–89], while closed-loop systems, relying on sensors like LDRs and photodiodes [81,83], deliver higher accuracy but require more energy and maintenance. Hybrid systems that combine real-time feedback with programmed algorithms [92–94] optimize performance with reduced actuation, and recent advancements in AI-based tracking demonstrate up to 7.83% efficiency improvement in cloudy conditions [96]. These findings underscore the ongoing evolution of solar tracking technologies toward higher precision, reliability, and cost-effectiveness across diverse application domains.

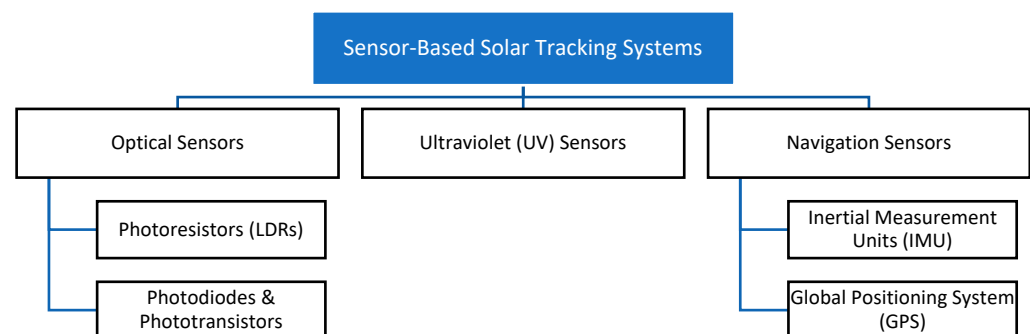
## 3. Microcontrollers and Sensor-Based Systems

To maximize solar energy capture, an STS must always accurately orient the PV panels or solar concentrators perpendicular to the sun's rays. Achieving this requires a precise sensing mechanism that continuously determines the sun's position and sends feedback to a control unit, ensuring optimal alignment. Sensors and microcomputers play a crucial role in both single-axis and dual-axis tracking systems, enabling automated, real-time adjustments based on environmental conditions and solar positioning algorithms. Sun sensors play a crucial role in solar tracking systems, offering a balance between cost, accuracy, and efficiency. A recent prototype developed using an Arduino MEGA2560 microcontroller and quadrant LDR sensors demonstrated effective dual-axis tracking, achieving a net efficiency of 32.16% over fixed systems during a 13-day evaluation period [101]. Analog sun sensors (ANSSs) are widely used due to their low cost, mass, and power consumption, though they are typically less accurate than digital alternatives [102]. One of the primary challenges affecting ANSS accuracy is external errors, particularly Earth's albedo. To

address this, Soken et al. [102] proposed a Deep Neural Network (DNN)-based calibration method, which significantly reduces measurement errors from  $10^\circ$  to  $0.5^\circ$  without requiring extensive training, making it a promising approach for long-term accuracy. An improved perturbation and observation (PO) maximum power point tracking (MPPT) technique demonstrated superior efficiency, achieving tracking accuracy up to 99.88% with rapid convergence in less than 0.2 s, effectively overcoming traditional limitations associated with the classical PO method [103].

### 3.1. Sensor-Based Systems

Optical sensors, such as photoresistors (LDRs), photodiodes, and phototransistors, are widely used in active solar tracking systems due to their ability to detect sunlight intensity and direct the solar panels accordingly [104,105]. An active single-axis solar tracker utilizing LDR sensors has been designed to enhance solar energy capture while minimizing power consumption [106]. The system features a compact, wall-mountable structure, making it suitable for space-limited environments. To optimize energy use, the tracker operates in different modes, including a “sleep” mode at night, reducing unnecessary motor activation. A MATLAB™/Simulink™ model was developed to predict efficiency gains, power output, and PV system performance before implementation. Experimental testing validated the tracker’s effectiveness, though external disturbances like wind and mechanical friction introduced minor deviations from the simulation results. Future improvements focus on refining disturbance modeling and integrating the system into smart grid networks for large-scale solar applications. The different types of sensors used in solar tracking systems, as reviewed in this study, are illustrated in Figure 12.



**Figure 12.** Overview of the different sensors’ technologies reviewed in the present study.

A novel UV sensor-based dual-axis solar tracking system has been introduced to overcome the limitations of conventional LDR-based trackers. Unlike LDR sensors, which detect visible light and suffer from saturation and low-visibility inefficiencies, UV sensors leverage the enhancement of UV radiation during overcast conditions, improving tracking accuracy in diffuse light environments. The proposed system employs four UV sensors mounted on a pseudo-azimuthal structure, enabling precise daily and elevation tracking. Comparative analysis revealed that the UV sensor-based tracker outperforms conventional LDR-based tracking systems, increasing energy generation by 11.00% and achieving a 19.97% gain over fixed PV panels. Furthermore, economic evaluation confirms the profitability of this approach, highlighting its potential for more reliable and efficient solar tracking technology [107].

A two-axis solar tracker utilizing LDR sensors has been designed to enhance photovoltaic energy efficiency by continuously adjusting panel orientation based on sun movement detection. The system employs independent rotational movement in two perpendicular axes, with one motor for north–south inclination adjustments and another for east–west

azimuth tracking. Experimental evaluation over 152 days in southern Brazil demonstrated monthly energy gains between 17.2% and 31.1%, with an average increase of 23.4%, even accounting for 40% cloudy or rainy days [108]. To improve efficiency, the tracker includes an embedded algorithm that optimizes energy capture strategies, preventing unnecessary movements during low-light conditions and returning the panel to its midday position overnight. This adaptive motion control ensures that tracking remains energy-efficient, with daily average power consumption kept below 1 W. These findings reinforce the advantages of LDR-based tracking, particularly in reducing losses caused by the sun's trajectory shifts and maximizing power generation under diverse climate conditions [108]. Muthukumar et al. [109] proposed an IoT-integrated DAST system to enhance solar energy efficiency. The system employs light-dependent resistors (LDRs) to detect ambient light and a microcontroller to dynamically adjust the panel's position for optimal sunlight exposure. IoT connectivity via Wi-Fi enables real-time monitoring of power output, ensuring efficient energy harvesting and system performance. With a rapid response time of 0.2 s, the system can promptly adjust to changing sunlight conditions, enhancing power generation reliability. This approach provides an effective and scalable solution for maximizing solar energy utilization while reducing dependence on conventional energy sources.

Advanced fiber-optic sensors offer significant advantages in solar PV monitoring, addressing the limitations of conventional temperature sensors in terms of response time and accuracy. Fiber Bragg Grating (FBG) sensors enable real-time, high-precision temperature tracking across PV panels, enhancing thermal management strategies. Their ability to measure rapid temperature fluctuations and radiation flux effects provides critical insights for optimizing panel performance and integrating efficient cooling mechanisms. The scalability of FBG sensors makes them particularly suitable for large-scale solar farms, where precise, distributed temperature monitoring is essential for improving efficiency and extending panel lifespan [110].

Boukdir and EL Omari [105] developed a dual-axis solar tracker using three LDRs for high-precision sun tracking in solar concentrators. A 3D-printed support holds the sensors, with an alveolus hollow tube ensuring elevation accuracy of  $0.26^\circ$ . The system is low-cost, avoiding expensive components like lenses and servomotors, and efficiently enhances solar water heating. However, in cloudy conditions, tracking is interrupted, limiting its effectiveness for PV systems. The authors propose a sensorless mode with position encoders to improve tracking under variable weather.

Wang and Lu [111] introduced a dual-axis solar tracking PV system utilizing a four-quadrant LDR sensor and a simple electronic control circuit for precise sun tracking. The system employs a single AC motor and a stand-alone PV inverter, eliminating the need for complex programming or external power sources. Experimental results from a scaled-down prototype demonstrated a 28.31% energy gain on a partly cloudy day, confirming the efficiency and feasibility of the design. The study highlights the cost-effectiveness, adaptability, and reliability of LDR-based tracking, offering valuable insights for future solar energy applications.

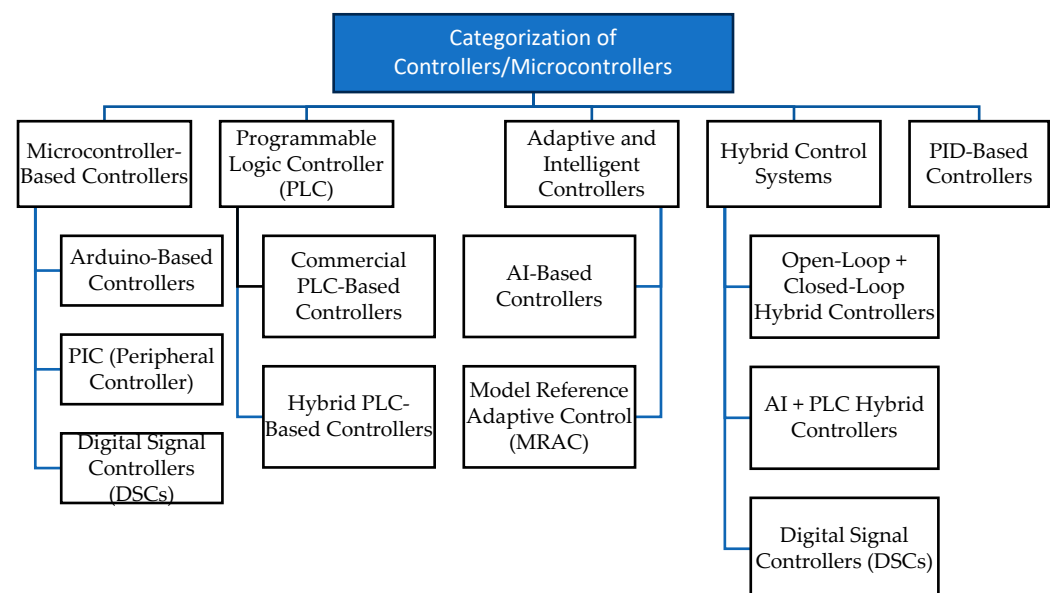
### 3.2. Role of Microcontrollers in Sensor-Based STSs

Microcontrollers play a crucial role in processing sensor data and executing real-time adjustments to optimize panel orientation. Common microcontrollers include ATmega 328 microcontroller [112], AT89C51 [113], Arduino microcontroller (ET-EASY MEGA 1280) [104], and PLC-based two-axis solar tracking systems [114].

Aljafari et al. [115] proposed a Gorilla Troop Reconfiguration combined with Power Line Communication (GTR-PLC) method for enhancing the performance of PV systems under partial shading conditions. This low-cost, microcontroller-based approach significantly

reduces the required number of switches, simplifying the architecture while effectively monitoring and mitigating shading losses. Validated through simulations and real-time testing on various array sizes ( $5 \times 5$ ,  $9 \times 9$ ,  $2 \times 3$ , and  $12 \times 4$ ), the system achieved a notable 38.37% average power increase compared to existing techniques, a power extraction efficiency of 98.99%, and rapid calculation time averaging just 0.09 s, demonstrating its suitability for practical implementation in dynamic shading environments.

Chellakhi et al. [116] present an enhanced Incremental Conductance (IMP-IC) MPPT method implemented on an ATmega328 microcontroller using an Arduino Uno. The improved strategy introduces an adaptive step-size mechanism and current perturbation, significantly increasing tracking efficiency (99.88% dynamic) and response speed (0.12 s) compared to conventional methods. The low-cost microcontroller-based approach ensures reliable and cost-effective MPP tracking for PV systems under fluctuating weather conditions. The various controllers and microcontrollers utilized in solar tracking systems, as reviewed in this study, are illustrated in Figure 13. This figure not only categorizes the control strategies but also implicitly reflects their scalability; systems such as commercial PLC-based, hybrid PLC-based, and digital signal controllers (DSCs) are widely adopted in industrial-scale deployments, while Arduino-based, PIC, and certain AI-driven or adaptive controllers are primarily utilized in laboratory-scale or prototyping environments.



**Figure 13.** Overview of different controllers and microcontrollers used in solar tracking systems, highlighting their roles and classifications based on the reviewed literature.

Thungsuk et al. [104] analyzed a microcontroller-driven five-position angle solar tracking system, comparing single-axis and dual-axis tracking with a fixed panel setup. The system, controlled by LDR sensors and a stepping motor, adjusted solar panels eight times per day for one-axis tracking and sixteen times per day for two-axis tracking, significantly reducing energy consumption compared to continuous tracking systems. Results showed energy production gains of 16.71% for one-axis tracking and 24.97% for two-axis tracking, highlighting the efficiency of periodic tracking adjustments. The study further emphasized that geographical location impacts tracking efficiency, with Thailand's equatorial position requiring minimal azimuth and altitude adjustments, reducing the energy needed for movement. Tharamuttama and Ng [117] developed a microcontroller-based hybrid solar tracking system that integrates sensor-based and mathematical model-based tracking algorithms to maximize solar energy capture under all weather conditions. The system

incorporates LDR sensors, an Arduino MEGA microcontroller, a Wi-Fi shield, a stepper motor, a servo motor, and a magnetometer, allowing precise dual-axis adjustments. The stepper motor controls north–south rotation, while the servo motor adjusts the east–west position based on LDR feedback. Experimental tests compared the hybrid, active, and chronological tracking algorithms by measuring solar voltage output every 30 min from 8 A.M. to 7 P.M. under both sunny and cloudy conditions. Results demonstrated that the hybrid algorithm consistently outperformed traditional tracking methods, yielding higher solar energy output. Additionally, a real-time monitoring webpage was developed to enhance data collection and system control. The study highlights the potential of large-scale hybrid solar tracking to reduce carbon emissions and electricity costs, making it a viable solution for public and private organizations.

Lu et al. [118] introduced a microcontroller-based global maximum power point tracking (global-MPPT) algorithm designed to enhance solar energy efficiency under varying irradiance conditions. By dynamically analyzing irradiance levels, temperature, voltage, and load, the system eliminates the limitations of conventional P&O techniques, ensuring that the maximum power point (MPP) is accurately tracked even under partial shading conditions. The proposed method achieved high MPPT efficiency, reaching 99.9% under uniform irradiance conditions and 99.7% under partial shading, outperforming traditional tracking approaches. With a simplified circuit design and reduced computational complexity, this approach offers a cost-effective and practical solution for applications like rooftop solar power systems. Future improvements focus on reducing sensor requirements and integrating a novel power electronic converter to further optimize performance in shaded environments.

Ji et al. [119] proposed a microcontroller-based MPPT algorithm using Gaussian particle swarm optimization (GPSO) to enhance solar energy capture under partial shading conditions. Unlike traditional MPPT methods, the approach integrates simulated annealing and particle replacement techniques to refine particle distribution and improve tracking accuracy. The algorithm operates in two stages, first narrowing the search range and then optimizing power tracking, ensuring faster MPPT response and greater PV output stability. Experimental results confirmed its superiority over conventional particle swarm optimization (PSO) methods, making it a more efficient and reliable solution for solar power systems.

González-Castaño et al. [120] introduced a microcontroller-based MPPT algorithm using the Artificial Bee Colony (ABC) optimization technique to enhance solar energy extraction in PV systems with DC–DC converters. Unlike conventional Perturb and Observe (P&O) methods, the proposed approach identifies the optimal voltage from PV data and applies MPPT through a PI control loop and predictive digital current control. The system was implemented using a real-time simulator (PLECS RT Box 1) and a digital signal controller (DSC), demonstrating high efficiency with low computational cost. Results confirmed that the ABC MPPT strategy significantly outperforms traditional methods, making it a more effective and cost-efficient solution for PV systems.

Recent advancements in optical sensing for solar tracking also include imaging-based sensors such as Charge-Coupled Device (CCD) and Complementary Metal-Oxide Semiconductor (CMOS) cameras. Unlike traditional optical sensors (LDRs, photodiodes, phototransistors), which detect solar intensity directly, CCD and CMOS imaging sensors capture detailed solar images to accurately determine the sun's position, thereby significantly enhancing tracking precision. For instance, recent studies have integrated CCD imaging to correct open-loop tracking system alignment errors, achieving exceptional accuracy of up to  $0.171^\circ$  by compensating for installation defects through real-time image processing algorithms [88]. Similarly, CMOS-based systems offer high-speed, low-power image acquisition,

suitable for real-time adaptive control under varying environmental conditions. Integrating these imaging technologies into solar tracking improves reliability and precision, making them particularly valuable for high-precision and CPV applications. To provide a clearer overview, Table 3 classifies the main types of sensors used in solar tracking systems based on their operating principles, accuracy, advantages, and limitations.

**Table 3.** Classification of common sensors used in solar tracking systems, detailing their principles of operation, precision, strengths, and limitations.

| Ref.                  | Sensor Type                | Operating Principle                                     | Accuracy and Efficiency                                  | Advantages                                              | Limitations                                                    |
|-----------------------|----------------------------|---------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------|
| [104–106,108,109,111] | Photoresistor (LDR)        | Detects visible light intensity variations              | Moderate accuracy ( $\pm 0.1^\circ$ to $\pm 0.5^\circ$ ) | Low-cost, simple implementation                         | Saturation in high irradiance, poor cloudy weather performance |
| [43]                  | Photodiode/Phototransistor | Semiconductor-based photon detection                    | High accuracy ( $\pm 0.01^\circ$ to $\pm 0.1^\circ$ )    | Fast response, reliable, compact                        | Higher complexity and cost compared to LDR                     |
| [44]                  | UV Sensor                  | Detects ultraviolet radiation                           | Improved accuracy under diffuse conditions               | Effective under cloudy skies, reduces saturation issues | Sensitive to sensor alignment                                  |
| [45]                  | Fiber Bragg Grating (FBG)  | Fiber-optic-based temperature and radiation measurement | Very high accuracy, rapid response                       | Excellent thermal management, precise monitoring        | Higher cost, complex integration                               |
| [46]                  | CCD Imaging Sensor         | Captures solar images for position determination        | High accuracy ( $\pm 0.01^\circ$ to $\pm 0.2^\circ$ )    | Real-time misalignment correction, high precision       | Computational complexity, higher energy consumption            |
| [47]                  | CMOS Imaging Sensor        | Captures solar images using CMOS technology             | High accuracy, fast response                             | Low-power consumption, rapid image processing           | Slightly lower sensitivity compared to CCD sensors             |

### 3.3. PLC-Based Solar Tracking System

The PLCs are widely used in solar tracking systems for their reliability, automation capabilities, and scalability [121–123]. A PLC-based tracker controls the movement of PV panels, ensuring optimal alignment with the sun while also collecting and storing operational data. These systems offer high precision, the ability to connect multiple PV modules, and remote monitoring options. Additionally, PLC-controlled trackers help reduce operational costs and improve energy efficiency, making them a practical choice for large-scale solar applications. Al-Mohamad [121] developed a PLC-based solar tracking system, where a PLC unit was used to control and monitor the movement of a PV module. The system automatically adjusts the panel to follow solar radiation, optimizing energy capture. The PLC unit not only manages the mechanical movement but also collects and stores solar radiation data, allowing for real-time monitoring via a computer connection. Experimental results showed a daily power output increase of over 20%, with even greater efficiency gains (up to 40%) during morning and evening hours. Additionally, the PLC-based control enables multiple PV modules to be connected in series or parallel, reducing costs and improving scalability, making it a cost-effective solar tracking solution [121].

Sungur [122] developed a PLC-based dual-axis solar tracking system designed to optimize solar energy capture by adjusting panels based on azimuth and solar altitude angles. The system was tested at 37.6° latitude (Konya, Turkey), where a 42.6% increase in energy output was observed compared to a fixed-panel system. The PLC-controlled tracker ensured precise automation, improving efficiency while reducing the need for additional PV panels, ultimately lowering investment costs. The system was designed with an electromechanical mechanism controlled via a PLC and an analog module, allowing reliable sun tracking on both axes. Experimental results demonstrated that the system operated without issues, confirming the feasibility of PLC-based solar tracking for large-scale implementation. The study emphasizes that using such tracking systems can lead to significant energy savings and better utilization of solar exposure, making them particularly beneficial for regions with high solar radiation like Turkey. Additionally, increasing the sensitivity of the tracking system by integrating higher-bit analog modules could further enhance its performance. These findings highlight the economic and technical advantages of PLC-based tracking, offering a cost-effective solution for improving solar power generation.

Abdallah and Nijmeh [124] developed a PLC-based dual-axis solar tracking system using an open-loop control method to optimize solar energy collection. The system was programmed using a LOGO 24 RC PLC unit, selected for its simplicity and cost-effectiveness. The control mechanism included manual and automatic tracking modes, allowing for both user adjustments and autonomous solar alignment. Experimental tests compared the energy collected by the tracking system and a fixed panel tilted at 32°, demonstrating a 41.34% increase in energy output with the dual-axis tracking system. The hardware and software components were successfully integrated, confirming the reliability of PLC-based tracking for solar applications. Future research aims to explore its performance in photovoltaic systems and other solar applications in Jordan, highlighting its potential for enhancing solar energy efficiency in regions with high solar exposure.

Abu-Khader et al. [125] conducted an experimental study to evaluate the impact of multi-axis solar tracking on PV system performance under Jordanian climate conditions. A PLC-based LOGO 24 RC control system was implemented to automate the movement of a north–south (N–S), east–west (E–W), and vertical tracking system. The tracking algorithm was designed using software-calculated solar angles, dividing daylight hours into four-time intervals (T1–T4) to optimize motor activation and minimize energy consumption. Results showed a 30–45% increase in output power with N–S tracking, identified as the most efficient configuration. The energy consumption of the motors and control system remained below 3% of the collected energy, demonstrating the cost-effectiveness and efficiency of the PLC-controlled tracking approach.

Das [114] investigated the impact of a PLC-based dual-axis solar tracking system on the thermal performance of a solar air collector (SAC), demonstrating significant efficiency improvements. The PLC controller effectively adjusted the SAC's orientation, leading to a 40% increase in received solar radiation and a 12% rise in output temperature compared to a fixed system. Additionally, the energy and exergy efficiency values of the movable SAC were 47% and 2.4 times higher, respectively. The system also improved heat transfer rates and environmental sustainability, making PLC-controlled tracking an effective and practical solution for enhancing SAC performance in applications such as heating, cooling, and food drying.

In the field of solar tracking, control systems play a crucial role in ensuring precise alignment with the sun to maximize energy capture. While PLCs have been widely adopted due to their reliability and automation capabilities, recent advancements in control strategies have introduced adaptive control mechanisms to enhance tracking accuracy under

dynamic environmental conditions. Palomino-Resendiz et al. (2025) [123] proposed a Model Reference Adaptive Control (MRAC)-assisted solar tracker, which significantly improves tracking accuracy compared to conventional PID controllers. Through simulation and testing, the study demonstrated that under disturbance conditions, such as wind loads, the MRAC system reduced tracking errors by approximately 87% compared to PID-based tracking. The proposed system leverages adaptive learning principles to adjust tracking in real time, making it highly effective for applications in PV, CPV, and HCPV systems. Given its simple implementation and robust performance, MRAC presents a promising alternative to traditional PLC-based solar tracking, particularly in environments where unpredictable external forces affect tracking stability [123].

The integration of PLCs in PV systems plays a crucial role in enhancing performance, particularly in mitigating power losses due to partial shading. Aljafari et al. [115] proposed a Gorilla Troop Reconfiguration–Power Line Communication (GTR-PLC) approach, which optimizes PV array configurations to reduce power loss and improve efficiency during shading conditions. The system employs a switching matrix architecture controlled by an optimization algorithm, inspired by gorilla troop behavior, to dynamically reconfigure PV arrays and equalize current distribution. This method ensures accurate shading detection and monitoring, achieving an average power increase of 38.37% and a power extraction efficiency of 98.99% under dynamic shading conditions. The PLC integration further enables real-time communication and monitoring, allowing for efficient system adjustments without requiring extensive hardware modifications. The low-cost architecture and reduced switch count make this approach practical for large-scale PV installations, although improvements in cost, complexity, and automation are suggested for future research.

### 3.4. AI Applications in Solar Tracking Systems

Artificial intelligence (AI) has significantly advanced the capabilities of solar tracking systems by optimizing their performance and efficiency. AI techniques, such as machine learning (ML), deep learning (DL) [95], and neural networks [102], enable solar trackers to adapt to varying environmental conditions, predict solar irradiance, and adjust positioning in real time for maximum energy capture.

Recent advances in artificial intelligence, particularly DL, have significantly enhanced the precision and adaptability of solar tracking systems. DL-based trackers can forecast solar positions and adapt to varying weather conditions, leading to improved energy yield. However, these benefits often come with increased processing demands and energy consumption, especially when real-time inference or image-based data are involved. As such, the total energy overheads and computational costs must be considered to assess the feasibility of deploying AI-driven trackers in real-world scenarios. Although DL models have shown superior performance in solar irradiance prediction and tracking accuracy, many existing studies lack standardized datasets and overlook preprocessing or feature engineering techniques that can optimize model efficiency. As highlighted by Phiri et al. [95], this gap limits generalizability and can increase operational load. Therefore, future research should not only focus on improving algorithmic accuracy but also on minimizing processing costs and evaluating overall system efficiency to ensure scalable and sustainable AI-based solar tracking solutions.

In addition to improved tracking precision and adaptability, recent developments in smart solar tracking systems demonstrate that AI can also play a crucial role in reducing operational costs and managing energy overheads. By enabling real-time data processing and dynamic angle adjustments, AI-based controllers ensure that solar panels remain optimally oriented even under variable atmospheric conditions. For instance, predictive algorithms based on environmental inputs such as wind speed, solar irradiance, and

humidity allow systems to anticipate changes and respond proactively. These intelligent features not only increase energy output—often by up to 30% compared to fixed systems—but also minimize energy waste during periods of suboptimal irradiance [126].

Furthermore, AI-enhanced automation significantly reduces the need for manual intervention and routine maintenance, leading to tangible cost savings over the lifespan of a solar installation. Cloud-based data analytics and edge computing strategies also reduce the dependency on high-power onboard processing, helping to balance energy efficiency with computational performance. As highlighted in recent industry analyses, the integration of smart actuators, predictive maintenance functions, and automated control schemes contributes to improved reliability, component longevity, and an overall higher return on investment [126]. These findings reinforce the value of AI not only in enhancing energy generation but also in addressing the practical concerns of energy use and economic viability, both of which are central to the future scalability of intelligent solar tracking systems.

Further advances in AI-based solar tracking algorithms also demonstrate promising results in optimizing energy output while accounting for operational constraints and cost efficiency. A recent study by Araújo et al. [96] introduced an AI-powered tracking strategy that integrates weather conditions, panel distance, and irradiance dynamics to improve the energy yield of bifacial panel systems. Their algorithm, validated in a commercial-scale PV plant in Brazil, achieved an average energy gain of 1.2%, with gains of up to 7.83% under cloudy conditions compared to a standard commercial tracking algorithm. Importantly, these improvements were achieved without requiring hardware changes to existing tracker infrastructure, as the AI model operated as a software plug-in within the existing automation architecture via Modbus TCP. This highlights the potential for low-cost integration of intelligent control layers in existing solar tracking systems.

In addition to energy gains, the study addressed practical aspects critical to minimizing processing and energy overheads. The algorithm was designed to infer optimal tracker angles at intervals matching conventional update cycles (every 4 min), thus avoiding excessive energy consumption from frequent motor movements. Furthermore, the use of smoothed sensor data via moving averages reduced the risk of reaction to transient weather anomalies, preserving computational efficiency and system stability. By limiting the number of model inferences and tailoring the application windows to specific periods of the day—such as sunrise and sunset—the system reduced unnecessary actuation while still outperforming conventional methods. These findings underline the practical feasibility of deploying AI-based tracking in large-scale PV installations, balancing computational complexity with measurable performance improvements and contributing to both energy and cost efficiency [96].

To facilitate practical decision-making, a synthesized set of recommendations is presented in Table 4, outlining the appropriate applications, advantages, and deployment environments for each solar tracking configuration. This summary is derived from the comprehensive classification, performance data, and system characteristics discussed in Sections 2 and 3. It provides guidance on selecting suitable tracking systems based on key factors such as installation scale, climate conditions, control complexity, and cost efficiency.

**Table 4.** Summary of recommended solar tracking systems and their optimal applications based on control strategy, environmental conditions, and system scale.

| System Type          | Best Use Case                                                                  | Key Advantages                                                       | References Support |
|----------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------|--------------------|
| Fixed System         | Small-scale installations, off-grid setups, low-budget rural areas             | Lowest cost; simplest to install; no moving parts                    | [45,46,108]        |
| Single-Axis Tracker  | Utility-scale PV farms in low-to mid-latitudes, agrivoltaics with flat terrain | 20–35% higher yield than fixed; lower cost and complexity than DATs  | [44–46,48]         |
| Dual-Axis Tracker    | Agrivoltaics, CSP, high-latitude regions, areas with seasonal variability      | 30–43% higher yield; precise sun alignment year-round                | [50–52,97–99]      |
| Passive Tracker      | Off-grid rural settings, regions with limited technical support                | Low power requirement; low maintenance                               | [18,19,73]         |
| Semi-Passive Tracker | Medium-scale systems, low-energy scenarios                                     | Compromise between performance and energy savings                    | [64]               |
| Astronomical Tracker | Stable clear-sky environments, CSP or heliostat systems                        | Efficient; requires no sensors; low maintenance                      | [62,63,87–90]      |
| Hybrid Tracker       | Sites with mixed weather, uneven terrain, or shading-prone setups              | Combines strengths of active/passive methods                         | [64,92–94]         |
| AI-Based Tracker     | Large-scale farms, agrivoltaics, commercial use with real-time climate changes | Up to 7.83% gain in cloudy climates; predictive and adaptive control | [95,96,126]        |

### Summary of Section 3

Section 3 highlights the essential role of sensors and microcontrollers in improving solar tracking accuracy and system responsiveness. Among sensor technologies, LDRs remain the most widely used due to their affordability and ease of integration. Multiple studies report energy gains between 17% and 31% with LDR-based dual-axis systems, even under cloudy conditions. To reduce energy waste, many of these trackers incorporate smart features like sleep modes and adaptive movement algorithms. For environments with diffuse sunlight or higher precision requirements, UV sensors and fiber-optic sensors are gaining prominence. UV-based systems demonstrate up to 20% improvement over fixed panels and outperform LDRs by 11%, especially under overcast skies. Fiber Bragg Grating sensors offer high-resolution thermal monitoring and are particularly effective for large PV arrays. Microcontrollers such as Arduino, ATmega328, and PLC units manage sensor data and real-time motor control. Enhanced MPPT strategies implemented on these platforms (e.g., PO, Incremental Conductance) show efficiencies up to 99.88%, surpassing traditional approaches. PLC-based trackers show consistent gains of 30–45% and support scalability and real-time monitoring, making them suitable for industrial use. Finally, AI-based control systems are pushing the boundaries of tracking efficiency. By learning from environmental inputs, these models increase energy yield by up to 30% over static systems and reduce unnecessary actuator movements. A commercial-scale AI tracker achieved 7.83% gains under cloudy conditions without modifying hardware, illustrating the potential of low-cost AI integration. Together, these findings provide a clear comparison of sensor technologies and control strategies, enabling informed decisions for solar tracker design based on cost, complexity, and application scale.

#### 4. Tracking Strategy in Different Climate Conditions

Solar tracking systems are highly dependent on weather conditions and climate variations, as different sky states can significantly impact energy gains. Research has demonstrated that tracking performance varies across clear, partially cloudy, and overcast days, necessitating adaptive tracking strategies. Studies indicate that on completely clear days, dual-axis tracking systems yield the highest energy gains due to their ability to follow the sun's position throughout the day. However, on cloudy days, where direct solar radiation is minimal, tracking systems offer no significant advantage over fixed panels, as diffuse radiation dominates [127]. To optimize energy capture in variable climates, different tracking mechanisms have been explored. A vision transformer-based model using sky images has been proposed to improve irradiance estimation, allowing for more accurate tracker positioning based on cloud movement predictions. This approach can enhance sun-tracking algorithms and improve tracking efficiency, even under unpredictable weather conditions [128]. Additionally, tracking strategies must be adjusted based on sky conditions. A schedule-based tracking system has been shown to outperform LDR sensor-based trackers in cloudy and rainy conditions, as pre-programmed movements reduce unnecessary motor activity and optimize energy consumption. This suggests that hybrid tracking approaches, which combine real-time sensors with scheduled adjustments, could be more effective in regions with frequent cloud cover or dynamic weather patterns [129]. Moreover, backtracking algorithms can be a valuable solution to minimize shading losses especially in regions with high variability in solar radiation. By adjusting panel orientation based on the sun's expected position, backtracking can improve system efficiency by reducing unnecessary panel movement and power consumption. As research advances, integrating machine learning models with sun-tracking strategies could further enhance system adaptability and performance across different climates.

##### 4.1. Backtracking Strategy

Solar tracking systems are designed to maximize energy capture by continuously adjusting panel orientation to follow the sun. However, in certain conditions, such as low sun angles, shading from adjacent panels, or cloudy weather, conventional tracking can lead to inefficiencies. Backtracking offers a solution by adjusting the tilt of PV panels to minimize shading effects rather than strictly following the sun's position. This technique is particularly beneficial in densely packed PV installations or on uneven terrain, where shading can significantly reduce overall system performance. By incorporating backtracking into tracking strategies, PV plants can optimize energy yield even under suboptimal conditions, ensuring more consistent power generation throughout the day.

Fernández-Ahumada et al. [130] introduced an advanced backtracking strategy designed to prevent shading and enhance energy production in PV facilities. Unlike traditional astronomical tracking, which aims to keep panels perpendicular to sunlight as much as allowed by the system geometry, this method incorporates diffuse and reflected irradiance while actively preventing shading between collectors. The proposed methodology determines when shading occurs and dynamically shifts panel angles to avoid energy loss. The results demonstrated a 1.31% increase in energy production compared to standard astronomical tracking. Furthermore, this strategy is applicable to a wide range of PV installations, including those with non-rectangular surface collectors, irregular geometric layouts, and real-world topographical variations. By utilizing solar vectors and vector algebra, the algorithm ensures quick and efficient tracking adjustments without complex polygon intersection calculations, making it a practical and effective solution for maximizing solar energy capture under diverse environmental conditions.

Keiner et al. [131] conducted a comprehensive study on backtracking strategies across multiple global test sites, assessing their impact on the techno-economic performance of single-axis tracking systems under different climatic conditions. Their research introduced three backtracking approaches: standard backtracking (avoiding mutual shading), advanced backtracking (adjusting tilt only when irradiation is improved), and advanced sophisticated backtracking (simulating irradiance for all possible angles and selecting the optimal one). The study found that standard backtracking is not always the most effective solution, particularly in regions with high diffuse radiation. Instead, advanced backtracking strategies led to up to 12% higher full-load hours and reduced the levelized cost of electricity (LCOE) by the same margin. Moreover, these refined approaches demonstrated improved energy yields by 8.9% and 12.0% over conventional backtracking methods. A key takeaway from their research is the importance of backtracking in adapting PV systems to different sky conditions. The study highlighted that on cloudy days, optimizing tilt angles to capture maximum diffuse irradiation is more beneficial than strictly avoiding shading. Advanced backtracking models account for total irradiance rather than just direct sunlight, allowing for better energy harvesting in overcast conditions. This adaptive approach ensures that PV systems operate efficiently across varying geographic locations and weather patterns, reinforcing the importance of intelligent tracking strategies in the future of solar energy.

Casares de la Torre et al. [132] explored the integration of backtracking strategies in agrivoltaics systems, particularly for PV installations with north–south (N–S) horizontal single-axis trackers. Their study examined the shading impact of tree crops planted in hedgerows between PV rows and proposed an optimized tracking/backtracking strategy to minimize shading losses while maintaining agricultural productivity. The analysis identified a geometric non-shading zone where crops do not affect PV generation, ensuring energy efficiency. However, when crops exceed this zone, the proposed adaptive backtracking strategy reduces shading effects and optimizes solar radiation capture. Their findings suggest that converting traditional N–S PV installations into agrivoltaics systems can increase land efficiency (Land Equivalent Ratio) by 28.9% to 47.2%, promoting a sustainable balance between energy production and agriculture.

The NREL laboratories have proposed practical formulas for calculating the backtracking motion law for single-axis tracking systems, taking into account the position of the sun, row-to-row spacing, module height, row orientation, and cross-axis slope [133].

In conclusion, the backtracking approach prevents self-shading and optimizes the capture of direct solar radiation on the front side of the modules. This method is particularly effective when the direct component dominates over the diffuse component (clear sky conditions).

#### 4.2. Tracking Strategies for Cloudy Weather

Under cloudy conditions, where the diffuse component of sunlight is predominant, standard tracking and backtracking strategies do not necessarily result in the optimal tilt angle.

Kelly and Gibson [129] analyzed solar tracking optimization for both sunny and cloudy conditions using four identical solar arrays over an eight-month study. Their findings showed that dual-axis tracking effectively captures direct beam solar radiation, yielding up to twice the energy of a fixed horizontal (H) configuration on clear days. However, on cloudy days, the H orientation collected up to 50% more energy than a DTS system, with an observed H/DTS ratio of 1.37 under heavy cloud cover. They proposed an adaptive tracking strategy where DTS is used on sunny days and horizontal orientation is adopted on cloudy days, improving annual energy output by approximately 1%. This hybrid approach

helps stabilize solar power generation, particularly for applications requiring consistent daily output, such as solar-powered home fueling systems for electric and fuel-cell vehicles.

Antonanzas et al. [134] investigated a tracking strategy for cloudy conditions, emphasizing the advantage of adjusting PV panels to a horizontal position during overcast skies. Unlike concentrated solar systems, PV panels can utilize diffuse irradiance, which is more evenly distributed under cloud cover. Their study analyzed potential irradiation gains across Europe and found that yearly irradiation increased by up to 3.01% in northern regions, while daily increases reached up to 19.91%.

To optimize PV tracking under such conditions, they developed two predictive models. Model 1, based on real-time irradiance persistence, demonstrated annual irradiation increases of up to 2.51%, whereas Model 2, using numerical weather prediction (NWP), underperformed due to a high rate of false positives. These findings suggest that adaptive tracking strategies for cloudy environments can enhance PV efficiency, particularly in high-latitude and overcast-prone regions. The study highlights the importance of real-time tracking adjustments and suggests that future work should incorporate sky cameras to refine prediction models further.

Kelly and Gibson [135] explored how solar tracking systems perform during overcast conditions, emphasizing that while two-axis tracking systems excel in sunny weather, their effectiveness declines significantly in cloudy conditions. Their research revealed that positioning solar modules horizontally during overcast periods enhances energy capture by approximately 50% compared to conventional sun-tracking methods. This improvement occurs because diffuse solar radiation, which dominates in cloudy weather, is more evenly distributed across the sky, making horizontal orientation more efficient. To address this challenge, they proposed a hybrid tracking method, where PV panels follow the sun on clear days but switch to a horizontal position when cloud cover is detected. Their study suggested that integrating simple sensors and control algorithms into existing tracking systems can enhance energy production, minimize storage needs, and ensure a more stable daily energy output. These findings highlight the importance of adaptive solar tracking approaches, particularly in regions where cloud cover is frequent, as a strategy to optimize solar energy efficiency under varying weather conditions.

Merie and Ahmed [136] investigated the impact of cloudy weather on the efficiency of a PV/solar chimney system, demonstrating that cloud cover significantly reduces solar radiation intensity, leading to lower energy output. Their experimental study compared system performance on two consecutive days, one clear and one overcast, revealing that on a cloudy day, electrical power generation dropped from 341.92 W to 187.88 W at noon, while thermal efficiency decreased from 56.08% to 42%. Additionally, the system's overall efficiency was reduced from 69.65% in clear conditions to 54.12% under cloud cover, highlighting the substantial effect of diffused radiation. Their findings emphasize the need for adaptive tracking strategies that can optimize energy capture under varying weather conditions, particularly for hybrid solar technologies, where both electrical and thermal performance are affected by solar availability.

Al-Othman et al. [137] proposed an advanced hybrid solar tracking system aimed at optimizing PV power generation in diverse weather conditions, particularly under cloudy and overcast skies. Traditional tracking methods rely on direct sunlight to determine panel orientation, but in diffuse irradiance conditions, these systems often fail to position panels optimally. To address this issue, the study introduced a hybrid controller that integrates an open-loop sun monitoring system with an active search algorithm-based dynamic feedback controller, enabling real-time adjustments based on instantaneous irradiance levels. The proposed circular path-finding method activates when solar irradiance drops below a predefined threshold, guiding the panel toward the MPPT under cloudy conditions. The

algorithm effectively reduces convergence and divergence errors, ensuring that the panel remains oriented for maximum energy capture despite the absence of direct sunlight. To enhance accuracy, a 0.6 Wp c-Si PV module irradiance sensor was calibrated using linear regression analysis against half-hour Solcast GHI values, achieving a coefficient of determination of  $R^2 = 0.8649$ , indicating strong correlation between sensor data and actual irradiance. Experimental testing demonstrated that the hybrid system significantly outperforms conventional open-loop tracking methods, increasing power output by 37.67%, 35.98%, and 30.92% in three consecutive search operations, with search times ranging from 23 s to 2 min 59 s, depending on the circle radius. Additionally, MATLAB simulations closely matched real-world results, validating the system's efficiency. The findings highlight the importance of adaptive tracking algorithms in compensating for the challenges posed by cloudy weather, offering a practical solution for maximizing PV efficiency in regions with unpredictable solar conditions [137].

Koshkarbay et al. [138] developed an adaptive control system for dual-axis solar trackers that optimizes energy production during cloudy conditions by dynamically adjusting the panel orientation. Unlike conventional trackers that follow the sun's movement to maximize direct irradiance capture, this system recognizes that under overcast conditions, diffuse radiation can make a horizontal panel configuration more effective. To achieve this, the study utilized machine learning algorithms and spatiotemporal weather assessments through the Clear Sky Index (CSI) to determine the most efficient panel positioning. Six different machine learning models, including LSTM, GRU, 1D Conv, XGBoost, NARX, and ARIMA, were tested, with XGBoost demonstrating the highest accuracy at 99.3% for predicting solar power output across different tracking configurations. When CSI values drop below 0.4, the system automatically switches to a horizontal orientation to maximize energy capture, with additional measures in place to prevent excessive adjustments by incorporating a moving average ( $CSI_{mean} = 0.4$ ) and variance ( $CSI_{var} = 0.1$ ). Experimental results showed that the proposed system generated 18.3% more energy than a fixed horizontal panel, 14.9% more than a single-axis tracker, and 10.01% more than a conventional dual-axis tracker. By integrating intelligent tracking adjustments, the study presents a more efficient approach to mitigating energy losses in cloudy weather conditions, making solar tracking systems more adaptable to varying environmental factors.

Wang and Lu [111] demonstrated the effectiveness of their dual-axis solar tracking PV system under partly cloudy conditions, highlighting the advantages of LDR-based tracking in fluctuating irradiance. Their experimental validation on a cloudy day in New Taipei City, Taiwan, showed a 28.31% increase in energy yield compared to a fixed panel. The system's ability to continuously adjust to varying light conditions ensures improved performance, even when direct sunlight is intermittent. These findings suggest that LDR sensors remain functional during cloudy weather, making them a reliable choice for solar tracking in regions with frequent overcast conditions.

#### 4.3. Tracking Strategies at High Latitudes

In high-latitude regions, optimizing solar tracking strategies is crucial due to the unique challenges posed by extreme seasonal variations in solar radiation. During summer, long daylight hours allow for significant energy generation, but cloudy conditions can reduce the effectiveness of conventional tracking methods. In winter, the low sun angle and frequent snow cover influence the best positioning of PV panels. Studies suggest that while sun tracking generally enhances energy yield, cloudy conditions may sometimes favor a horizontal panel orientation to maximize diffuse radiation capture. Backtracking and adaptive control strategies can further optimize energy output by adjusting to varying sky conditions and seasonal factors. Quesada et al. [139] conducted an extensive analysis

of solar tracking performance in Montreal, Canada, a high-latitude location with significant seasonal variation. Their study aimed to determine the optimal tracking strategy under different weather conditions. A key finding was that on cloudy summer days, keeping PV panels in a fixed horizontal position often resulted in higher energy capture than using a dual-axis solar tracker. However, in winter, solar tracking remained advantageous due to ground snow cover, which increased reflectivity and contributed to higher energy yield. The study introduced the concept of critical hourly solar radiation ( $I_c$ )—a threshold below which horizontal positioning is more effective than tracking. Experimental results confirmed that in spring, dual-axis solar trackers produced up to 25% less energy than fixed horizontal panels on cloudy days. Furthermore, tracking was found to be ineffective in 96% of cases when solar radiation levels were below the critical threshold. These findings highlight the importance of dynamically adjusting solar tracking strategies based on seasonal and weather variations. The study suggests integrating predictive algorithms based on weather forecasts to further optimize PV panel orientation for maximum energy generation. Future research will focus on testing these strategies over a full year and evaluating their impact on grid-connected PV systems.

Ruelas et al. [140] introduced a novel methodology for designing PV sun trackers that leverage latitude-specific orientation efficiency to optimize performance. Their study focused on a dual-axis tracker implemented at  $27.5^\circ$  latitude, demonstrating its feasibility for locations near  $30^\circ$ . The proposed system offers a cost-effective alternative, reducing costs by 27% compared to traditional commercial trackers using slew drives, while increasing energy collection efficiency by 24% over fixed PV installations. The methodology enables the development of low-cost, high-availability tracking mechanisms adaptable to various locations and solar tracking technologies. Additionally, their approach allows for further research opportunities to refine tracking strategies based on latitude-specific efficiency charts.

#### 4.4. Solar Tracking Strategies and Applications in Agrivoltaics

Recent advancements have increasingly emphasized integrating solar tracking systems (STSs) into agrivoltaic settings to optimize land-use efficiency and energy production. A prominent example is the innovative methodology presented by Varo-Martínez et al. [97], who proposed a geometric modeling approach specifically designed for dual-axis solar trackers in photovoltaic plants undergoing transformation into agrivoltaic systems. Utilizing detailed simulations of solar irradiance and spatial geometry, this methodology effectively defines non-shaded zones suitable for agricultural activities beneath photovoltaic collectors equipped with tracking-backtracking features. Their case study at the “El Molino” photovoltaic facility in Córdoba, Spain, demonstrated how careful spatial analysis could identify significant areas—specifically pentagonal and trapezoidal arable zones—suitable for various crop heights, thus maximizing land utilization without impacting tracker operation.

The practical implications of integrating dual-axis tracking systems into agrivoltaic farms are substantial. According to the detailed analysis in [97], approximately 74% of the space between collectors was deemed cultivable for crops with heights up to 1.4 m, a proportion decreasing gradually as crop height increased. This spatial optimization highlights the capability of dual-axis trackers, combined with advanced backtracking algorithms, to balance energy generation and crop productivity efficiently. Furthermore, the flexibility of this methodology supports various agricultural configurations, including hedge-type and spherical-crowned crops, thus enhancing its adaptability and economic attractiveness. Such integrated solutions not only improve the economic viability and sustainability of large-scale photovoltaic installations but also represent a critical step forward in addressing

conflicts between energy production and agriculture, reinforcing agrivoltaics as a valuable approach for sustainable rural development and climate change mitigation.

Complementing the advances in geometric optimization discussed earlier, Valle et al. [98] further highlighted the significant potential of dynamic solar trackers within agrivoltaic systems. By directly comparing stationary and orientable photovoltaic panel (PVP) configurations in an experimental setting in Montpellier, France, the authors illustrated the substantial benefits dynamic trackers can offer, not only for electrical output but also for crop productivity. They specifically evaluated two tracking modes: regular solar tracking, where panels continuously adjusted to maintain optimal alignment with the sun throughout the day, and controlled tracking (CT), designed to optimize shading during peak solar intensity periods. Results demonstrated that dynamic tracking provided a notable improvement in electricity production—up to 74% higher under sunny conditions compared to stationary panels—while simultaneously enhancing biomass production by up to 15%, due to improved radiation transmission patterns at crop level. Interestingly, the introduction of transient shading through solar trackers created highly dynamic microclimatic conditions, positively influencing plant morphology and productivity. Under fluctuating shade, plants developed longer, thinner, and more horizontally oriented leaves, significantly improving their efficiency in using available radiation. Consequently, despite lower overall radiation compared to full-sun conditions, biomass production in dynamic tracking systems (both ST and CT) remained remarkably high, achieving yields close to those observed under full solar exposure. Importantly, the Land Equivalent Ratio (LER)—a critical indicator of combined agricultural and photovoltaic land-use efficiency—consistently exceeded unity in all tested agrivoltaic configurations, underscoring the clear advantage of dual-use strategies. The ST mode achieved the highest LER values, frequently exceeding 1.5, by significantly enhancing photovoltaic productivity without substantially compromising crop yield. Conversely, the CT mode maximized biomass by strategically limiting midday radiation, though at the expense of reduced electricity generation. Furthermore, Valle et al. [98] emphasized that the economic feasibility of agrivoltaic systems could be substantially improved through optimized solar tracking strategies tailored to specific crop needs and economic scenarios. Despite CT mode yielding lower electricity outputs compared to the regular ST approach, it notably increased biomass production, particularly relevant for high-value crops. Given that agricultural yield typically represented at least 65% of the total economic value per land unit, the ability to selectively prioritize biomass production through controlled tracking strategies could offer critical economic advantages. Such adaptable tracking policies, potentially responsive to instantaneous weather conditions or specific crop growth stages, underline the flexibility and economic potential inherent in modern agrivoltaic designs employing dynamic solar tracking systems. These findings reinforce the broader viability and adaptability of integrating sophisticated solar tracking strategies into agricultural settings, providing valuable insights into optimizing land-use productivity and addressing competing land-use demands for food and renewable energy production.

In addition to optimizing light management and crop productivity, solar tracking systems in agrivoltaics also play a crucial role in managing water distribution across cultivated land. Elamri et al. [99] introduced a novel application of solar panel orientation for rain redistribution, demonstrating how tilting angles of dynamic panels can significantly affect the spatial uniformity of rainfall reaching the soil. In their year-long field study, solar trackers installed over a cultivated plot in Montpellier, France, were programmed with real-time avoidance strategies to minimize rainfall interception during events. These strategies reduced the coefficient of variation in rainfall distribution from 2.13 (with flat panels) to as low as 0.22, a level comparable to well-calibrated irrigation systems. Such dynamic adjustment of panel tilt can mitigate water stress, erosion, and runoff risks while maintain-

ing soil structure and supporting crop health—factors critical for sustainable agricultural production. Importantly, this study emphasized that tracking systems in agrivoltaic settings can be optimized not only for light interception but also to respond to short-term weather events, such as rain and wind, through automated control strategies. The AVrain model developed by the authors enabled real-time simulation of rain redistribution patterns, guiding panel positioning to avoid concentrated water fluxes beneath panel edges. These adaptive control strategies contribute to a more balanced soil water profile and reduce the need for supplemental irrigation, ultimately enhancing resource efficiency. Coupled with earlier findings on yield retention under dynamic shading, these results underscore the broader multifunctionality of solar tracking systems in agrivoltaics—not only as tools for energy and light optimization, but also as key enablers of microclimate regulation and water resource management.

#### Summary Section 4

Section 4 provides a comprehensive analysis of adaptive solar tracking strategies across diverse environmental conditions, emphasizing their technical performance, control methods, and application-specific benefits. It demonstrates that solar tracking effectiveness is highly influenced by climatic variability, where dual-axis trackers perform optimally under clear skies, while horizontal panel orientations are more efficient under overcast conditions dominated by diffuse radiation. To enhance adaptability, hybrid tracking systems combining schedule-based algorithms and real-time sensor inputs have shown improved performance in regions with dynamic weather. Advanced vision transformer models and machine learning techniques, such as XGBoost, have been employed to enhance irradiance estimation and panel positioning accuracy, achieving prediction accuracies of up to 99.3% and energy gains exceeding 18% compared to conventional trackers. The section also explores backtracking strategies that mitigate shading losses, with advanced approaches boosting energy yield by up to 12% and reducing the LCOE. In high-latitude regions, research highlights the importance of dynamically adjusting panel orientation according to solar angles and seasonal sky conditions, with findings showing that horizontal orientation can outperform tracking systems on cloudy days, while tracking is more beneficial during snowy winters due to increased ground reflectance. Additionally, significant attention is given to agrivoltaic systems, where dual-axis trackers with advanced geometric modeling have enabled up to 74% of space to remain cultivable, and dynamic tracking modes have improved both electricity generation (up to 74%) and biomass production (up to 15%). Controlled tracking strategies further allow tailored shading for specific crops, enhancing Land Equivalent Ratios beyond 1.5, while panel tilt optimization has been shown to reduce rainfall distribution variability from 2.13 to 0.22, improving soil moisture uniformity. These findings collectively underscore the value of intelligent, climate-responsive tracking systems for enhancing solar energy efficiency, particularly in complex agricultural and high-latitude environments.

## 5. Conclusions

This review has comprehensively examined solar tracking systems (STs), their classifications, control strategies, sensor integrations, and climate-adaptive tracking methodologies. The analysis underscores the vital role of STs in improving PV performance, with energy gains of approximately 20–35% for single-axis and 30–45% for dual-axis systems compared to fixed panels, depending on latitude, climate conditions, and design optimization. Fixed-tilt systems remain suitable for low-budget or off-grid applications in areas with consistently diffuse radiation or where system simplicity is paramount. Single-axis trackers, especially HSAT and VSAT configurations, are recommended for large-scale utility

installations in regions with moderate to high solar irradiance and lower land availability, as they provide a cost-effective balance between performance and complexity. For locations in the range of latitudes 3–26°, inclined east–west (IEW) trackers are optimal, whereas VSATs perform better above 57° latitude. Dual-axis trackers are particularly advantageous for high-performance applications, including concentrated solar power (CSP) and equatorial regions, where continuous alignment with solar angles is critical for maximizing energy yield. These systems are also recommended for regions with variable solar angles throughout the year or installations integrated into agrivoltaic systems, where maximizing both energy production and crop yield is desired.

Control system evaluation highlights that closed-loop controllers, often employing LDRs, UV sensors, or photodiodes, offer high accuracy in real-time sun positioning. In contrast, open-loop systems—based on astronomical algorithms—are more energy-efficient and suitable for clear-sky regions. Hybrid control strategies, which combine real-time sensing and algorithmic forecasting, emerge as a robust solution for partly cloudy or variable climates, reducing motor actuation while maintaining precision. Microcontroller-based systems (Arduino, ATmega, PLCs, and DSPs) demonstrate scalable applicability: low-cost systems such as Arduino are ideal for prototyping and residential deployments, while PLC-based controllers dominate industrial-scale and high-reliability applications. Modern AI-based tracking strategies—leveraging machine learning, deep learning, and environmental data—show energy yield improvements of up to 7.83% over standard commercial tracking algorithms and are poised to drive the next generation of intelligent solar trackers.

Tracking under challenging conditions—such as cloudy weather and high latitudes—requires adaptive solutions. Backtracking algorithms are essential for dense PV farms to minimize shading losses, while horizontal or semi-static tracking may outperform active systems under persistent overcast conditions. In these scenarios, vision-based systems, cloud classification models, and irradiance-forecasting algorithms are crucial for dynamic angle optimization.

This study also highlights the growing importance of agrivoltaic applications, where dual-axis tracking integrated with adaptive shading and rain redistribution techniques can improve both electricity generation (up to 74%) and biomass productivity (up to 15%), achieving Land Equivalent Ratios exceeding 1.5 in optimized scenarios.

In summary, the optimal choice of tracking system should be context-specific—factoring in site irradiance, latitude, economic constraints, land-use efficiency, and application sector. Future research should prioritize the development of low-energy adaptive controllers, real-time predictive systems, and AI-integrated frameworks to further enhance energy output, resilience, and scalability. This will be especially critical in advancing the dual goals of renewable energy expansion and alignment with Sustainable Development Goals (SDGs 7 and 13).

#### *Future Trends and Research Directions*

Looking ahead, the future of solar tracking systems will be shaped by advancements in automation, artificial intelligence, and decentralized energy solutions. AI-powered tracking algorithms, integrating historical and real-time meteorological data, will allow for predictive sun positioning and self-learning control mechanisms, reducing reliance on mechanical components and enhancing long-term system reliability. Additionally, integration with smart grids and IoT-based monitoring systems will enable remote operation and real-time performance optimization, making solar tracking systems more resilient, cost-effective, and adaptable.

The application of solar tracking in agrivoltaics and urban energy systems is another promising avenue. By optimizing land-use and combining solar energy production with agricultural activities, agrivoltaics tracking systems can enhance food and energy security while reducing environmental impacts. Future research should also explore the role of energy storage technologies, adaptive power management, and advanced materials in improving the sustainability of solar tracking solutions. In conclusion, solar tracking technology is rapidly evolving, with ongoing research and innovations contributing to greater efficiency, lower costs, and increased applicability in diverse settings. As the world transitions toward renewable energy dominance, enhanced tracking mechanisms, AI-driven optimizations, and hybrid control strategies will play a crucial role in maximizing solar power generation and ensuring a more sustainable energy future.

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## Abbreviations

|                |                                                        |
|----------------|--------------------------------------------------------|
| 1D Conv        | One-Dimensional Convolution                            |
| AI             | artificial intelligence                                |
| ANSS           | Analog Sun Sensors                                     |
| ARIMA          | AutoRegressive Integrated Moving Average               |
| CCD            | Charge-Coupled Device                                  |
| CPV            | Concentrated Photovoltaic                              |
| CSP            | concentrated solar power                               |
| CSI            | Clear Sky Index                                        |
| DAST           | Dual-Axis Solar Tracking                               |
| DAT            | Dual-Axis Tracker                                      |
| DNN            | Deep Neural Network                                    |
| DSC            | Digital Signal Controller                              |
| DTS            | Dual-Axis Tracking System                              |
| E–W            | East–West                                              |
| FBG            | Fiber Bragg Grating                                    |
| FLC            | Fuzzy Logic Control                                    |
| FPGA           | Field-Programmable Gate Array                          |
| FOV            | Field of View                                          |
| FTPV           | Fixed-Tilt Photovoltaic                                |
| GHI            | Global Horizontal Irradiance                           |
| GPS            | Global Positioning System                              |
| GPSO           | Gaussian particle swarm optimization                   |
| GRU            | Gated Recurrent Unit                                   |
| GTR-PLC        | Gorilla Troop Reconfiguration-Power Line Communication |
| H              | Fixed Horizontal Configuration                         |
| HCPV           | High-Concentration Photovoltaic                        |
| HSAT           | horizontal single-axis tracker                         |
| I <sub>c</sub> | Critical Hourly Solar Radiation                        |
| IEEE           | Institute of Electrical and Electronics Engineers      |

|                |                                                |
|----------------|------------------------------------------------|
| IoT            | Internet of Things                             |
| LCOE           | Levelized Cost of Electricity                  |
| LDR            | light-dependent resistor                       |
| LSTM           | Long Short-Term Memory                         |
| MCU            | Microcontroller Unit                           |
| ML             | Machine Learning                               |
| MPPT           | Maximum Power Point Tracking                   |
| MRAC           | Model Reference Adaptive Control               |
| NARX           | Nonlinear AutoRegressive with eXogenous inputs |
| N–S            | North–South                                    |
| NWP            | Numerical Weather Prediction                   |
| PID            | Proportional-Integral-Derivative               |
| PLC            | Programmable Logic Controller                  |
| PO             | Perturbation and Observation                   |
| PSAT           | Polar-Aligned Single-Axis Tracker              |
| PSO            | particle swarm optimization                    |
| PV             | Photovoltaic                                   |
| R <sup>2</sup> | Coefficient of Determination                   |
| SAT            | Single-Axis Tracker                            |
| SDG            | Sustainable Development Goal                   |
| SDGs           | Sustainable Development Goals                  |
| SMA            | Shape Memory Alloy                             |
| SPIE           | International Society for Optics and Photonics |
| SPB            | solar panel blinds                             |
| SPA            | Solar Position Algorithm                       |
| STC            | Standard Test Conditions                       |
| STS            | Solar Tracking System                          |
| STSs           | Solar Tracking Systems                         |
| TAT            | Title, Abstract, and Topic                     |
| TR-Axis        | Tracking Rotation Axis                         |
| USA            | United States of America                       |
| UV             | Ultraviolet                                    |
| VSAT           | Vertical Single-Axis Tracker                   |
| XGBoost        | eXtreme Gradient Boosting                      |
| YAREA          | Yield–Area Ratio Efficiency Assessment         |
| ZV             | Zone Voltage                                   |

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