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Solar Tracking Device for Photovoltaic Solar Energy System: A Review

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Abstract

In the face of the traditional fossil fuel energy crisis, solar energy stands out as a green, clean, and renewable energy source. Solar photovoltaic tracking technology is an effective solution to this problem. This review delves into the sustainable development of solar photovoltaic tracking technology, analyzing its current state, limiting factors and future trends. The adjustment of solar panel orientation using solar tracking technology to maximize energy generation efficiency has been widely implemented in various fields, including solar power plants. Currently, limiting factors for this technology include energy generation efficiency, costs and the complexity of various environmental conditions. In terms of sustainable development, this article emphasizes the importance of photovoltaic materials and manufacturing innovation, energy efficiency improvements, as well as the integration of smart and digital technologies. Future trends include higher precision, broader applications, and lower costs. Solar photovoltaic tracking technology will play a pivotal role in global energy production, fostering the realization of a clean and sustainable energy future.

Subject Areas

Applied Physics

Keywords

Solar, Tracking, Photovoltaic, Energy

1. Introduction

The majority of everyday activities in today's world are greatly influenced by electricity. Such activities include daily operations in homes and businesses [1]. Many methods can be used to generate electricity from the public supply for consumers, such as using gas, water, wind, or steam energy to power a turbine [2]. Nuclear energy, solar energy, and generators are additional sources of electricity [3]. Solar energy holds incredible promises that renewable energy will meet the world's already high and constantly increasing energy demand [4]. The conversion of solar energy into electricity is performed by both flat PV and concentrating solar power (CSP) systems [5] [6]. The output power generated by these devices depends on the quantity of solar energy they collect [7] [8]. Ideal ST allows PV panels and CSP systems to precisely point to the position of the sun and compensate for changes in daily altitude angle and seasonal latitude offset as well as changes occurring in the azimuth angle of the sun [9] [10].

With the advancement and progression of industrialization, the demand for energy has steadily climbed [11]. Traditional fossil fuels are gradually depleting, and their usage has adverse effects on the global climate. Solar energy derived from the Sun's radiation, can be converted into electricity or thermal energy using solar panels [12]-[16]. It finds applications in electricity generation, heating, and various other energy needs. Solar energy is a clean and environmentally friendly source with vast potential [17]. It can reduce dependency on fossil fuels, decrease greenhouse gas emissions, and contribute to achieving sustainable energy goals [18]. The conversion of solar energy into electricity is accomplished through photovoltaic (PV) cells; with the output power of these cells depending on the amount of solar energy they collect [19]. The principle behind this process is that when sunlight strikes the solar panel, photons excite electrons within the semiconductor, causing them to move and generate an electric current [20] [21].

Scholars have carried out extensive research to further examine the effects of passive and active control on ST technology. Systems for passive tracking depend on the physical characteristics of substances like chlorofluorocarbons and shape memory alloys [22]. When photovoltaic panels are not oriented vertically toward the Sun, uneven heating on their sides causes expansion on one side and contraction on the other, aligning the panels as closely as possible with the Sun to achieve tracking objectives. Active tracking systems, on the other hand, employ microcontrollers, sensors, actuators, etc., to continuously track the Sun [23]-[26]. Typically, a signal is sent to the motor by the microcontroller or sensor when it detects the Sun's movement, causing the solar panels to shift in order to track the Sun [27]. The purpose of tracking systems is to maximize the solar radiation received by the solar panels. Active tracking systems are further categorized into two types based on degrees of freedom: single-axis STS(s) and dual-axis STS(s) [28]. The motion mechanism of a single-axis tracking system usually offers one rotating degree of freedom. Its structure is simpler, and its control complexity is lower [29]. Considering the ground as a reference, the Sun's movement relative to the ground can be divided into north-south and east-west motions, which mainly influence changes in elevation and azimuth angles [30]. Dual-axis tracking systems were introduced, featuring two mutually perpendicular rotational degrees of freedom [31]. Therefore, dual-axis tracking systems have more complex structures and control strategies [32].

1.1. Solar Energy

Solar energy is the total amount of energy that is captured by the sun's rays. Many technologies, including solar heating, solar cells, solar thermal thermoelectric, solar architecture, and artificial photosynthesis, have a tendency to use radiant light and heat from the strong sun [33] [34]. Earth receives an estimated 1 KW/m^2 at high noon, but there has already been a direct conversion of photon energy to electricity, and solar power facilities are presently being established on a significant scale [35]. One advantage of solar energy over all other energy sources is that it doesn't emit any noise and doesn't reject heat, carbon dioxide, or radioactive particles. It is therefore the most environmentally friendly [36].

In remote areas and hilly regions of the planet, where power line transmission is sometimes expensive or extremely unlikely, solar energy provides a dependable energy source [37]. Additionally, urbanized electrification using photovoltaic panels to power street lighting is gaining traction. Contemporary electrical devices can also be powered by solar energy. These days, solar energy is being widely used in smart grid systems, electric cars, and building-integrated solar systems. There is no other source of energy available to spacecraft or satellites that are launched into space for an extended period of time except solar [38] [39].

1.2. Photovoltaic Cell

A PV system refers to a system that utilizes the PV effect of semiconductor materials to convert solar energy into electrical energy [40]. The key parameter for assessing the performance of PV cells is conversion efficiency, which refers to the ability of a PV cell to convert solar energy into electrical energy [41]. Conversion efficiency is closely related to the material characteristics of PV panels and can be categorized into four generations, which compare different materials used in PV cells [42]. The first-generation PV cell materials include monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), and amorphous silicon (a-Si) [43].

The second-generation PV cells focus on thin-film technology, where cell materials are manufactured in the form of thin films [44] [45]. Materials in this category include cadmium telluride (CdTe), cadmium sulfide, copper indium selenide, and copper indium gallium selenide (CIGS) [46]. The third-generation photovoltaic cells incorporate organic materials and nanotechnology, building upon the previous generation [47]. This category includes photochemical solar cells, dye-sensitized solar cells (DSSCs), polymer solar cells, and nanocrystal solar cells [48]. The fourth-generation cells are characterized by flexibility and low cost [49]. These cells consist of stable and advanced inorganic nanostructures (such as metal nanoparticles and metal oxides) combined with organic nano-materials like carbon nanotubes, graphene, and their derivatives [50].

In 1948, Ohl utilized silicon as the material for PV cells; it marked the initiation of the era of PV power generation [51]. Until today, silicon remains the primary material for PV cells. Silicon, as the predominant material in PV cells, boasts advantages such as abundant resources, mature technology, high conversion efficiency, and reliability [52]. However, its band gap structure limits the absorption range of the solar spectrum, and its weight, resistance to light weighting, high energy consumption in the manufacturing process, and relatively elevated production costs are considered drawbacks [53]. Despite these challenges, silicon PV cells remain the current mainstream and reliable technology. Gallium arsenide (GaAs), as a material for PV cells, presents advantages such as high efficiency, temperature stability, and radiation tolerance, particularly excelling in broad-spectrum responsiveness and high-temperature environments [54].

The challenges persist in widespread commercial application due to high costs and the relative scarcity of gallium [55]. The application of thin-film technology in GaAs photovoltaic cells offers potential for flexible manufacturing, yet addressing cost and material supply issues is imperative for the extensive deployment of GaAs in the photovoltaic sector [56] [57]. Cadmium telluride (CdTe) serves as a prominent material for PV panels, showcasing several advantageous characteristics [58]. Demonstrating high-efficiency conversion, thin-film manufacturing techniques, relatively low production costs, and adaptability to high-light environments, CdTe PV cells excel in the realm of photoelectric conversion [59] [60]. Their inherent lightweight and flexibility, which are conducive to flexible design, afford increased versatility for diverse application scenarios. Simultaneously, the production process of CdTe is relatively environmentally friendly, mitigating adverse environmental impacts [61].

High photovoltaic conversion efficiency is exhibited by multifunction solar cells, which increase total efficiency by absorbing a wide range of sunlight wavelengths through various band gap designs [62]. In the realm of solar cells, graphene and its derivatives have attracted a lot of interest. An effective electrode material is graphene, which is renowned for its exceptional conductivity and transparency. Certain derivatives of graphene retain these qualities [63] [64]. Their adjustable optical properties help to increase the photoelectric conversion efficiency of the solar cell. These materials are appropriate for a range of solar applications due to their adaptability in design and capacity to modify electrochemical performance [65].

For example, graphene oxide has better electrical characteristics than graphene. The potential uses of carbon nanotubes in solar cells are exceptionally promising [66]. They are the perfect electrode material due to their remarkable electrical conductivity, which efficiently promotes electron transfer and improves solar cells' overall efficiency [67].

1.3. Sun Path, Azimuth and Altitude Angle

The change of position of the moving sun varies at different times and season to season due to earth's continuous and periodic rotation and revolution [68]. Consequently, it is now essential to determine the sun's orientation at a specific time. The azimuth angle, elevation angle, sun pathways throughout time, and sunrise and sunset times were all described in a sun path diagram [69]-[71].

1.3.1. Declination Angle (δ)

The declination angle is the angle between the equator and a line drawn from the centre of the Earth to the centre of the sun [72] [73]. It is the angular distance of the sun's position in the north or south of the earth's equator. The declination angle, denoted by δ, varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun [74]-[77]. The declination would always be 0˚ if the Earth were not tilted on its axis of rotation. Nonetheless, the declination angle fluctuates by plus or minus the Earth's 23.45˚ tilt. The declination angle is equal to 0˚ only at the spring and fall equinoxes [78]-[80].

$$\delta = \sin^{-1} 0.4 \sin\left(360 \frac{d_n - 82}{365}\right) \tag{1}$$

$$\delta = -23.45 \sin\left(360 \frac{d_n + 284}{365}\right) \tag{2}$$

Where δ is the declination angle and d_n is the number of days in a year.

1.3.2. The Altitude Angle or Elevation Angle (α)

It shows how high the sun appears in the sky. The angle is measured between an imaginary line between the observer and the sun and the horizontal plane the observer is standing on. The altitude angle is negative when the sun drops below the horizon [81].

$$\alpha = 90^{\circ} + \varnothing - \delta_{\alpha} \tag{3}$$

1.3.3. Solar Azimuth Angle (γ_s)

This is the angle change from the south to the horizontal plane where beam radiation is projected. A position east of south is indicated by a positive solar azimuth angle, and a position west of south is indicated by a negative azimuth angle [82].

$$\gamma_s = \sin^{-1}\left(\frac{sinhcos\delta}{\sin\theta_z}\right) \tag{4}$$

Where γ_s is the solar azimuth angle.

1.3.4. The Latitude (*w or L*)

A point or location is defined as the angle formed by the radial line that connects it to the earth's centre and is projected onto the equatorial plane. At 90˚ latitude (the North Pole) and −90˚ latitude (the South Pole), the earth's axis of rotation crosses the surface of the planet. The intersection of a longitude angle and a latitude angle can therefore be used to define any place on Earth's surface [83] [84].

1.3.5. Angle of Incidence (θ_i)

This is the angle between the beam radiation on a surface and the normal to that surface [85]-[88].

$$\theta_i = \cos^{-1}\left(\sin Lst \sin\delta + \cos Lst \cos\delta \cos ST\right) \quad (5)$$

Where θ_i is the angle of incidence.

1.3.6. Hour Angle (ω_s)

This is the angular displacement of the sun east to west of the local merridean due to rotation of the earth. On its axis at 15˚ per hour, morning is negative and afternoon is positive [89].

$$\boldsymbol{h} = \mathbf{15^{\circ}\ (solartime - 12\ noon)} \quad (6)$$

$$\boldsymbol{\omega_s} = \cos^{-1}(\mathbf{tan\ L\ tan}\ \boldsymbol{\delta}) \quad (7)$$

where h and ω_s are the hour angle.

1.3.7. Zenith Angle (θ_z)

This is the angle between the vertical and the line to the sun, i.e., angle of incidence of beam radiation on a horizontal surface. That is, it is the angle between the sun and a line perpendicular to the earth's surface. It is the complement of solar altitude [90].

1.3.8. Solar Attitude Angle (α_s)

This is the complement of the zenith angle, or the angle between the horizontal and the line to the sun. This represents the sun's angular height as measured from the horizon. Positive is above the horizon, and negative is below. The solar altitude of the sun, which is situated in the center of the sky, is 90 degrees [91].

1.3.9. Surface Azimuth Angle (γ)

This is the projection of the site-to-sun line on the horizontal plane and the angle formed by the horizontal plane and due south. That is the sun's direction from the observer, as indicated by the hour angle between the line's north point and the intersection of the horizon and a vertical circle that passes through the sun [92].

1.3.10. Solar Irradiance

The measurement of sunlight's power density is called solar irradiance. It is an instantaneous quantity with the unit W/m^2. The planet receives 1367 W/m^2 of irradiance from solar radiation [93]. The radiation becomes 1000 W/m^2 at the surface after being absorbed by the atmosphere and travelling through it. Solar radiation is a crucial component in this sector since it influences the performance of the solar cell's output [94]. The energy that makes up sunlight has wavelengths that fall within a broad spectrum of electromagnetic waves. However, no solar cell is able to absorb all forms of energy. The primary purpose of a solar cell is to absorb a specific percentage of the entire spectrum of energy. The visible spectrum is the only wavelength that photovoltaic solar cells are intended to absorb [95] [96]. Solar irradiance is a parameter directly related to solar energy received by solar panels and maximum when rays are perpendicular to the panel plane. To achieve maximum solar energy it is necessary to rotate the panel face towards the sun. The device that is used for this purpose is called Solar Tracker [97].

2. Solar Tracking System

Solar tracking devices are essential for optimizing the efficiency of photovoltaic (PV) solar energy systems. These devices adjust the orientation of solar panels to follow the sun's path, maximizing the amount of sunlight captured throughout the day. Advanced control algorithms play a crucial role in enhancing the performance of these tracking systems. However, the components of solar tracking system include; tracker mount, driver, sensors, motor, algorithm and microcontroller.

(1) Tracker mount: The structural support that holds the solar panel at the correct angle [98] [99].

(2) Driver: Controls the rotation of the motor shaft. Positioning system moves the solar tracker according to the preference of control unit [100]. It can be either electronic or hydraulic. Electrical systems utilize encoders and variable frequency drives or linear actuators to monitor the current position of the panel and move to desired positions [101]. The drive mechanism includes mechanical devices-rotary motors, linear actuators, linear drives, hydraulic cylinders, swivel drives, worm gears, planetary gears, and threaded spindles. These drives can be of different types according to design method [102].

(3) Sensors: Detects relevant parameters from the sun and provides output. Sensors are used to detect position of sun accurately [103]. For open-loop system light sensors are implemented to correct calculation and mechanical errors. Closed-loop system solely depends on several light sensing devices [104]. Light intensity detecting device includes photo resistor, photo-transistor, solar cell etc. Solar power based stations also use temperature, pressure, humidity, wind velocity, solar irradiance and other necessary parameters monitoring systems with trackers [105].

(4) Motor: Controls the movement of the tracker [106].

(5) Algorithm: Calculates the sun's position using the time, date, and geographical location. Solar tracking can have open loop control algorithm or closed-loop control algorithm [107]. Open-loop control algorithm involves calculation of azimuth and altitude angle of sun on a purely mathematical platform based on astronomical references. The open-loop component is needed because the sun can be obscured by clouds, eliminating or distorting the feedback signals [108]. Closed-loop control algorithm includes detection of the position of sun by real-time light-sensing method and is needed to eliminate errors due to variability in installation, assembly, calibration, and encoder mounting [109]. These two methods can be combined together to keep balance between economic design and increased efficiency [110].

(6) Microcontroller: this can be programmed to generate internal interrupts. The control unit executes the sun tracking algorithm and necessary calculations. It can also coordinate the movement of the positioning system [111]. A microprocessor or a computer can be used as the centre of control unit. It normally has command input and data output mechanism for interfacing. For the trackers placed in remote region automatic tracking control mechanism is best suitable [112].

2.1. Types of Solar Tracking Systems

There are mainly two types of solar tracking systems: single-axis and dual-axis. Single-axis trackers follow the sun's movement from east to west, while dual-axis trackers can also adjust the tilt angle to follow the sun's elevation.

2.2. Control Algorithms

Advanced control algorithms are used to optimize the tracking performance. These algorithms can be categorized into:

a) Scheduled-based algorithms

These use pre-defined schedules based on the sun's path.

b) Light-dependent algorithms

These use sensors to detect the sun's position ireal-time.

c) Hybrid algorithms

These combine both scheduled-based and light-dependent approaches to improve accuracy and efficiency.

2.3. Performance Improvements

Studies have shown that dual-axis tracking systems can increase energy generation by more than 27% compared to stationary systems. Scheduled-based tracking systems have been found to enhance efficiency by 4.2% under diverse weather conditions compared to light-dependent resistor-based trackers.

2.4. Challenges and Advancements

Despite the benefits, there are challenges such as the initial cost, maintenance, and the need for precise control mechanisms. Recent advancements focus on improving the reliability and cost-effectiveness of these systems.

3. Solar Tracking System Technological Advancements and Classifications

3.1. Classification Based on Drive Mechanisms

3.1.1. Passive Tracking Systems

Unlike active tracking, passive tracking does not rely on sensors. A passive tracker responds to pressure imbalance between two locations at the tracker's ends to move, rather than using sensors [113]. Heat from the sun generates gas pressure, and compressed pressure moves the structure, causing this pressure imbalance. This approach uses very little electricity to function and does not require electrical sensors. But in order to preserve accuracy, the mechanical design must be extremely important [114].

Relatively easy to use, passive solar tracking systems don't need an external power source. Their goal is to increase solar panels' exposure to sunlight in order to boost solar energy systems' efficiency in producing energy [115]. Passive tracking systems, in contrast to active tracking systems, do not use motors or control systems to change the solar panels' orientation. Rather, they make use of a number of material properties and physical concepts [116].

Usually employing shape memory alloys or chlorofluorocarbons, passive tracking systems take advantage of the physical characteristics of materials, such as thermal expansion and contraction [117]. In order to line the solar panels as vertically as possible with the Sun, one side of the panels expands while the other contracts due to uneven heating on both sides when they are not perpendicular to the Sun. Compared to fixed solar panels, Zomeworks 1969 introduction of the first commercial passive STS efficiently caught sunlight, increasing the output of electricity [118] [119].

3.1.2. Active Tracking System

Throughout the day, the sensors continuously determine the sun's location. The sensor directs the motor or actuator to move such that the solar panel faces the sun at all times during the day [120]. With the aid of sensors, active tracking is precise. However, the primary issue arises on overcast days when the sensors are unable to distinguish between data and either miss the original trigger or produce a fake one. Devices like microcontrollers, sensors and actuators are used in an active tracking system to continuously monitor the Sun's position [121].

By tracking variations in ambient light intensity, the solar tracking system uses LDRs as photosensitive parts to determine the Sun's position [122]. In order to create a thorough model of the differences between the actual and predicted positions, the microcontroller reads the resistance values of LDRs with high accuracy and extensively compares them with the theoretical light intensity corresponding to the expected solar position [123]. The microprocessor uses the comparison results to run a complex algorithm for calculating errors, producing an electric signal that is proportionate to the variation in solar position [124]. To guarantee adherence to the accuracy and responsiveness specifications of the system design, this signal is carefully calibrated [125].

The microprocessor then sends the adjustment signal to the actuator, which precisely regulates the adjustment mechanism to align the solar panel with the Sun based on the signal properties (such as voltage and current) [126]. In order to maintain the solar panel's orientation toward the Sun during ongoing monitoring, the actuator performs the adjustment movements. The system continuously senses changes in sun position, calculates errors, generates adjustment signals, and executes corrective operations in a persistent iterative loop [127]. This iterative procedure maximizes the efficiency of solar energy gathering by ensuring that the system responds to changes in the sun's position promptly and accurately [128].

3.2. Classification Based on Degrees of Freedom

3.2.1. Single-Axis Solar Tracking System

A single-axis tracking system typically refers to a mechanism providing one rotational degree of freedom, and it can be classified into three types: horizontal single-axis, vertical single-axis, and tilted single-axis [129]. Tilted single-axis systems work well in mid-latitude areas; vertical single-axis tracking systems work well in high-latitude areas, and horizontal single-axis STS(s) work well in equatorial and low-latitude areas. There is enormous potential for the sustainable development of single-axis STS(s) [130] [131]. More sophisticated control systems, possibly including artificial intelligence and machine learning algorithms, will be used by future single-axis STS(s) to track solar positions and light levels in real time, allowing for accurate modifications of PV panel orientations [132].

By improving system response time, this development will guarantee that PV panels are constantly oriented toward the best possible positions. To minimize the impact on the environment and lessen reliance on finite resources, STS(s) shall be manufactured using ecologically benign and renewable materials [133]. In order to lower energy costs, future single-axis tracking systems might connect with alternative energy sources, such wind or energy storage systems. Furthermore, self-powering techniques may be incorporated into future single-axis STS(s). In conclusion, future single-axis STS(s) have the potential to be a significant technological advancement in the realm of sustainable energy due to their increased dependability and efficiency [134]. These developments will help lessen dependency on conventional energy sources, opening the door to a more sustainable and clean energy future [135].

Advantages of Single-Axis Solar Tracking System

The advantages of single axis tracking system are more reliable and long lasting, lower complexity so fewer maintenance issues, cheaper to purchase and operate, more efficient than stationary mounts and generate 15% - 16% more annual power than fixed panel [136] [137].

Disadvantages of Single-Axis Solar Tracking System

The disadvantages of single axis tracking system are producing less energy than dual-axis model during peak sunny times and limited technology upgrades capabilities [138].

3.2.2. Dual-Axis Solar Tracking System

Two degrees of rotation appear to be present in a dual-axis solar tracker. It might be able to follow the sun both vertically and horizontally [139]. This kind of tracker ensures optimal efficiency in using solar energy and may be used anywhere in the world [140]. Solar power structures and dish systems are examples of concentrated solar power (CSP) systems that use dual axis tracking [141]. Because the angle error matters for longer distances between the reflectors and the central receiver located in the tower structure, dual-axis tracking is extremely critical in solar power tower procedures. Compared to single-axis tracking, dual-axis tracking systems are more difficult to design and operate. Nonetheless, dual axis tracking is more cost-effective for large-scale solar energy generation [142].

The main elements affecting variations in tilt angle and azimuth angle are the Earth, which can be regarded as a reference, and the Sun's movement with respect to the Earth, which can be separated into annual and daily motions [143]. Consequently, a dual-axis tracking system with increased tracking precision is introduced. Two rotating degrees of freedom that are perpendicular to one another make up a dual-axis tracking system. The dual-axis STS is a cutting-edge solar power generation system that continuously tracks the position of the Sun to optimize the energy collection efficiency of solar panels [144]. Usually, this system uses sensors and motors to track the Sun's location and automatically reorient the solar panels [145].

Dual-axis STS(s) will become increasingly intelligent as machine learning and artificial intelligence continue to progress. These systems can maximize energy collecting efficiency by using machine learning algorithms to forecast the Sun's position and make judgments in real time based on illumination and weather data [146] [147]. Furthermore, intelligent systems can save downtime by proactively managing maintenance and detecting faults. Dual-axis STS(s) will heavily rely on digital technologies. Real-time monitoring and gathering of enormous volumes of data, such as temperature, humidity, solar radiation, and other environmental parameters, will be made possible by sensor networks and Internet of Things technology [148] [149]. These data will be utilized for remote monitoring and system performance optimization. These systems can help reduce reliance on fossil fuels, decrease greenhouse gas emissions, and drive dual-axis STS(s) to become an integral part of sustainable development [150].

Advantages of Dual-Axis Solar Tracking System

The advantages of dual axis solar tracking system are maximize power output by continually following the sun, help manage grid power limitations, require less land area to produce more total energy and generate 45% - 50% more annual power than fixed panels [151] [152].

Disadvantages of Dual-Axis Solar Tracking System

The disadvantages of dual axis solar tracking system are more prone to technical glitches due to complexity, shorter life span and lower reliability and higher maintenance cost [153] [154].

3.3. Factors Limiting the Efficiency and Utilization of Solar Trackers

Generally, most of researchers have agreed that the solar trackers increase the overall efficiency of a PV panels and CSP systems [155]. However, clear indications should be provided indicating where, when and how maximum power efficiency can be achieved. Consistent with the aforesaid, many problems have been identified and each of these problems has been addressed individually including miss-tracking and failure of the control systems and/or the electronics of the trackers among others [156]. More importantly, the studies confirmed that most of the problems limiting the overall efficiency of both the fixed and tracking PV systems are similar. Moreover, different types of solar trackers present different advantages and challenges when considering their performance and efficiency, and studies have shown that tracking the sun position significantly increases the efficiency especially in cloudy days [157] [158]. For this reason, using ST could be the ideal way to boost up the efficiency and performance of both the PV panels and the CSP systems irrespective of what the weather looks like [159] [160].

3.3.1. Cost

Installing a solar tracking system necessitates the purchase of additional hardware, such as electric drives, sensors, controllers, and mechanical structures [161]. These parts are frequently very expensive to purchase, particularly for large solar fields or PV power plants. Compared to stationary solar systems, the installation of an STS or STSs is more complicated, and frequent maintenance is necessary to guarantee that the mechanical and electronic components are operating as intended [162]. Cleaning, lubrication, problem detection, and repairs are all part of this upkeep. It is anticipated that STS(s) technology will develop and grow throughout time [163]. Cost-effective sensors and electronic components, robust mechanical constructions, and more effective control systems might all be part of this. These developments in technology have the potential to lower the systems' manufacturing costs [164] [165].

3.3.2. Geographical Environment and Climatic Conditions

The varying geographical locations on Earth result in significant disparities in both the intensity and trajectory of solar radiation [166]. For the majority of the year, places nearer the equator see comparatively high levels of sun radiation, which lessens the severity of STS(s). However, the solar trajectory gets more inclined at areas that are farther from the equator, particularly at higher latitudes [167]. As a result, in order to adapt to the Sun's shifting position in the sky, STS(s) must be designed and controlled with greater sophistication. Geographical considerations also comprise topography and shading effects, which can impact the angle and intensity of solar radiation reaching a surface [168] [169]. Because of topographical factors like mountains and buildings, some areas may not receive direct sunlight at particular times, which reduces the effectiveness of solar energy systems [170] [171].

By monitoring the Sun's movement, solar tracking systems in high-altitude areas help photovoltaic panels be oriented to maximize radiation reception [172]. This improves energy output by lessening the effect of complicated terrain and a sparse atmosphere on system performance. Climate factors that affect solar tracking systems' effectiveness include temperature, wind speed, cloud cover, and seasonal fluctuations [173].

Solar tracking systems should be designed to adapt to various geographical environments, including high-latitude regions, deserts, mountains, coastal areas, etc [174]. In these locations, the trajectory of the Sun and climatic conditions may vary, requiring flexibility in tracking systems to accommodate diverse scenarios [175]. When facing extreme weather conditions, STS(s) need to possess features such as wind resistance, rain protection, and snow resistance. By continuously monitoring the Sun's position and meteorological conditions, tracking systems can adjust the angles of solar panels in real-time to maximize solar radiation absorption or seek shelter [176] [177]. Similarly, the number of axes used to track the sun has a significant impact on the overall efficiency of the solar radiation harvested by the module. It studied the effect of tracking on the performance of PV modules based on the number of tracking axes for the system [178].

4. Conclusions and Prospects

The solar PV tracking system continuously adjusts the angle of solar panels to maximize energy collection throughout the day by tracking the Sun's position. This article provides a comprehensive review of PV cells made from different materials, with a particular focus on comparing and analyzing their manufacturing processes, performance, and research trends. Based on driving mechanisms and degrees of freedom of motion, the low-cost cases, tracking strategies, control methods, and limiting factors of solar tracking systems are classified and reviewed. Advancements in tracking technology, including sophisticated sensor technology, intelligent control systems, and cloud computing, contribute to improving the performance and reliability of these systems. As economies of scale are realized, and technological costs decrease, the construction and maintenance costs of solar PV tracking systems are gradually decreasing, making solar energy more economically viable. Additionally, the development of more affordable, environmentally friendly, and efficient PV cell materials is a crucial research direction. Combining technological progress with the expansion of solar PV systems in the field of power generation can significantly reduce carbon emissions, contribute to addressing climate change, and mitigate global warming.

In the future, solar PV tracking systems will further enhance energy collection efficiency, including dual-axis tracking systems and systems employing advanced optical technologies. These systems will enable solar panels to track the Sun more accurately and perform exceptionally well under various lighting conditions. Simultaneously, tracking systems will become more intelligent and digitized. By utilizing artificial intelligence, big data analysis, and internet connectivity, the systems can achieve real-time monitoring, fault diagnosis, and remote operation. Solar tracking systems can be applied not only in electricity generation but also in various fields such as agricultural irrigation, water treatment, and integrated energy systems.

In conclusion, solar PV tracking system technology continues to play a crucial role in the field of sustainable energy, contributing to mitigating climate change, reducing energy costs, and promoting the transition to green energy. With ongoing technological advancements and the expanding market, solar PV tracking systems are expected to achieve broader applications and increased sustainability in the future.

Conflicts of Interest

The authors declare no conflicts of interest.

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