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Innovations and advancements in solar tracker systems: A comprehensive review

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Abstract

This review paper demonstrates an in-depth discussion of the technological development in different solar tracking systems, which is one of the important components of solar power generation. These systems play a distinctive role in raising the energy generated by moving solar panels towards the sun. This paper is concerned with shedding light on the different classifications of tracking systems, control methods, and major modern smart components, including remote system monitoring and control, with an emphasis on the importance of increasing efficiency and cost-effectiveness. The study of solar tracker systems is crucial to consolidate current knowledge, recognize gaps in research, and foster revolution in this area. It offers a comprehensive thoughtful of up-to-date developments in control systems, classifications, and evolving technologies such as the internet of things (IoT) and artificial intelligence (AI). The study highlights limitations in prevailing systems, directorial future studies and, research to improve scalability, reliability and, affordability. Besides, they play a critical role in encouraging sustainability by capitalizing on the utilization of solar energy and donating to global goals of renewable energy. Moreover, this review paper acts as a valuable and distinct resource for industry leaders, policymakers, and researchers, offering awareness of the greatest practices and inspiring collaboration of interdisciplinary for progressing technologies of solar tracking.

Keywords: internet of things (IoT); single-axis solar tracker; dual-axis solar tracking; classifications of solar trackers.

I. Introduction

It is known that human life requires energy. The provision of adequate energy supplies is necessary for the sustainable development of societies. A permanent source of energy that does not run out is needed, such as renewable energy sources. Most countries are concerned with using renewable sources of energy, like wind energy, solar energy, and geothermal energy. Solar energy is a plentiful energy source and research about it is being widely conducted [1][2]. One of the most reliable and abundant renewable sources of energy is solar energy. The effectiveness and efficiency of solar energy capturing systems are highly dependent on the solar cell's direction, which should always orient

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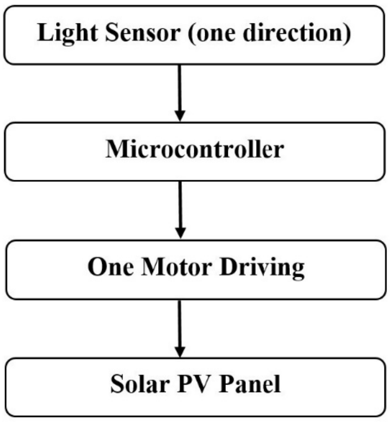

Figure 1. Single-axis solar tracking system.

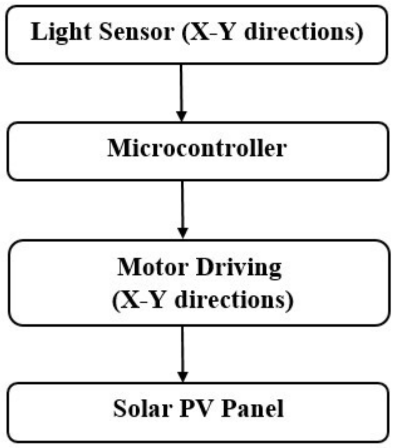

Figure 2. Dual-axis solar tracking system.

toward the sun perpendicularly. This requirement makes the installation of a solar tracking system essential to boost the solar panels' energy output [3][4][5].

Solar tracking systems are classified into different types, such as passive, active, and chronological, other than freedom-based classification, like trackers with one and two axes [6]. Single-axis trackers move solar panels perpendicular to the sun's east-west direction, as presented in Figure 1 while dual-axis trackers move them based on the angles of solar elevation and azimuth, as given in Figure 2 [7]. Table 1 shows the comparison of solar tracker types.

The dual-axis tracking method offers a higher energy efficiency level than the single-axis. Many studies found that the electrical output from a dual-axis solar tracking system established greater efficiency when contrasted with single-axis trackers or fixed panels [8][9][10]. Therefore, dual-axis solar tracking system installation is important to maximize the solar panel's power output.

In recent years, solar tracking technologies have evolved significantly, leading to the employment of internet of things (IoT) solutions that enable remote system control and monitoring via the internet. The first solar tracker was created by C. Finster, although it had little energy gains, testing, study, and development have led to improvements in energy output and the emergence of advanced solar tracking technologies [4][11]. The effectiveness of solar tracking devices has risen with technological advancements; there are now more kinds of systems that have emerged, including solar tracking devices with one or two axes that can determine the sun's position based on the time of day and the season. Although the fixed solar collector type is easy to install even in harsh environmental conditions, the solar tracking system is still widely preferred to efficiently collect solar energy despite the additional side preparation, such as wiring, trenching, and grading [12]. Solar systems performance is enhanced using the IoT, where embedded monitoring systems continuously measure variables like solar radiation, panel location, and environmental conditions.

The benefits of IoT-enabled solar tracker systems are numerous, such as monitoring and safety, controlling energy use, assessing solar radiation captured, and keeping an eye on the production of renewable energy. IoT is used to ensure reliable control over solar trackers, minimize downtime, and maximize the performance of the solar installation [13][14]. Moreover, the integration of IoT technology enhances the overall system efficiency by enabling effective energy management and load balancing. Through data-

Table 1.
Comparison of solar tracker types [7][11][12].

Types		Advantages		Efficiency improvement (%)
Fixed	Stationary panels with no movement	Low-cost, simple installation	Lower energy capture, not optimized for the sun's movement	Baseline
Single-axis	Rotates on one axis (horizontal or vertical)	Increased energy capture compared to fixed systems, relatively simple design	Limited optimization compared to dual-axis, moderate cost	36.4 % increase over fixed
Dual-axis	Rotates on both horizontal and vertical axis	Maximizes energy capture by fully tracking the sun's movement	Higher cost, more complex installation and maintenance	Up to 32.2 % increase over fixed

driven optimization algorithms, IoT-enabled solar tracker systems can adapt to changing environmental conditions, grid demands, and energy storage requirements [15][16][17].

Many studies have been conducted to discuss solar tracker systems [8][18]. In [18], the article aims to implement an IoT-based system with dual-axis tracking to maximize solar panel effectiveness. The system is designed to maneuver and remotely monitor the orientation of the solar tracking system (STS) and leverages IoT technology to remotely align the orientation of the solar panels as described in [19]. This involves utilizing angle data obtained from the internet, enabling users to optimize the solar panel's positioning from any location for enhanced solar energy collection. The paper describes the mechanical and electrical systems and the use of sensors to ensure accurate orientation.

The use of Proteus software in designing an IoT-based mechanism for tracking the sun to increase output energy by tracking the movement of the sun is showcased in [20]. The article highlights the need for renewable energy sources and how solar energy can be transformed into electricity using solar panels. The increase in the usefulness coefficient of solar panels will result in an increase in energy conversion. The research also discusses the problems with the low efficiency of solar panels and how to make the solar panels bigger or the intensity of lighting on the surface is not an effective solution due to increased costs and the need for more space. The solution is to enhance the quantity of power by obtaining the most energy derived from the capacitance of solar panels. Besides, a block diagram of a solar tracking system and its control system is demonstrated in this paper. In this system, a simulation of the solar tracking system was conducted using Proteus software. Like in [21], this system is composed of light dependent resistor (LDR) sensors, voltage and current sensors, a liquid crystal display (LCD), a solar panel, and a servo motor. In [22] the different types of solar trackers and different types of controllers for solar tracking systems are presented, such as using a proportional-integral-derivative (PID) controller. This system gives high efficiency. However, it is more expensive than other methods. The article also illustrates the use of Arduino with the MATLAB simulation to control solar tracking systems. In conclusion, the article highlights the importance of solar energy and the need for maximum efficiency in power plants.

Authors in [23] present an effort to enhance the efficiency of solar systems using a solar tracking system to achieve maximum power output. The utilized tracking system relies on the IoT, which is an effective system for remotely controlling the solar tracking system. Two-axis tracking systems are recommended to achieve maximum solar energy efficiency. The proposed solar tracking system consists of LDR, a microcontroller, a solar panel, and an LCD display. By implementing automated solar tracking, the system can increase energy efficiency and reduce manual supervision and maintenance time. In [8], the paper concludes with the need to incorporate advanced remote management and control capabilities into the system. The systems of solar trackers have been widely developed and studied as they show a crucial role in improving the efficiency of solar photovoltaic (PV) systems by maximizing the production of energy for solar systems [10][14][15]. Numerous technologies and designs containing single and dual-axis trackers have been offered to enhance energy harvest under changing environmental conditions [1][5][7]. Modern improvements comprise innovations in integration with the IoT, control algorithms, and hybrid schemes that syndicate solar tracking with supplementary renewable sources of energy. While important development has been completed, current studies mostly emphasize specific advancements in technology or narrow topographical case studies. However, there is a shortage of comprehensive reviews that holistically compare and analyze the cost-effectiveness, performance, and scalability of various solar tracker systems. Furthermore, the incorporation of emerging technologies such as machine learning (ML), and artificial intelligence (AI) in solar trackers systems is underexplored.

The paper systematically reviews and introduces recent developments in solar tracker systems by considering peer-reviewed literature. A comparative evaluation and analysis of present technologies is offered, followed by a study of emerging trends and their prospective impact on the efficiency of solar energy. The review contribution of the paper could be summarized in the following points.

1. Provide a comprehensive study of tracker for solar systems, containing their performance, design, and challenges.
2. Evaluate the scalability and cost-effectiveness of various types of solar trackers.
3. Highlight the prospect of integrating progressive technologies such as IoT and AI into trackers of solar systems.
4. Identify upcoming opportunities and trends for development and research in this field.

The layout of this paper is described as follows. Section I describes the introduction. Section II demonstrates the methodology. Section III shows the solar tracker classification. Section IV presents the control system for solar tracker. Section V presents tracking PV systems installation. IoT technology for solar tracking systems is given in section VI. Future vision and research opportunities is depicted in section VII. The conclusions are stated in section VIII.

II. Materials and Methods

This paper review was established to offer an in-depth assessment of the emerging trends, recent developments, and challenges in systems of solar tracker. The process of review followed an organized style to guarantee reproducibility and transparency, concentrating on published literature within the last decade.

The search for literature was performed across various databases, including Web of Science, Scopus, IEEE Xplore, ScienceDirect, Google Scholar, and SpringerLink. These databases were chosen for their wide-ranging coverage of optimization topics, renewable energy, and engineering. The search involved a wide area of keywords and topics in the field of the presented review paper. The paper was additionally refined by containing most of the research published in the last ten years (2014 - 2024) to guarantee the review replicates the state-of-the-art technological developments. Moreover, only studies published in peer-reviewed conference proceedings or journals were taken into account to confirm the quality and reliability of the included studies.

The selection process was performed in two stages. Initially, the abstracts and titles of the manuscripts recognized in the search were studied to govern their significance to the solar tracker system development. Articles that discussed mechanisms of tracking, energy optimization, algorithms, and interrelated technologies were chosen for full-text review. In the second stage, the articles were carefully observed to guarantee they met the inclusion criteria. The inclusion criteria for this review were: (1) studies published between 2014 and 2024; (2) peer-reviewed articles or conference proceedings; (3) research focused on the design, optimization, control algorithms, and technological developments of solar tracker systems; and (4) articles written in English. Studies that focused exclusively on unrelated renewable energy systems or lacked sufficient technical depth were excluded. To combine the findings, studies were gathered into groups depending on their strategies of control and their mechanisms of tracking. A comparative analysis was carried out across various kinds of tracking systems, seeing their effectiveness in enhancing energy capture, reducing errors in tracking, and minimizing costs [1][6]. Developing trends in the design of solar trackers, mainly those integrating IoT and AI, were emphasized to evaluate their prospective for future improvement [16][17]. The review also examined the geographical focus of the studies, noting that environmental factors such as irradiance, latitude, and temperature could significantly affect the performance of solar tracker systems [7][9][10].

Lastly, a quality evaluation was directed to guarantee the presence of high-quality research. This includes the evaluation of how well-thought-out the methodological accuracy of each study is, comprising the clearness of experimental setups, the data reliability, and the significance of the findings. Studies with clear performance metrics, distinct approaches, and robust analysis of data were prioritized for presence in the review paper.

III. Solar Tracker Classifications

Solar trackers could be categorized according to the technology used to regulate the motion of solar panels, and this classification includes passive, active, and chronological solar trackers [6][24] (see Figure 3).

A. Passive solar trackers

Passive solar trackers could efficiently align themselves with the path of solar without the need for mechanical motors; these trackers typically feature two actuators, which may be filled with a gas that expands or is made of an alloy with shape memory properties. The system takes advantage of the expansion of thermal or imbalance at a pressure between both tracker ends. As soon as the PV panel is oriented toward the sun, both sides of the tracker remain balanced. When the sun moves, the side of the solar tracker facing the sun is heated and expands while contracting the other side, resulting in the solar panel's rotation (see Figure 4).

The concept of implementing solar tracking systems for PV applications has led to a proposed novel approach for expansion produced from the thermal of thin flat strips, which is the basis for passive solar tracking [25]. It also describes the design, build, and testing of a passive solar tracking system prototype depending on a lever mechanism connected to three vertical strips with different orientations, as a consequence of which energy production increased by 28 % in comparison with stationary PV panels [25]. However, the prototype has limitations in its design, and improvements to materials and maintenance requirements are necessary for further improvements [26].

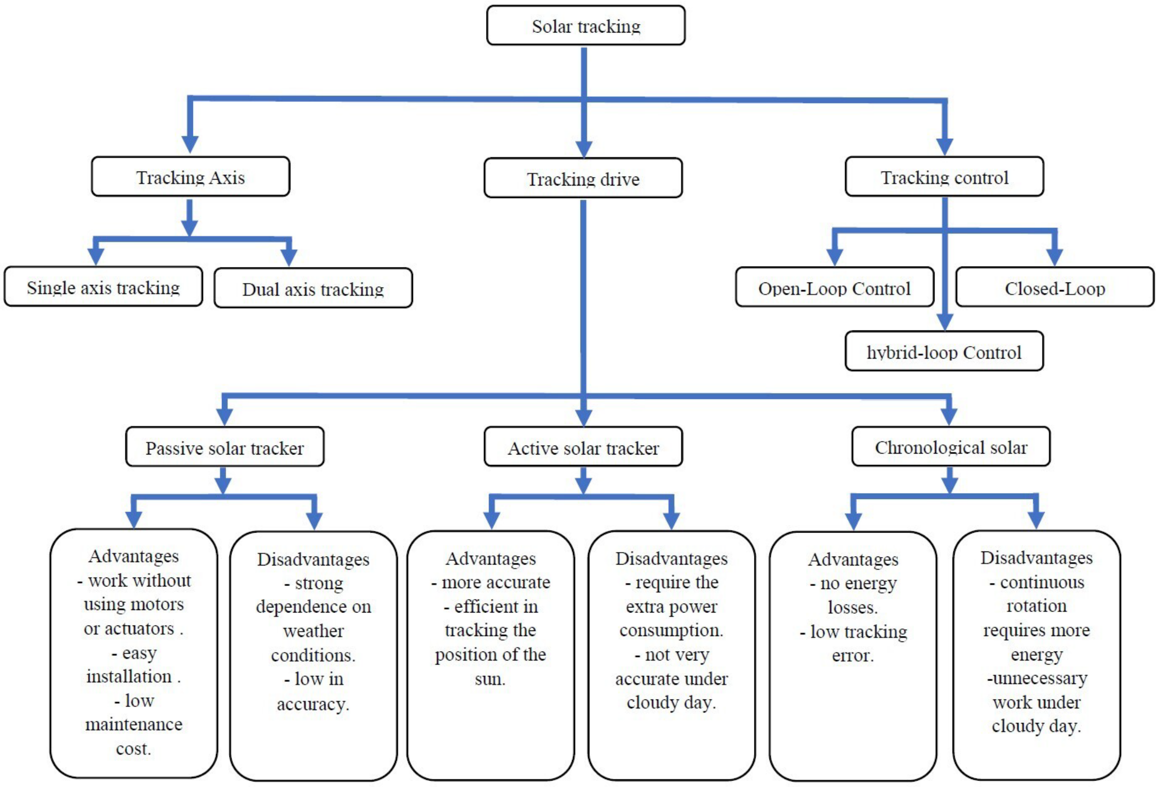

Figure 3. Type of solar tracking system.

B. Active solar trackers

An active system of solar tracking employs sensors to continuously identify the sun's position during the day (see Figure 5). The actuator or motor is triggered by these sensors in order to adjust the positioning of the fixture and track solar radiation. This adjustment is necessary when sunlight is inclined on the tracker, and the tracker's direction is changed by altering the illumination reaching the sensors to become perpendicular to the sun [27]. Currently, there are two kinds of solar trackers based on their movement technology: single and dual-axis trackers [25][28].

The creation and production process of a single-axis solar tracker device to adjust and increase the solar cell's efficiency is presented in [29]. Cell efficiency is influenced by a number of factors, including cell temperature, the maximum power point tracker (MPPT), and the efficiency of conversion energy [29]. The solar tracker system developed in this study improves electricity conversion optimization by using

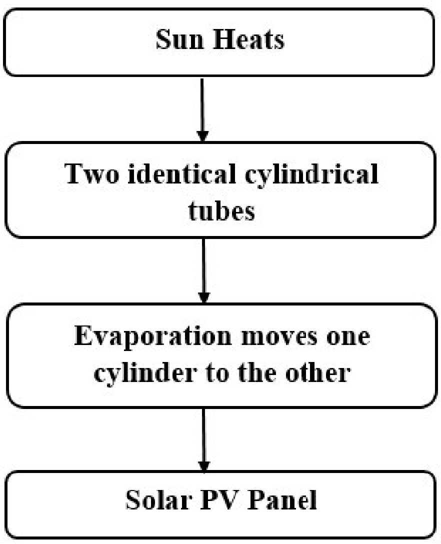

Figure 4. Passive solar trackers.

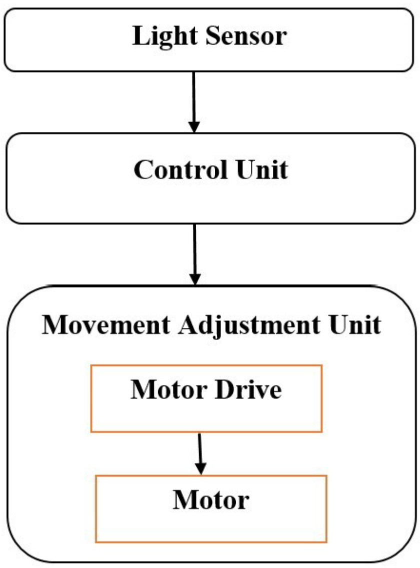

Figure 5. Active solar trackers.

oriented photovoltaic panels to conform to the sun's direction [30]. In the experimental system, a dedicated drive circuit intelligently controls a DC motor to change solar panel orientation determined by signals from light sensors. The study showcases the effectiveness of incorporating a tracking system, as PV output is almost double compared to stationary photovoltaic panels. The findings suggest that this solar tracker system can be used to charge batteries and fulfill home energy requirements. Future recommendations include improving the design to reduce structural weight and make it more efficient by applying concentrators to reflect sunlight to the PV panel to increase power output [31].

In [32], the research suggests a tracking system using dual-axis and how to change the angle in the east-west direction and inclination using sensors to manage the system. The control of the system is done through a programming controller that uses precise electric motors to control the solar panels. It contains radiation power density sensors used to determine solar radiation. There are also integrated micro-inverters that convert energy into household current, including tracking MPPT. The system accurately stores data for both tracking and fixed solar panels in sunlight. In addition, the system is compatible with a vane anemometer that can accurately assess both wind speed and direction. If the predetermined wind speed threshold is exceeded, the system ensures the protection of the mechanical integrity by adjusting the solar panels to a horizontal position [33].

C. Chronological solar trackers

Chronological solar trackers (see Figure 6), are tracking systems that rely on time, where the tracker mechanism rotates at a constant angle based on the time of day and month. The motor rotation rate is controlled at a slow rate. This method is considered the most energy-efficient tracking method because there are no losses in energy.

The implementation of the chronological tracking system is dependent on the time when the module or collector moves at the same daily and monthly rate of angle as proposed in [34]. The motor rotates at a slow rate, making it an energy-efficient open-loop control tracker. Researchers have studied and investigated this system, mainly for photovoltaic applications. Some researchers have concentrated on single-axis solar tracking, while others have studied dual-axis tracking [34].

The highlights of the risks of fossil fuels and their impact on the environment, and that sources of renewable energy are the greatest choice is given in [35].

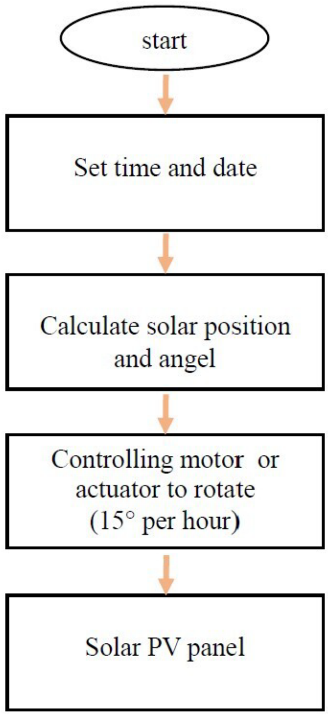

Figure 6. Chronological solar trackers.

Solar energy is sustainable and environmentally friendly. A practical time-based single-axis sun tracking system evolved, utilizing an axis-based design. The rotation angle varies by 15 degrees per hour, and sometimes the tracking angle is 10 degrees or 20 degrees per hour, indicating that there is a deviation of approximately ±5 degrees per hour [36][37][38]. It was explained that the best angle for the tracking system is 15 degrees per hour compared to other rotation angles because it provides a high-performance ratio [39][40][41].

IV. Control Systems of Solar Tracker Systems

A different strategies of control system for solar tracker are shown in tree shape as in Figure 7. A PV tracker's principal goal is to automatically and precisely track the movement of the sun while minimizing pointing errors. Automation is achieved through a variety of control circuits and feedback.

A. Open-loop control

In this operating mode, positional errors are minimized by eliminating the need for a feedback element. Stepper motors are commonly utilized as drives in an open-loop control mode. However, without feedback, any errors resulting from overshooting or variations in load cannot be corrected [42].

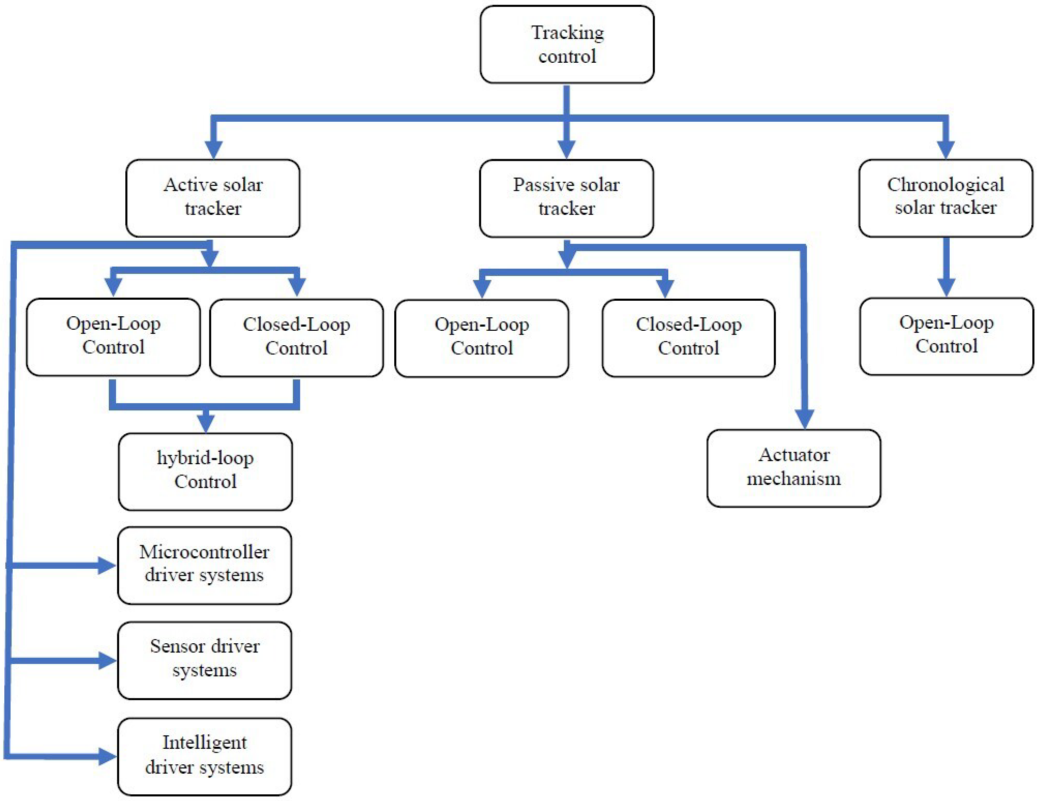

Figure 7. Control system for solar tracker.

B. Closed-loop control

Closed-loop control is the opposite of open-loop control in a PV tracker that incorporates feedback mechanisms to correct any errors in the stepper motor drive steps. Sensors are employed to detect deviations between the amount of sunlight hitting the PV module surface and the ideal orientation of the PV panel. Closed-loop control allows the exact location of the sun to be given accurately throughout the day. Light sensors, typically positioned on the solar panel, measure variations in light intensity, enabling the PV panel to be accurately realigned to be perpendicular to the incident sunlight [42].

C. Microcontroller for active solar trackers

There are multiple types of controllers that are used in sun-tracking instruments, which are employed to control the performance of the tracking system and manage the elements and components in the system [43][44]. Table 2 presents various control algorithms for solar tracking systems.

A design of a control system for solar tracking using a programmable logic controller (PLC) S7-1200 from SIEMENS has been done [43]. The system performed function such as processed analog inputs from solar irradiance sensors, controlled the solar tracker, and managed the outputs for linear actuators. The control

Table 2.
Control algorithms for solar tracking [45][46].

Types		Advantages		Efficiency improvement (%)
PID control	Proportional-integral-derivative control for error minimization	High	Used in real-time tracking systems for smooth and responsive adjustments	Moderate
Fuzzy logic	Utilizes fuzzy set theory to handle incertainties in tracking	Moderate to high	Effective in varying weather conditions where precise medeling is difficult	High
Artificial Neural Networks (ANN)	Learns and predicts optimal tracking positions based on historical data	High	Applied on complex environments with non-linear patterns	High

strategy was implemented using a ladder programming language in the PLC, enabling the detection of the maximum solar irradiance among different inclination angles of the photovoltaic cells [43].

Another different control method was implemented, and the system's performance was assessed [22]. The traditional control method and the programming environment method using two (LDRs) were utilized. Furthermore, the two-axis sun tracking system with four sensors was produced and compared to the one-axis system with two sensors. Simulink environment with embedded code was also used in the research. In addition to the previous methods, the PID control was applied using PID controllers. The (PID) settings were practically computed using the actual values and PID tweaking tool with MATLAB. The system required LDRs to detect the sun's location, and the error signal came from PID input, which was the distinction between the solar panel and the sun's angle. The integrated controller managed the system to repair the erroneous signal and provide optimal performance [22].

The solar tracking system has been improved and developed using a photovoltaic panel, Arduino microcontroller, and sensors [47]. Where the LDRs are utilized to measure the amount of the solar panels' incoming light, and the information is sent to the precise controller that controls the DC servo motor circuit. The servo motor circuit is constructed, and a potentiometer is used to control the motor speed [47]. A simulation of the system was performed using Proteus software to ensure it would yield the expected performance [44][48].

V. Tracking PV Systems Installation

An algorithm for a closed-loop solar tracking system aimed at achieving optimal response from the solar panel to track the sun as light of the sun falls on it is presented in [49]. The Arduino controller is used in this system, and photodiodes and operational amplifiers are employed to generate error voltage feedback. Control in this model is achieved using Arduino to drive the motor [49]. Also, a dual-axis solar tracker using two linear actuators and a PLC was utilized to control this dual-axis solar tracker, and its performance was compared to a fixed solar system [50]. The short circuit current of a cell was standardized using a current transducer and scaled to solar irradiance using ladder programming language and the IEC-61131-3 standard [43].

In [51] it is presented a hardware description of the elements used in a solar tracker system prototype. The paper provides brief definitions of components such as LDR sensors, servo motors, solar panels, and Arduino [51]. The algorithm of the solar tracker system is examined in depth, including a closed-loop system block diagram and a table summarizing the different tracking situations. The paper also includes a design of a prototype and a simulation of the circuit section that uses the Proteus program for the electric scheme. The analog part of the Arduino is described using A0-A3 input pins. The paper concludes by showing the four LDR sensors reading voltage outputs in real-time. Overall, the paper provides valuable insights and details about the hardware components used in a solar tracker system prototype [52]. Table 3 depicts the materials and components used in solar tracker systems.

VI. IoT Technology for Solar Tracking Systems

The IoT is a huge networking platform for the control and interaction of multiple tools of electronic through the Internet. It is a combination of processors, sensors, and controllers for actuation, which all communicate by means of the Internet. The data streams from the sensors or any other smart devices that acknowledge the change in environmental factors get stored in a common platform where the necessary information gets processed, computed, and analyzed. This filtered data can either be stored for future reference or can be utilized instantaneously to take actions such as controlling. The idea of IoT is to act as a bridge that establishes connections between actual physical objects and the virtual world through the internet [55][56][57].

Kevin Ashton initially used the phrase IoT in 1999 in an exhibition for Procter & Gamble, connecting the concepts of radio-frequency identification (RFID) to the supply chain of the company [58]. However, the first usage of the IoT, as we see it now, was even before

Table 3.
Materials and components used in solar trackers [53][54].

Component	Material	Cost	Durability	Efficiency impact
Tracker frame	Recycle steel	Moderate	High	Support structural integrity, enabling optimal panel positioning
Actuators	Electric motors	Variable	Moderate to high	Pecise movement enhances sun tracking accuracy
Sensors	Light sensors (LDR)	Low	Moderate	Detects sunlight intensity for real-time tracking adjustments

Table 4.
Technological advancements in solar tracker systems [57][58][59].

Technology/ feature	Application	Benefits
AI-based tracking	Utilizes artificial intelligence to optimize panel positioning	Enhance efficiency by predicting sun paths and weather conditions
Terrain-adaptive trackers	Trackers that adjust to uneven terrain without extensive land grading	Reduces installation costs and environmental impact, expands viable installation sites

the term was coined. The concept first appeared in the mid-1970s at the Computer Science Department of Carnegie Mellon University in a Coke vending machine. It permitted students to look at the status of the vending machine, such as knowing when the vending machine was full/empty or whether the drinks inside the vending machine were hot or cold. As the years progressed from the mid-1970s, computers became smaller, faster, and more available. In 1991, author Mark Weiser wrote an article, "The Computer for the 21st Century". Table 4 presents technological advancements in solar tracker systems.

IoT has revolutionized solar tracking by making it possible for real-time data gathering, analysis, and control (see Figure 8). Here are some key ways in which IoT is utilized in solar tracking.

A. Remote monitoring and control

IoT makes remote monitoring of solar tracking systems possible, allowing operators to collect and analyze data on panel performance, energy production, and weather conditions. Users can monitor the system's status via internet connectivity, eliminating the need for physical presence. Remote control of devices through smartphones further enhances convenience and control, helping to prevent electricity wastage [60].

B. Sensor integration

IoT devices incorporate a variety of sensors used in a single system that operates synchronously, and the sensors are integrated together into a main controller responsible for sensor scanning and data transmission, enabling precise tracking of the sun [61]. Data from the tracking system can be analyzed, and data processing issues can be studied. Control devices are used to analyze and manage the system effectively. Data analysis helps improve the positioning of solar panels and predict future movements of the sun [62]. With solar tracking, solar system efficiency is increased, leading to enhanced energy production and improved solar system efficiency [63][64]. Solar energy tracking systems that utilize the IoT can monitor system performance and detect faults or errors [65][66].

C. Mobile application

Creating a mobile application has the purpose of displaying all measurements related to the solar system (radiation, temperature, voltage, current, and efficiency) and showing alerts for solar tracking system failures, such as battery issues or motor problems, as shown in Figure 9 [59][64][65]. The application should be able to identify the faulty system in case multiple solar tracking systems are connected. It should also provide alerts for high-temperature failures in the tracking system to avoid potential fire hazards. Figure 9 displays a mobile application for solar tracking system failures.

VII. Future Vision and Research Opportunities

The development of trackers for solar systems has unlocked weighty potential for enhancing the sustainability and efficiency of the generation of solar

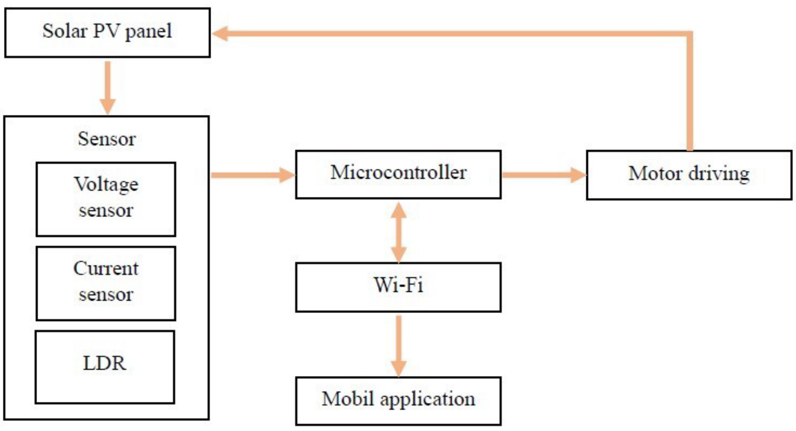

Figure 8. IoT in solar tracking.

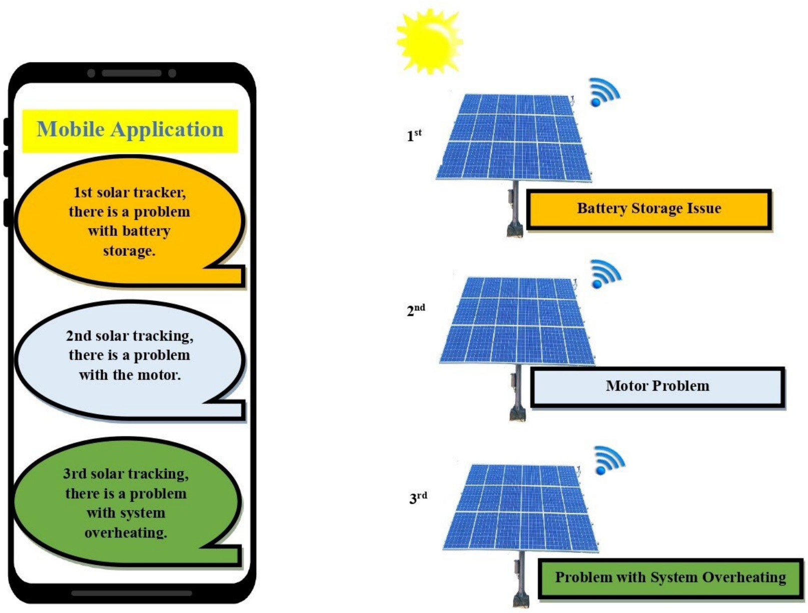

Figure 9. Mobile application showing alerts for solar tracking system failures.

energy [50][54][56]. Conversely, numerous promising areas of research remain underexplored, giving exciting prospects for future exertion. These gaps are present not only due to limitations of technology but also as a result of the challenges related to executing innovative thoughts in applications in the real world. Below, we plan crucial areas for prospect research, deliberate why these areas still open issues and problems, and highlight the challenges obstructing their realization.

One promising way is the integration process of ML and AI into systems of solar trackers [50][54][56]. ML and AI can improve the performance of solar trackers by forecasting output energy under variations of weather conditions, allowing cutting-edge scheduling of maintenance, and predicting demand for energy. Conversely, their extensive adoption is imperfect because of the lack of labeled, large datasets that replicate diverse conditions of environmental. Emerging generalized and robust models of AI also demand trivial resources of computational and capabilities of processing in real-time. Furthermore, many solar farms depend on legacy hardware, making the incorporation of systems-based-AI a costly and complex endeavor.

A different area with enormous potential is the integration of technology of IoT into systems of solar trackers [50][59][62]. IoT-enabled systems could assist in fault detection, remote monitoring, and seamless integration of data, enhancing whole efficiency and decreasing downtime. Even with the fast advancement of IoT, its employment in trackers is delayed by limitations of infrastructure, concerns about the security of data, and the lack of standardized protocols. Moreover, the high costs related to communication networks and hardware of IoT, mainly in large-scale or remote installations, further obstruct development. Furthermore, susceptibilities to cyber attacks increase significant worries about the safety and reliability of IoT-enabled methods.

The enlargement of autonomous hybrid systems of solar tracking is another exhilarating outlook. Hybrid systems that syndicate the topographies of single and dual-axis trackers might make the most of the efficiency of energy while decreasing costs [60][65][66]. Though, these systems are still mostly investigational due to contests in complexity, performance, and balancing cost. The increased complexity of the mechanical issue for hybrid systems primes complex maintenance necessities, while limited testing under varied environmental conditions makes it problematic to confirm their theoretical benefits.

Research into progressive materials for components of solar trackers also presents great potential. Materials such as surfaces with self-cleaning or lightweight alloys could develop the performance and durability of solar trackers, mainly in tough environments [55][60][66]. On the other hand, scaling up and developing such materials need time for difficult testing, momentous funding, and observance of standards of safety. Furthermore, improbability regarding recyclability and the impact on the environment of these materials are additional challenges to their implementation and adoption.

Optimization in real-time for trackers of solar systems via forward-looking algorithms, such as particle swarm optimization (PSO) or generic genetic algorithm (GA), denotes an additional critical opportunity for the research. Although these algorithms are well-established in hypothetical studies, their real-world application faces logistical and

Table 5.
Opportunities and challenges in emerging solar tracker technologies [52][55][57].

Research area	Opportunity	Why it remains unavailable	Challenges
Integration of AI and ML	Optimize solar tracker performance using predictive models for energy output, maintenance, and demand forecasting	Limited availability of large, diverse datasets; reliance on legacy hardware in solar farms	High computational power requirements, real-time processing demands, and cost of integrating AI into existing systems
IoT-enabled solar trackers	Facilitate remote monitoring, fault detection, and seamless data integration	Infrastructure limitations, lack of standardized protocols, and data security concerns	High implementation costs; vulnerability to cyberattacks; scalability challenges in large or remote installations
Autonomous hybrid systems	Combine single-axis and dual-axis features for optimal energy efficiency at lower costs	It is still in the experimental stages due to mechanical complexity and difficulty in balancing cost and performance	High maintenance requirements, limited field testing; and difficulty validating theoretical gains in diverse environments
Advanced materials	Use lightweight alloys or self-cleaning surfaces to improve durability and performance	High costs and time required for material development and testing; uncertainty about environmental impacts	Scalability issues; adherence to safety standards; recyclability concerns for new materials
Real-time optimization algorithms	Enhance tracker efficiency using bio-inspired algorithms like Genetic Algorithms or Particle Swarm Optimization	Computational demands and hardware compatibility issues hinder practical implementation	High processing requirements; continuous retraining of models; challenges integrating algorithms into low-cost systems
Energy storage integration	Pair solar trackers with advanced storage systems for grid stability and energy availability during off-peak hours	High capital investment and limited technological maturity of storage systems	Battery degradation over time; environmental concerns about recycling and disposal; high long-term costs

computational barriers. Real-time systems require great processing power to perform complex techniques, and incorporating these methods with hardware investigation systems is mainly challenging for trackers to keep it low-cost. Furthermore, continuous upgrades and re-educating of optimization strategies are required to familiarize with varying conditions of environmental, adding to the deployment complexity.

The future of trackers for solar systems compromises exhilarating opportunities; these parts continue as open issues and problems due to practical, economic, and technological challenges [50][59][65]. Overcoming these obstructions will need interdisciplinary partnerships among data scientists, scientists of material, engineers, and policymakers. Solving these challenges will bridge the gap between applications in real-time and theoretical innovations, paving the way for solar tracker systems to play an essential role in the global transition to renewable energy. Table 5 depicts opportunities and challenges in emerging solar tracker technologies.

VIII. Conclusion

Solar tracker system is considered as a directive technology for improving the harvesting of solar energy. Through a comprehensive study of their control systems, categorizations, and incorporation with IoT technologies, this study emphasizes the substantial developments in the field. The strategies reviewed prove the developing sophistication in implementing and designing trackers of solar systems, which can meaningfully enhance the cost-effectiveness and efficiency of solar systems. Furthermore, the literature highlights the advancement of control approaches, from simple designs of mechanical systems to automated, intelligent systems integrating various sensors and data processing in real-time. Looking ahead, the incorporation of evolving technologies such as AI, ML, and cutting-edge IoT frameworks offers exhilarating opportunities for additional innovation in systems of solar trackers. These technologies are able to improve prognostic maintenance, enhance performance, and qualify adaptive behavior and responses to variations in environmental conditions. Future studies should focus on converging challenges linked to system scalability, affordability, and reliability, paving the way for the prevalent approval of solar trackers in both industrial and residential applications. By adapting these solutions, solar energy systems can play an essential role in the powerful goals of global sustainability.

Declarations

Author contribution

All authors contributed equally as the main contributor to this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] S. Dehshiri and B. Firoozabadi, "Comparison, evaluation and prioritization of solar photovoltaic tracking systems using multi-criteria decision-making methods," *Sustainable Energy Technologies and Assessments*, vol. 55, p. 102989, 2023.

[2] A. N. AL-Rousan, "Integration of logistic regression and multilayer perceptron for intelligent single and dual axis solar tracking systems," *International Journal of Intelligent Systems*, vol. 36, pp. 3067–3078, 2021.

[3] K. Klimek and K. Kamila, "Orientation and exposure efficiency of a solar tracking surface in clear sky," *Applied Sciences*, vol. 12, p. 1557, 2022.

[4] H. Fathabadi, "Novel high efficient offline sensorless dual-axis solar tracker for use in photovoltaic systems and solar concentrators," *Renewable Energy*, vol. 92, pp. 267–276, 2016.

[5] T. Ackermann, *Wind Power in Power Systems*, Wiley, 2012, pp. 123–145.

[6] J. L. Pérez-Gudiño *et al.*, "The low-cost mechanism of a defined path guide slot-based passive solar tracker intended for developing countries," *Technologies*, vol. 12, no. 12, p. 250, 2024.

[7] A. El Hammoumi *et al.*, "Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels," *Energy Reports*, vol. 8, pp. 11992–12010, 2022.

[8] C. Jamroen, C. Fongkerd, W. Krongpha, P. Komkum, A. Pirayawaraporn, and N. Chindakham, "A novel UV sensor-based dual-axis solar tracking system: Implementation and performance analysis," *Applied Energy*, vol. 299, p. 117295, Oct. 2021.

[9] A. Gupta and Y. K. Chauhan, "Detailed performance analysis of realistic solar photovoltaic systems at extensive climatic conditions," *Energy*, vol. 116, pp. 716–734, 2016.

[10] T. Demirdelen, H. Alıcı, B. Esenboğa, and M. Güldürek, "Performance and economic analysis of designed different solar tracking systems for Mediterranean climate," *Energies*, vol. 16, no. 10, p. 456, 2023.

[11] E. K. Mpodi, Z. Tjiparuro, and O. Matsebe, "Review of dual-axis solar tracking and development of its functional model," *Procedia Manufacturing*, vol. 35, pp. 580–588, 2019.

[12] A. Awasthi, A. K. Shukla, M. M. Srivastava, C. Dondariya, K. N. Shukla, D. Porwal, and G. Richhariya, "Review on sun tracking technology in solar PV systems," *Energy Reports*, vol. 6, pp. 392–405, 2020.

[13] Q. Ha and M. D. Phung, "IoT-enabled dependable control for solar energy harvesting in smart buildings," *IET Smart Cities*, Nov. 2019.

[14] R. Kodali and S. Mandal, "IoT-based smart energy management system for a renewable energy microgrid," *IEEE Internet of Things Journal*, vol. 4, pp. 422–429, Apr. 2017.

[15] L. Atzori, A. Iera, and G. Morabito, "Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm," *Ad Hoc Networks*, vol. 65, pp. 122–140, 2017.

[16] P. K. Mani, P. Sunagar, N. S. Madhuri, A. J. L. Rajah, D. Ramya, and I. Kathir, "IoT-based solar panel tracking system to enhance the output power," *2022 3rd International Conference on Smart Electronics and Communication (ICOSEC)*, 2022, pp. 488–493.

[17] Saheed Gbadamosi, "Design and implementation of IoT-based dual-axis solar PV tracking system," *Przegląd Elektrotechniczny*, pp. 59–64, 2021.

[18] D. Neha S. Deshmukh, "A smart solar photovoltaic remote monitoring and controlling," in *Proc. 2018 Second International Conference on Intelligent Computing and Control Systems (ICICCS)*, 2018.

[19] N. Thungsuk, T. Tanaram, A. Chaithanakulwat, T. Savangboon, A. Songruk, N. Mungkung, and T. Yuji, "Performance analysis of solar tracking systems by five-position angles with a single axis and dual axis," *Energies*, 2023.

[20] G. Pasam, R. Natarajan, R. Alnamani, S. Al-Alawi, and S. Al-Sulaimi, "Integrated heuristic approaches to get maximum power from fixed and moving PV solar panels," in *Proc. 2023 Third International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT)*, 2023.

[21] K. E. Khujamatov, D. T. Khasanov, and E. N. Reypnazarov, "Modeling and Research of Automatic Sun Tracking System on the Bases of IoT and Arduino UNO," *2019 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2019, pp. 1-5.*

[22] O. Shahin and S. Ozerdem, "A PV solar tracking system controlled by Arduino/MATLAB/Simulink," *International Journal on Technical and Physical Problems of Engineering*, vol. 5–10, p. 6, 2014.

[23] M. Subhi, J. Hameed, and H. Mohammed, "Dual-axis solar tracker system using optimal hybrid controller,"

Indonesian Journal of Electrical Engineering and Computer Science, vol. 26, pp. 1379–1387, 2022.
[24] L.Kumar, M. Hasanuzzaman, and N. A. Rahim, "Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review," *Energy Conversion and Management*, vol. 195, pp. 885–904, Sep. 2019.
[25] A. Musa, E. Alozie, S. A. Suleiman, J. A. Ojo, and A. L. Imoize, "A review of time-based solar photovoltaic tracking systems," *Information*, vol. 14, no. 4, 2023.
[26] M. Brito, J. Mário Pó, D. Pereira, F. Simões, and R. Rodriguez, "Passive solar tracker based on the differential thermal expansion of vertical strips," *Journal of Renewable and Sustainable Energy*, vol. 11, p. 013501, 2019.
[27] B. Abderezzak, A. Ladmi, K. Arbaoui, et al., "Design and simulation of a solar tracking system for PV," *Applied Sciences*, vol. 12, p. 8377, 2022.
[28] A. R. Amelia, Y. M. Irwan, I. Safwati, W. Z. Leow, M. H. Mat, and M. S. A. Rahim, "Technologies of solar tracking systems: A review," in *IOP Conference Series: Materials Science and Engineering*, vol. 884, 2020, p. 012121.
[29] C. Alexandru, "Optimal design of the dual-axis tracking system used for a PV string platform," *Journal of Renewable and Sustainable Energy*, vol. 11, p. 063702, 2019.
[30] R. Xu, X. Ji, C. Liu, J. Hou, Z. Cao, and H. Qian, "Design and control of a wave-driven solar tracker," *IEEE Transactions on Automation Science and Engineering*, vol. 19, pp. 1434–1443, Oct. 2022.
[31] G. Mehdi, N. Ali, S. Hussain, A. A. Zaidi, A. H. Shah, and M. M. Azeem, "Design and fabrication of automatic single axis solar tracker for solar panel," *2019 International Conference on Computing, Mathematics and Engineering Technologies – iCoMET 2019*, 2019, p. 4.
[32] R. Xu, H. Liu, C. Liu, Z. Sun, T. L. Lam, and H. Qian, "A novel solar tracker driven by waves: From idea to implementation," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, Paris, France, 2020, pp. 3804–3810.
[33] G. Frydrychowicz-Jastrzębska and A. Bugała, "Solar tracking system with new hybrid control in energy production optimization from photovoltaic conversion for Polish climatic conditions," *Energies*, vol. 14, no. 10, p. 2938, 2021.
[34] A. Z. Hafez, A. M. Yousef, and N. M. Harag, "Solar tracking systems: Technologies and trackers drive types – A review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 29–42, 2018.
[35] A. Chan and C. S.-H. Roong, "Laboratory-scale single-axis solar tracking system: Design and implementation," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 7, pp. 403–410, 2016.
[36] N. Mohammad and T. Karim, "Design and implementation of hybrid automatic solar-tracking system," *ASME Journal of Solar Energy Engineering*, 2013.
[37] K. Rajan, "Solar tracking system – A review," *International Journal of Sustainable Engineering*, 2016.
[38] A. Chan and C. S.-H. Roong, "Design and implementation of a laboratory-scale single-axis solar tracking system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 7, pp. 254-264, 2016.
[39] A. Mensah, S. Wang, Qian, and U. Benjamin, "Optimization of the cost of power generation of an evolving load profile in a solar photovoltaic-integrated power system," *Energy Exploration & Exploitation*, pp. 145–167, 2019.
[40] J. Kim and Y. Kim, "Development of a novel spherical light-based positioning sensor for solar tracking," *Sensors*, vol. 19, pp. 1–12, 2019.
[41] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, pp. 439–449, Jun. 2007.
[42] A. Musa, E. Alozie, S. A. Suleiman, J. A. Ojo, and A. L. Imoize, "Chapter 14: A review of sensor-based solar trackers," Springer Science and Business Media LLC, 2023.
[43] E. Larico and A. Gutierrez, "Solar tracking system with photovoltaic cells: Experimental analysis at high altitudes," *International Journal of Renewable Energy Development*, vol. 3, p. 11, 2022.
[44] A. P. Aigboviosa, A. Anthony, A. Claudius, S. Uzairue, S. Timilehin, and V. Imafidon, "Arduino-based solar tracking system for energy improvement of PV solar panel," *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Oct. 2018.
[45] T. K. Lee, K. W. Lim, and R. Y. Zhong, "Optimal design of solar tracking systems for maximum energy conversion efficiency," *Renewable Energy*, vol. 45, pp. 25-32, 2012.
[46] H. A. Kazem, M. Chaichan, A. Al-Waeli, and M. Chaichan, "Recent advancements in solar photovoltaic tracking systems: An in-depth review of technologies, performance metrics, and future trends," *Solar Energy*, vol. 282, article 112946, 2024.
[47] I. A. Ayoade, O. A. Adeyemi, O. A. Adeaga, R. O. Rufai, and S. B. Olalere, "Development of smart (light dependent resistor, LDR) automatic solar tracker," *2022 5th Information Technology for Education and Development (ITED)*, 2022.
[48] S. Babars, S. Abdraboo, M. E. M. Essa & S. Y. El-Mashaad, "Modelling and Control of an Experimental Fuzzy Logic Controlled Dual Axis Solar Tracking System based on Field Programmable Gate Array," *International Research Journal of Engineering and Technology*, 11(2), 139-147, 2024.
[49] C. Morón, D. Ferrández, P. Saiz, G. Vega, and J. P. Díaz, "New prototype of photovoltaic solar tracker based on Arduino," *Energies*, vol. 10, p. 9, 2017.
[50] E. Larico, "Intelligent dual-axis solar tracking system in the Peruvian highlands: Implementation and performance," in *2021 IEEE Engineering International Research Conference (EIRCON)*, 2021.

[51] H. Fathabadi, "Comparative study between two novel sensorless and sensor-based dual-axis solar trackers," *Solar Energy*, vol. 135, pp. 1–7, 2016.

[52] M. J. Fadhil, R. A. Fayadh, and M. K. Wali, "Design and implementation of smart electronic solar tracker based on Arduino," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 5, p. 17, 2019.

[53] H. Mosa, A. J. Ali, and A. A. Saleh, "Performance improvement of the single axis solar tracker," *AIP Conference Proceedings*, vol. 3232, p. 050022, 2024.

[54] A. G. U. Rajendra, P. N. Kumar, and K. H. Kumawat, "A review on solar tracking systems: Technologies and challenges," *International Journal of Energy and Environmental Engineering*, vol. 8, no. 1, pp. 45-55, 2017.

[55] S. Li, L. D. Xu, and S. Zhao, "The Internet of Things: A survey," *Information Systems Frontiers*, vol. 17, pp. 243–259, Apr. 2015.

[56] M. R. Palattella, M. Dohler, and A. Grieco, "Internet of Things in the 5G era: Enablers, architecture, and business models," *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 510–527, Mar. 2016.

[57] S. Babars, S. Y. El-Mashaad, S. Abdraboo, and M. Essa, "Design of model predictive control and IoT for experimental dual axis solar tracker system based on FPGA," *International Journal of Applied Energy Systems*, vol. 6, no. 2, pp. 53–64, 2024.

[58] F. A. N. F. B. H. Dipal Halder, "A low-power IoT-enabled smart monitoring system for efficient product delivery," *2021 IEEE International Midwest Symposium on Circuits and Systems (MWSCAS)*, 2021.

[59] S. A. H. Al-Mohammad, A. S. Al-Shaer, and J. M. Al-Shuhail, "Advances in solar tracking systems: A comprehensive review of technologies, control strategies, and performance evaluation," *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 342-358, 2018.

[60] K. Jothikrishna, S. M. Rithika, S. V. Swetha, and K. Kavitha, "Solar power remote monitoring and controlling using IoT," *2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, vol. 1, 2023, p. 6.

[61] U. Khaira, Y. Riduas Hais, M. Wahyudi, and H. Pathoni, "Integration of multi-sensor system for IoT-based smart home application," *AIP Conference Proceedings*, vol. 2609, no. 1, 2023, p. 6.

[62] M. Beshley, O. Hordiichuk-Bublivska, H. Beshley, and I. Ivanochko, "Data optimization for industrial IoT-based recommendation systems," *Electronization of Businesses - Systems Engineering and Analytics*, vol. 12, p. 17, 2022.

[63] C. K. Metallidou, K. E. Psannis, and E. A. Egyptiadou, "Energy efficiency in smart buildings: IoT approaches," *IEEE Access*, vol. 8, pp. 63679–63699, 2020

[64] S. K. Vishwakarma, P. Upadhyaya, B. Kumari, and A. K. Mishra, "Smart energy efficient home automation system using IoT," *IEEE*, vol. 1, p. 4, 2019.

[65] A. Khanna, R. Sharma, A. Dhingra, and N. Dhaliwal, "Preventive breakdown and fault detection of machine using industrial IoT in maintenance and automation," *Materials Today: Proceedings*, 2023.

[66] H. A. Raja, K. Kudelina, B. Asad, and T. Vaimann, "Perspective Chapter: Fault Detection and Predictive Maintenance of Electrical Machines," *Technology and Applications*, IntechOpen, Spain, 2020.