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A Comprehensive Review of Solar Tracking Technologies: A Survey with Future Directions

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Abstract

Solar tracking systems offer significant benefits in solar energy applications, including increased power and efficiency compared to fixed systems. They are classified according to their components and drivers, into include active, passive, semi-passive, manual, and chronological system. Active trackers are the most efficient among other categories, as they contribute to boosting harnessed solar energy by 28.8-43.6 %, depending on the season. Single-axis tracking improves efficiency by 13% while, passive trackers can improve efficiency by 25%. Manual trackers improve efficiency by 15%, and chronological tracking systems provide the same efficiency as active trackers under similar climatic conditions. This paper presents a literature survey on solar tracking systems. It summarizes multiple comprehensive reviews that studied different literature on solar tracking technologies aiming to provide guide to researchers and practitioners relate their work to existing research. The review concludes with a summary of future recommendations and insights on designing and building effective and reliable solar tracking system.

Keywords: Solar tracking system; Time-based tracker; Semi-passive tracker; Passive tracker; Manual tracker; Future directions.

1. Introduction

Solar energy has gained popularity as a clean and sustainable alternative to fossil fuels due to rising energy demands, greenhouse gas emissions, and environmental pollution since the 1960s [1]. It is widely distributed and used in numerous applications [3].

The amount of solar radiation incident on earth’s surface is variable and depends on several geographical and meteorological conditions. Therefore, before installing a PV system, it is essential to assess the solar potential of the location in order to optimize the technical and economic performance of the system [10]. Due to limited on-site data availability, mathematical models and algorithms are being developed to estimate solar power efficiency. However, predictions are prone to inaccuracies due to geographical factors [11].

Solar tracking systems are crucial in various solar energy applications because they offer advantages over fixed systems in terms of power and efficiency enhancement as well as the economics of the system [9]. Tracking systems enable optimal collection of solar radiation by solar collectors and panels [31].

Solar trackers use motors and sensors to track sunlight daily and seasonally by rotating mount-holding panels to determine the optimal orientation of the panels under varying solar radiation conditions. Sensors determine sun location based on shadow and light. Collected data are sent to a microprocessor to determine the optimal tilt and azimuth angles [18,33].

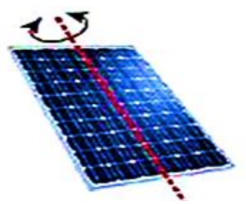
There are two principal types of solar tracking systems: single-axis and dual-axis [5]. Both types require a certain level of flexibility in movement [5,7].

The remaining part of this manuscript is structured as follows, section 2 discusses the different types of solar tracking systems as well as their main components. Section 3 presents the operation principle and mechanisms of solar trackers. Recommendations for future research and conclusions of the review are listed in section 4 and 5, respectively.

2. Types and components of Solar Tracking Systems

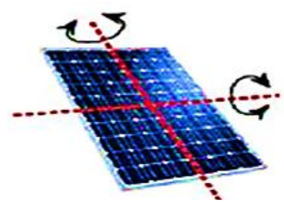
Based on their tracking technologies, the solar tracker systems are divided into five categories: active tracking [17,23,36], passive tracking [12,45,50], semi-active tracking [34,46], manual tracker [13,22,56], and time-based monitoring system [37,41,57].

Recent investigations have categorized solar tracking systems into numerous subtypes, primarily falling under the five main classifications: single-axis tracking (north-south orientation) and dual-axis tracking [4,9,21], azimuth tracking [8,44], polar tracking [12,38], dual-axis tracking [22,26,27].

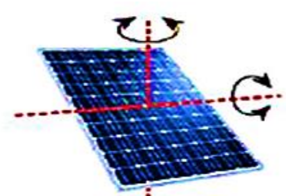


A – Horizontal 1- axis tracker

B- Vertical 1- axis tracker



C- Tip - tilt 2- axis tracker



D- Azimuth 2- axis tracker

Figure 1: Solar Tracker Types [26].

Two of the most prevalent kinds of tilt and azimuth-tilt tracking have unique characteristics. Fig. 1 shows the solar tracker systems' types of one-axis and two-axis trackers [27]. Dual-axis tracking systems outperform single-axis systems by continuously optimizing solar panel orientation to account for both diurnal and seasonal solar zenith angle variations [10]. On the other hand, dual-axis tracking is more complex, expensive, and requires more additional components and machines. Compared to a single tracking system, this benefit increases the efficiency of dual tracking and its solar power gain [39].

2.1 Dual-axis tracking system

Dual-axis trackers continuously face the sun since they move in two different directions. The tilt and azimuth angles are two types of dual monitors. Tracking the sun in vertical and horizontal directions allows these devices to maximize energy output [22]. This kind of solar system produces and provides dependable electricity to any location worldwide. Dual-axis monitoring is used in concentrated solar energy methods, such as dish systems and PV solar structures [27].

Active tracking systems with two-axis tracking often employ a microcontroller, two motors, and four distributed light-dependent resistors (LDRs) on the solar panel. When the control system receives a signal from the four LDRs positioned at different angles around the system, each motor spins the system in single axis [40].

A new sensorless dual-axis solar tracker with great precision was introduced and managed by the photovoltaic systems' maximum power point tracking unit. This tracker was proposed by Fathabadi [26], to execute solar tracking operations focused on the vertical and horizontal axes of the solar cell panel.

Single-axis tracking systems, classified as horizontal or vertical, optimize solar panel orientation by tracking the sun's daily azimuthal motion [18]. Dual-axis tracking systems, including azimuth-altitude and tip-tilt configurations, optimize solar panel orientation by tracking the sun's diurnal azimuthal and seasonal zenith angle variations [25]. The primary benefit of using the proposed solar tracking system is to increase in energy efficiency by 28.8-43.6%, depending on the season.

An algorithmic model was proposed in [42] to forecast the thermal efficiency, usable power gain, and absorbed energy of a solar collector in Brazil.

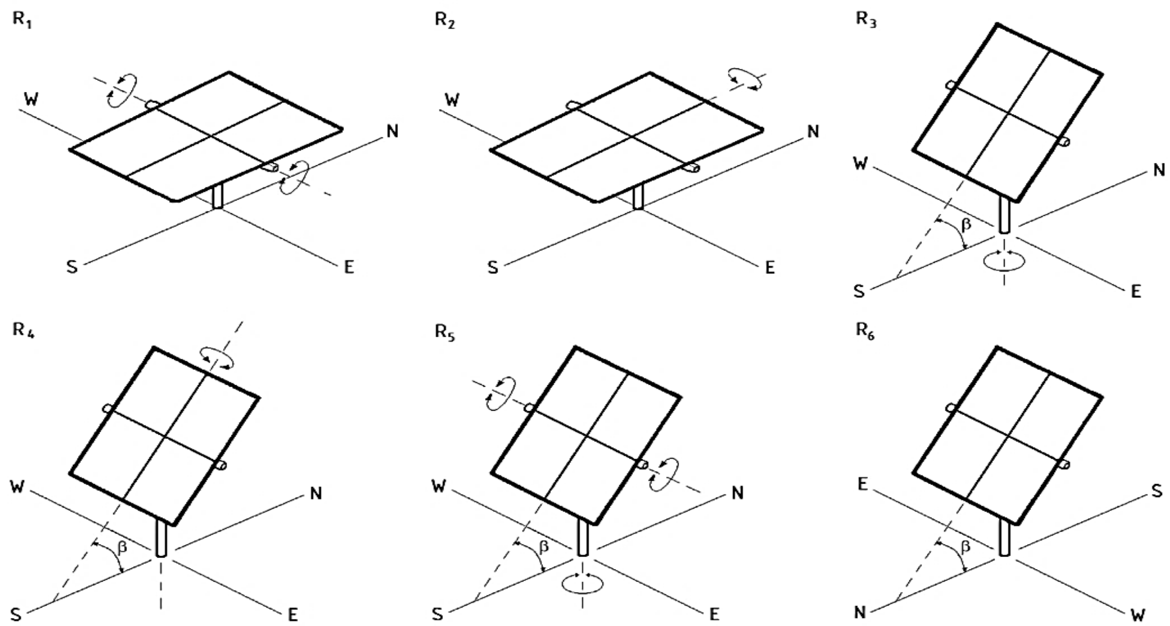


Figure 2: Solar Tracking Types [25].

Figure 2 demonstrates six tracking strategies that are assessed using computational modeling to forecast the thermal efficiency, useable energy gains, and absorbed energy of a solar panel collector in Brazil. A graphic illustrates the tracking configurations in comparison to stationary solar panel collectors. The following are the six tracking methods that are employed in the evaluation:

A plane rotated about a horizontal east-west axis in (R1), a horizontal north-south axis in (R2), and a fixed-slope plane rotated about a vertical axis in (R3). All of these rotations were made with continuous adjustments to minimize the angle of incidence. When both the surface azimuth and sun azimuth angles are equal in this situation, the angle of incidence is reduced. The local latitude's absolute value served as the tilt angle's definition.

To reduce the angle of incidence, (R4) a plane revolved around a north-south axis that was parallel to the Earth's axis and was continuously adjusted; (R5) a plane tracked continuously around two axes; (R6) A slope facing that is fixed facing north, with a tilt angle of 20°[25].

Chen and his colleagues proposed a mathematical model for a solar power system that uses a curved mirror to focus sunlight onto a receiver. This system can move in two directions, always pointing at the sun and using heat to generate electricity. The model considers factors like wind and uncertainties in the system's components. The tracking system's central component aligns the condenser's axis with the sun's rays. Based on the sun's location data, the biaxial mixed mode determines the deflection angle. The condenser is driven by a servo motor to track, and sensors adjust the position deviation. The mixed mode decreases the tracking cumulative error. At the same time, minimizing the impact of the weather is possible. Figure 3 shows an example of this kind of system [29].

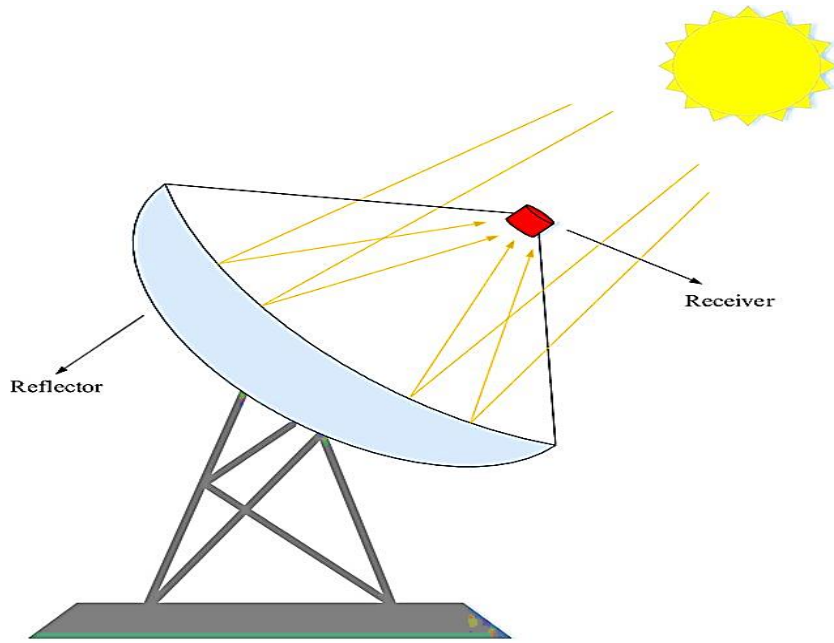


Figure 3: Dual Axis Tracking for Solar Dish [29].

Many academics attempted to design inventive and economical methods for dual-axis tracking systems to optimize solar energy absorption, therefore augmenting the total gain and electrical output. However, the primary obstacle facing researchers studying this kind of tracking is the system's higher expense and complexity than single-axis tracking. Rather than employing LDRs, some focus on constructing precise controllers (maximum power point tracking) to simplify double-axis monitoring [26]. When comparing the average power output of dual-axis and fixed-mount solar panels, it's evident that dual-axis systems produce significantly higher energy yields. Dual-axis solar trackers have 49% higher power efficiency than fixed mounts [54].

2.2 Single-axis tracking system

A single pivot point is used in a single-axis solar tracker system to revolve to track the solar beam from one side to another. The horizontal, vertical, and diagonal single-axis tracking systems are the three primary types of this system. The face of the system panel or module is positioned parallel to the axis of rotation in a horizontal single-axis tracking system, where the axis of rotation is horizontal concerning the ground. This type of system is typically employed in tropical locations [21]. Vertical single-axis tracking systems employ a rotational axis oriented orthogonally to the ground plane.

A primary limitation of single-axis tracking systems is their inability to account for the sun's annual movement, restricting their tracking to daily east-west motion. Furthermore, their single-axis design can significantly reduce their effectiveness on cloudy days [44].

Using a PLC and hydraulic drive, an autonomous sun-tracking system was created for a parabolic trough solar concentrator. The tracking error is about 0.6° [4].

A method is provided for estimating the optical losses caused by a single-axis solar tracker's placement angle inaccuracy using a small parabolic trough collector [6].

Throughout summer, winter, autumn, and spring, the assessment was made for the efficiency of a tilted-wick solar still with a flat vertical plate reflector that tracks azimuth in a single step at a latitude of 30° [20]. Compared to stationary solar still, the solar still developed by Abdallah and Badran [21] with a sun tracking system achieved a 22% increase in production and a 2% improvement in total efficiency. This study employed the surface azimuth angle (αw) for single-axis tracking, as depicted in Fig.4. The perpendicular sun tracker actuator turns the joint vertically to control α_w during four daily intervals.

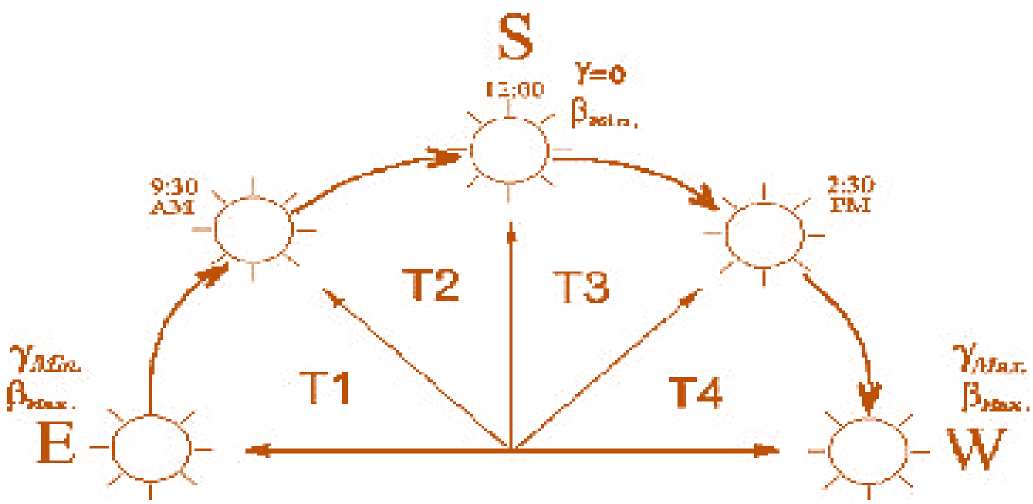


Figure 4: Four Intervals During the Day [21].

Comparative analyses between single-axis tracking and fixed-axis systems have underscored the enhanced energy yield and system performance benefits associated with solar tracking technologies [18,21,24].

They also used mathematical methods to evaluate how well the system focused light by changing its position or comparing different types of solar trackers [51].

Energy yield assessments for single-axis and fixed-mount systems, conducted on a daily basis, indicate a 13% increase in energy production for single-axis tracking configurations [53].

3. Solar Tracker Mechanisms

Solar trackers can be classified into five categories based on how they move: active, passive, semi-active, manual, and time-based [43]. There are five basic types of tracker drives, each with unique advantages, limitations, features, components, and principles of operation. Scholars prefer active solar tracker drive systems above the other four varieties.

3.1 Active tracker

An active solar tracking system uses sensors to estimate the sun's position in the sky throughout the day. Sensors activate the motor or actuator to direct the driving system towards the sun throughout the day [17]. Suppose the sun's beams are not orthogonal to the solar tracking system. In that case, it can cause a variation in the level of light on one sensor compared to another, requiring the tracking system to be perpendicular to the sunlight beams [36].

Active tracking systems use several kinds of control, including microprocessor-based, electrical sensor-based, date and time methods, and extra photovoltaic cells [36]. The system computes the differential signal between two input variables and provides this signal as input to the actuator [47].

3.1.1 Microprocessor and Electrical Sensor

Active tracker systems rely on feedback circuits and concepts, mainly microprocessors and electrical sensors. Sensor inputs are used to detect and convey pertinent parameters to the controller. The controller analyzes the parameters and determines the output. High-precision solar tracking systems rely heavily on solar power arrays. Solar tracking systems are commonly employed in large-scale PV systems for many applications [48].

An autonomous single-axis, three-positioned solar tracker system was created, as shown in Fig. 5 (b). The device detects sunlight intensity by Light Dependent Resistor (LDR) sensors, as shown in Fig. 5 (a). The system was set to be simple, cost-effective, and tested accordingly [28].

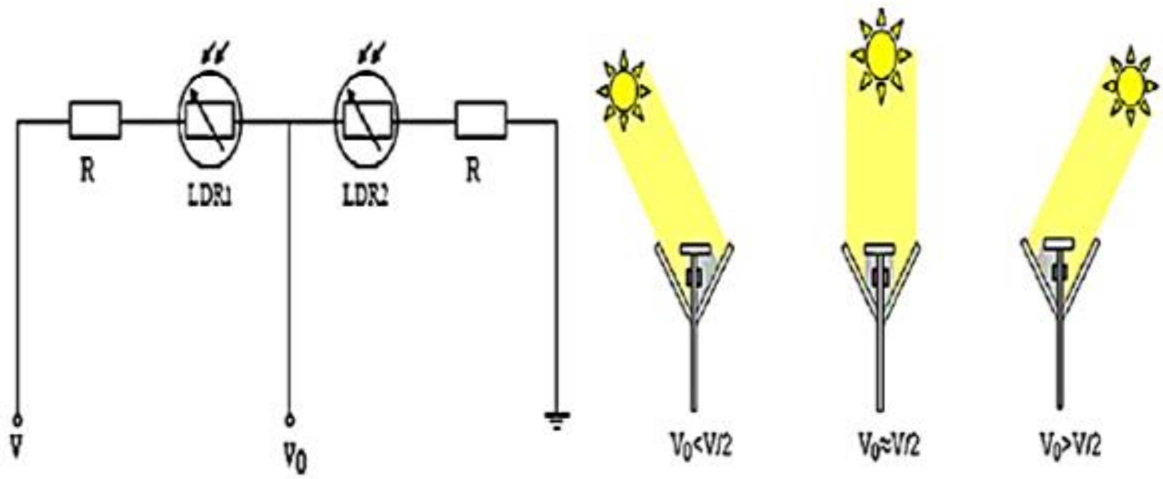


Figure 5 (a): LDR Sun Detector (b) Sun Position During the Day [28].

A two-axis solar tracker was designed and constructed using the ATMEGA-8 L microprocessor. Fig. (6) illustrates a diagram of an intelligent two-axis tracker with four LDR sensors [30].

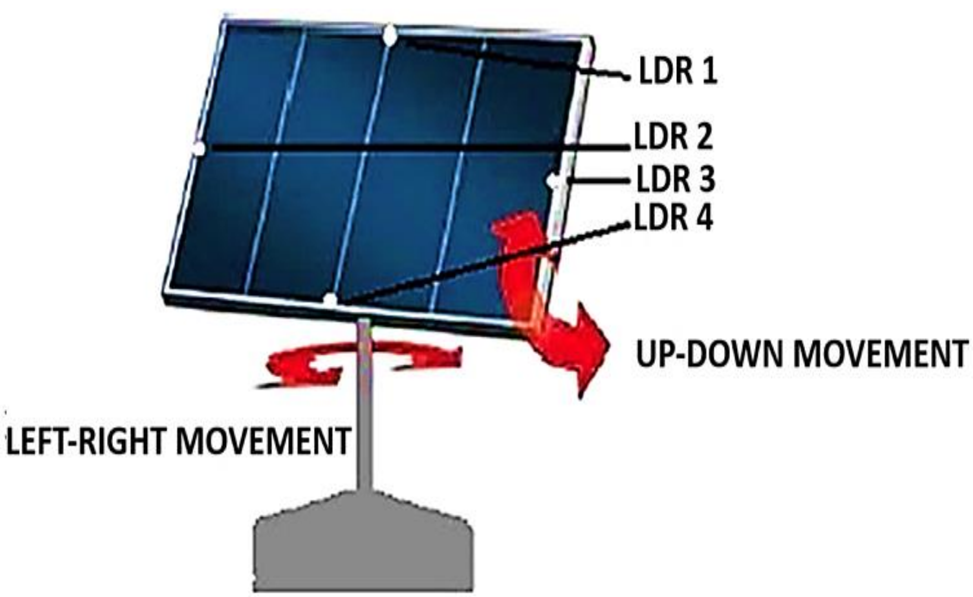


Figure 6 Dual-axis tracking system using four LDRs [30].

Ghosh and Haldar [35] created a solar tracking system with an AT89 family microprocessor and LDR sensors to manage the direction of a solar PV panel. An integrated two-axis solar tracker system was designed and tested, and its efficiency was compared to static and continuous two-axis systems [36]. Meanwhile, a fuzzy-logic controller for a solar tracker system was developed and executed on an

ATMEGA 8353 microcontroller, resulting in a 47% increase in power gain over fixed panels [14]. Bentaher and his team created a simple solar tracker using light-sensitive sensors. They measured the tracker's accuracy by calculating the angle between the sensors. They found the best angle for the sensors through computer simulations and experiments [32].

3.1.2 Supplementary dual-sided solar-based tracker

This type of solar tracker uses active technology, requiring external power to move. It has two solar panels facing opposite directions and a motor that rotates them, as shown in Fig. 7. The panels are attached to a rotating axis, and a DC motor actuator controls the motor. Karimov and his colleagues showed a solar tracker with four panels attached to a rotating motor. They manually adjusted the angle of the second axis to find the best position [52].

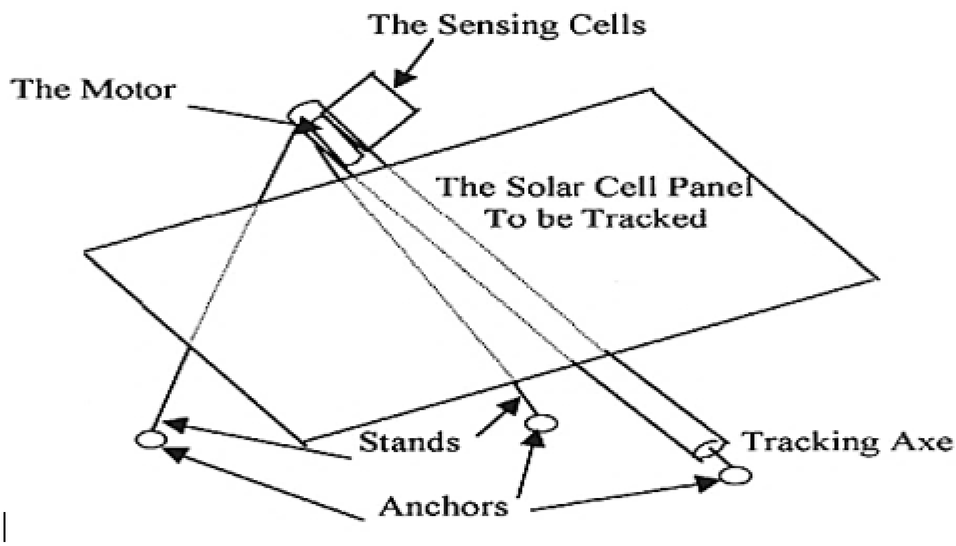


Figure 7: Solar Cell-Based Sensor [52].

3.2 Passive tracker

Passive solar tracking devices rely on thermal expansion or pressure imbalance between two sites at either end of the tracker. These materials are often liquids or gases. The fluid is inserted into two opposed reservoirs with a unique design to evaporate and change its characteristics based on the sun's course. The link between the two tanks sends the condensate fluid from the most significant incidence reservoir to the smaller one [45].

Zomewords, an American company founded in the 1960s, was a pioneer in passive solar tracking systems. In 1994, Poulek introduced a passive tracker system that employed shape memory alloy (SMA) actuators [49]. SMAs, which undergo shape changes based on temperature fluctuations, exhibit a 2% higher efficiency compared to traditional bimetallic actuators [50].

A passive tracker for photovoltaic modules was demonstrated, which uses gravity and heat generated by the sun to transfer liquid from one side to the other to trace the sun's path from east to west. A tracker does not require motors, gears, or control circuits [9].

Farooqui proposed a one-dimensional tracking technique, as shown in Fig. 8, for box-type solar cookers that eliminate manual tracking requirements [15]. The new approach relies on gravitational potential energy stored in the spring to provide tracking power, eliminating the requirement for external control.

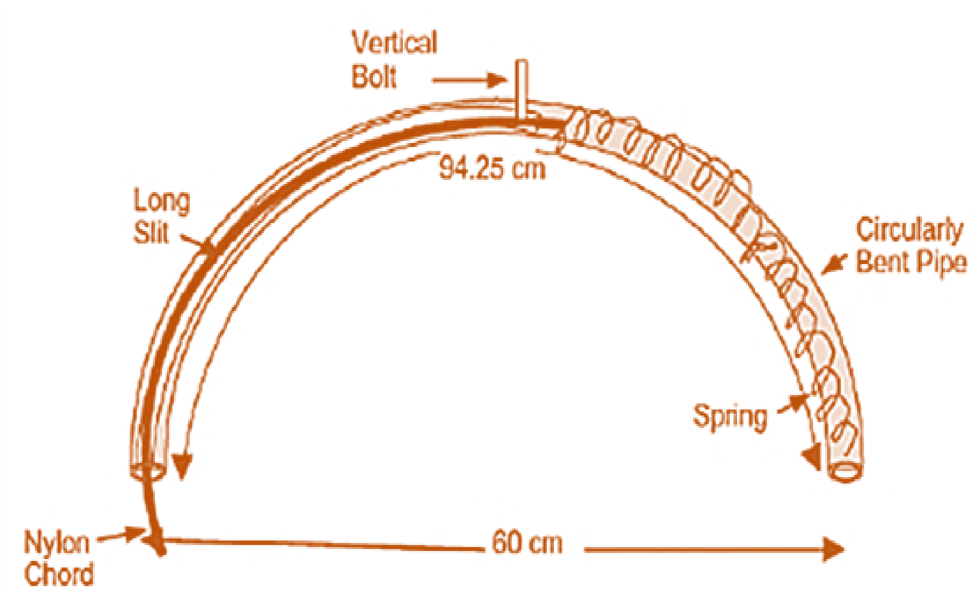


Figure 8: Spring Along Steel Pipe [15].

In conclusion, a one-dimensional tracking tracker device utilizes changing fluid characteristics to monitor the sun and has been examined in the literature. New meduim, such as moving liquids, are quickly impacted.

The proposed system also achieved 24.86% greater energy collection efficiency than the fixed system [55].

3.3 Semi-active tracker

A semi-active solar tracker uses a unique lens to focus sunlight on a small area. This system requires less energy to move than a fully active system. It has a group of tiny solar cells, a receiver, and a Fresnel lens [34].

León et al. [46] employs a semi-active solar tracking concentrator, depicted in Fig. 9, a micro-heliostat array and a Fresnel lens to achieve solar concentration with reduced mechanical complexity. The micro-heliostat grid, which tracks the solar azimuth and zenith angles, directs concentrated solar radiation onto the Fresnel lens. Keeping the lens horizontally reduces wind stresses throughout the system. As a result, the receiver can be fixed on the lens focus to minimizes the power required for system motion [46].

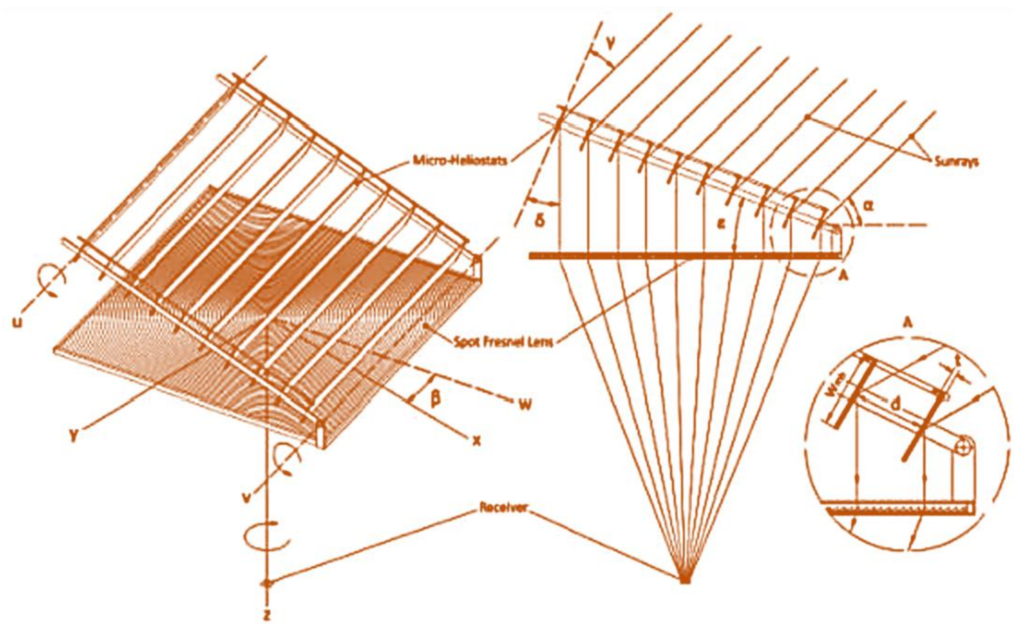


Figure 9: Semi-Passive Tracker [46].

Semi-passive tracker systems are distinct types that have received little attention in the literature compared to active and passive trackers due to their constricted applications [46]. This sort of tracker aims to save mechanical energy compared to regular trackers. Researchers are exploring systems that use tiny mirrors or lenses to reflect sunlight onto a Fresnel lens, thereby reducing the need for mechanical movement [34].

4.3 Manual tracker

A manual solar tracker system uses a hand-driven actuator to adjust the tilt angle according to the season, making constructing and maintaining the system easier. By incorporating a manual tilt angle axis, dual-axis tracking systems can reduce costs compared to previous models that required two motors for both axes of movement. Mwithiga and Kigo [22] created a solar drying device with limited sun tracking and a 15° incremental to dry seeds of coffee in two days instead of a week. The tracking system's performance is tested horizontally once, three, five, or nine times daily. In Fig. 10, a solar dryer with a flat plate absorption and a box with no top measuring 8 m^2 base and 0.3 m high can track the sun in a west-to-east direction. The selector disc on the stand allows for easy adjustment of the orthogonal angle with the horizontal axis by at least 15°.

Gönül suggested a manual solar panel tracking system with a 1MW PV power system in Turkey manually adjusted seasonally, semi-seasonally, and annually. Manual tilt adjustment has a significant net present value (NPV) increase in Turkey, ranging from 12.4% to 14.9% above fixed tilt [56].

Figure 10: Solar Dryer [22].

Manual tracker systems are not as standard in literature as semi-passive ones. The system relies on human adjustments to reduce complexity, facilitate maintenance, and lower component costs. Few studies have focused on this type of research, limiting it to specific applications like solar dryers (similar to solar cookers) [22] and floating photovoltaic systems (PV) [13].

3.5 Time-based tracker

A time-based solar tracking system moves the panel or module at a constant speed and angular displacement daily or monthly. The motor rotates at a low rate of approximately 15° for one hour.

This tracking system is an open-loop control tracking device that follows a chronological motion model. This system is more power efficient due to its low tracking error, resulting in negligible energy losses during calibration [41].

Sidek et al. [37] developed dual-axis sun tracking with a micro-controller-based control system and a method that utilizes global positioning systems and mathematical models linked to astronomy. Additionally, the system employs a PID controller. Fig. 11 depicts the bidirectional solar tracking structure.

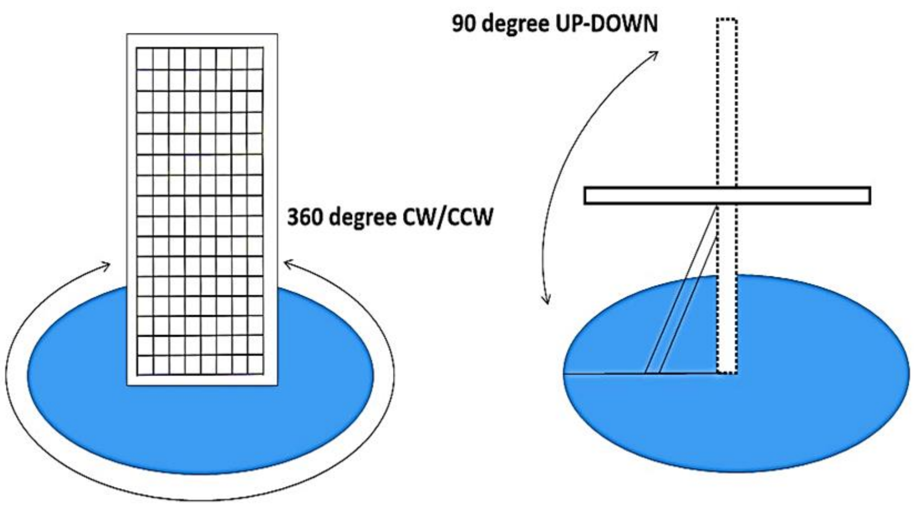


Figure 11: Time-Based Tracker [19].

Al-Qrimli and Kashan [57] used a mathematical model to improve the efficiency of the solar panel in Iraq, using the solar sun equations and Matlab/Simulink model to find the optimum tilt and azimuth angles as shown in Fig. 12. These angles can be computed as follows [57]:

$$\alpha = sin^{-1}(sin\,\delta\,sin\,\emptyset + cos\,\delta\,cos\,\omega\,cos\,\emptyset) \qquad (1)$$

where α, ϕ, and δ are the tilt, latitude, and altitude angles, respectively. δ may be expressed as follows:

$$\delta = 23.45\sin\left[\frac{360(n+284)}{365}\right] \qquad (2)$$

Where n represents the day count, e.g., the 1st of January n = 1 and the 15th of September n = 31+29+31+30+31+30+31+31+15 = 259.

Moreover, ω is the hour angle and is found by:

$$\omega = 15(t_s - 12) \tag{3}$$

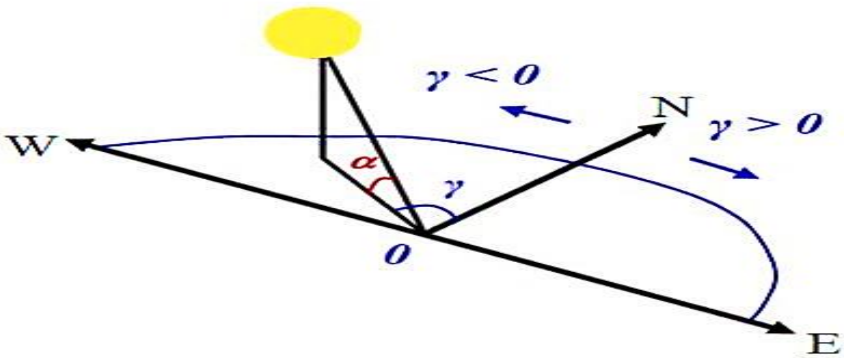


Figure 12: Solar Angles [57].

Where t_s is the solar time, in addition, the azimuth angle (γ) is calculated as follows:

$$\gamma' = \sin^{-1}\left(\frac{-\cos\delta \times \sin\omega}{\cos\alpha}\right) \tag{4}$$

Applying these equations to the Karbala\ Iraq location during the year to find the best azimuth and tilt angle to set the solar tracking system on it in case of an axis solar tracking system and taking the average of these angles during the season to get the optimum angle for the fixed panel or manual tracking system. The results are shown in Table 1. which demonstrates the azimuth and tilt angle in twelve months during the year. For the two-axis tracking system, the controller drives the solar panel by dual-axis according to the solar angle results using a simple timer with a linear actuator. For a single-axis tracking system, the controller will drive the solar panel either to the optimum tilt angle with a fixed azimuth angle or to the optimum azimuth angle with a manually set tilt angle. The fixed angle in either way selected as an average angle during the month, while the other angle will reference the controller that will drive the solar panel. In the case of a fixed-mounted panel system, the solar angle will be chosen by taking the noon angle for a specific month, which will be adjusted during the year.

Table 1:Annual solar angles for solar tracking system.

System/ month	Two-axis tracking system		Single-axis tracking system		Fixed-mounted solar system	
	Tilt angle	Azimuth angle	Tilt angle	Azimuth angle	Tilt angle	Azimuth angle
Jan.	36° peak	100°-250°	36°	150°	36° **fixed**	180° **fixed**
Feb.	43° peak	100°-256°	43°	156°	43° **fixed**	180° **fixed**
Mar.	55° peak	92°-266°	55°	174°	55° **fixed**	180° **fixed**
Apr.	66° peak	82°-275°	66°	193°	66° **fixed**	180° **fixed**
May	76° peak	75°-285°	76°	210°	76° **fixed**	180° **fixed**
Jun.	81° peak	74°-290°	81°	216°	81° **fixed**	180° **fixed**
Jul.	79° peak	72°-287°	79°	215°	79° **fixed**	180° **fixed**
Aug.	71° peak	79°-280°	71°	201°	71° **fixed**	180° **fixed**
Sept.	60° peak	88°-270°	60°	182°	60° **fixed**	180° **fixed**
Oct.	48° peak	98°-260°	48°	162°	48° **fixed**	180° **fixed**
Nov.	38° peak	100°-250°	38°	150°	38° **fixed**	180° **fixed**
Dec.	34° peak	110°-248°	34°	138°	34° **fixed**	180° **fixed**

Researchers commonly analyze and investigate the chronological solar tracking system, as discussed in the literature survey in [2]. The solar tracking system uses chronological data, as shown in Fig. 11, to accurately determine the sun's position. Some experts argue against using this tracker system for single-axis solar tracking [19]. Meanwhile, other studies discuss its efficiency with dual-axis monitoring. It is important to note that most studies on these tracking drivers have focused on photovoltaic applications [37].

4. Recommendations for future research directions

4.1 The structure of the solar tracking system

An essential parameter of the solar tracker is the design of the structure of the tracker itself. It is necessary to explore the structure's design, which means how the solar panel will be installed, the location of the actuator concerning the panel, and the rotation of the solar panel, whether it is linear or circular. All these parameters will be set according to the panel and its installation ground.

4.2 The actuator of the solar tracking system

One of the critical elements of the solar tracking system is the actuator that drives the panel. For future surveys, one must focus on the actuation system, whether it is electrical or pneumatic, its parameters, drivers, power dissipation, and cost on the market. It is beneficial to explore the feasibility study for the actuation system for dual or single-axis tracking systems by studying how much system efficiency will increase compared with how much power the actuator needs for a specific tracking system.

4.3 Control system of the solar tracker

Several efficient control systems will process the input signals from the sensors to actuate the solar panel to the optimum location. It is essential to focus on the studies that investigate the control system used in the solar tracking systems, whether it is a simple closed loop system with a simple sensor or an advanced system that uses artificial intelligence techniques such as fuzzy logic control or adaptive neuro-fuzzy inference system controller, or just an open loop system with a lookup table for solar angle and a timer that drives the actuator to achieve the optimal solar angles. It is also significant to discuss the effect of control systems on the efficiency of the tracking process taking into consideration weather parameters like temperature and cloudiness.

5. Conclusion

In recent years, there has been an increased interest in solar tracking systems. Components and drivers classify solar tracking systems into active, passive, semi-passive, manual, and chronological trackers. Active trackers are the most efficient, increasing solar energy by 28.8–43.6%, depending on the season. Single-axis tracking increases efficiency by 13%, passive trackers by 25%, semi-passive trackers use thermal energy harvesting, manual trackers improve efficiency by 15%, and chronological tracking systems provide the same efficiency if the location has similar climatic conditions. This study offered several recommendations and future directions to improve the performance of solar tracking systems. These include using time-based tracker; semi-passive tracker; passive tracker; and manual tracker. Furthermore, this study highlights the need to investigate different strategies for solving the prediction problem. The future work based of this review is to apply and implement some of the artificial intelligence methodologies in solar tracking systems.

References:

[1] Zhao D, Xu E, Wang Z, Yu Q, Xu L, Zhu L. Influences of installation and tracking errors on the optical performance of a solar parabolic trough collector. Renew Energy 2016;94:197–212. http://dx.doi.org/10.1016/j.renene. 2016.03.036.

[2] Roong ASC, Chong S-H. Laboratory-scale single axis solar tracking system: Design and implementation. Int J Power Electron Drive Syst 2016;7:254–64. http://dx.doi.org/10.11591/ijpeds.v7.i1. pp254-264.

[3] Basnayake BADJCK, Jayathilaka WADM, Amarasinghe YWR, Attalage RA, Jayasekara AGBP. Smart solar tracking and on-site photovoltaic efficiency measurement system. [2016, Moratuwa]. Moratuwa Eng Res Conf (MERCon) 2016:54–9. http://dx.doi.org/10.1109/MERCon. 2016.7480115.

[4] Wang J, Zhang J, Cui Y, Bi X. Design and implementation of PLC-based automatic sun tracking system for parabolic trough solar concentrator. MATEC Web Conf 2016;77:1–4. http://dx.doi.org/10.1051/matecconf/ 20167706006.

[5] Avarand S, Pirmoradian M. Solar tracking system with momentary tracking based on operational amplifiers in order to be used in photovoltaic panels for following the sun. Bull La Société R Des Sci Liège 2016;85:269–77.

[6] Sallaberry F, Pujol-Nadal R, Larcher M, Rittmann-Frank MH. Direct tracking error characterization on a single-axis solar tracker. Energy Convers Manag 2015;105:1281–90. http://dx.doi.org/10.1016/j.enconman. 2015.08.081.

[7] Li L, Li H, Xu Q, Huang W. Performance analysis of Azimuth Tracking Fixed Mirror Solar Concentrator. Renew Energy 2015;75:722–32. http://dx.doi.org/10.1016/j.renene. 2014.10.062.

[8] Patel RR, Patil A j, Shewale AN. Intelligent sun tracking system using FLC implemented on FPGA. Int J Adv Found Res Comput 2015;2:33–41.

[9] Parmar NJ, Parmar AN, Gautam VS. Passive solar tracking system. Int J Emerg Technol Adv Eng 2015;5:138 45.

[10] Lazaroiu GC, Longo M, Roscia M, Pagano M. Comparative analysis of fixed and sun tracking low power PV systems considering energy consumption. Energy Convers Manag 2015;92:143–8. http://dx.doi.org/10.1016/j.enconman. 2014.12.046.

[11] Huang F, Li L, Huang W. Optical performance of an azimuth tracking linear Fresnel solar concentrator. Sol Energy 2014;108:1–12. http://dx.doi.org/10.1016/j.solener. 2014.06.028.

[12] Neagoe M, Visa I, Burduhos BG, Moldovan MD. Thermal load-based adaptive tracking for flat plate solar collectors. Energy Procedia 2014;48:1401–11. http://dx.doi.org/10.1016/j.egypro. 2014.02.158.

[13] Choi Y-K, Kim I-S, Hong S-T, Lee H. A study on developing azimuth angle tracking algorithm for tracking-type floating photovoltaic system. Adv Sci Technol Lett 2014;51:197–202. http://dx.doi.org/10.1007/s12541-014 0613-5.

[14] Abadi I, Soeprijanto A, Musyafa A. Design of single axis solar tracking system at photovoltaic panel using fuzzy logic controller. In: Proceedings of the 5th Brunei International Conference Eng. Technol. (BICET 2014). 2014. doi: http://dx.doi.org/10.1049/cp. 2014.1086.

[15] Farooqui SZ. A gravity-based tracking system for box-type solar cookers. Sol Energy 2013;92:62–8. http://dx.doi.org/10.1016/j.solener. 2013.02.024.

[16] Sen PK, Ashutosh K, Bhuwanesh K, Engineer Z, Hegde S, Sen PV, et al. Linear fresnel mirror solar concentrator with tracking. Procedia Eng 2013;56:613–8. http://dx.doi.org/10.1016/j.proeng. 2013.03.167.

[17] Mahendran M, Ong HL, Lee GC, Thanikaikumaran K. An experimental comparison study between single-axis tracking and fixed photovoltaic solar panel efficiency and power output: Case study in east coast Malaysia. Sustain. Dev. Conference Bangkok, Thail; 2013.

[18] Bhattacharya P, Mukhopadhyay S, Ghsoh BB, Bose PK. Optimized use of solar tracking system and wind energy. Procedia Technol 2012;4:834–9. http://dx.doi.org/10.1016/j.protcy. 2012.05.137.

[19] AG M, Abdul Rahman AM. The performance of three different solar panels for solar electricity applying solar tracking device under the Malaysian climate condition. Energy Environ Res 2012;2:235–43. http://dx.doi.org/10.5539/eer. v2n1p235.

[20] Tanaka H, Nakatake Y. One step azimuth tracking tilted-wick solar still with a vertical flat plate reflector. Desalination 2009;235:1–8. http://dx.doi.org/10.1016/j.desal. 2008.01.011.

[21] Abdallah S, Badran OO. Sun tracking system for productivity enhancement of solar still. Desalination 2008;220:669–76. http://dx.doi.org/10.1016/j.desal. 2007.02.047.

[22] Mwithiga G, Kigo SN. Performance of a solar dryer with limited sun tracking capability. J Food Eng 2006;74:247–52. http://dx.doi.org/10.1016/j.jfoodeng. 2005.03.018.

[23] Grass C, Schoelkopf W, Staudacher L, Hacker Z. Comparison of the optics of non-tracking and novel types of tracking solar thermal collectors for process heat applications up to 300 °C. Sol Energy 2004;76:207–15. http://dx.doi.org/10.1016/j.solener. 2003.07.031.

[24] Imad Abdul-Rida Hameed, Ali Abdul Razzaq Altahir, and Hayder Salim Hameed; An investigation of solar PV systems coupled with dieselerators: Opportunities and challenges. AIP Conf. Proc. 16 May 2023; 2631 (1): 040002. https://doi.org/10.1063/5.0133658.

[25] Youssef Boukdir, Hamid EL Omari, Novel high precision low-cost dual-axis sun tracker based on three light sensors, Heliyon, Volume 8, Issue 12, 2022, e12412, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2022.e12412.

[26] Fathabadi H. Novel high accurate sensorless dual-axis solar tracking system controlled by maximum power point tracking unit of photovoltaic systems. Appl Energy 2016;173:448–59. http://dx.doi.org/10.1016/j.apenergy. 2016.03.109.

[27] Khalaf, H. M., Mohammed, J. A. K., & Altahir, A. A. R. (2024). Simulation of Pneumatic Actuators under Fuzzy Logic Control for Driving Solar Tracking System. Evergreen, 11(3), 1848-1855.

[28] Parthipan J, Nagalingeswara Raju B, Senthilkumar S. Design of one axis three positions solar tracking system for paraboloidal dish solar collector. Mater Today Proc 2016;3:2493–500. http://dx.doi.org/10.1016/j.matpr. 2016.04.167.

[29] Chen C, Li P, Ping X. Robust variance control algorithm for the dish solar generation tracking system. Proc Second Int Conf Mechatron Autom Control Lect Notes Electr Eng 2015:237–45. http://dx.doi.org/10.1007/978-3-319-13707- 0_27.

[30] Das S, Chakraborty S, Sadhu PK, Sastry OS. Design and experimental execution of a microcontroller (μC)-based smart dual-axis automatic solar tracker. Energy Sci Eng 2015;3:558–64.

[31] Su Y, Kulacki FA, Davidson JH. Experimental and numerical investigations on a solar tracking concentrated photovoltaic-thermal system with a novel non-dimensional lattice Boltzmann method. Sol Energy 2014;107:145–58. http://dx.doi.org/10.1016/j.solener. 2014.05.033.

[32] Bentaher H, Kaich H, Ayadi N, Ben Hmouda M, Maalej A, Lemmer U. A simple tracking system to monitor solar PV panels. Energy Convers Manag 2014;78:872–5. http://dx.doi.org/10.1016/j.enconman. 2013.09.042.

[33] Stamatescu I, Făgărăşan I, Stamatescu G, Arghira N, Iliescu SS. Design and implementation of a solar-tracking algorithm. Procedia Eng 2014;69:500–7. http://dx.doi.org/10.1016/j.proeng. 2014.03.018.

[34] León N, Ramírez C, García H. Rotating prism array for solar tracking. Energy Procedia 2014;57:265–74. http://dx.doi.org/10.1016/j.egypro. 2014.10.031.

[35] Ghosh S, Haldar N. Solar tracking system using AT89C51 microcontroller and LDR. Int J Emerg Technol Adv Eng 2014;4:403–7.

[36] Ferdaus RA, Mohammed MA, Rahman S, Salehin S, Abdul Mannan M. Energy efficient hybrid dual axis solar tracking system. J Renew Energy 2014:1–12. http://dx.doi.org/10.1155/ 2014/629717.

[37] Sidek MHM, Hasan WZW, Kadir MZAA, Shafie S, Radzi MAM, Ahmad SA, et al. GPS based portable dual-axis solar tracking system using astronomical equation. 2014 IEEE Int Conf Power Energy 2014:245–9. http://dx.doi.org/10.1109/ PECON.2014.7062450.

[38] Batayneh W, Owais A, Nairoukh M. An intelligent fuzzy-based tracking controller for a dual-axis solar PV system. Autom Constr 2013;29:100–6. http://dx.doi.org/10.1016/j.autcon. 2012.09.006.

[39] A.Z. Hafez, A.M. Yousef, N.M. Harag, Solar tracking systems: Technologies and trackers drive types – A review, Renewable and Sustainable Energy Reviews, Volume 91, 2018, Pages 754-782, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.03.094.

[40] Panagopoulos AA, Chalkiadakis G, Jennings NR. Towards optimal solar tracking: a dynamic programming approach. Proc Twenty-Ninth AAAI Conf Artif Intell 2015:695–701.

[41] Maia CB, Ferreira AG, Hanriot SM. Evaluation of a tracking flat-plate solar collector in Brazil. Appl Therm Eng 2014;73:953–62. http://dx.doi.org/10.1016/j.applthermaleng. 2014.08.052.

[42] Li Z, Liu X, Tang R. Optical performance of vertical single-axis tracked solar panels. Renew Energy 2011;36:64–8. http://dx.doi.org/10.1016/j.renene.2010.05.020.

[43] Ma Y, Li G, Tang R. Optical performance of vertical axis three azimuth angles tracked solar panels. Appl Energy 2011;88:1784–91. http://dx.doi.org/10.1016/j.apenergy. 2010.12.018.

[44] Abd Elmaged HK. Passive Solar Tracking System. University of Khartoum; 2005.

[45] León N, García H, Ramírez C. Semi-passive solar tracking concentrator. Energy Procedia 2014;57:275–84. http://dx.doi.org/10.1016/j.egypro. 2014.10.032.

[46] Loschi, Hermes & Iano, Yuzo & León, Julio & Moretti, Angelo & Conte, Fabrizzio & Braga, Horacio. (2015). A Review on Photovoltaic Systems: Mechanisms and Methods for Irradiation Tracking and Prediction. Smart Grid and Renewable Energy. 6. 187.

[47] Luque A, Andreev V. Concentrator Photovoltaics 130. Berlin, Heidelberg: Springer Berlin Heidelberg; 2007. http://dx.doi.org/10.1007/978-3-540-68798-6.

[48] Imad Abdul-Rida Hameed, Jabbar S Hussein, and Ali Abdul Razzaq Altahir. Design a grid-connected wind turbine system to feed active and reactive power to electrical load. Int J Adv Electr Eng 2024;5(2):06-15..

[49] Rizman, Z.I., Ishak, M.T., Hashim, F.R., Yassin, I.M., Zabidi, A., Zaman, F.H., Yeap, K.H., & Kamarudin, M.N. (2018). DESIGN A SIMPLE SOLAR TRACKER FOR HYBRID POWER SUPPLY. Journal of Fundamental and Applied Sciences, 10, 333-346.

[50] Zhong H, Li G, Tang R, Dong W. Optical performance of inclined south-north axis three-positions tracked solar panels. Energy 2011;36:1171–9. http://dx.doi.org/10.1016/j.energy. 2010.11.031.

[51] Karimov K, Saqib M, Akhter P, Ahmed M, Chattha J, Yousafzai S. A simple photovoltaic tracking system. Sol Energy Mater Sol Cells 2005;87:49–59.

[52] Rengasamy, Dr. Dhanabal & Bharathi, Venuturla & Ranjitha, R. & Ponni, A. & Deepthi, S. & Mageshkannan, P.. (2013).

[53] Comparison of efficiencies of solar tracker systems with static panel single-axis tracking system and dual-axis tracking system with fixed mount. Intern. J. Eng. Technol.. 5. 1925-1933.

[54] Priyam, A. (2023). Solar Tracking Systems – a review. Journal of Mines Metals and Fuels, 1725–1736. https://doi.org/10.18311/jmmf/2023/35863

[55] Mintesinot Alemayehu, Bimrew Tamrat Admasu, Passive solar tracker using a bimetallic strip activator with an integrated night return mechanism, Heliyon, Volume 9, Issue 7, 2023, e18174, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2023.e18174

[56] Gönül, Ö., Duman, A. C., Barutçu, B., & Güler, Ö. (2022). Techno-economic analysis of PV systems with manually adjustable tilt mechanisms. *Engineering Science and Technology an International Journal*, *35*, 101116. https://doi.org/10.1016/j.jestch.2022.101116

[57] Al-Qrimli, F. a. M., & Kashan, K. A. (2020). Improving photovoltaic efficiency by tilting angle Tracking System (TATS) in the south of Iraq. *2020 International Conference on Electrical,*

Communication, and Computer Engineering (ICECCE). https://doi.org/10.1109/icecce49384.2020.9179229

مراجعة شاملة لتقنيات تتبع الطاقة الشمسية :دراسة استقصائية وتوجهات مستقبلية

الخلاصة: تقدم أنظمة تتبع الطاقة الشمسية فوائد كبيرة في تطبيقات الطاقة الشمسية، بما في ذلك زيادة الطاقة والكفاءة مقارنة بالأنظمة الثابتة. تقدم الورقة الحالية دراسة استقصائية حول نظام تتبع الطاقة الشمسية. يتم تصنيفها حسب مكوناتها ومحركاتها، والتي تشمل النشطة والكامنة وشبه الكامنة واليدوية والتسلسلية. تعد المتتبعات النشطة هي الأكثر كفاءة، حيث تعزز الطاقة الشمسية بنسبة 28.8-43.6 في المائة اعتمادًا على الموسم. يحسن التتبع أحادي المحور الكفاءة بنسبة 13٪، والمتتبعات الكامنة بنسبة 25٪، وتستخدم المتتبعات شبه الكامنة في حصاد الطاقة الحرارية، وتحسن المتتبعات اليدوية الكفاءة بنسبة 15٪، وتوفر أنظمة التتبع التسلسلية نفس كفاءة المتتبعات النشطة في ظروف مناخية مماثلة. تلخص هذه الدراسة مراجعات شاملة متعددة لدراسات ومراجعات مختلفة حول تقنيات تتبع الطاقة الشمسية. يهدف هذا العمل إلى توجيه الباحثين والممارسين في ربط عملهم بالبحوث الحالية واكتساب رؤى حول ما يمكن أن يساهم به عملهم في هذا المجال. تختتم المراجعة بملخص للتوصيات المستقبلية للتغلب على هذه التحديات وبناء نظام تتبع شمسي عملي وموثوق.

الكلمات المفتاحية:نظام تتبع ،متتبع على اساس الوقت،متتبع شبة كامن،متتبع يدوي،توجهات مستقبلية.