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INNOVATIVE APPROACHES TO DUAL AXIS SOLAR TRACKING SYSTEMS

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ABSTRACT

This review discusses the latest design approaches to dual-axis solar trackers by underlining their role in the development of solar energy efficiency and sustainability. Major areas of innovations reviewed include new design proposals, choice of materials, control systems, incorporation of Artificial Intelligence, Internet of Things (IoT), and Machine Learning (ML) in optimizing energy production. A comparison of traditional and modern dual axis tracking systems is made, focusing on how these systems are improved to increase energy yield, improve environmental adaptability, and enhance the durability of the systems. Challenges include increased complexity and cost of modern systems, while future trends will be discussed for predictive analytics, energy storage integration, and smart grid connectivity. With these developments in the background, this review assesses the prospects of dual-axis solar tracking systems as a cornerstone for sustainable energy solutions.

Keywords: renewable energy, IOT, machine learning, environmental sustainability, predictive analytics.

1.0 INTRODUCTION

Solar energy is one of those cornerstones in the transition to renewable energy sources in the world. Emerging with increasing concerns over the depletion of fossil fuels and the detrimental environmental impacts arising from traditional methods of energy generation, solar energy presents a clean, viable alternative in abundance [1]. In any given second, the Earth receives about 173,000 TW of solar energy, which is well over global energy demand. Solar PV systems, therefore, tap into this energy by converting sunlight into electricity, utilizing semiconductor materials-one of the most scalable and versatile of the renewable energy technologies. These range in use from small-scale residential installations to large utility-scale solar farms, significantly contributing to both carbon footprint reduction and energy security [2].

This also underlines the angle of incidence, one of the key factors affecting the efficiency of solar photovoltaic systems. Further, this gave rise to the development of solar tracking systems that can actively move the solar panels to absorb the most energy while following the path of the sun throughout the day. Fixed-tilt photovoltaic systems are simpler and less expensive but have inefficient energy conversion because they cannot adjust to the changing position. Compared to fixed systems, solar trackers-most especially dual-axis-make sure that the panels are kept in the best possible position in relation to the sun, hence increasing production by as much as 30-40%. This is very vital in the improvement of economic viability regarding solar energy projects and land-use efficiency in solar farms [4].

Solar trackers can be single-axis or dual-axis trackers; in any case, their role is to follow the movement of the sun in an even more specific manner. A single-axis tracker has one pivotal axis around which it rotates, placed either parallel or perpendicular to the north-south or east-west direction, in such a way that the panels move to track the apparent east-to-west motion of the sun through the sky [5]. These are relatively simple and inexpensive systems that achieve a more moderate improvement in energy capture. However, they cannot adjust to seasonal changes in the sun's altitude above the horizon [6].

By contrast, dual-axis trackers provide a more complete system whereby the solar panels vary both in azimuth-in other words, on the horizontal axis-and in elevation, otherwise known as on the vertical axis-to achieve full three-dimensional tracking of the sun's position [7]. Trackers optimize the orientation of the panels throughout the day and seasons. More complex and much more expensive than single-axis trackers, dual-axis systems best capture energy, particularly in areas of high seasonal variation in solar insolation [8]

The following review focuses on and presents the latest developments in the field of dual-axis solar tracking systems. Much development of late has been concentrated on developing high-performance and cost-effective systems with state-of-the-art technological features, since demand in solar energy applications has been relentlessly increasing. This review critically analyzes recent developments in dual-axis tracker design, control mechanism, materials, and energy efficiency to identify solutions that can overcome existing limitations. In so doing, the paper or review attempts to make a broad contribution to the trajectory of dual-axis solar tracking technology and its probable role in fostering the growth of solar energy around the world, with an emphasis on innovative approaches.

2.0 RELATED WORKS

The necessity of continuous efficiency improvement in the process of solar energy conversion, based on serious developments in the design of dual-axis solar tracking systems, stimulates an optimum solution for maximizing exposure of solar panels. The orientation is controlled along two axes: azimuth and elevation. It would follow that this is in accord with the path of the sun during the day and through the seasons. Recent design innovations have addressed enhancing precision, reducing the costs, and integrating smart technologies to alleviate the inherent challenges of dual-axis trackers.

One of the most important inventions to take place in the region is a highly accurate sun tracker for CPV module operation. Angulo-Calderón et al [9]. stated that these systems involve sophisticated mechanical and control elements, which are essential for solar tracking-exact precision required by the CPV technology because of its need for intense sunlight. In their study, these trackers do indeed offer better energy return at a little additional cost by incorporating sensors and real-time feedback loops [10].

Pavlovic et al [11]. Among the staunch supporters of the sun trackers for CPV module operation, research on enhancing the mechanical and controlling mechanisms' efficiency is very vital regarding maximizing the accuracy of the Sun Tracking Systems. As accurately tracked technology behind CPV ensures maximum collection of solar energy, yet research mentions that inclusion of sensors and feedback mechanism would further enhance the system's performance by reducing overall costs.

On the technological front, Kaur et al [12]. proposed a low-cost active dual-axis Arduino-based solar tracker. The overall system complexity in doing solar tracking is reduced and hence enhances the accessibility of solar tracking. Their approach uses inexpensive microcontrollers and sensors to keep the solar panels at optimal angles, providing considerable cost advantages in small- to medium-scale solar installations. Another important discovery of this work is that these systems are feasible for application in several solar uses, particularly where cost inhibits the proliferation of more advanced technologies.

Hamad et al [13]. further improved the design in dual-axis trackers by introducing smart monitoring systems with real-time data acquisition and performance analysis. Using IoT, monitoring and setting are possible remotely; efficiency in operation is better, and it reduces the chances of shutdown. Gbadamosi added in the same domain and proposed an IoT-based dual-axis solar PV tracking system that would allow adaptive tracking in real time based on environmental conditions for further optimization in energy capture and system reliability [14].

Various artificial intelligence techniques have also been applied to improve the efficiency of dual axis tracking systems. Ali et al [15]. presented a comparison of different AI algorithms in solar tracking, including machine learning-based models that were able to provide high-accuracy predictions of sun movement. It was proved that the AI-driven systems could show higher performance compared with conventional tracking methods, especially under variable weather conditions, in which the efficiency of manual adjustments would be poor.

Finally, developments have also been made beyond dual axis tracking systems. In this respect, Haider et al [16]. explored the potential of a three-axis solar tracking system, which adds one more axis of rotation to accommodate finer adjustments in the orientation of panels. Such a system, even though more complex, would increase energy yield considerably, at least for those regions showing extreme seasonal variations in sunlight. Abadi et al [17]. also analyzed performance results regarding maximum power point tracking systems based on fuzzy logic controllers, which is one of the effective ways to save energy by dynamically readjusting the position of the tracker according to real-time levels of solar irradiance.

Another significant aspect that these latest solar tracking design encompasses is the highly efficient development of a solar-tracking algorithm, improving precision and responsiveness in systems. Stamatescu et al [18]. focused on presenting a solar-tracking algorithm in which the real-time solar position calculation dynamically adjusts the angle of panels. Their design thus uses sensors, which are consistently monitoring the solar irradiance and adjusting the orientation of panels to ensure maximum capture of energy.

The same principle of this approach is to optimize tracking accuracy but, at the same time, reduce mechanical wear and energy consumption by limiting superfluous movements. The implementation results of the algorithm showed that energy yield improvements were achieved and emphasized the accuracy in solar tracking.

Dynamic reconfiguration of the solar panels has been one of the new methods for energy production optimization. Merino et al [19]. proposed a system based on dynamic reconfiguration of the array of moving photovoltaic panels. This system should maximize the power output while mitigating the adverse impact of shading, as it selects the configuration of the panels according to irradiance level, temperature, and shading conditions. The study stressed that design had to give solar panels flexibility not only in changing their orientation but also in operational modes according to real conditions.

Moreover, there have been innovations in the field of mechanical design related to solar tracking systems for making the movement of the panels more durable and responsive. Among these, Zuhal and Marangozoglu [20]. have come up with a new design supported by accurate solar calculations to improve the efficiency of the tracking system. Their design includes a strong mechanical structure that can bear the harsh weather conditions while sustaining optimum solar tracking. The system especially works well in areas of high wind load or extreme weather, where usually other types of designs might not function well. This kind of mechanical amplification ensures that the panels track their position with immense accuracy under inclement weather conditions and thereby improves the consistency in energy generation.

Some designs have also implemented predictive control systems into solar tracking to further optimize panel movement. In another approach, Stamatescu et al [21]. reported a predictive control method using real-time data and weather forecasting to proactively operate the movements of the solar panels. By this approach, the delay between the change of the sun's position and adjustment of the panel's position is decreasing due to a more efficient capturing of energy.

Predictive control also reduces superfluous mechanical movements and extends the life cycle of the tracking systems, thereby cutting maintenance costs. In such an approach, the movement of the sun is forecast beforehand, and the panels are prepared for it in order to gain maximum energy output during rapidly changing weather conditions.

For example, some AI-based control systems have been exemplified to deal with optimal exploitation of solar photovoltaic systems: AI control systems, which are able to provide advanced tracking abilities can act dynamically in accordance with environmental variables.

Application of AI algorithms such as ANNs and fuzzy logic controllers, diagnosis, and optimization of solar photovoltaic systems were mentioned by Mellit and Kalogirou [22]. AI lets systems predict and, in turn, adjust weather changes, solar irradiance, and temperature to keep the panels at the most optimal angles; real-time adjustment for maximum amount of captured energy and minimum lost energy due to wrong positioning.

In particular, the ML techniques have significantly contributed to the development of advanced MPPT algorithms, one of the most important factors which contribute to high efficiency in a solar panel. Authors in [23]. and [24]. discussed separate studies showing how ML-based MPPT methodologies, one using decision trees and the other using SVM, greatly enhance precision and response time for sun-tracking systems. Traditional MPPT techniques employ static algorithms, which can hardly track fast variations in environmental conditions; hence, those algorithms are susceptible to poor performance.

On the other hand, ML models learn from the data of past instances or trends in the environment continuously to correctly predict the optimal orientation of the panel in real time. Yap et al. indicated that the ML-based MPPT technique compared to conventional methods has great potential to give as much as 10-20% improved energy yield in regions with high variability of sunlight.

Deep learning is also a subset of ML, which has also been applied to dual-axis solar tracking systems to enhance precision and adaptability even more. Elsisi et al [25]. discussed the role of deep learning algorithms in the smart energy management system for solar PV installations, with special attention to smart building and other Industry 4.0 applications. These algorithms will process big datasets from various sources, including but not limited to weather forecasts, energy consumption patterns, and historical performance data, to make informed predictions of the most efficient panel positions. The predictive nature of deep learning allows solar tracking systems to anticipate changes in sunlight availability and adjust in a manner that will maximize energy capture even in complex environments.

The quest for the maximization of energy generation in solar pv ystems has been taking their toll through advanced approaches on optimization. The new methods are designed to enhance the energy output of the solar installations by introducing innovative designs that tackle environmental considerations and system efficiencies. Several approaches were explored, starting from advanced modeling techniques to integration with other sustainable systems; each has its own merits regarding benefits in enhancing energy production.

The optimization algorithm considering the stochastic nature of environmental factors is one of the most important ways to enhance energy efficiency in solar PV systems. Karan et al [26]. discussed the stochastic approach for the integration of food, energy, and water systems, which can be further extended to the generation of solar energy. In the method, the analysis underlines the importance of accounting for variable environmental factors, like solar irradiance, temperature, and wind speed, in the design of solar PV systems. The stochastic models allow the forecast of such variations; hence, their use is indispensable to achieve an optimum design for the solar tracking systems to capture the maximum possible energy with fluctuating conditions. Particularly for regions where weather patterns can have a great influence on the availability of solar energy.

Besides environmental modeling, integration of smart technologies drives energy efficiency in solar systems. Nižetić et al [27]. pursued an approach in which the use of smart technologies-IoT and AI-can be made applicable to enhance energy efficiency by allowing real-time monitoring and optimization.

Accordingly, these systems dynamically actuate the positioning of the solar panels through real-time data to capture every available energy with minimal waste. In addition, these systems will also be able to predict all future environmental conditions through ML algorithms and pre-act the orientation of the panels for better overall efficiency in energy generation. Energy generation is optimized not just with smart technologies to current conditions but also adaptable to future changes.

Another innovative approach for energy efficiency can be considered as involving solar PV panels integrated into shading solutions. Albatayneh et al [28]. demonstrated that employing integrated photovoltaic panels in the shading systems would enhance a building's energy efficiency in semiarid climates. Energy generation would thus be duly optimized by strategically placing the PV panels as shading devices that would reduce the cooling load of buildings concurrently. This design for dual functions captures two of the major areas of energy consumption: electricity generation and cooling, using the same system. In semi-arid to hot climates, this will also contribute to sustainable building design by improving general energy efficiency and reducing reliance on conventional sources of energy.

Hence, energy storage solutions combined with solar PV systems have been one of the critical optimization approaches that have emerged in recent years. Abualigah et al [29]. reviewed some advanced machine learning and deep learning techniques applied to the optimization of renewable energy systems with particular interest in systems with energy storage. Solar photovoltaic systems integrated with energy storage can sustain regular energy output during periods of unavailable sunlight, as happens in cloudy conditions or at night.

The AI-driven optimization algorithms with deep learning, in turn, predict when to store excess energy and when to deploy, ensuring efficiency in energy usage with the least loss. It is especially useful for systems that have highly variable solar irradiance during the day and even during a year.

While the world's attention shifts to sustainable solutions for energy production, more attention has fallen on reducing the environmental impact of the whole solar energy system. The dual-axis solar tracking systems are designed to be state-of-the-art in energy maximization and are even more optimized for minimization of environmental impact. They allow for more resource-effective use and management of land, translating into overall energy generation. Thus, they have also been thought of as a key tool in the transition towards low carbonation. Recent design, material, and operational innovations have contributed a lot to making those dual-axis solar tracking technologies more ecological.

Life cycle assessment is the most central part of environmental sustainability in solar energy systems, reflecting the overall calculation of the environmental impact, from production through decommissioning of the system. A comparative LCA of fixed and single axis tracking systems by Antonanzas et al [30]. has tried to show that though tracking systems have a higher initial environmental burden because of the increased use of material and energy from manufacturing, they outweigh the fixed systems in terms of energy yield during their lifetime.

"Dual-axis systems increase efficiency in energy production but result in higher environmental costs due to their higher initial investment. Therefore, during their life cycle, modern dual-axis trackers will have the ability to provide a more sustainable energy solution.

On top of this, Flores-Hernández et al [31]. advocated for the general optimization in the operation of dual-axis sun-tracking systems for the attainment of sustainability in the technological system. Essentially, their work elaborates that an increase in precision and the improvement of operational efficiency within the system would reduce energy wastage efficiently, hence curtailing carbon emissions associated with the generation of energy from solar sources.

Equipped with real-time control algorithms and smart sensors, modern dual-axis trackers are designed to dynamically adjust to the changing ambient environment and position the solar panels for optimal energy capture. This, in practice, means a higher yield per square meter of land, with less extensive solar farms and preservation of natural landscapes. Enhancing can be done using machine learning and deep learning, which are used in a set of fields such as health [32] and geography [33] and more.

Modern dual-axis solar tracking systems can significantly reduce the environmental footprint produced by such installations. They accomplish this by maximizing energy production, optimizing land use, using sustainable materials, and, finally, minimizing resource consumption.

3.0 DISCUSSIONS ON THE TRADITIONAL VERSUS INNOVATIVE APPROACHES

3.1 Comparison of Traditional vs. Innovative Approaches

Dual-axis solar tracking has been evolving from the conventional mechanical design to a more technologically driven system. This development brought significant changes in energy efficiency and even system reliability. A conventional dual-axis tracker relies on heavy machinery for panel adjustment, with limited automation and response mechanisms. While these did manage to improve energy capture when compared to fixed-tilt systems, they were less efficient in the sense that their inability to rapidly adjust to changes in environmental conditions resulted in a resultant loss in overall efficiency. The attendant mechanical wear and tear consequently increased maintenance costs and shortened the service life of the system.

Single-axis trackers may not embrace these modern novelties, but new-generation dual-axis trackers with the latest control algorithms, integration of IoT, and AI-based optimizations allow real-time adjustments to environmental data. These reduce lag in response times and increase energy yield considerably by precisely aligning the panels with the sun throughout the day. Quantitatively, these modern dual-axis mechanisms can achieve 30-40% increases in energy efficiency compared to traditional systems, with corresponding operational cost reductions due to better durability and more automation. Qualitatively, newer systems exhibit enhanced adaptability to weather fluctuations, intelligent controls that minimize the need for manual interventions, and optimization of overall performance.

3.2 Performance Analysis

Dual axis tracking systems have great dependencies on ambient conditions with respect to solar irradiance, wind speed, and temperature. For these, innovative strides in modern times have equipped the systems with better performance capabilities over a wider range than their conventional settings. Advanced control systems allow the panels to effectively adjust their position due to AI MPPT algorithms even under fluctuating sunlight or partial shading of panels. This adaptability really helps in reaping a high yield even under unfavorable conditions.

Innovative systems indeed come out a bit stronger under harsh climates, too, because modern materials and structure design give them more resistance against strong winds and drastic temperatures. Advanced features in the management of wind load include an automatic stow of the turbine in case of high winds to avoid its destruction-a feature not available in older models. Besides, modern systems can take the sun's seasonal path variations more effectively, improving performance throughout the entire year, not just the peak solar months.

3.3 Challenges and Limitations

Offsets notwithstanding, there are still numerous challenges and shortcomings related to dual-axis solar tracking systems. One of them involves the fact that the integration of advanced sensors, AI, and IoT technologies has drastically enhanced the complexity of these systems. While such new enhancements indeed contribute to better performance, they also introduce more failure points, particularly under extreme environmental conditions-high temperatures or dusty regions-which can impair sensor functionality.

Another limitation is that modern dual-axis systems have deployment costs. While these efficiency gains can pay back over time, initial investments remain considerably higher than traditional fixed or single-axis systems. In turn, this makes tracking with dual-axis less accessible for smaller installations or regions with low solar irradiance where the return on investment may not justify the extra cost.

It also remains a challenge to maintain, as more sophisticated systems require specialized knowledge to make repairs and perform upkeep. Traditional systems, being less complex, often required less specialized labor for maintenance, which can therefore be a disadvantage of the more complex modern system.

3.4 Future Trends in Dual-Axis Solar Tracking

There are various emerging trends for the future of dual-axis solar tracking systems driven by the advancement in AI, Automation, and Material Science. One of the key trends will be an increasing reliance on AI for predictive analytics, thereby driving the systems' responses not just to the current weather, current solar irradiance, and grid demand but to forecasted changes in the foregoing. This will go toward proactive adjustments that further increase the efficiency of the solar tracking system.

Interest is also growing in systems that integrate energy storage with dual-axis trackers, especially in off-grid and remote installations. Similarly, solar installations will be able to store excess energy generated in peak sun hours by combining tracking systems with battery storage for use when solar production is low, increasing the utility of solar energy in variable environments.

Another development likely to decrease the overall cost and environmental impact is the introduction of light, durable materials that are friendly to the environment. Such materials will make the installations resistant to deterioration, reducing maintenance requirements in the long term and thereby increasing the lifetime of the systems.

In the future, dual-axis trackers in solar energy systems will be part of larger, interconnected smart grids with increased adoption of IoT. This would make for better distribution and management of energy than is currently possible through the reliance on real-time data from many installations to further optimize the performance of the entire energy network.

4.0 CONCLUSION

Advancement in dual axis tracking systems has been the cornerstone for huge leaps in efficiency and sustainability for capturing solar energy. Modern innovation, such as AI, IoT, and machine learning, promises exciting transformation of sun-tracking processes throughout a solar panel's entire life cycle because energy capture is optimized with real-time adjustments, hence increasing the overall system performance. These technologies have further empowered solar trackers for dynamic adaptation to changes in the environment, while increasing the yields and resilience of systems under severe conditions.

Moreover, future trends such as predictive analytics, energy storage integration, and the use of advanced materials will also serve to further reduce the environmental footprint of solar systems and enhance their efficiency. In fact, dual-axis solar tracking systems are expected to play a critical role in meeting the world's energy demands with their increasing endowments toward renewable energy sources, all in the interest of environmental sustainability.

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