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ORIGINAL

Automation Across the Energy Spectrum: Intelligent Systems for Oil and Gas Operations and Real-Time Solar Tracking

Automatización en todo el espectro energético: sistemas inteligentes para operaciones de petróleo y gas y seguimiento solar en tiempo real

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ABSTRACT

Fast moving automation technologies are profoundly changing the energy sector, a change that is affecting not only carbon-based energy systems but also clean energy systems. Oil and gas exploration is becoming more and more the domain of intelligent monitoring platforms, adaptive control architectures, and sensor-rich robotic tools that can precisely operate, detect faults quickly, and ensure safety in complex subsurface environments.. The fast worldwide movement towards renewable energy has led to intense research on solar energy systems, highlighting their indispensable role in providing sustainable energy. However, traditional fixed photovoltaic (PV) panels have an inherent drawback - their non-moving nature makes it impossible for them to be in continuous contact with the sun's rays, which results in less energy being captured and lower conversion efficiency. In order to address this problem, real-time solar tracking devices have been invented to change the direction of the panels automatically, thus ensuring maximum exposure to solar irradiance during the day. Although these solutions show substantial increases in energy output, their popularity is limited by the expensive and intricate nature of typical commercial designs, especially in the case of domestic and small-scale applications. As a result, lately, developments have been focusing on creating low-cost, sensor-based, and easily operable tracking devices that use simple elements like Light Dependent Resistors (LDRs) and photodiodes. This paper introduces a comprehensive review of the innovative ideas in this field by highlighting the features, hardware setups, and control methods of the single- and dual-axis systems besides this comparative assessment of sensor-based and astronomical models provides insights into system simplicity, dependability, and cost-effectiveness trade-off. The paper ends with an overview of potential future topics such as the use of intelligent control algorithms, Internet of Things (IoT) units, and hybrid renewable systems that, when combined, may lead to the emergence of the next generation of solar tracking technologies that are adaptive and highly efficient.

Keywords: Solar Tracking; Light Dependent Resistor (LDR); Real-Time Control; Renewable Energy; Low-Cost Systems.

RESUMEN

Las tecnologías de automatización en rápida evolución están transformando profundamente el sector energético, un cambio que afecta no solo a los sistemas energéticos basados en carbono, sino también a los sistemas de energía limpia. La exploración de petróleo y gas se está convirtiendo cada vez más en el dominio de plataformas de monitorización inteligente, arquitecturas de control adaptativo y herramientas robóticas con sensores que pueden operar con precisión, detectar fallos rápidamente y garantizar la seguridad en entornos subterráneos complejos. La rápida transición mundial hacia las energías renovables ha impulsado una intensa investigación sobre sistemas de energía solar, destacando su papel indispensable en el suministro de energía sostenible. Sin embargo, los paneles fotovoltaicos (FV) fijos tradicionales presentan una desventaja inherente: su inmovilidad les impide estar en contacto continuo con los rayos del sol, lo que resulta en una menor captación de energía y una menor eficiencia de conversión. Para abordar este problema, se han inventado dispositivos de seguimiento solar en tiempo real que cambian la dirección de los paneles automáticamente, garantizando así la máxima exposición a la radiación solar durante el día. Si bien estas soluciones muestran aumentos sustanciales en la producción de energía, su popularidad se ve limitada por el alto coste y la complejidad de los diseños comerciales típicos, especialmente en el caso de aplicaciones domésticas y a pequeña escala. Como resultado, últimamente, los avances se han centrado en la creación de dispositivos de seguimiento solar de bajo coste, basados en sensores y de fácil manejo, que utilizan elementos sencillos como resistencias fotoeléctricas (LDR) y fotodiodos. Este artículo presenta una revisión exhaustiva de las ideas innovadoras en este campo, destacando las características, las configuraciones de hardware y los métodos de control de los sistemas de uno y dos ejes. Además, esta evaluación comparativa de modelos basados en sensores y astronómicos proporciona información sobre la simplicidad, la fiabilidad y la relación coste-eficacia del sistema. El artículo finaliza con una visión general de posibles temas futuros, como el uso de algoritmos de control inteligente, unidades del Internet de las Cosas (IoT) y sistemas híbridos de energías renovables que, al combinarse, podrían dar lugar a la próxima generación de tecnologías de seguimiento solar adaptativas y altamente eficientes.

Palabras clave: Seguimiento Solar; Resistencias Fotoeléctricas (LDR); Control en Tiempo Real; Energías Renovables; Sistemas de Bajo Coste.

INTRODUCTION

The dramatic increase in worldwide energy demand has been a major contributor to the focus on renewable energy technologies, along with growing worries about greenhouse gas emissions and resource depletion. In fact, one of the main reasons is their modular structure, non-polluting operation, and easy scalability in different geographical areas.[1,2,3,4,5] Still the performance of photovoltaic (PV) grids is so vulnerable that the power generated depends on the momentary solar irradiance and the angle between the light source and the module surface.[6,7,8,9,10] In fact, any slight deviation of the solar vector from the panel orientation can result in a significant power output drop and even system efficiency reduction over the years.[2,4,11,12] There is a large number of both experimental and computational research papers which have come to the conclusion that system yield depends not only on local weather conditions, but also on the degree to which the arrays can follow the apparent movement of the sun along the sky. Therefore, the best use of the angle of the modules during the day and at different seasons is still one of the principal ways of increasing energy density without augmenting the

PV footprint.[3,5,9] Fixed-tilt installations of the solar arrays are still the most popular ones due to their less complex supporting structures, low maintenance, and absence or very little control electronics. The main disadvantage of these systems is that they cannot incorporate compensation for the dynamically changing sun's trajectory and thus the solar energy received is drastically and predictably lowered.[2,4,11] Active solar tracking facilities on the other hand have the ability to adjust the PV modules in situ to achieve the maximum power point and thus they have already proven their effectiveness in terms of daily and annual energy yield. The real installation onsite tests usually give evidence that single-axis trackers are able to moderately improve the system performance and therefore also the energy yields whereas dual-axis configurations can further increase that up to even ten percent and more, especially when the sky is clear and sun irradiance is at its maximum.[5,6,7,9,11] However, there exist difficulties in implementing a fully automated tracking system regulation mechanism in a wide range of locations due to the additional mechanical intricacies that caused by the requirement for a wide and heavy installation design structure, the actuator power demanding and the extension of set-up and maintenance costs, which may cancel out the economic benefits that are present in this application in some cases.[4,12] Hence, research nowadays is more concentrated on techno-economic optimization, which is sensitive to the local context, than on explicitly proclaiming that one type of tracking configuration is better than another.[11,12]

Sensor-based, low-cost tracking systems have become the focus of attention in this domain during the last couple of years. The discussed systems generally exploit optical sensors as LDRs, photodiodes, or phototransistors combined with a low-power microcontroller or an embedded processor to provide a nearly real-time sun-tracking solution with minimal energy consumption.[6,8,10,13,14] Implementations in literature have relied on comparator-based circuits, proportional–integral–derivative (PID) controllers, or fuzzy logic methods to ensure that the angular correction is accurate, and the oscillations and overshoot are at a minimum.[10,15,16,17] The IoT connectivity and edge computing integration have, therefore, extended the capabilities of such systems to remote monitoring,[18,19,20,21] predictive diagnostics, and cloud-based performance analytics of distributed PV networks.[10,12,22,23,24,25] Properly engineered low-cost, smart trackers can provide a great compromise of accuracy, scalability, and power saving, i.e., qualities that make them highly attractive for decentralized rural electrification, domestic rooftop systems, and smart microgrid applications.[10,12,22,23,24]

However, the full potential of sensor-driven solar tracking is still limited by a few long-lasting issues that persist alongside it. Cheap optical sensors sometimes have nonlinear reactions to extreme irradiance situations, temperature drift, and aging-related degradation, which, when combined, point accuracy diminish over long periods of operation.[6,16] Besides that, mechanical wear, actuator inefficiencies, and parasitic energy losses from control electronics can reduce net system gains if not taken care of by proper design optimization, thus increasing the extra work for the system.[11,15,17] The latest study on this topic revealed that hybrid control strategies, i.e., the integration of predictive algorithms like Artificial Neural Networks (ANNs) or Model Predictive Control (MPC) with the real-time sensor feedback, may help to stabilize and reduce the transient error during weather condition changes.[17,18,19,20] These methods, however, require more computational resources and calibration effort and, therefore, still being considered as a possible way of getting a resilient, adaptive, and low-maintenance tracking system in the future.[18,19,21,22]

Besides, the transition of AI-enabled and IoT-integrated hybrid frameworks is significantly changing the solar tracking field. Researches that use fuzzy logic, neural networks, and machine vision methods have proven that it is possible to have the tracking very close to the sub-degree with the energy used being also very low.[15,16,17,18,23] Meanwhile, combining optical, infrared, and camera-based sensors has allowed the multi-spectral tracking to be able to keep the accuracy even in the case of diffuse or partially shaded conditions.[21,22,23] These improvements, when

combined with cloud-based supervisory control, can result in self-calibrating systems that change sensor degradation and environmental variability. Nevertheless, the extensive use of such smart trackers is constrained by the expenses of the hardware, the difficulties of the computational part, and the problems of data connectivity, mainly in rural and developing areas.[10,22,24] It is necessary to overcome these practical obstacles if intelligent solar tracking technologies are to go beyond being mere experimental prototypes and to become solutions viable in the commercial market.

Automation

In the energy sector, automation has been a feature that not only changed the mode of the energy sector but also the whole technology development and utilization sector. By the adoption of real-time analytics, sensor-laden monitoring networks, and machine-assisted decision frameworks, field operations have become safer and less prone to risks in the oil and gas sector. Indeed, the array of publications and reports in the literature are unequivocally in favor of automation in drilling supervision, the use of autonomous downhole tools, and digitally integrated reservoir workflows, which, as a result, have a tremendous impact on operational uncertainty reduction and subsurface characterization enhancement.[25,26,27] Such technological advances are the lifeline of the situation in which geological operators confront complex environments and need to interpret high-frequency data fast to keep drilling performance and equipment integrity. Hence, the changes mean a deep upheaval in upstream engineering as automated systems are slowly becoming the core operational infrastructure rather than just being optional ones.[28,29] A sensor tech up-to-date has been a great help in finding new paths of collecting solar energy more efficiently just like that the breakthrough renewable energy innovations are reshuffling the energy scene. Dual-axis solar trackers and minimalist light-intensity sensors have been shown to accomplish substantial efficiency gains chiefly in decentralized or resource-poor environments, as per the research of Rashid et al.[28] and Rhatigan et al.[30]. The invention of self-powered environmental monitoring and stable control logic has been the reason for the transition of such instruments and thus their reliability is guaranteed even in variable weather conditions.[29] Although solar tracking is a completely different technological concept from hydrocarbon exploration, both industries share the same dependence on distributed sensing, adaptive control, and continuous performance optimization. As a result, these concepts' interconnection can speed up the progression of high-tech, advanced, and energy-diverse engineering systems that are not only more intelligent but also more flexible due to cross-sector knowledge sharing.

Moreover, there is still a considerable research gap regarding the long-term validation and comparative evaluation of low-cost tracking systems. While some prototype experiments have announced energy gains of 25–45 % under idealized conditions,[2,6,9,10] hardly any study has systematically looked at durability, actuator lifespan, and calibration drift due to real-world environmental fluctuations.[11,15,17,20] In the same vein, most of the commercially available dual-axis systems are still depending on precision encoders and astronomical algorithms that increase costs and limit the applicability for small-scale and domestic users.[5,8,14] The literature hardly discusses hybrid sensor–algorithmic approaches that use optical feedback with predictive modeling[9,16,18] and also does not provide a complete evaluation of the trade-offs between cost, energy consumption, and long-term reliability.[4,11,20] Therefore, a holistic cross-disciplinary framework, which includes electronics, control engineering, and energy economics, is required to implement advances in low-cost, energy-efficient, and field-resilient solar tracking technologies.[17,19,25]

Objectives of the Study

This review is centered on gathering, synthesizing, and critically evaluating recent low-cost

innovations in sensor-based solar tracking systems with an emphasis on real-time performance optimization, energy efficiency, and scalability. The broad aims are to:

1. Combine and situate the innovations of the latest developments of real-time solar tracking systems in the context of the utilization of simple optical sensors like Light Dependent Resistors (LDRs), photodiodes, and phototransistors.[5,6,8]
2. Regulate the existing methods that are to be local implementations—comparator-based, PID, fuzzy logic, and AI-assisted algorithms—to be accurate, stable in the response, and to consume less energy. Compare and evaluate these methods.[10,15,18]
3. To be Performance metrics such as the efficiency improvement, the response time, the cost-effectiveness, and the reliability of single-axis and dual-axis tracking configurations, both experimental and simulation-based, are to be analyzed from the literature.[2,6,11,20]
4. Delve into the issues that accompany low-cost tracking systems and thus hamper device deployment in the rural, domestic, and hybrid renewable energy sectors, particularly in the case of mechanical wear, power consumption, and calibration drift.[12,16,22]
5. The affordable, intelligent, and autonomous solar-tracking architectures of the next generation with a combination of research trends of IoT-enabled, AI-based, and hybrid sensor fusion approaches[17,19,25] are to be identified.

Principles, Classification and techniques of Solar Tracking

Principles of Solar Tracking

Solar tracking describes the process whereby photovoltaic (PV) panels or collectors are constantly adjusted to maintain the most favorable angle towards the sun, thus increasing the amount of solar radiation reaching the active surface.[2,4] Tracking is done by figuring the sun's position on earth at that very time by means of optical sensing, using coordinate calculations or a hybrid control approach, which involves both methods.[6,9,10] In sensor-based tracking that is done in real-time, devices such as Light Dependent Resistors (LDRs), photodiodes, or phototransistors detect the differential light intensity between the paired sensors, and the corresponding actuator signals propel the panel to reorient it in such a way that equilibrium is restored.[5,8,12]

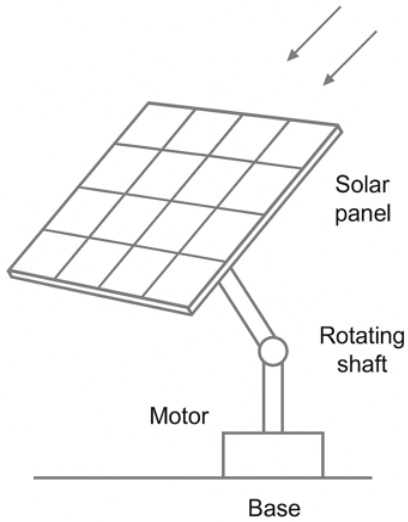


Figure 1. Schematic diagram of a Single axis solar tracking system[2,6,13]

From the mathematical point of view, any time solar position can be represented by two basic angular coordinates: azimuth (the horizontal direction of the sun relative to true north) and elevation (the vertical angle above the horizon), both of which change continuously with time and location on earth.[7,9,11] Usually tracking hardware is employed as a single-axis system, which traces the sun's apparent movement in one plane (generally east–west), or as a dual-axis system, which is able to alter both azimuth and elevation for the exact direction to be obtained during the day as well as for the changes in the seasons.[2,6,13] Figure 1 shows a diagram of a single-axis solar tracking setup which basically entails the main functional components of sensor-based actuation and feedback control.

Classification of Solar Tracking Systems

Usually, solar tracking devices are split into two major segments—passive as well as active systems— based on their operating and controlling methods.[2,4,6] Passive trackers rely on thermal or mechanical actuations, most of the time, utilizing the differential expansion of the working fluid or gas to change the collector's orientation due to solar heating. Even though this kind of design is intrinsically simple and doesn't require any energy, the response of such a system is usually slow and less accurate in the case of sudden changes in weather.[5,11] On the other hand, active tracking systems make use of sensors, actuators, and electronic control units to constantly change the panel's orientation in the direction of the highest solar irradiance.[6,8,9] Depending on the number of degrees of rotational freedom, active trackers may also be single-axis or dual-axis. A single-axis tracker revolves around one fixed axis—either azimuthal (east-west) or elevational (north–south)—and is generally used in low-medium precision applications like rooftop PV arrays and small-scale solar farms.[2,6,12] Whereas a dual-axis tracker, which is depicted in figure 2, varies in both azimuth and elevation angles so that it can always have the closest to perpendicular incidence to the sun during both diurnal and seasonal cycles.[7,9,13]

Table 1. Comparative summary of single-axis and dual-axis tracking systems

Type of System	Axis of Motion	Control Principle	Tracking Precision (°)	Typical Efficiency Gain (% vs Fixed)	Approx. Cost Level	Common Applications	Key Ref
Fixed System	—	Stationary frame, fixed tilt	—	0	Very Low	Rooftop PV, small off-grid units	[2,4]
Passive Tracker	1 or 2	Thermal expansion / fluid displacement	5 – 10	10 – 20	Low	Stand-alone collectors, solar heaters	[5,11]
Single-Axis Active Tracker	1 (azimuth *or* elevation)	Sensor-based or algorithmic rotation using one actuator	1 – 3	15 – 25	Medium	Rooftop PV arrays, mid-scale solar farms	[2,6,9]
Dual-Axis Active Tracker	2 (azimuth + elevation)	Independent control of two actuators; feedback or predictive algorithms	< 1	25 – 45	High	Utility-scale PV, CPV systems	[6,13]
Hybrid Tracker	2	Sensor + astronomical + AI or IoT-assisted logic	< 0,5	30 – 50	Medium – High	Smart grids, research demonstrators	[9,15]

Even though dual-axis devices usually result in the largest additional energy yields (25–45 %), their better accuracy and daily energy capture capability are associated with increased mechanical intricacy, higher cost, and greater maintenance requirements.[6,13,15] Table 1 presents a comparative overview of the single-axis and dual-axis tracking systems, which is the main differences in precision, energy gain, and cost-effectiveness that are being pointed out.

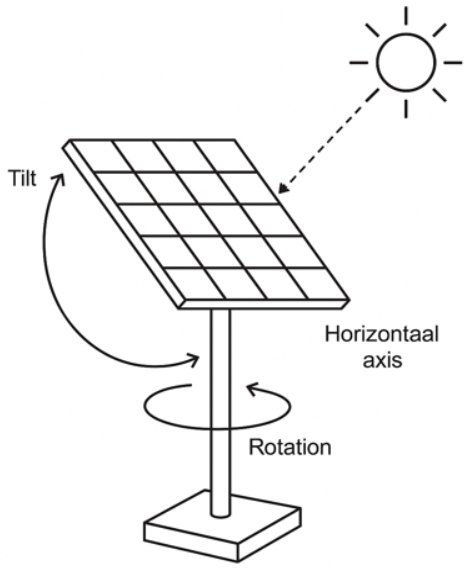


Figure 2. Schematic diagram of dual axis solar tracking system

Sensor Technologies for Real-Time Tracking

The efficacy of solar tracking mechanisms operating in real-time conditions is largely dependent on the precision and promptness of the sensors that are employed to identify the changes in solar irradiance. In the case of various optical sensors, the three options that have been most extensively used for low-cost experiments due to their easy-to-handle, small size, and low power consumption features are Light Dependent Resistors (LDRs), photodiodes, and phototransistors. It should be noted that among these, LDRs are especially interesting because of their high sensitivity to the range of the visible light and cheap production, which make them the best-fitted for small-scale as well as educational purposes.[6,9,12] An LDR is a photo resistive device whose resistance varies inversely with the intensity of the incident radiation and hence it directly analogically represents the light changes.[5,8] Normally, solar tracking hardware contains either two or four LDRs that are aligned in the same direction, and an opaque partition is placed between them to create a differential light-sensing unit. This method allows the unit to detect orientation changes of the solar flux: the voltage difference between these sensors serves as an instruction signal for the controller when one sensor is illuminated more than its counterpart.[9,10] Firstly, the error signal can be manipulated through analog comparator circuits or microcontroller-based logic by which stepper or DC motors are turned on to reorient the photovoltaic (PV) module until both sensors are at the same level of light. Secondly, the controlled signal can directly command the movement of a motor having the photovoltaic (PV) module mounted on the axis to achieve a balance state of light illumination whereby both sensors have the same intensity.[8,12,13] LDR-based tracking systems that are properly calibrated can lead the solar energy harvesting process to yield from 25 up to 40 percent as compared to fixed locations according to factors such as weather condition, orientation, and mechanical response, this has been evidenced by several experimental investigations.[6,10,12,18] Although

these sensor systems are of low complexity, they still have a great capability to be used in IoT-enabled, AI-supported, and hybrid tracking schemes, thus opening up the way for the next generation of smart photovoltaic systems.[13,15,18]

Control and Automation Techniques

The performance of a solar tracking device depends to a large extent on the control and automation system that not only helps achieve high tracking accuracy but also energy saving. Analog comparator-based systems represent the most straightforward solutions of a low-cost local control of a panel tracking system. Essentially they use operational amplifiers to compare the voltage signals from two light sensors such as LDRs in each one of the four directions. The analog versions of such devices provide an instant response to the changing environment with minimal hardware and power-demand and in general, have the disadvantage of a very limited adjustment possibility, temperature dependence, and irradiance calibration drift.

Figure 2 a schematic diagram of a dual-axis solar tracking system that uses Light Dependent Resistors (LDR1 and LDR2) as optical sensors for differential light detection. The comparator circuit receives the output from the sensors and sends control signals to the microcontroller, which through motor drivers azimuth and elevation motors control the precise horizontal and vertical alignment of the photovoltaic panel with the sun's position.[6,8,9] To deal with these limitations, microcontroller-based control architectures have become a trend. Control units based on Arduino, PIC, or ARM Cortex can effectively manage the differential input from the sensors, determine the angular deviation, and at the same time operate a stepper or DC motor for the accurate alignment of the solar panel.[10,12,14]

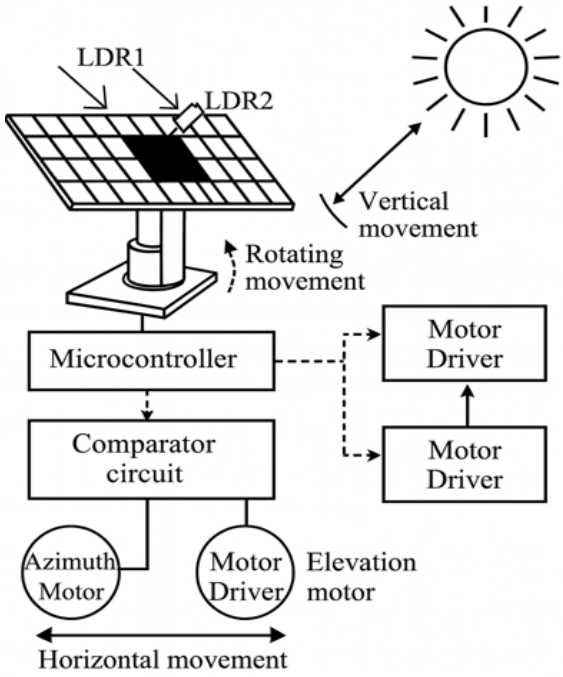


Figure 3. Block diagram of a dual-axis solar tracking system using LDR sensors, microcontroller, and motor drivers for azimuth and elevation control

Table 2. Comparison of Sensor Technologies for Real-Time Solar Tracking Systems

Sensor Type	Operating Principle	Response Time (ms)	Relative Cost (USD)	Sensitivity / Accuracy	Typical Applications	Advantages	Limitations	Ref
Light Dependent Resistor (LDR)	Photoresistive element; resistance decreases with incident visible light intensity	50 – 200	< 1	Medium (±2–3°)	Low-cost single/dual-axis trackers, educational kits	Simple, inexpensive, wide spectral range	Temperature-sensitive; lower long-term stability	(5,6,8,9)
Photodiode	Semiconductor junction converts light energy to proportional current	< 10	1 – 2	High (±1–2°)	Medium-precision trackers, industrial sensors	Fast response, stable output, linear response	Requires amplifier and precise biasing	(9,10,13)
Phototransistor	Light controls transistor current flow; acts as amplified photodiode	20 – 50	2 – 4	Very High (±0,5–1°)	High-sensitivity tracking, robotic and mechatronic systems	High gain, moderate cost, robust	Non-linear response at high irradiance	(8,13,15)
Pyranometer	Thermopile or photodiode measures total hemispherical solar irradiance	> 1000	> 100	Reference-grade	Calibration and benchmark systems	High accuracy, standardized measurement	High cost, bulky, needs maintenance	(5,9,11)
Infrared (IR) Sensor	Detects solar IR spectrum or temperature gradient for direction estimation	5 – 25	3 – 5	Medium (±2°)	Cloudy / diffused-light tracking	Works in low-visibility; unaffected by visible shading	Limited precision under direct high irradiance	(15,18,22)
Image Sensor (CCD/CMOS)	Captures sun's image; software computes centroid for orientation control	< 50	> 30	Very High (< 0,3°)	AI-assisted and astronomical trackers	Extremely precise, enables predictive control	Complex processing; high cost & power use	(15,18,20)

Such systems enable the use of closed-loop feedback, adaptive correction, and additional features like data logging and wireless monitoring.[10,15] Additionally, microcontrollers enable pulse-width modulation (PWM) for detailed motor control and can easily connect IoT communication modules (e.g., ESP32, NodeMCU), thus, their usage can be extended to distributed smart-grid environments.[12,20] To countenance precision and also to industrial applications, the extent of controllers—like programmable logic controllers (PLCs) and digital signal processors (DSPs)—are used to handle multivariable operations with more robustness and reliability.[14,17] PLC-based systems, besides, are mainly acclaimed for their heaviness and real-time interrupt capability, however, they are more expensive and not very compatible with small-scale or educational-type projects. Over the past few years, a variety of intelligent control methods, such as PID (Proportional–Integral–Derivative) control, fuzzy logic controllers (FLCs), and artificial neural networks (ANNs), have been implemented to improve system stability and also to make them more resilient in the case of rapidly changing environmental conditions.[15,17,18] These predictive and data-driven algorithms hardly encounter transients because they eliminate transient errors, lessen actuator overshoot, and on top of that, they are able to adaptively tune parameters based on previous performance. The figure 2 delineates a conceptual schematic of a closed-loop LDR-based tracking configuration incorporating sensor feedback, control logic, and actuator response for real-time orientation correction.[6,8,12,18,22]

Comparative Performance Analysis

Repeatedly, empirical and experimental evidence have been ahead of the game in showing that sensor-based solar tracking systems are the primary factor in the increased energy conversion efficiency when compared to both fixed-tilt and time-based tracking configurations.[2,5,6,8] Performance evaluations under varying climatic conditions show that the use of light sensors, microcontroller-based control loops, and adaptive correction mechanisms results in a substantial increase of the energy captured, especially in the situations of partial cloudiness or transient irradiance, where static systems are not effective, i.e., they do not respond.[6,9,10] The major argument for the reported greening of the technology, which in most of the cases has been between 20 % and 45 %, is the improvement of energy output as demonstrated in table 3, and the reasons influencing it being the level of freedom of the axis, the precision of the actuator, and the control method used.[8,12,15] By putting the two main types side-by-side, dual-axis trackers are the ones having the highest potential for the capture of solar radiation because they are able to simultaneously make the adjustment along the azimuth and elevation planes, thus, keeping the almost perpendicular alignment during the diurnal cycle.[2,9,13]

While this geometry provides the largest energy gains, it also results in increased mechanical complexity, higher costs, and greater maintenance requirements, which generally limit its use to utility-scale or high-concentration photovoltaic (HCPV) systems.[5,13,15] However, improvements in low-power microcontrollers, stepper-motor actuation, and optimized feedback algorithms have recently made small dual-axis devices viable for the domestic, off-grid, and small-scale sectors, thus providing a good compromise between the enhancement of the efficiency and the affordability of the system.[10,12,17] Besides this, comparative studies indicate that smart and hybrid controllers, e.g., PID, fuzzy-logic, or ANN-based algorithms, have better dynamic stability, faster convergence, and lower energy loss in changing cloud conditions.[15,17,18,20] The results of the studies indicate that the integration of sensor-driven feedback with predictive or data-adaptive models is a fruitful area of research that can lead to the cost-to-performance ratio of next-generation real-time tracking systems getting improved.

Table 3. Comparison of Control Algorithms and Hardware Platforms for Real-Time Solar Tracking Systems

Control / Algorithm Type	Hardware Platform	Control Nature	Tracking Precision (°)	Power Consumption (W)	Cost Level	Key Advantages	Typical Limitations	Ref
Comparator-Based Analog Control	Operational amplifier (Op-Amp) circuits	Open-loop	3 – 5	< 2	Very Low	Simple, low power, easy to implement	No feedback, temperature-dependent offset	(6,8,9)
Microcontroller-Based PID Control	Arduino / PIC / STM32	Closed-loop	0,5 – 2	2 – 5	Low – Medium	Adaptive, precise, easily re-programmable	Requires tuning and calibration	(6,10,12)
PLC-Controlled System	Siemens S7 / Delta DVP	Closed-loop	0,5 – 1	5 – 8	Medium – High	Rugged industrial performance, multi-axis synchronization	High cost; limited flexibility for small systems	(14,15)
Fuzzy Logic Controller (FLC)	DSP / Microcontroller	Adaptive closed-loop	< 0,5	3 – 6	Medium	Handles nonlinearities; self-adjusting	Requires complex rule base; computational overhead	(15,17)
Artificial Neural Network (ANN)	ARM Cortex / Raspberry Pi	Predictive / Adaptive	< 0,3	4 – 6	Medium – High	Learns dynamic solar behavior; predictive capability	Requires training data; higher memory need	(17,18)
Model Predictive Control (MPC)	FPGA / Embedded system	Predictive / Hybrid	0,2 – 0,5	5 – 7	High	Fast convergence; robust to constraints	Complex implementation; expensive	(18,20)
IoT-Integrated Hybrid Control	NodeMCU / ESP32	Adaptive / Remote	0,4 – 1	3 – 4	Medium	Enables cloud monitoring; real-time analytics	Relies on network stability	(10,12,20)

Performance Optimization and Energy Yield Enhancement

The extent to which they can accurately follow the sun in real-time using solar sensors largely relies on the precision of the sensor and the fineness of the control. However, factors such as the mechanical action, weather conditions, and algorithmic adaptation still significantly influence the process. Research has shown that angular variations resulting from actuator inertia, backlash, and calibration errors may cause the energy output to be lowered by 5–10 % over a long period of time.[15,17,18] Thus, besides positional accuracy and stability over time, the mechanical part of the work is also very important in that not only does it raise the performance level but also makes it safer. Some of the means through which positional accuracy and stability over time may be enhanced are plastic or composite linkages of aluminum, low-friction bearings, and stepper drives with backlash compensated. Moreover, temperature and wind-speed sensors can also be employed to provide data for the adaptive control strategies that the system is performing. Actually, to prevent mechanical stress or overshoot, the system may choose to barely move during a period of instability caused by a sudden gust of wind. Adaptive gain tuning is one of the software-level methods that uses fuzzy logic or machine-learning models. It is a method that enables the system to foresee the necessity of changing the direction of the panel most likely in the case of cloud intermittency. Besides, in the case of hybrid systems, real-time irradiance data are always compared with the astronomical solar position models so as to shorten the tracking time. Figure 4 depicts the mutual dependencies between the tracking accuracy, actuator response time, and net energy gain. Therefore, it shows the idea of diminishing returns due to very high precision under low irradiance conditions.

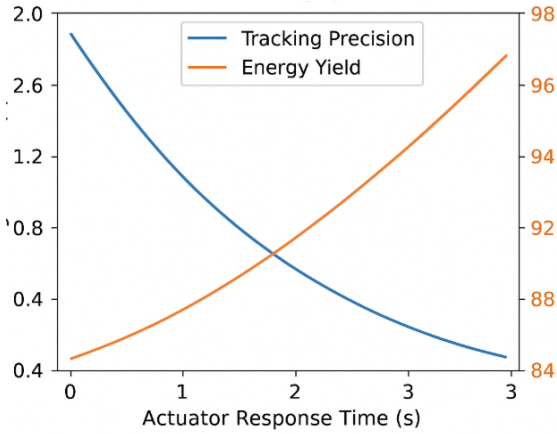


Figure 4. Relationship between actuator response time, tracking precision, and energy yield in sensor-based solar tracking systems

Environmental and Economic Considerations

Even though active solar tracking systems can significantly increase energy gains, their lifecycle benefits should still be weighed against other aspects such as cost, environmental impact, and system reliability. The total ownership cost is not only limited to the hardware (sensors, actuators, controllers) but also includes maintenance and calibration expenses in the long run. In a small-scale situation, should the actuation be done too frequently, it can result in the wear of components, therefore the system's economic advantage may be diminished. Hybrid control strategies that limit the number of movements by setting dead-band thresholds or regulating actuation intervals are usually employed to address the problem of the trade-off between efficiency and mechanical lifespan.[10,14,17] From the environmental perspective, solar tracking is an indirect means to the goal of sustainability because it allows for more efficient

use of land and reduces the number of PV modules required for the production of a unit of energy. However, the selection of materials for the mechanical parts remains the key problem. The adoption of recycled alloys, bio-based lubricants, and low-power electronics is consistent with the circular economy principles and decreases the embodied energy. Table 4 compares representative lifecycle parameters for fixed, single-axis, and dual-axis systems such as capital cost, energy payback time (EPBT), and maintenance frequency.

Table 4. Lifecycle and Sustainability Parameters of Solar Tracking Systems

System Type	Initial Cost (USD/kWp)	Energy Payback Time (Years)	Maintenance Frequency	Recyclable Component Share (%)	Expected Lifespan (Years)	References
Fixed Tilt	450-600	1,8-2,2	Annual	70-80	25-30	(5,10,14)
Single-Axis Tracker	650-800	1,5-1,8	Biannual	65-75	20-25	(6,13,15)
Dual-Axis Tracker	800-1100	1,2-1,6	Quarterly	60-70	18-22	(13,15,18)

Figure 5 compares the lifecycle cost and payback period of three photovoltaic (PV) configurations fixed, single-axis, and dual-axis solar tracking systems indicating figures in Indian Rupees (INR). The total lifecycle cost (in lakhs of INR) is shown by the blue bars, and the payback period in years, corresponding to it, is indicated by the red line with the square markers. The figure is an economic comparison that makes visible the trade-off between the investment cost and the financial return over time for various system architectures.

Firstly, fixed systems are reported to have the lowest capital and operational costs, which are about ₹15-20 lakh per installation on average, however, the payback period of such systems is still quite long (approximately 8 years) due to a low daily energy yield and the fact that the system is immobile. Single-axis trackers that keep the sun on one plane have a higher initial cost (around ₹35-40 lakh) but a payback period is shorter (5-6 years) because of the increased solar capture efficiency and the energy generation being stable throughout the day.When it comes to dual-axis systems, the need for more actuators, the control circuitry, and the increased maintenance make them the ones with the highest lifecycle cost that goes beyond ₹65-70 lakh.

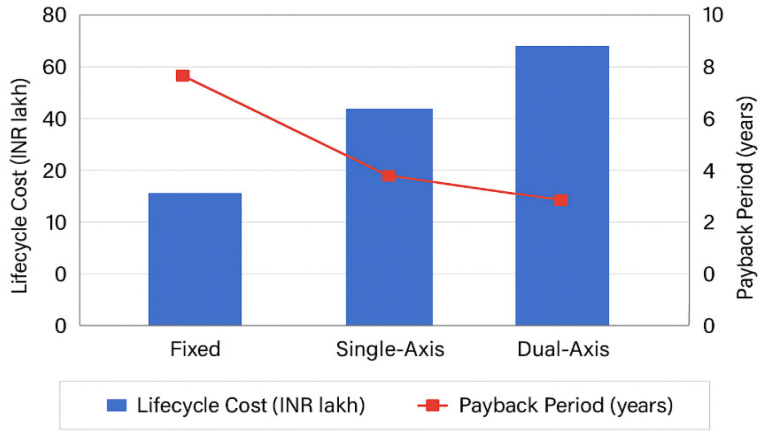


Figure 5. Comparative lifecycle cost and payback period for fixed, single-axis, and dual-axis solar tracking configurations

Still, their capacity to keep an almost perpendicular alignment with solar irradiance leads to maximum energy conversion and less dependence on seasonal tilt adjustments. The better yield can be a reason for the use of such systems in the utility-scale and high-concentration photovoltaic (HCPV) sectors despite the higher initial cost, where efficiency gain is more important than cost issues. The figure, in fact, conveys that system complexity increases the cost, but smart control algorithms, predictive tracking, and IoT-assisted monitoring can significantly decrease operational losses—thus enhancing both the economic return and the environmental benefit. Consequently, from a techno-economic viewpoint, single-axis active trackers frequently compose the best compromise between cost-effectiveness and performance for the majority of distributed and small-to-medium scale solar installations in India.

Future Research Trends and Technological Integration

Next-generation solar tracking systems are expected to digitally incorporate distributed intelligence, predictive analytics, and edge computing to become more adaptable and autonomous. The use of Internet of Things (IoT) platforms allows for remote diagnostics, energy forecasting, and performance optimization through cloud-based analytics. As an example, Node MCU and ESP32 modules with MQTT protocols can report the irradiance, voltage, and orientation in the local area in real time to the central dashboard for predictive maintenance.[18,20,22] Besides that, the latest research also indicates the development of reinforcement learning algorithms which optimize tracking schedules dynamically by using weather and energy yield data from the past. Essentially, the system learns how to save on the number of times it moves the tracker while still getting the maximum power output, thus reducing mechanical wear and maintaining high performance at the same time. Additionally, there are a number of concepts of self-powered tracking devices which generate the energy necessary for their operation from small auxiliary photovoltaic cells and therefore do not need an additional source of control power. The coming together of these digital and mechanical worlds is likely to set a new limit of cost-efficiency for solar tracking technologies. A conceptual model for AI integrated solar tracking ecosystem as shown in figure 6, therefore, is a fully interconnected system combining sensors, controllers, data analytics, and energy management interfaces within a single intelligent framework.

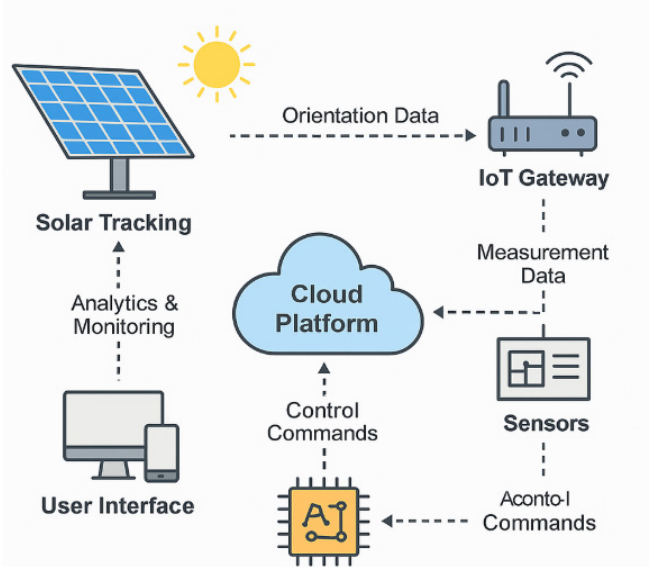


Figure 6. Conceptual architecture of an AI-integrated IoT-based real-time solar tracking ecosystem

Comparative Analysis of Emerging Sensor Technologies

To let the drift to intelligent monitoring systems, work in the sensor fusion field have been ongoing continuously. Sensor fusion refers to combining different sensing modalities such as optical, thermal, and inertial input to increase system resilience and get accurate readings.[5,9,13,17] This kind of fusion increases the system's capability to work under partial shading or diffused light conditions, scenarios in which an optical sensor might give contradictory feedback. A comparative analysis of the emerging and the conventional sensor technologies has been conducted in terms of their sensitivity, cost, and the potential for integration, as shown in Table 5. The comparison has shown that hybrid sensors and intelligent fusion architectures are most adaptable to changing environmental conditions.[15,18,20] Multi-sensor arrays that encapsulate more than just standard optical setups and combine Light Dependent Resistors (LDRs) with Micro-Electro-Mechanical Systems (MEMS)-based inclinometers or gyroscopes for obtaining orientation with an error of less than one degree are gradually being accepted.[13,17,19] Such a system becomes more robust as it is capable of offsetting the external disturbances like wind-induced vibration or intermittent irradiance variations. MEMS sensors, in particular, enable very short time intervals between each measurement of tilt and angular displacement thus allowing high-frequency monitoring with very low latency and great repeatability, and hence, they can be the perfect companions to optical detectors in hybrid control architectures.[17,19,22] Moreover, the ongoing miniaturization of MEMS components is also contributing to less energy consumption as well as the reduction of the structural weight—these being the features, for instance, of great use to lightweight or rooftop solar tracking platforms.[15,18]

Recent innovations in AI-aided data fusion algorithms have essentially broadened the functional scope of newly sensor technologies.[17,18,20] In particular, convolutional neural networks (CNNs) and ensemble regression models, which are machine learning techniques, have been employed to process multivariate sensor data streams. This is done to distinguish irradiance drops caused by atmospheric variations from those resulting to mechanical misalignment.[18,20] The proposed systems enable the realization of correction and the acquisition of adaptive calibration in real-time, which thus enhances the operational stability during the occurrence of weather transients. In addition, the use of pyranometer-based irradiance sensors and infrared (IR) detectors lead to the spectral responsiveness of the tracking system whereby the alignment is guaranteed under different solar conditions.[15,18,22]

Table 5. Comparative Characteristics of Emerging Sensor Technologies for Smart Solar Tracking Systems

Sensor Technology	Measurement Principle	Average Power (mW)	Data Fusion Capability	Precision (°)	Integration Suitability	Ref
LDR Array	Photoresistive light intensity differential	10–15	Moderate	±2–3	High (low-cost)	[5,6,8]
CCD Image Sensor	Sun centroid computation via image processing	150–300	High	±0,2	Medium (AI-based)	[15,18,20]
MEMS Inclinometer	Measures tilt angle via acceleration sensing	50–100	Very High	±0,5	High (industrial)	[17,19,22]
Hybrid Pyranometer-LDR	Combines irradiance and directional sensing	80–120	Very High	±0,4	High (research-grade)	[15,20,22]

Taken together, these developments point to a definite move towards self-calibrating, intelligent sensor networks that are able to learn continuously and optimize their functioning—

being the foreseen solar tracking ecosystems that are autonomous and predictive.[18,20,22]

Reliability, Maintenance, and Field Performance Evaluation

Long-term reliability is still a very important factor that largely decides whether solar tracking systems can be economically viable, especially if they are used outdoors, where the temperature varies, and the equipment is exposed to dust and mechanical wear. To maintain the highest possible alignment accuracy and to avoid the degradation of the actuator, regular maintenance is necessary. In their findings, researchers have highlighted that contamination of the sensor lens and wear of the bearing are the most common reasons for the inaccuracy of tracking, which results in losses of energy up to 5 % per year if no actions are taken to rectify the situation.[13,15,17] The implementation of different measures, such as periodic sensor recalibration, installation of protective housings and the use of automated fault detection algorithms, noticeably contribute to the equipment's availability time and decrease the time when the equipment cannot be used due to an operational fault. Vibration sensors and current feedback loops, which are part of the control system, are additionally used in condition-based maintenance to locate defects and to schedule maintenance only when it is necessary in very reliable and sophisticated setups. Besides that, the use of IoT dashboards for real-time performance monitoring provides an opportunity for remote fault diagnostics and, thus, enables the scheduling of component replacement in a predictive manner, which in turn leads to a reduction of the average time of repair (MTTR). Various failure modes that can be compared, their causes, and the methods of overcoming them for single- and dual-axis tracking configurations are given in table 6.

Table 6. Common Failure Modes and Maintenance Strategies in Real-Time Solar Tracking Systems

Failure Mode	Primary Cause	Affected Component	Impact on System Performance	Recommended Mitigation / Maintenance Strategy	Ref
Sensor Drift or Misalignment	Dust accumulation, thermal stress	LDRs / Photodiodes	Reduced tracking precision (±3–5° deviation)	Regular cleaning, calibration, sealed sensor enclosure	[13,15,17]
Actuator Backlash	Mechanical wear, insufficient lubrication	Stepper / DC Motors	Increased positioning error, energy loss (2–4 %)	Use of anti-backlash gears, scheduled lubrication	[14,16,18]
Control Circuit Failure	Voltage spikes, humidity	Microcontroller / PLC	System shutdown, tracking halt	Surge protection, conformal coating, temperature monitoring	[10,12,17]
Structural Deformation	High wind loads, weak mounts	Tracker frame / support	Misalignment, loss of tracking range	Reinforced joints, wind-speed-based stow mode	[15,18,20]
Communication Failure	Network dropout, software fault	IoT / Communication module	Loss of data logging and remote control	Backup communication protocol, periodic firmware update	[18,20,22]

AI-Driven Predictive and Adaptive Solar Tracking Systems

The integration of advanced artificial intelligence (AI) technologies has led to the evolution of traditional solar tracking systems into smart, autonomous, and adaptive units that derive their

knowledge from operational data.[17,18,20] Such systems have machine learning (ML) and deep learning (DL) algorithms embedded in them for the purposes of solar irradiance forecasting, anomaly detection in the system's performance, and hence they are able to make the tracking of the solar radiation incident angles non-interrupted and accurate in real-time by themselves. For example, Artificial Neural Networks (ANNs) receive training by matching the examples of past irradiance and angular position data tuples so that they can later predict the most efficient tilt and azimuth even before the changes in the surroundings have taken place.[18,20] Such an act of anticipation drastically cuts down on the number of times the actuator has to be moved, saves energy, and at the same time diminishes mechanical wear as compared to reactive feedback mechanisms.[17,22] To foresee solar trajectories on a very short basis, a combination of a Convolutional Neural Network (CNN) and a Recurrent Neural Network (RNN) is being looked into more and more in which the opening of the sky and weather conditions at that moment are the inputs.[18,21] The diagram in figure 7 depicts the underlying structure of an AI-driven adaptive solar tracking system that gathers data from various sensors, uses cloud-based models for prediction, and then sends the control feedback to the actuator.

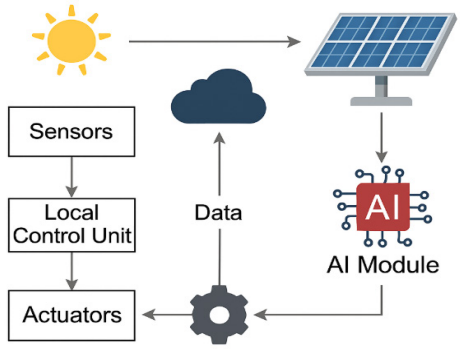


Figure 7. Schematic representation of an AI-assisted predictive solar tracking system

Here, the local control unit is responsible for the initial filtering and normalization of the sensor signals, and the cloud-based inference model carries out the computationally intensive prediction tasks. Such a hybrid computing architecture is energy management optimized and is made scalable for PV plants of large capacity. Besides, the use of reinforcement learning (RL) algorithms is becoming the next generation challenge in this field, thus giving the possibility to the systems to improve by themselves the control policies through rewarding energy gains and punishing the unnecessary actuator operations.[17,20,22]

IoT-Based Monitoring and Cloud Connectivity

Internet of Things (IoT) technology integration with solar tracking makes it possible to have a continuous, remote monitoring of performance metrics, fault conditions, and energy analytics.[10,12,18] IoT-enabled trackers use an embedded microcontroller (e.g., ESP32, Node MCU) with Wi-Fi or LoRa connectivity to send real-time data such as irradiance, temperature, current, and voltage to centralized cloud servers.[12,20] This up-to-the-minute monitoring allows for smart diagnostics that can be used for predictive maintenance and anomaly detection through cloud-based dashboards. Figure 8 shows the standard IoT-based solar tracking setup, consisting of locally controlled tracking units communicating via a cloud network. Each unit is equipped with sensors, a microcontroller, and actuator drivers connected to a web or mobile interface for live monitoring.

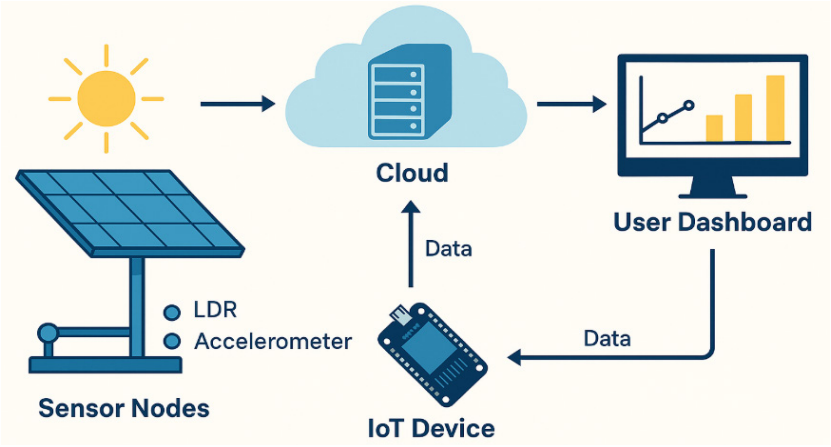


Figure 8. Architecture of an IoT-enabled real-time solar tracking network

The integration of AI with IoT devices paves the way for smart devices at the edge, where first-level analytics are locally handled to cut down on the delay and the expense of data transfer.[18,20] As an example, local anomaly detection can be carried out by simple ML models that are hardware-in-the-loop within ESP32 units, with only the processed summaries being sent to the cloud. The method energy consumption is thus drastically reduced, and system reliability is increased.

Table 7. Comparison of IoT Communication Protocols Used in Real-Time Solar Tracking Systems

Protocol	Frequency Band	Range (m)	Data Rate (kbps)	Power Requirement	Suitability / Application	References
Wi-Fi (IEEE 802,11)	2,4 / 5 GHz	50-100	1500 - 6000	Moderate	Short-range, high data transmission	[10,12,20]
LoRaWAN	868 / 915 MHz	2000 - 10000	0,3-50	Very Low	Rural/off-grid solar farms	[15,18,22]
Zigbee	2,4 GHz	100-300	20-250	Low	Mesh-based residential tracking systems	[12,15,20]
MQTT (over TCP/IP)	-	Cloud-linked	-	Low	Cloud communication protocol for monitoring	[18,20,22]
Bluetooth BLE	2,4 GHz	10-30	125-2000	Very Low	Local configuration and calibration	[10,12,18]

Sustainable Design and Techno-Economic Feasibility

Solar tracking systems' design and their implementation are deeply influenced by sustainability factors that aim to become, in the near future, the main concern of the indus- try. In India and other emerging solar markets, techno-economic optimization is the process of balancing capital expenditure (CAPEX), operational efficiency, and environ- mental impact.[6,14,17] The change of heavy metallic frames to the light- weight composite structures or recycled aluminum alloys lowers not only the cost but also the embodied energy, while modular assembly enables easy maintenance and component reuse. The sustainability assessment model in figure 9 exemplifies

the interac- tion of the design parameters (material selection, control algorithm efficiency, and maintenance frequency) with the overall lifecycle cost.

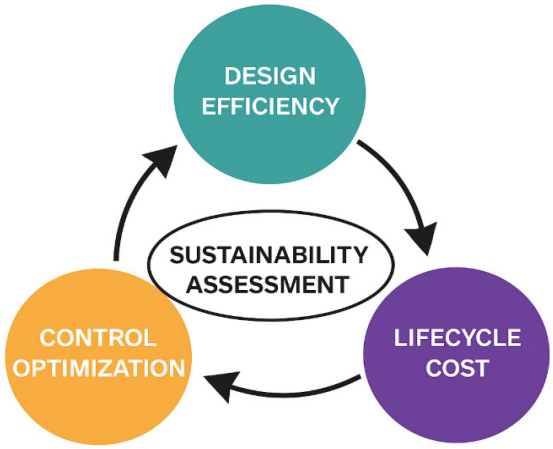


Figure 9. Sustainability Assessment Model (flow/interaction diagram) in solar tracking systems

The techno-economic study across various Indian PV setups suggests that the use of single-axis active trackers can lower the levelized cost of energy (LCOE) by about 8–12 % as compared to fixed systems. At the same time, dual-axis devices provide a higher energy yield but entail a longer payback period.[6,15,18] Environmental indicators such as energy payback time (EPBT) and CO_2 offset reveal that hybrid sensor-equipped systems may reduce emissions by as much as 20–25 % during their total operational time because of better irradiance capture.[14,18,20] These findings put the emphasis on the decisive leverage of smart automation and eco-friendly design for economically and environmentally sustainable solar energy systems.

Oil and Gas Automation

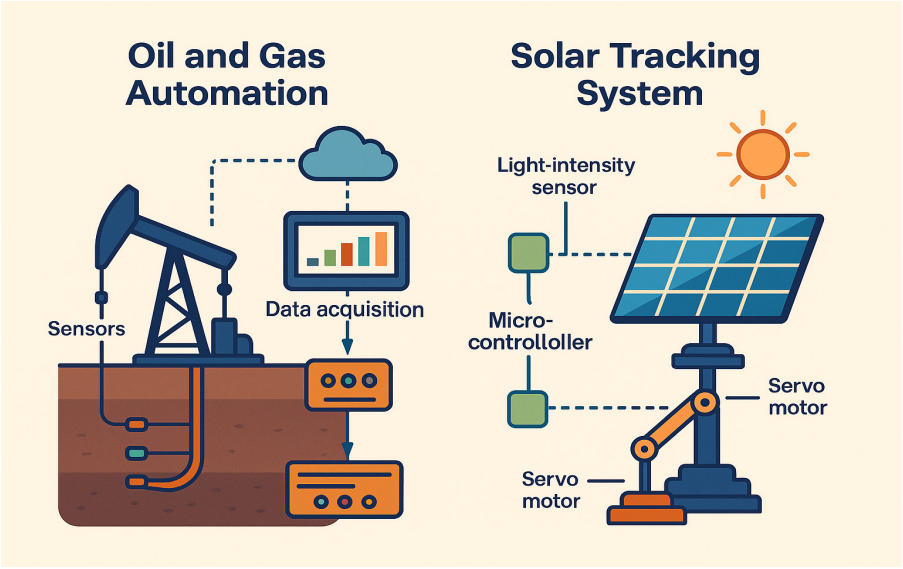


Figure 10. Oil and Gas Automation with Solar Tracking System

Table 8. Key Components and Functional Roles in Oil & Gas Automation and Solar Tracking Systems

System	Component	Function / Description
Oil & Gas Automation	Subsurface Sensors (Pressure, Temperature, Vibration)	Capture real-time wellbore and equipment conditions for monitoring and control.
	Data Acquisition Unit	Aggregates signals from distributed sensors and transmits data for processing.
	Processing & Control Module	Interprets sensor trends and executes automated adjustments to operational parameters.
	Supervisory Control System	Oversees system-wide behavior and coordinates automated valve or pump actuation.
	Automated Actuators / Valves	Implement control actions such as regulating flow, pressure, or drilling parameters.
Solar Tracking System	Light-Intensity Sensors	Detect differential sunlight intensity to identify optimal panel orientation.
	Microcontroller	Processes sensor input and calculates necessary panel adjustments.
	Servo Motors (Dual-Axis)	Reposition the solar panel to maintain perpendicular alignment with sunlight.
	Solar Panel Assembly	Converts incident solar radiation into electrical energy with enhanced efficiency under tracking.

Applications in Domestic and Industrial Energy Systems and Challenges and Future Trends

Due to their easy operation, flexibility, and increased power output low-cost, sensor-based solar tracking systems have been rapidly adopted in the domestic and industrial energy sectors. In the case of residential applications, these trackers can be found on rooftop photovoltaic (PV) modules, street lighting, agricultural irrigation, and stand-alone hybrid systems, where small size and low power consumption are the most important factors.[5,6,8] Real-time LDR and photodiode-based tracker devices that can adapt to changing solar conditions and keep the panel in the optimal orientation are the main factors for the daily energy yield increase, especially in distributed renewable microgrids and rural electrification projects.[6,9,12] On the other hand, solar tracking systems are used as extensively as possible in big-scale photovoltaic farms, solar thermal power plants, and concentrated photovoltaic (CPV) setups in the industrial scenarios, where higher precision and dual-axis control lead to conversion efficiency and thermal capture increase.[9,13,15] Furthermore, when contemporary tracking systems are combined with IoT structures they make it possible to perform remote monitoring, data logging, and predictive maintenance, thus facilitating real-time performance analysis and smart-grid compatibility.[10,12,20] The same connectivity also improves energy management by synchronizing generation profiles with load demand on a short-term basis, thus allowing for grid stability and distributed energy optimization.[15,20,25]

Even so, a variety of technical issues have been impeding the large-scale deployment of such devices. Some of the frequently reported problems are the wearing of the actuator, the degradation of the device by the environment, and calibration drift of optical sensors in dusty,

humid, or UV-radiated places.[8,13,15] Besides, sensor saturation under a strong irradiance along with the temperature cause resistance variations that can lower detection accuracy and, thus, misalignment can occur over time.[6,9,17] Additionally, it is still a tough and long-term challenge to find a solution that will provide mechanical robustness and at the same time low energy consumption will be balanced in tracking motors, especially for those that are designed for continuous outdoor operation.[12,18] The emergence of research on this topic is predicted to be focused on the implementation of artificial intelligence (AI) and machine learning algorithms for predicting solar position and making decisions dynamically.[17,18,20] By integrating optical, infrared, and astronomical feedback, sensor fusion architectures will be less dependent on changes in the sky that are due to the weather.[22,25] In addition, the progress in energy-efficient motor drivers and low-power microcontrollers will lead to further system sustainability improvements. The creation of hybrid solar trackers which exploit the advantages of both sensor-based and astronomical models is, in fact, the most considerable potential to overcome the accuracy issue, provide the device with the ability of self-calibration and make it resistant to the environmental fluctuations.[15,17,25]

CONCLUSIONS

The use automation integration across both traditional and renewable energy systems is a clear example of how advancements in sensing, real-time data processing, and intelligent control can significantly change the level of operational efficiency and reliability. In the case of oil and gas environments, distributed sensor networks and automated supervisory systems provide the ability to control and stabilize complex subsurface operations as well as reduce the variability that depends on humans. On the other hand, solar tracking systems that depend on lightweight, inexpensive sensor arrays demonstrate how similar control principles can be used to improve photovoltaic performance without the need for advanced technological intervention. The comparison reveals that behind the frontier of contrasting energy domains there is a common engineering foundation—adaptive sensing, continuous monitoring, and responsive actuation. The evolution of energy systems into hybrid and interconnected infrastructures makes the knowledge obtained in both sectors the possible source of the future smarter, more resilient, and more sustainable automation frameworks. The review charts the development and increasing significance of real-time, inexpensive solar tracking devices that are pivotal in the efficient conversion of photovoltaic (PV) energy. From the study of sensor technologies, control algorithms, and the resulting performance, it is very clear that sensor-based tracking systems, especially those using Light Dependent Resistors (LDRs), are a technically and economically viable solution. These systems, by constantly adjusting the solar panels to the sun's position, are capable of increasing the energy output by 20–45 % as compared to fixed ones, the control precision and the prevailing weather conditions being the factors influencing the variation of the range. The research also points out that although the dual-axis systems have the potential to capture maximum solar irradiance, their mechanical intricacy and the power requirement of the actuators are the major issues that limit their large scale usage. However, the progress in microcontroller platforms, IoT integration, and the development of intelligent control algorithms like PID, fuzzy logic, and neural-network-based predictive control has started to close this gap by enhancing the system's responsiveness, flexibility, and optimization based on data.

Also, the addition of cloud connectivity and remote diagnostics has made modern trackers key elements of the smart energy systems of the future. While significant advancements have been made, the issue of long-term operational stability is still heavily reliant on the need to further sensor durability, enhance their calibration, and improve their mechanical parts even when it is difficult to have them outdoors in the nature. Several new directions in the field of study reveal to the creation of hybrid tracking architectures that combine sensor-based feedback with astronomical and AI-driven predictive models, thus giving better accuracy and

robustness at different sky conditions. The emergence of energy-efficient actuators, self-learning algorithms, and adaptive sensor fusion frameworks will be instrumental in the evolution of the next generation of eco-friendly, intelligent solar tracking technologies that can be used both at home and in industry.

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FINANCING

None.

CONFLICT OF INTEREST

None.

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