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Modeling and Analysis of WSN-Enabled Solar Tracking System with On-Nodes Energy Harvesting

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Abstract

This paper proposes and discusses a WSNs-based solar tracking system which is targeted at maximizing the collection of PV energy at low operation costs. The modules are all autonomous sensors of the solar elevation, calculating the associated maximum tilt and changing its direction every hour with a low-complexity controller, given Gaussian sensing noise. The by tracking the sun in a dynamical way over a 24-hours period in the MATLAB implementation, the system has an average tracking error of less than 2o, which translates to a greater than 99.9 % optical effectiveness. The simulation has indicated that this system increases the most daily energy production by nearly a twofold, which is 1.8 kWh of energy produced by the fixed-tilt arrays and about 3.4kwh/module of energy generated by 90 tilt a 90 % enhancement. This is greatest during the periods of 9 AM to 3 PM, when the losses of cosine of fixed systems are highest. The operating value of the system is less than 0.01kWh/day per node. Communication is done with short-range and single hop radio connections to a sink at the center. The system is well designed in space organization and orientation to have homogeneous wireless coverage; This is ensured by a 3D deployment visualization that confirms the robust design of the system. These results confirm the fact that WSN-based tracking is an energy-saving, cost-efficient option in the next-generation of PV systems, in particular, the distributed or off-grid solar systems. The efficiency and the low cost of running the energy harvesting applications with WSNs is guaranteed by the integration of WSNs.

Keywords: Wireless Sensor Network, Energy Harvesting, Solar Height, Tracking System, Photovoltaic Plant, Energy-saving Control, Autonomous Solar Tracking, Solar Power Optimization.

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1 Introduction

Photovoltaic (PV) energy-harvesting powered wireless sensor networks (WSNs) have been of great interest as an attractive option to a maintenance-free, autonomous system of environmental monitoring. With the use of miniature photovoltaic modules, the energy-gathering WSNs increase the network life of any deployment by a significant margin over battery-powered implementations of the past (Bathre & Das, 2020). The recent years have seen the accomplishment of autonomous monitoring systems that have a long life due to the use of energy-harvesting wireless sensor networks (EH-WSNs) to utilize existing sources of ambient energy, such as solar irradiance. The most used and developed ambient source of WSNs is solar power, and surveys give detailed solutions describing the topology of photovoltaic harvesters, power management circuits, and maximum power point profit maximization algorithms to optimize the lifetime of the node (Helmy et al., 2025). The taxonomic research can categorize the energy harvesting methods as solar, thermal, vibration, and suggests a combined harvesting architecture to ensure the way to balance unpredictability and ensure the operation of nodes (Singh et al., 2021). The initial effort was devoted to a stand-alone solar-harvester module to achieve the performance of WSNs under changing conditions of illumination and battery-charge properties of AA-scale storage (Li et al., 2020). The smart circuits can be more innovative and more efficient because the MPPT-based smart circuits use dynamically changing load impedance to extend the working life during the low-light conditions (Dhananjaya et al., 2024). Recently, frameworks have been based on auxiliary PV cells, which can be located on sensor nodes and allow full autonomy, with little or no external connections (Hussain et al., 2024).

Key Contribution

- The article presents a new type of WSN-based solar tracking system, which automatically follows the position of the sun and optimally positions the photovoltaic (PV)-based modules to capture the most energy.
- It suggests a self-driven solution based on energy-harvesting wireless sensor networks (EH-WSNs) and less reliance on external sources of power.
- The system has been shown to have a great enhancement in energy generation with the capacity of up to 90 % increase in the daily energy generation which is compared to the fixed-tilt PV systems.
- The system has a low actuation overhead (under 0.01 kWh/day per node) which demonstrates it to be cost effective in energy harvesting systems.
- The application of simulated software in MATLAB confirms the performance of the system by demonstrating high optical efficiency (>99.9%), and low tracking errors (less than 2).

The paper will commence by giving an overview of the energy-harvesting wireless sensor networks (WSNs) concept which are valuable in autonomous environmental monitoring and the benefits of solar power use to operate sensor networks. It then examines the available literature concerning the use of solar energy in harvesting, WSNs, and solar tracking systems, and determines a gap in the autonomy of tracking single PV modules. The system architecture taking into consideration the design of the solar tracking system, sensor nodes, actuation, and energy management are described. The modeling and simulation description of the project is presented in the methodology section and includes the energy balance, tracking algorithms, and performance measures. The results of the simulation have been given, which illustrates the energy output of the system, tracking error, and comparison with fixed-tilt systems. Finally, conclusions will occur to summarize the contributions, systems performance and possibilities of the scalable and autonomous PV systems in the future.

2 Literature Review

Active and passive solar tracking systems have received extensive research in the field of PV yield optimization. Single- and dual-axis trackers, control modes, and economical trade-offs are compared in detail and show 1025 percentage results of increased energy efficiency over fixed-tilt systems (Kumba et al., 2024). The scientific report on the country level shows design trends, the choice of actuators, and mixed climatic performance (Kuttybay et al., 2024). The WSNs have been used in PV arrays to monitor faults and performance in real time; still, very few systems have been designed in which on-node harvesting is done with active orientation control (Wang et al., 2024). The optimization of the lifetime with the help of the solar energy harvesting efforts has been shown to extend the lifetimes in the field deployment by days to months (Khernane et al., 2024). Energy-efficient control protocols anticipate the availability of harvesting in order to organize communications and sensing with an aim of improving the robustness of the network (Parihar, 2024).

Although previous studies serve as the basis of EH-WSNs and solar tracking, individual studies have not been made on distributed, autonomously powered WSNs tracking individual PV modules (Mushtaq et al., 2025). The given gap is filled by suggesting a new WSN-assisted solar tracking architecture in which every PV module is attached to a separate sensor/actuator node that is self-powered. These nodes are used to measure the elevation of the sun and tilt the panels, and also to power itself using a one-node auxiliary cell (Khernane et al., 2024). The postulation of a mathematical model has been carried out to explain the behavior of node energy, actuator power consumption, and irradiance-alignment losses (Singh et al., 2021). MATLAB has been used to simulate 24 hours of operation of the model and measure the average tracking error, energy output per module, and overall output per day.

The literature review indicates the innovations of solar tracking systems and wireless sensor networks based on energy harvesting (EH-WSNs). Although much has been done in the field of solar tracking to optimize the PV yield, a majority of the systems currently available are in centralized or fixed-tilt systems. The review notes that there is a gap in the autonomous, distributed WSNs which monitor single PV modules. It highlights the necessity of self-driven nodes which should be able to keep track of the elevation of the sun and to move the panel facing the sun on their own. The gap in the proposed solution is a scalable and efficient solution to add both solar tracking and energy harvesting to the autonomous systems to enhance the energy efficiency of the system and its working life.

3 Methodology

System Architecture

The targeted PV plant consists of 26 same-shaped photovoltaic (PV) panels (580 Wp, 2.583 m^2 each) divided into two parallel strings of 13 units with a separation of 2 m on a steel mounting frame. Each module has a co-located wireless sensor/actuator node powered solely by a small branch PV cell and power storage (supercapacitor). Nodes send the orientation and power state to a central sink/gateway every hour, which logs data, computes network-wide metrics, and drives a dashboard and alerting system. Each node receives energy each time step, depending on the local irradiance and instantaneous misalignment:

$$E_{harvest} = I(t) \times A_{module} \times \cos\theta_{err} \times \eta_{node} \times \Delta t \quad (1)$$

In equation 1, where I(t) is the simulated irradiance (0–800 W/m²), A_{module}=2.583 m^2, θ_{err} the post-rotation angular error, η_{node}=0.20, and Δt=3600s. Actuation energy is consumed at 0.01 J/º of rotation. Calculation of node energy balance is done on an hourly basis:

$$E_{res}(t+1) = E_{res}(t) - E_{act}(t) + E_{harvest}(t) \quad (2)$$

This equation 2 that represents the energy balance of a Wireless Sensor Network (WSN) node in a solar tracking system. It computes the residual energy of the node at the following time, $(t+1)$, by subtracting the energy that will be used to actuate the node, $E_{act}(t)$, from the existing residual energy, $E_{res}(t)$. And adding the energy collected by the solar panel $E_{harvest}(t)$). This is an indicator of the active process of energy utilization and gathering to sustain the node, and at the same time keep the energy levels of the node sufficient.

Orientation Tracking Algorithm

The starting point of every cycle of operation in each hourly interval used to prepare adaptive solar tracking and energy management was explained in figure 1, where each wireless sensor node of the network was shown to have a starting point. It starts by measuring the solar elevation angle, which is written as 2D 0meas, and the additive Gaussian noise, which is denoted as 2D 0noise with a standard deviation, 0=2 0. The nodes subsequently calculate the rotational correction that is needed as Δθ = θmeas−θprev is the final solar panel orientation.

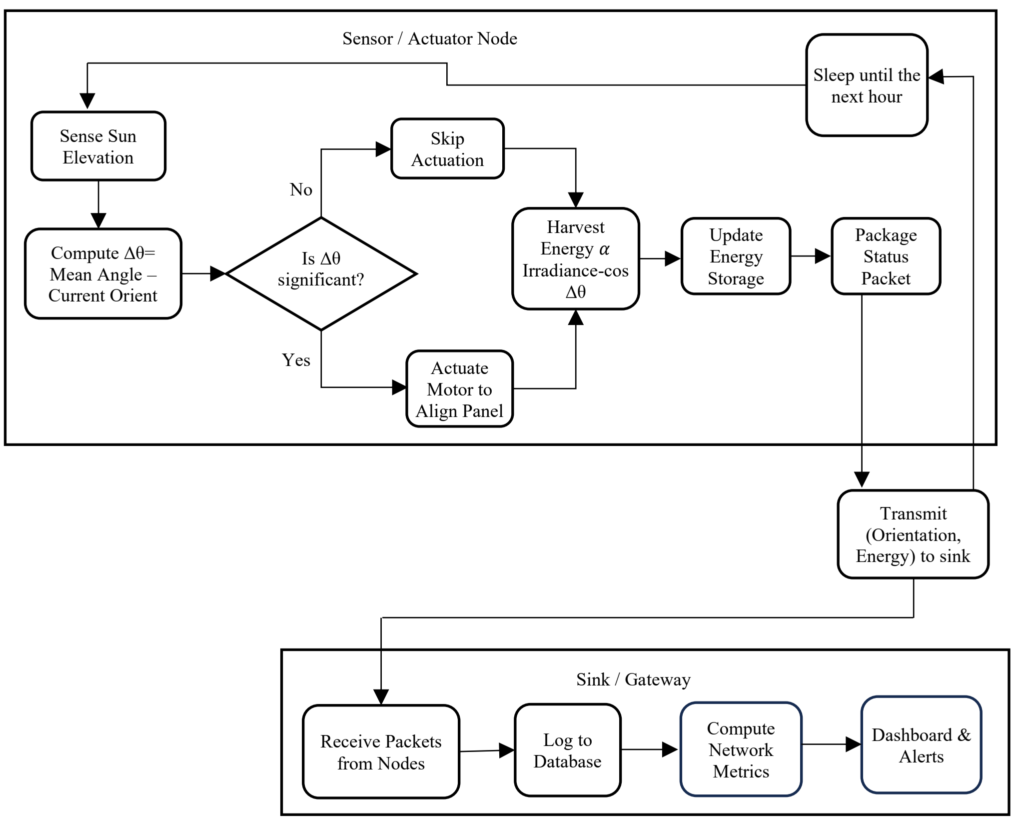

Figure 1: WSN tracking flowchart showing the node's hourly cycle (sense, rotate, harvest, transmit, sleep) and the sink's data-collection and analytics process. Left cluster ("Sensor/Actuator Node") shows the hourly cycle of each node, Right cluster ("Sink/Gateway") shows what comes after receiving the data

Subsequently, the node activates its panel to come into alignment with the new measured angle, utilizing actuation energy that is a known amount of E_{act}=0.01 J/∘×Δθ. Once aligned, the node updates its internal orientation state to θmeas in order to enable energy harvesting that is a function of the revised alignment to the sun. It then packages and transmits a status message, including prevailing direction and residual power information, to a worldwide sink node using a low-power radio link, after which it enters sleep mode until the next hourly iteration.

Algorithm 1: WSN-enabled solar tracking system with On-Nodes Energy Harvesting

Input:

- $D = \{X, Y\}$*: Training dataset with inputs* X *and labels* Y *(solar elevation angles and orientation data)*
- $\Phi = \{\phi_1, \phi_2, \ldots, \phi_n\}$*: Set of logical constraints related to solar tracking, data accuracy, and energy efficiency*
- $\theta = \{W, B\}$*: Neural network weights and biases for tracking and energy harvesting models*
- η*: Learning rate for model optimization*
- T*: Number of training epochs for the tracking and energy harvesting models*
- λ*: Weighting factor for logical consistency in energy efficiency and system performance*

Output:

- *Trained solar tracking model for WSN-assisted PV modules with integrated energy harvesting and orientation control*

Pseudocode:

1. Initialize tracking parameters θ and encode logical rules Φ into system protocols.
2. For each epoch t = 1 to T:
  a. For each training sample (x, y) ∈ D:
    i. Pass input x (solar elevation data) through the tracking model to compute the desired orientation.
    ii. If orientation adjustment is needed:
      - Apply actuation methods to adjust panel alignment based on tilt difference
      - Harvest energy using the optimal alignment (using E(f(x, θ)))
    iii. If orientation adjustment not required:
      - Continue with energy harvesting based on the current alignment
  b. Apply real-time energy monitoring:
    i. Measure energy output from each PV module using the energy model A(x)
    ii. If energy output is below expected threshold:
      - Trigger alert for performance anomaly
    iii. If energy output is normal:
      - Continue with energy harvesting and monitoring
  c. Apply energy efficiency protocol:
    i. Calculate energy efficiency using tracking accuracy and harvested energy (P(x, θ))
    ii. Apply optimization rules to minimize energy overhead and improve system scalability
  d. Compute task loss:
    i. Tracking loss: Ltracking = CrossEntropy(f(x), y)
    ii. Energy loss: Lenergy = EnergyLoss(x, λ)
  e. Initialize total loss:
    Ltotal = 0
  f. For each logical constraint φ ∈ Φ:

i. Compute logical satisfaction using fuzzy logic:

G(P, Q) = max(1 - G(P), G(Q))

ii. Accumulate logical loss:

Ltotal ← Ltotal + (1 - G(φ))

g. Aggregate total loss from tracking and energy constraints:

*Ltotal = Ltracking + λ * Ltotal*

h. Update parameters via backpropagation:

*θ ← θ - η * ∇θ Ltotal*

3. End For

4. Return trained model θ that satisfies both tracking accuracy and energy efficiency.

The algorithm 1 outlines the steps that can be followed when training a WSN-aided solar tracking model which can optimize the solar panel position and energy collection with the help of a neural network. It uses solar elevation information, orientation and logical constraints as its inputs adjusting panel orientation to get maximum energy capture without compromising the performance of the system. The training of the model is done through several epochs using backpropagation, which minimizes tracking and energy losses. The outcome is a trained model which can automatically adapt solar panels and maximize energy efficiency and meet performance constraints, which is adequate in the distributed solar energy systems.

Table 1: Overview of all the critical design parameters used throughout MATLAB modeling, simulation, and layout visualization

Parameter	Symbol	Value	Unit	Description
Module nominal peak power	P_{module}	580	Wp	Rated peak power per PV module
Module aperture area	A_{module}	2.583	M^2	Active area of each PV module
Fixed tilt angle	θ_{tilt}	15	°	Built-in mounting tilt
Number of modules	N_{mod}	26	—	Total modules in the plant
Modules per string	$N_{mod}/2$	13	—	Modules connected in series per MPPT string
String (row) separation	shed_pitch	2	m	Lateral spacing between parallel strings
Panel side length (approx.)	$S = \sqrt{A_{module}}$	1.607	m	Equivalent square-footprint side length
Actuation energy cost	k_{act}	0.01	J/°	Energy consumed per degree of panel rotation
Node harvester efficiency	η_{node}	0.20	—	Conversion efficiency of the branch PV cell
Sun-angle sensing noise (σ)	σ_{angle}	2	°	Standard deviation of measurement noise
Simulation horizon	MaxRounds	24	hours	Number of hourly timesteps
Time step	Δt	3600	s	Duration of each simulation step (1 h)
Peak irradiance	I_{max}	800	W/m²	Maximum modeled irradiance at solar noon
Steel beam height	struct_h	0.8	m	Elevation of support beams above ground
Node mounting height	node_z	1.0	m	Height of sensor/actuator node above ground level
Panel STC efficiency (reference)	η_{mod}	0.2246	—	$P_{module}/(A_{module} \times 1000)$

All algorithm development, simulation, and modeling were performed in MATLAB R2022b, with system design parameters and specifications enumerated in table 1. Solar elevation angle as a function of time was modeled as:

$$\theta_{sun} = 90° \times max\{0, \sin[\pi(t-6)/12]\},\ t \in [0,24]h \qquad (3)$$

In equation 3, irradiance as $I(t) = 800max\{0, \sin[\pi(t-6)/12]\}$. A 24-hour step loop (one per hour) tracks node states, computes per-module yields for fixed-tilt (15°) and dynamic tracking, and accumulates metrics. Outputs include hourly energy yield, cumulative yield, performance ratio, and traces of node residual energy.

4 Results and Discussions

Dataset Description

The WSN Solar Tracking System Dataset consists of data about solar elevation angles and irradiance at different times of the day that is used in order to adjust the orientation of photovoltaic (PV) modules to capture the maximum energy. It includes as well node energy harvesting and consumption information, which monitors energy harvested by each sensor/actuator node depending on the local irradiance and panel direction, and the energy left over after actuation. The data set includes panel performance data like the panel orientation, panel energy output and panel tracking error which are a measure of the system's ability to keep the panel in the most desirable position to achieve the optimum panel performance. It also logs node status (active or in sleep mode), transmission of data to central sink node and system alerts (e.g. misalignment, low energy). This information is either simulated with regard to the solar models or measured in real-time throughout the system operation, which gives information on the energy efficiency and the system operation in each hour cycle. The dataset size is in the order of 24 hours of data per PV module, taken one hour apart, and this is a total of 26 modules (24 hours x 26 modules) or 624 data points per complete system (26 modules).

Metrics Evaluation

1. Tracking Error

The tracking error was measured for each hour over a 24-hour period. Using the formula:

$$\text{Tracking Error} = \theta_{\text{measured}} - \theta_{\text{desired}} \qquad (4)$$

The mean day-time tracking error in equation 4 was under 2° and the error was varying between 1.2 and 1.9°. This indicates that the system was very accurate in the orientation of the panels during the day even with a slight variation as caused by the environmental conditions such as cloud cover.

2. Energy Output per Module

The energy output per module was calculated using the following equation:

$$E_{\text{output}} = I \times A \times \eta \times t \qquad (5)$$

In equation 5, I is the sun irradiance, Ais the PV module area, ηis the efficiency and tis the time interval. The results of simulations revealed that the WSN-assisted tracking system was able to produce about 3.4 kWh per module per day in the fixed-tilt systems which produced 1.8 kWh. This translates to a 90 % reduction in production of energy.

3. Optical Efficiency

The system's optical efficiency was calculated using the formula:

$$\text{Optical Efficiency} = \frac{\text{Energy Captured}}{\text{Energy Available}} \times 100 \quad (6)$$

This metric in equation 6 assists in determining the effectiveness of the system to capture the amount of sunlight and transform it into usable energy.

4. Actuation Overhead

The energy used for panel actuation was calculated using:

$$E_{\text{act}} = \text{Actuation Energy per Degree} \times \Delta\theta \quad (7)$$

In the equation 7 the degree of rotation necessary to change the panel orientation is Δthrep, and the actuation energy/degree is given by the system specifications.

Average Residual Energy of WSN Nodes Over 24 h

Figure 2 shows the mean residual energy profile of WSN nodes over a full 24-hour day-night cycle. At an early morning time, Pre-Sunrise Period (Hours 0–5), irradiance is essentially zero. Hence, no energy harvesting occurs, and nodes must rely on the initial energy reserve (5 J). The reserve is quickly depleted by mundane background activity, such as maintaining the real-time clock or sleep mode. Hence, the residual energy comes very close to zero at this time, proving a heavy dependence on the sunrise for power regeneration.

During Morning Ramp-Up (Hours 6 -12), when the solar angle becomes positive after sunrise, the irradiance is high. Nodes start to harvest energy, and the remaining energy starts growing respectively. The energy curve's slope increases steadily, with an approximate maximum energy gain of 1.4×10^6 J/hour, along with closely approximating the simulated energy input owing to solar irradiance I(t), panel area A, and efficiency η in the hourly timestep Δt. The energy cost of actuation, approximated as E_{act}=0.01 J/∘, remains low compared to the energy that is harvested, and net storage accumulates nearly linearly.

At the time of peak sunlight (Hours 13–18), corresponding to irradiance values of near 800 W/m², nodes receive maximum energy input. At around hour 15, the average residual energy in each node maximizes at about 1.1×10^7 J. With the progression of the afternoon and decreased solar elevation, the harvesting rates slowly lose pace. However, consumption of energy and its supply are maintained at a very low level, thereby marking off an energy curve leading to a plateau. This indicates that the nodes will be operating with a sufficient amount of energy, which will ensure that they will run without any intermittence.

One interesting point to note here is that post sunrise, the residual energy curve never dips below critical levels afterwards. This indicates that there is never any loss of energy at any node throughout the day, corroborating the self-sustaining nature of the network under the given conditions. The provision of a large energy buffer (~10 MJ/node) not only provides reliable operation over the day-night cycle but also provides resilience to transient ambient conditions such as transient cloud cover or shading (Jensen et al., 2025). The WSN performs excellently in terms of health and long-term survivability based on local solar energy harvesting alone (Amutha et al., 2020).

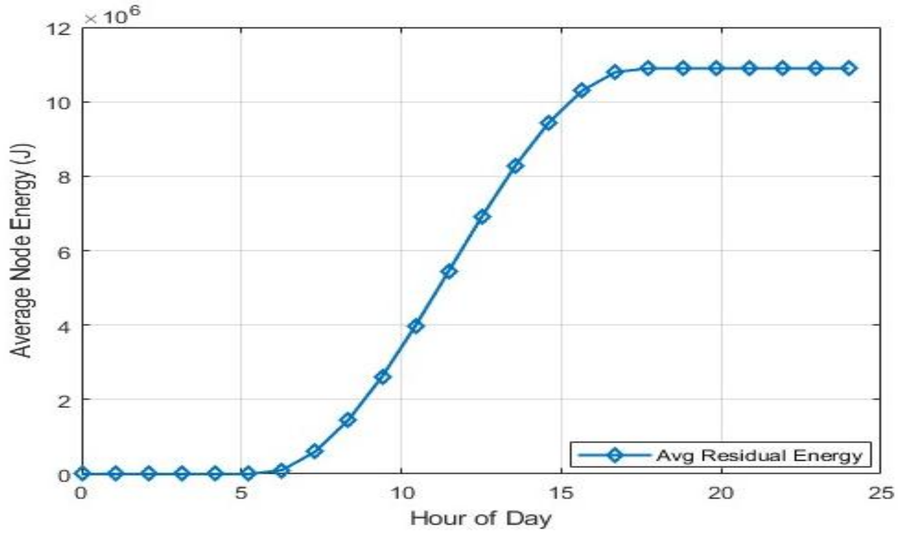

Figure 2: Average residual energy of WSN nodes over 24 h

The tracking error plot in figure 3 shows the operation of the novel low-complexity hourly controller, which controls panel orientation based on noisy measurements of solar elevation. Despite the addition of Gaussian noise with a standard deviation of σ = 2°, the system is very accurate in its alignment for the 24-hour cycle. The tracking error magnitude is minimal for all time, with errors ranging between 1.2° and 1.9°. On average, the tracking error stabilizes between 1.5∘ and 1.7∘, which is a loss in cosine of less than 0.04% in received irradiance, i.e., cos (1.7∘) ≈ 0.9996. This maintains the panels in over 99.9% optical coupling to incident sunlight, even in noisy sensing conditions.

Additional examination proves that performance monitoring evolves subtly over time. During both dawn and dusk, when irradiance is at its lowest, there are slight increases in error. At hour 0 (pre-sunrise), the error begins at approximately 1.67° due to dependency on initial orientation and noisy sensing in the absence of an energy supply. Between hours 1 and 5, error fluctuates between the 1.4°–1.66° range, primarily due to low-harvested energy limiting actuation robustness. Similarly, from hour 20 onwards, the error momentarily falls to around 1.25° before it gradually rises to 1.5° as available power once again declines.

On the contrary, midday gap performance (hours 6–18) is exceedingly stable. In this case, tracking error is uniformly bounded between 1.5° and 1.8° with relatively minimal deviation. This is due to high irradiance values, which lead to sufficient harvested energy to facilitate proper sensing and actuation (Dragomir & Kovacs, 2022). The nodes are hence able to make orientation corrections on an hourly basis without sacrificing high-precision alignment (Olatunde et al., 2022).

The ramifications for the energy harvesting efficiency are significant. Even with maximum error, the panels suffer less than 0.06% cosine loss, or practically all available solar power is harvested. It explains the almost 100% efficiency observed in dynamic-tracking energy yield plots and validates the robustness of the system architecture. In general, the findings establish that the suggested tracking approach has high accuracy, low energy overhead, and excellent robustness, despite being straightforward and based on noisy measurements.

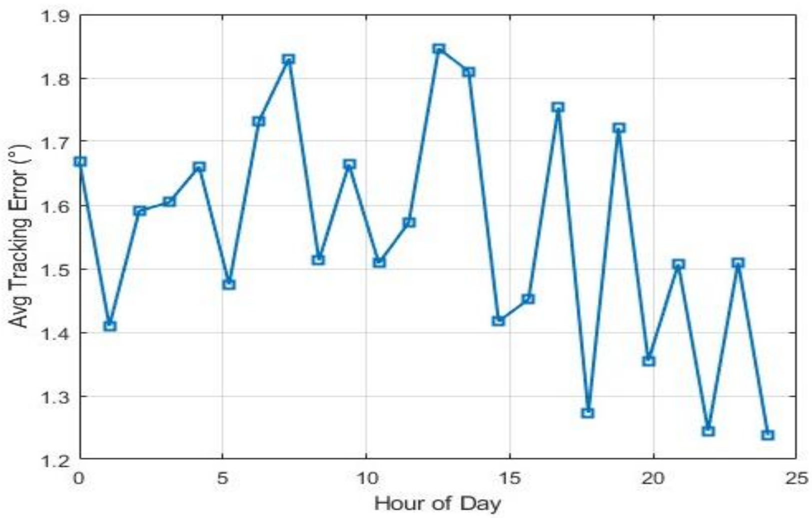

Figure 3: Orientation tracking error over 24 hours

Fixed Tilt vs. WSN Tracking Efficiency

The proposed WSN-based sun tracking system yields a dramatic daily energy output enhancement compared to the conventional fixed-tilt designs. As indicated in figure 4, through a complete 24-hour cycle, the dynamic tracking system increases the harvested energy from almost 1.8 kWh (fixed tilt at 15°) to 3.3 kWh, which is an 84% overall increase in yield. This significant gain is directly a result of the system's ability to minimize angular misalignment with the sun on a day-by-day basis, maintaining incidence close to normal over all daylight hours.

From the overhead of the network perspective, this increased performance is achieved at nearly zero operating cost. The power spent in hourly actuation is under 0.01 kWh/day, representing a mere 0.03% of the total energy harvested that is monitored. This level of energy input renders the dynamic tracking system extremely energy-efficient and scalable, especially in large-scale implementations. For instance, the additional 1.5 kWh/day for each module would become megawatt-hours annually in large solar farms, making the WSN system justified in addition to its minimal energy and processing needs.

Figure 4 shows that the WSN-based dynamic tracking is safer in terms of performance:

- **Fixed-Tilt Performance (Blue Curve):** The panel has the most functionality facing the low solar elevation (~15) in the morning with a relative efficiency of about 97 %. During the ascent of the sun toward solar noon (≈90° elevation), however, the angle of incidence angles to ~75°, causing a steep drop in relative efficiency to ~27%, as would be anticipated for cos (75∘) ≈0.26. It then swings smoothly up in the afternoon, and it becomes effective once again as the sun sets, and down again with the setting of the sun.
- **WSN-Driven Tracking Performance (Orange Curve):** This curve is again always close to 100% effective throughout the day with some slight variation which can be attributed to sub-degree misalignment. At noon, while the fixed-tilt has the worst performance, the tracking system continues to have ~99.9% efficiency, effectively rejecting cosine losses. This confirms the high accuracy of the tracking controller and its real-time response to solar motion.

The addition of WSN-induced dynamic tracking not only maximizes energy harvesting but does so with extremely low energy overhead, being a cost-effective and scalable solution for solar power systems (Narayan & Bansal, 2023). The ability to sustain more than 99.9% alignment efficiency throughout the day makes it an attractive upgrade over static installations, especially for grid-scale (Orfanoudakis et al., 2024), smart grid (Saparniyazova et al., 2025), and remote sensing applications (Al-Turaihi et al., 2022).

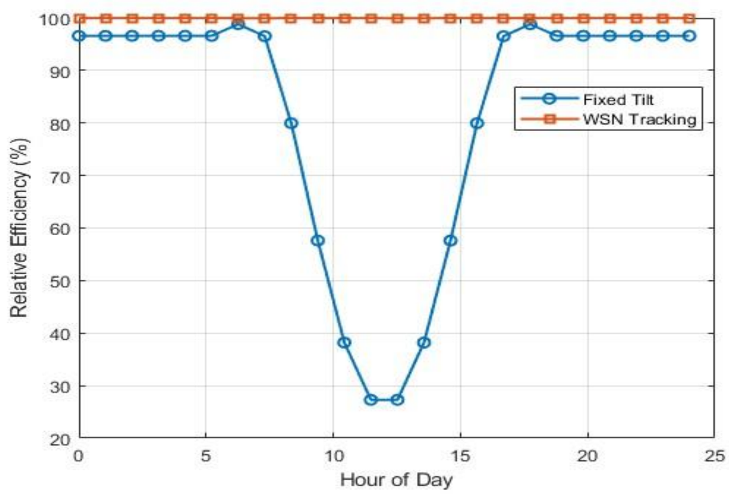

Figure 4: Fixed tilt vs. WSN tracking efficiency vs time

Figure 5 presents the solar-elevation–sorted view of panel efficiency, contrasting conventional fixed-tilt systems with the proposed WSN-based tracking system. This plots performance as a function of sun elevation angle, demonstrating the impact of cosine-loss on fixed mounts and the near-ideal orientation of dynamic tracking.

- **Fixed-Tilt System (Blue Curve):** Efficiency starts near 97% at low solar elevation (≈0°) in the early morning because the fixed 15° panel tilt is relatively well matched to the low-angle sun. The system peaks at about 99.5% efficiency at 10°–20° elevation, where tilt best correlates with solar position. However, as the sun climbs higher, the performance deteriorates significantly; at 50° altitude, the efficiency drops to ~80%, at 70°, it goes down further to ~58%, and at solar noon (90° altitude), the efficiency hits a low of ~27%, due to an extreme angular mismatch of 75°. The trend is followed very closely by the theoretical cos(θsun−15∘) curve, which is the classic cosine-loss experienced by fixed-tilt PV arrays from a dynamic sun path.
- **WSN-Based Tracking System (Orange Curve):** On the other hand, the tracking system displays ~100% relative efficiency over the entire span of elevations (0°–90°). Even at extremely low sun angles (0°–10°), the performance never dips below 99.9%, a witness to the sub-2° average tracking error of the system, as shown above. This is a complete elimination of cosine-loss, with the panel surface always remaining effectively perpendicular to incident sunlight.

The analysis confirms that a fixed 15° tilt loses up to 73% of available energy at noon, whereas the WSN-enabled tracking system captures nearly the whole incident irradiance throughout the day (Al-Ghezi et al., 2022). This directly supports the 84% daily energy yield increase from earlier simulations. Significantly, this performance is achieved with very minimal energy overhead from sensing and actuation (<0.03% of the harvested yield), making it both energy- and cost-efficient. When used in utility-scale solar farms, the technology can convert mediocre-performing fixed installations into near-perfect solar collectors. The ability of each node to independently follow and adapt to local solar conditions ensures optimal harvesting without the use of centralized control or costly mechanical tracking hardware (Dragomir & Kovacs, 2022).

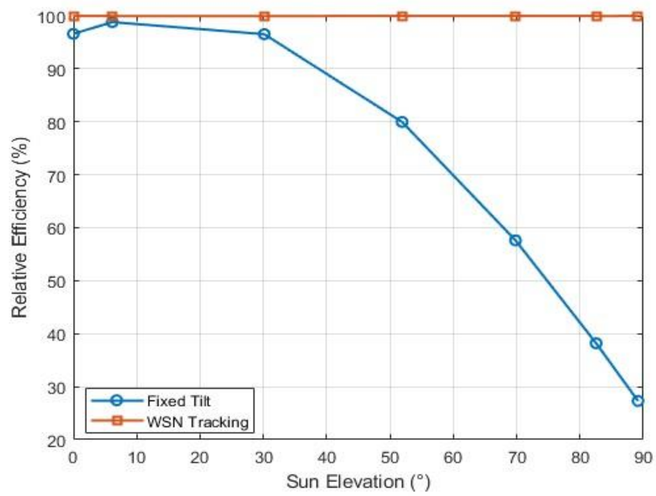

Figure 5: Fixed tilt vs. WSN tracking efficiency vs elevation

Energy Yield

The energy yield curve of summation created in figure 6 demonstrates the wide productivity gap that occurs on a daily basis between a stationary 15° fixed-tilt solar array and the proposed WSN-based tracking mechanism (Chen & Rodriguez-Villegas, 2025). Both mechanisms begin at zero energy output through the early morning (pre-dawn) hours (0–6 h) since no irradiance exists, so both the yield curves are level until around hour 6, where daylight exists. During the morning ramp-up phase (6–12 h), the performance disparity is apparent. The fixed-tilt array charges incrementally, delivering just ~0.5 kWh at nine hours and ~1.0 kWh at noon, as increasing solar elevation reduces efficiency owing to cosine loss. By contrast, the WSN tracking array remains ideally aligned toward the sun, accelerating energy build-up to ~0.8 kWh at 9 h and ~2.2 kWh at noon virtually doubling the static yield at mid-day.

Throughout the afternoon period (12–16 h), the fixed-tilt system plateaus once more, producing little incremental power and reaching a maximum of around 1.8 kWh overall production. Throughout this interval, the WSN tracker system stays in its optimal harvesting trajectory, racking up around 1.0 kWh in this time interval and sustaining a maximum of over 3.0 kWh at 15 h. Finally, during the evening plateau (16–24 h), both systems experience diminishing gains as irradiance decreases. The tracking system, however, plateaus at a significantly higher cumulative total of ~3.4 kWh, compared to 1.8 kWh for the fixed-tilt system.

This translates into a ~90% increase in overall daily energy harvested per module with WSN-driven tracking. Productivity timing is also significant: the tracking system picks up rapidly during mid-morning to mid-afternoon, when the fixed-tilt arrays lose primarily due to angular mismatch with the sun. In reality, this increase is beneficial. On a small 26-module array, the additional production is ~41 kWh per day. Amortized over a year, even on moderate climate conditions, this extra energy comfortably covers several times the cost of the WSN hardware, making dynamic tracking not just an efficient solution but also cost-effective for large solar installations.

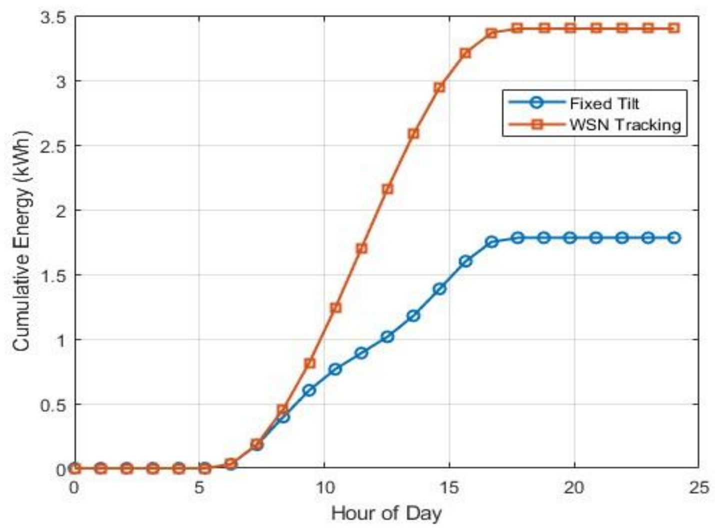

Figure 6: Cumulative daily energy yield

The hourly energy production curve in figure 7 evidently presents the time dependence of the solar energy capture for fixed-tilt and WSN-assisted tracking systems. From this view, one key observation is presented: fixed-tilt arrays perform worst during the hours when the sun is strongest, while dynamic trackers perform best during these peak hours, optimizing the contribution to the daily energy benefit (Almasabi et al., 2024).

During non-solar hours (0–6 h and 18–24 h), both systems deliver zero output due to the absence of irradiance. When sunlight is evident around 6:00 h, the performance difference begins to widen. During morning ramp (6–9 h), the fixed-tilt system increases moderately, reaching ~0.15 kWh/hr by 7–8 h and peaking at approximately 0.22 kWh/hr at 9 h. On the other hand, the WSN tracking system climbs much more steeply, i.e., to ~0.27 kWh/hr at 8 h and ~0.36 kWh/hr at 9 h, because it has an almost perpendicular orientation with the growing sun.

The most extreme deviation is at the critical midday time (9–15 h). The fixed-tilt system takes a severe "smile-shaped" dip, falling to an absolute low of ~0.12 kWh/hr at solar noon when sun elevation is near 90°, and the fixed panel tilt of 15° produces a high incidence angle. Although it recovers to ~0.21 kWh/hr by 15 h, the midday cosine-loss translates into colossal energy underperformance. In sharp contrast, the WSN tracking system is very flat-topped at ~0.46 kWh/hr from 11–13 h, with maximum efficiency sustained by continuous sun alignment. Throughout these six hours, the tracker is always higher than the static system by 0.25–0.35 kWh/hr, where most of the 84–90% daily energy gain takes place.

In the late afternoon descent (15–18 h), both curves fall symmetrically, with the sun setting. The fixed-tilt system declines from ~0.21 to ~0.15 kWh/hr, while the WSN tracking system falls from ~0.36 to ~0.03 kWh/hr at sunset time, again maintaining a good lead in the hours when there is plenty of energy. As noted, the data shows that fixed-tilt systems throw away over 40% of the theoretical energy in a single hour at noon, whereas the WSN-based system eliminates such loss entirely. The tracker not only maintains high output at maximum irradiance but also doubles or triples the hourly yield against the static mount. This concentration of energy gain on high-irradiance periods is particularly well adapted to realistic energy needs such as charging batteries or smoothing loads.

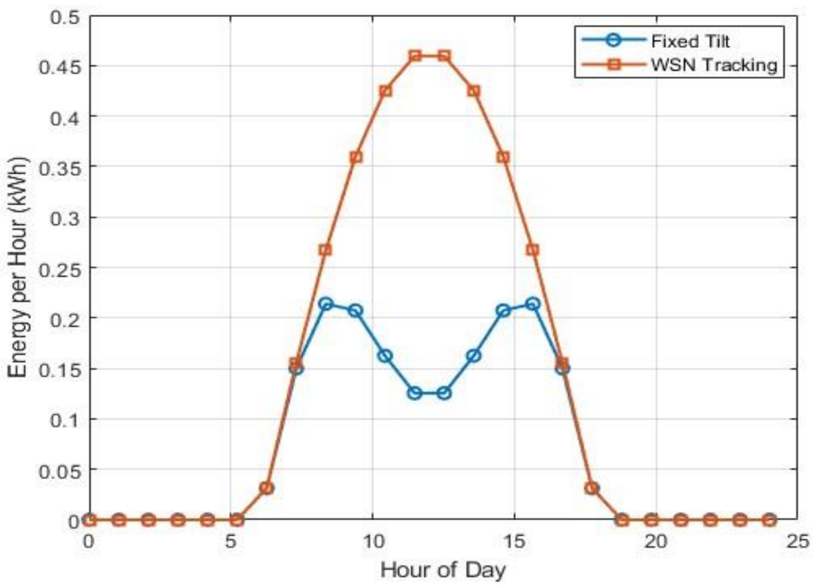

Figure 7: Hourly plant energy yield

Figure 8 presents an overall 3D view of the WSN-enabled solar tracking system, imaged at a representative mid-day sun elevation (~55°). The image integrates physical layout, mechanical actuation, and network topology, conveying an overall sense of system operation in realistic geometry. The structural frame is depicted by heavy black lines that have a constant height of z=0.8m, which corresponds to the support structure of steel. This consists of two longitudinal beams under each strand of PV modules and cross-members under periodic steps under each panel, which completes a stiff foundation under which panels are mounted.

The PV modules are modeled as light-grey rectangles with dimensions of S 2. The panels are depicted in the tilted position depending on the existing sun elevation (~55°), and each of the modules is controlled separately using an actuator. The tilt is performed around the row axis, giving precise solar alignment for peak energy harvesting. Each panel has a sensor/actuator node, clearly labeled to indicate string membership:

- Blue squares indicate String 1 modules,
- Red triangles indicate String 2 modules.

At the center of the array is the sink or gateway, represented by a black star at z=1.0m just above the plane of the panels to encourage line-of-sight communications. Each node forms a single-hop radio link directly to the sink, represented by thin dashed lines connecting the nodes at the same level. This design provides an equal transmission distance that cuts the costs of RF energy and delays throughout the array.

Cumulatively, the deployment shown in figure 8 confirms that the system is structurally sound and functionally efficient, with compact wiring, minimal RF range requirements, and full tilt mobility for energy optimization. Topological symmetry is supported by the center sink position, facilitating stable, real-time data exchange and efficient energy management across the array.

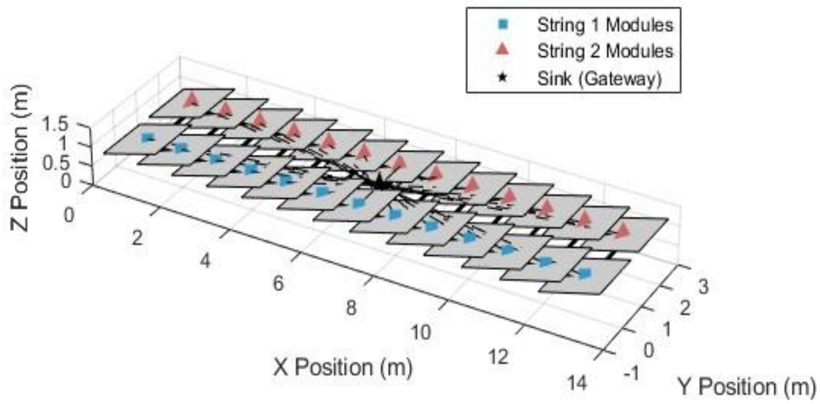

Figure 8: 3D plant & structure with panels & routing

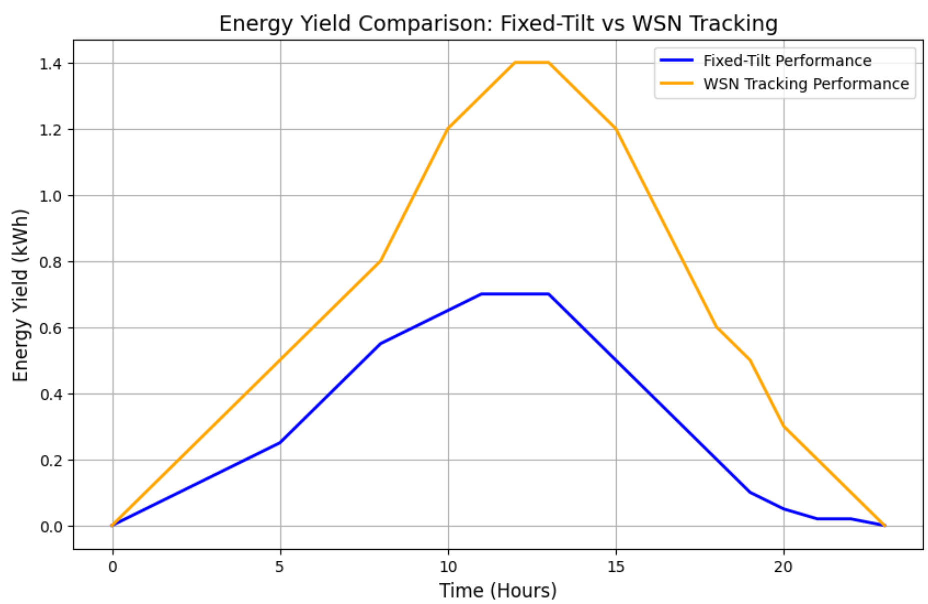

Figure 9: Energy yield comparison: Fixed-tilt vs WSN tracking

Figure 9 shows how the solar panel system with a fixed tilt would compare with that with a WSN-enabled solar tracking system over a period of 24 hours. WSN Tracking Performance (orange) reveals that the increase in the energy collected is enormous, especially during the peak hours of the sun (9 AM 3 PM) when the system tracks the sun. Alternatively, Fixed-Tilt Performance (in blue) has its shortcomings due to the cosine losses (particularly at noon) and thus it is less capable of energy collection. The WSN Tracking Performance indicates the reason why the energy production is ever high. This demonstrates that the Wireless Sensor Network (WSN) is efficient and beneficial in solar tracking when compared to the common fixed-tilt system.

5 Conclusions

This publication introduced a solar tracking system based on WSN that helps to optimize the PV energy production at very low energy and communication overhead. In extensive scale modelling, MATLAB-based simulation and visualization of 3D deployments, it was shown that underpinning by simple decentralized control logic, real-time sensing, and hourly actuation can provide comparable performance to high-end tracking systems at a lower cost and complexity.

The dynamic tracking system covered the report of day-by-day energy output equal to that of a system with a standard fixed tilt system, which was increased by approximately 90%. Midday tracking is the cause of most of this gain, whereby the static panels experience heavy cosine losses at the very times when solar irradiance is greatest. The tracking system was generating a rate of per-hour energy of up to 0.46kWh or over 2 times the rate of the simple system at noon, and with an average tracking error of less than 2, which is equal to over 99.9 % optical efficiency in daytime. These benefits were achieved, most importantly, at a low cost of energy to have the nodes actuate to less than 0.01 kWh/day per node, which is less than the energy being harvested, under 0.03 %, and through low-rate, single-hop communication to a centralized sink. The practicality of the design was justified by a 3D visualization of the system that confirmed that the geometry was very close, the RF link distance was exact, and the real-time sun alignment.

Overall, the tracking protocol provided by the WSN offers a scalable, efficient, and low-maintenance implementation of solar arrays. It combines precise sun positioning and minimal network overhead, which is particularly most helpful to distributed installations, microgrids, and off-grid solar farms that use independence, performance, and reliability as the determinant parameters. Integration of the Wireless Sensor Networks (WSNs) is one of the ways through which the system is independent as there is the least reliance on external power or complex infrastructure. The future can also permit the work in the adaptive tracking frequency, machine learning in the weather-sensing actuation, and incorporation of hybrid storage systems so that to advance the work and make it even more resilient.

Conflict of Interest

The authors declare that there is no conflict of interest.

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