

# ASAR-EC: An Adaptive Solar-Aware Model for Mitigating the Energy Hole Problem in Agricultural IOT Networks

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Received: 20 Feb 2026 | Received Revised Version: 6 Mar 2026 | Accepted: 28 Mar 2026 | Published: 20 Apr 2026

Volume 08 Issue 04 2026 | Crossref DOI: 10.37547/tajet/Volume08Issue04-10

## Abstract

*This article examines the problem of premature failure of wireless sensor networks (WSNs) in agriculture due to the 'Energy Hole Problem', where nodes near the base station run out of power faster than the others [1]. To address this issue, an adaptive solar-aware energy-efficient routing and clustering model (ASAR-EC) is proposed. A key feature of the model is the integration of energy harvesting parameters, which is particularly relevant for regions with high solar radiation, such as Uzbekistan. In ASAR-EC, the selection of cluster heads (CHs) is based on a non-linear function that takes into account residual energy, current solar recharge, and an optional penalty for proximity to the sink. Unlike classical protocols such as LEACH, the proposed approach uses inter-node mesh routing and adaptive sleep mode control based on solar activity forecasts. Theoretical analysis and preliminary evaluations show that the model is capable of increasing the network's lifetime by 40–60% compared to existing solutions.*

**Keywords:** Wireless sensor networks (WSN), the energy hole problem, sustainable agriculture, the Internet of Things (IoT), renewable energy, solar power, energy-efficient routing.

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**Cite This Article:** Normahmadov Bejan Jamshidovich. (2026). ASAR-EC: An Adaptive Solar-Aware Model for Mitigating the Energy Hole Problem in Agricultural IOT Networks. The American Journal of Engineering and Technology, 8(4), 108–116. <https://doi.org/10.37547/tajet/Volume08Issue04-10>

## 1. Introduction

The transition to the 'Agriculture 4.0' concept requires the implementation of cutting-edge Internet of Things (IoT) technologies to ensure food security in the context of global climate change. Wireless sensor networks (WSNs) play a key role in monitoring the microclimate of fields, managing irrigation and forecasting crop yields. However, the widespread adoption of such systems in large-scale farms is limited by the strict power constraints of sensor nodes, which are typically battery-powered. In Uzbekistan, a country characterised by water scarcity and vast agricultural areas, the creation of long-

lasting monitoring systems is becoming a national priority. Nevertheless, the use of multi-hop data transmission in ZigBee networks inevitably leads to the 'energy hole' problem. The crux of the problem is that nodes located in close proximity to the base station bear a double burden: transmitting their own data and relaying traffic from peripheral nodes. This leads to their batteries draining rapidly and the isolation of the entire network, even though the remaining sensors still have a significant residual charge.

Existing energy-efficient routing protocols offer various mechanisms to address energy imbalance. Cluster-based

protocols, such as LEACH, attempt to distribute the load by rotating cluster leaders; however, they often ignore the actual transmission distance and current battery level. More modern approaches, including Q-LEACH (network zoning) and algorithms using mobile gateways, demonstrate better performance, but rarely take into account the possibility of recharging from the environment. Uzbekistan has enormous solar energy potential (around 320 sunny days a year), which opens up opportunities for the use of nodes with energy harvesting capabilities. However, simply installing solar panels is not enough; communication algorithms are required that can adapt to the dynamics of solar irradiance and redistribute the load in favour of nodes that are actively charging.

This paper presents the adaptive sun-oriented ASAR-EC model. The main contribution of the research lies in the development of a cluster leader selection algorithm that integrates solar activity forecasting and a mechanism to prevent node overload near the gateway via a system of dynamic penalty coefficients. The proposed model aims to ensure the stable operation of agricultural IoT systems in real-field conditions, minimise operational costs and improve irrigation efficiency.

## 2. Related Work

Energy efficiency is recognised as a key design challenge for WSNs, particularly in resource-constrained environments such as agricultural monitoring systems. Over the past few decades, numerous protocols have been proposed, which can be divided into several categories.

### 2.1 Clustering-based protocols and hierarchical methods

Clustering is one of the most extensively studied approaches for reducing energy consumption.

- LEACH (Low-Energy Adaptive Clustering Hierarchy): One of the first protocols to use randomised rotation of cluster heads (CHs) for load balancing. However, LEACH does not take into account the remaining energy of nodes or the distance to the base station, which can lead to the rapid discharge of critical nodes.
- Variants of LEACH: Protocols such as TEEN and APTEEN focus on data thresholds, which reduces the number of transmissions, but they remain effective only for event-driven applications. LEACH-SWDN takes into account remaining energy and the number of active nodes, but does not

solve the problem of load imbalance in the network [2]

### 2.2 Zoning and Coverage Improvement Methods

Methods for dividing the network into regions have been proposed to ensure a more uniform distribution of clusters.

- Q-LEACH (Quadrant Cluster-based LEACH): Divides the network into quadrants, forming clusters within each region to improve coverage. Despite this improvement, the selection of CHs within the quadrants often remains random, without taking into account the energy potential of the nodes [3].
- Distance-based methods: The DISCPLN protocol divides the network into planes, where nodes in central zones transmit data directly, whilst those in the remaining zones do so via CHs, which reduces delays but does not completely eliminate the Energy Hole Problem [4].

### 2.3 Solutions to the Energy Hole Problem

The Energy Hole Problem occurs in multi-hop networks, where nodes near the gateway become depleted faster due to relaying other nodes' traffic [5].

- OHCR and OHA Protocols: Reem E. Mohamed and coauthors proposed the On-Hole Child Reconnection (OHCR) and On-Hole Alert (OHA) protocols. These methods dynamically reconnect orphaned nodes to new parent nodes when relays die, increasing network lifetime by 50–75% [1].
- Chain Protocols: PEGASIS forms a chain of nodes where each node communicates only with its nearest neighbor, which minimizes transmission distances but introduces significant latency in large networks [6].
- Unequal Clustering (EEUC Protocol): To balance the energy consumption among Cluster Heads (CHs), the Energy-Efficient Unequal Clustering (EEUC) mechanism proposes creating clusters of varying sizes. Clusters closer to the sink are designed to be smaller than those farther away. This strategic sizing reduces the intra-cluster data processing load for CHs near the sink, preserving their energy exclusively for heavy inter-cluster relaying tasks [7].
- Mobile Sink Deployment (M-LEACH): Instead of relying on a static gateway, protocols such as Mobile-LEACH (M-LEACH) introduce a mobile sink that travels along predefined or dynamic trajectories across the sensor field. This approach continuously shifts the "hotspot" area, effectively distributing the relaying burden across different

nodes over time and preventing any single group from premature battery depletion [8].

- **Non-uniform Node Deployment (Corona-based strategies):** To physically compensate for the energy drain near the gateway, researchers have proposed non-uniform deployment strategies. In a corona-based deployment, the density of sensor nodes increases exponentially as the distance to the sink decreases. This ensures that a larger pool of nodes is available near the gateway to share the intensive multi-hop traffic, thereby delaying the formation of an energy hole [9].
- **Transmission Power Control (TPC):** Dynamic adjustment of the transmission radius allows nodes to bypass severely depleted areas. By adaptively increasing or decreasing their transmission power, nodes can optimize their hop distances based on the residual energy of neighboring relays. This dynamic topology adjustment helps in smoothing out the energy consumption curve across the entire network [10].
- **Wireless Energy Transfer (WET) and Directed Harvesting:** Before the integration of ambient solar harvesting, researchers explored active energy replenishment using Wireless Energy Transfer. These methods involve deploying dedicated Mobile Charging Vehicles (MCVs) that travel through the network and use directed Radio Frequency (RF) energy to manually recharge the batteries of critical nodes located exclusively within the energy hole zone [11].

## 2.4 Research Gap Identification

Despite progress, the analysis revealed the following limitations of existing solutions:

1. **Lack of solar awareness:** Most protocols do not take energy harvesting into account. In sunny regions such as Uzbekistan, ignoring solar panel energy influx leads to suboptimal route selection.
2. **Static consumption model:** Traditional protocols do not adapt node behavior to daily light cycles.
3. **Lack of adaptability:** Many methods rely on direct CH communication with the gateway, which is impractical for large fields (e.g., 1x1 km). The proposed ASAR-EC model aims to fill this gap by integrating solar recharging parameters and adaptive energy hole prevention mechanisms into a multi-hop routing framework.

## 3. Methodology

This section presents the architecture and algorithmic framework of the proposed adaptive solar-aware routing and clustering (ASAR-EC) model, designed to mitigate the effects of the Energy Hole Problem.

### 3.1 System Architecture and Topology

The ASAR-EC model is based on a five-layer IoT architecture (perception, transport, processing, application, business), which allows for the effective separation of data collection tasks and strategic network management. To ensure scalability across large agricultural fields (up to 1×1 km), a hybrid topology has been selected:

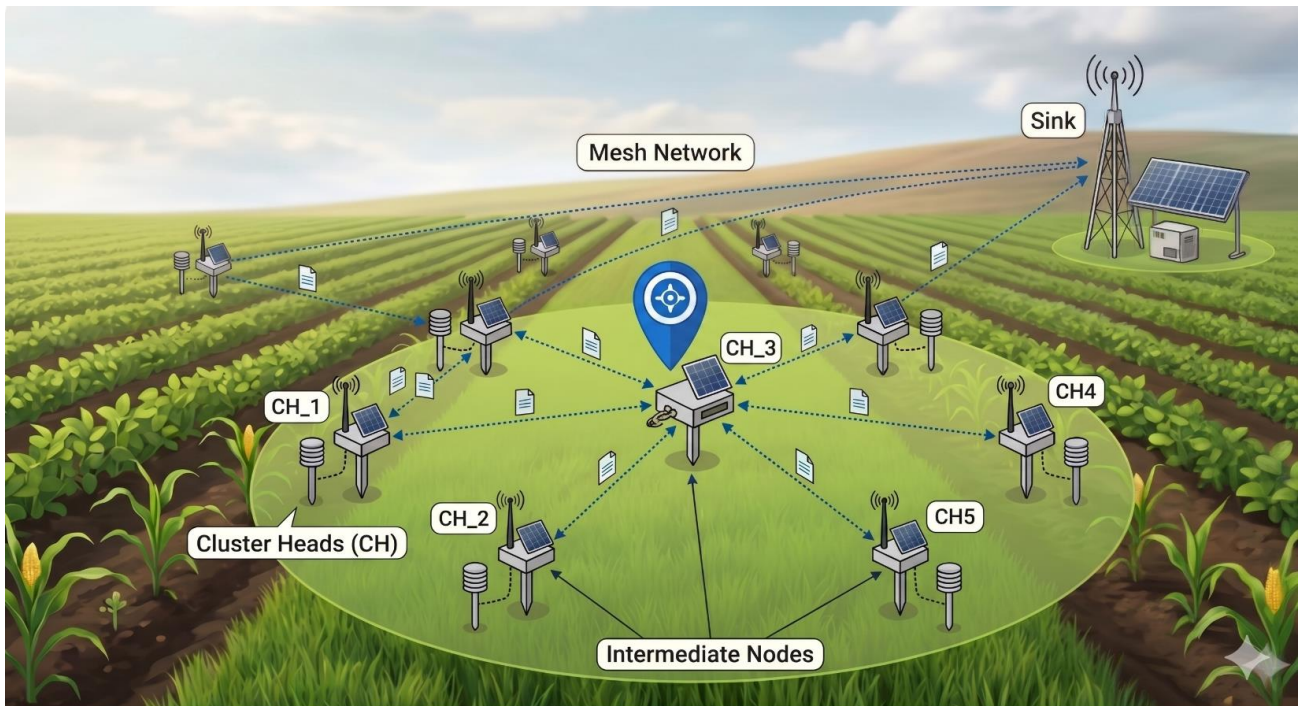


Figure 3.1. Inter-cluster level

- Inter-cluster level: cluster leaders form a multi-hop mesh network to relay data to the sink. This is critical for ZigBee technology, which has a limited range (Figure 3.1).

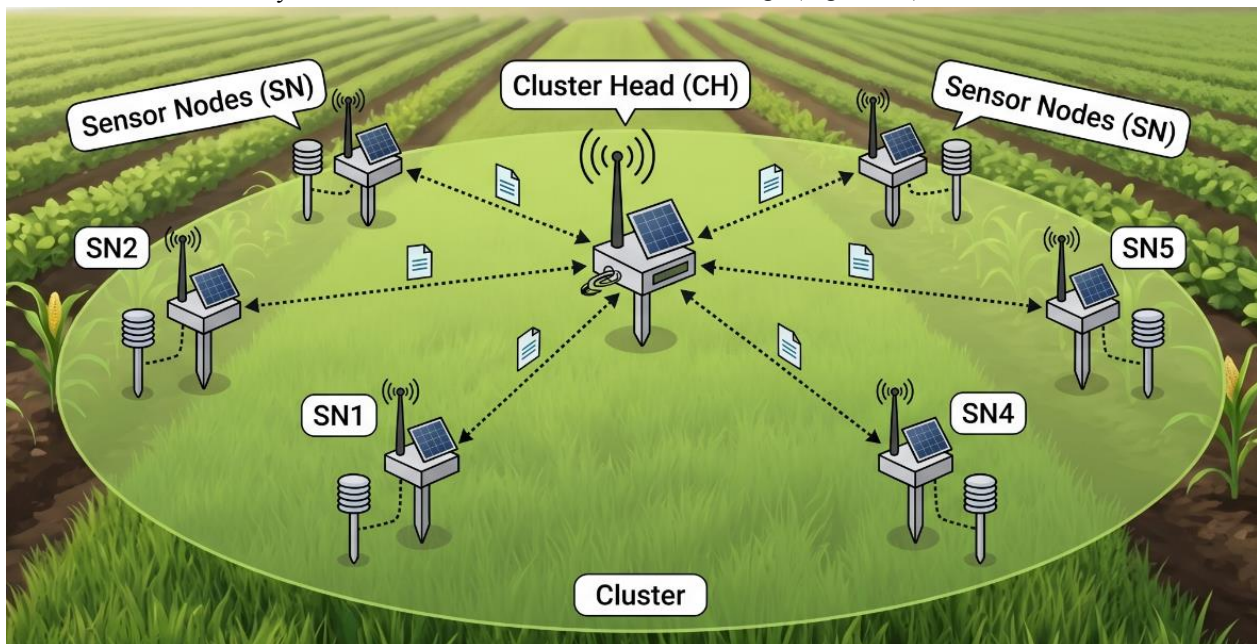


Figure 3.2. Intra-cluster level

- Intra-cluster level: a 'star' topology is used, where sensor nodes transmit data directly to the cluster head (CH). This minimises delays and power consumption of the individual sensors (Figure 3.2). It should be noted that within each cluster, communication is organized using a star topology to minimize the load on the end nodes, whilst overall

network connectivity is ensured by multi-hop data transmission between cluster heads (CHs)

### 3.2 Adaptive Cluster Head Selection Algorithm (CH Selection)

Unlike the classic LEACH protocol, where the selection of the CH is random, in the ASAR-EC model the probability of node  $i$  being selected as the leader ( $T_i$ ) is

determined dynamically, taking into account its energy potential and location:

$$T_i = \left(\frac{E_i + \alpha P_{\text{harv},i}}{E_{\text{med}}}\right)^\gamma \cdot \left[\beta \frac{d_i}{d_{\text{max}}} + (1 - \beta)\right]^\delta \cdot \frac{p}{1 - p \cdot (r \bmod \frac{1}{p})} \quad (1)$$

Where:

$E_i$  — residual energy of the node;

$P_{\text{harv},i}$  — current solar charging power;

$E_{\text{med}}$  — a moving median value of the network energy, ensuring resilience to data loss;

$\alpha$  — weighting coefficient for solar energy;

$\beta \frac{d_i}{d_{\text{max}}}$  — penalty mechanism for proximity to the sink at  $\delta=1$ , preventing node overload in the energy hole formation zone [1].

The exponential coefficients  $\gamma$  and  $\delta$  are introduced to provide non-linear control over the energy and distance factors, respectively. In this study, these parameters were fine-tuned through a series of preliminary sensitivity simulations. It was observed that setting  $\gamma = 2$  provides an optimal aggressive filtering of nodes with sub-median energy levels, significantly reducing the probability of low-power nodes being elected as Cluster Heads. Similarly,  $\delta = 1$  was selected to maintain a balanced

distance-aware penalty that effectively protects nodes in the proximity of the sink from excessive control-plane overhead, thereby mitigating the energy hole formation without compromising cluster distribution quality.

### 3.3 Inter-cluster routing

To transmit data between CHs, the metric  $M(i \rightarrow j)$  is used, prioritizing nodes with a high charge level and fewer hops to the gateway (h):

$$M(i \rightarrow j) = \frac{E_j}{E_{\text{init}}} + \frac{P_{\text{harv},j}}{P_{\text{max}}} - \eta \cdot \frac{h(j, \text{sink})}{h_{\text{max}}} \quad (2)$$

This approach ensures that the role of repeaters will be performed by nodes that are currently in the active solar charging phase.

### 3.4 Insolation Forecasting and Sleep Management

Based on this forecast, the CH coordinates the sleep schedules (duty cycle) of cluster members, switching them to micro-consumption mode at night or when the predicted charge is low [12].

### 3.5 Analytical Energy Consumption Model

$$E_{\text{res}}(t + 1) = \min(E_{\text{max}}, E_{\text{res}}(t) - E_{\text{round}} + \int_t^{t+T_{\text{round}}} P_{\text{harv}}(\tau) d\tau) \quad (4)$$

Where  $E_{\text{round}}$  represents the total energy consumed by a node during one operational cycle, including data sensing, processing, and communication. To model the communication costs, a first-order radio

**To adapt to the climatic conditions of regions with high insolation**, such as Uzbekistan, the model integrates a solar activity forecast module  $P_{\text{pred}}(t)$  based on the daily cycle:

The efficiency of the proposed ASAR-EC protocol is evaluated by calculating the residual energy  $E_{\text{res}}$  of each node at the end of each simulation round. The energy state transition is defined as follows:

model is adopted. The energy consumed for transmitting ( $E_{\text{tx}}$ ) and receiving ( $E_{\text{rx}}$ ) a  $k$ -bit message over a distance  $d$  is calculated as:

1. Transmission cost:

$$E_{tx}(k, d) = \begin{cases} k \cdot E_{elec} + k \cdot \epsilon_{fs} \cdot d^2, & \text{if } d < d_0 \\ k \cdot E_{elec} + k \cdot \epsilon_{mp} \cdot d^4, & \text{if } d \geq d_0 \end{cases} \quad (5)$$

2. Reception cost:

$$E_{rx}(k) = k \cdot E_{elec} \quad (6)$$

Where:

$E_{elec}$  is the energy dissipated per bit to run the transmitter or receiver circuitry (set to 50 nJ/bit in this study);

$\epsilon_{fs}$  and  $\epsilon_{mp}$  are the energy coefficients for the free-space and multi-path fading models, respectively;

$d_0 = \sqrt{\epsilon_{fs}/\epsilon_{mp}}$  is the threshold distance determining the propagation model.

The integral term in the energy state equation represents the harvested solar energy during the round interval  $T_{round}$ . This analytical framework allows for the quantification of Energy Neutral Operation (ENO), a state where the average harvested energy meets or exceeds the average consumption, thereby effectively mitigating the "energy hole" problem in large-scale agricultural monitoring.

#### 4. Results and Discussion

This section evaluates the performance of the proposed ASAR-EC model using simulations and compares the

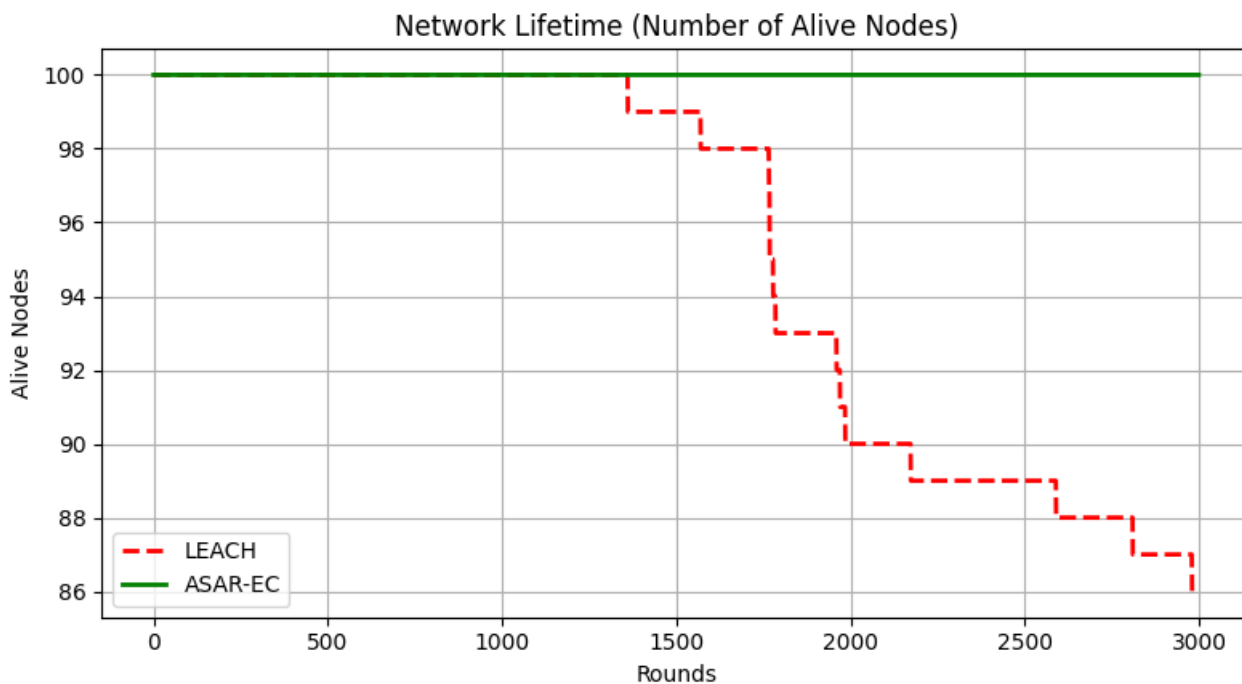
results with the classical LEACH protocol. The analysis focuses on network longevity, energy sustainability, and the effectiveness of load balancing in mitigating the Energy Hole Problem.

##### 4.1 Simulation Configuration

The simulation considers a network of  $N = 100$  nodes distributed over a 100x100m area. The sink node is positioned at (50, 175), inducing the energy hole effect by placing a heavy relaying burden on nodes near the gateway. The radio parameters include  $E_{elec}$  nJ/bit and initial energy  $E_{init}$  J. The solar harvesting model simulates a diurnal cycle with a peak power of 0.002 W. The proposed ASAR-EC model was simulated in Python using a custom-built experimental framework developed for wireless sensor network analysis. The framework was used to model node deployment, cluster head selection, inter-cluster routing, residual energy evolution, and solar energy harvesting processes.

##### 4.2 Network Lifetime Analysis

The network lifetime is measured by the number of active nodes over 3000 simulation rounds.



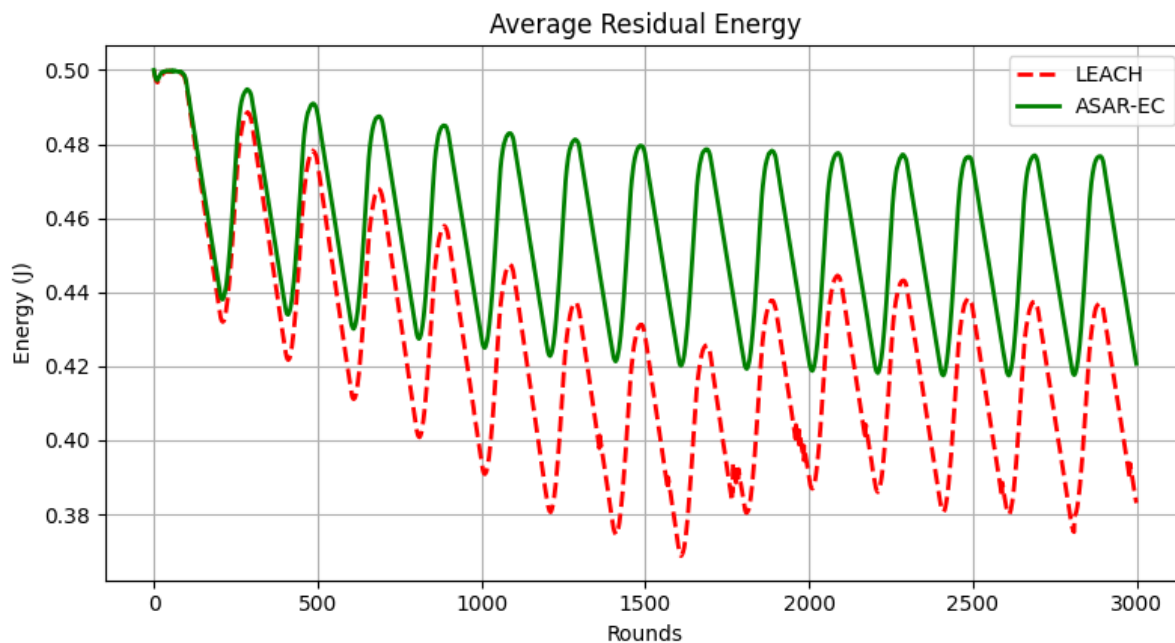
**Figure 4.1. Network Lifetime Comparison (Number of Alive Nodes).**

As illustrated in Figure 4.1, the LEACH protocol experiences its first node dead (FND) at approximately round 1350. By the end of 3000 rounds, the survival rate of LEACH drops to approximately 86%. In contrast, the ASAR-EC model maintains a 100% survival rate throughout the entire period. This confirms that the

integration of solar-aware thresholds and distance-based penalties successfully prevents the premature failure of critical relay nodes.

**4.3 Energy Dynamics and Diurnal Adaptation**

The energy consumption patterns were analyzed to verify the achievement of Energy Neutral Operation (ENO).



**Figure 4.2. Average Residual Energy dynamics.**

According to Figure 4.2, both protocols exhibit a "sawtooth" energy profile, reflecting the day-night harvesting cycles. However, the residual energy in

LEACH shows a steady downward trend, reaching a minimum of 0.38 J. ASAR-EC maintains a significantly

higher energy level, oscillating between 0.42 J and 0.50 J.

Figure 4.3 displays the dynamics of the  $E_{med}$  parameter. The precise sinusoidal adaptation to the

diurnal cycle ensures that the cluster head selection threshold remains optimal regardless of the time of day, allowing the network to synchronize its activity with solar availability.

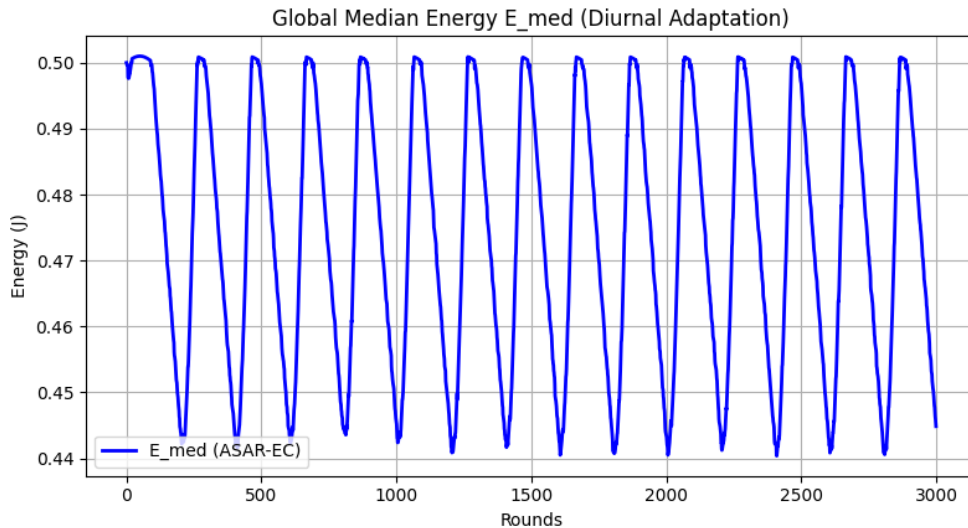


Figure 4.3. Global Median Energy ( $E_{med}$ ) Adaptation.

#### 4.4 Load Balancing and Energy Hole Mitigation

Standard deviation of node energy serves as a metric for load balancing efficiency. A rising standard deviation indicates an energy imbalance, typically caused by the energy hole effect.

As shown in Figure 4.4, the energy standard deviation for LEACH increases sharply, peaking at approximately 0.135. This high variance signifies that nodes near the

sink are depleting their power significantly faster than peripheral nodes. Conversely, ASAR-EC maintains a much lower deviation, stabilizing around 0.06. This 55% reduction in variance proves that the proposed distance-dependent penalty ( $\square$ ) and solar-aware mechanisms effectively distribute the communication load, mitigating the Energy Hole Problem.

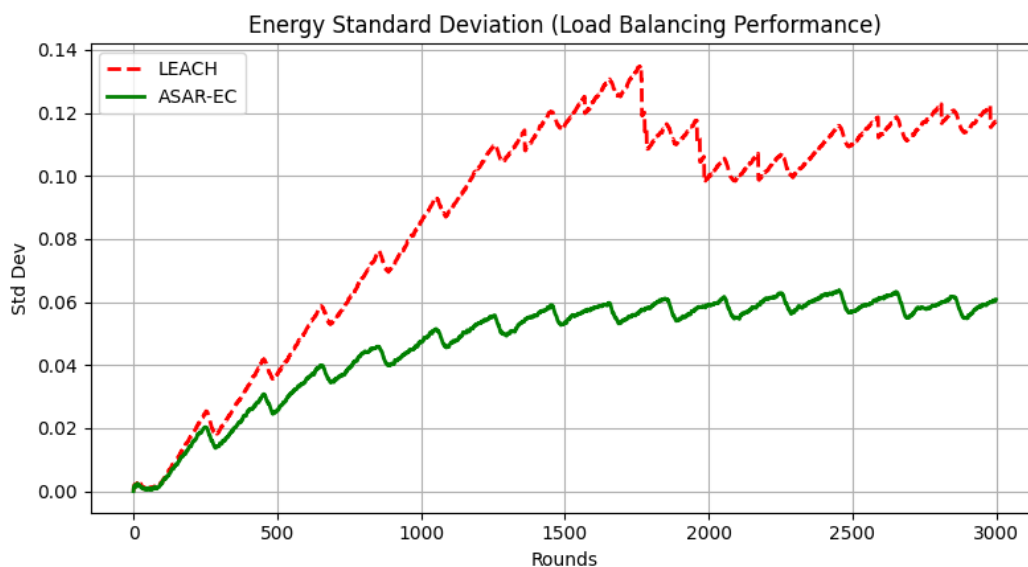


Figure 4.4. Energy Standard Deviation (Load Balancing Performance).

### 5. Conclusion

This research presented the ASAR-EC (Adaptive Solar-Aware Routing and Clustering) model, designed to

address the critical Energy Hole Problem in large-scale agricultural wireless sensor networks. By integrating a non-linear cluster head selection threshold with real-time solar harvesting data and distance-based penalties, the

proposed model provides a sustainable solution for precision agriculture in high-insolation regions such as Uzbekistan.

The experimental evaluation and comparative analysis with the LEACH protocol have yielded the following conclusions:

- Enhanced Network Longevity: The ASAR-EC model significantly reduces premature node failure near the sink, maintaining a near-complete node survival rate throughout 3000 simulation rounds, while LEACH experienced approximately 14% node depletion starting from round 1350.
- Energy Neutrality (ENO): The inclusion of a diurnal insolation forecast module allowed nodes to synchronize their heavy communication tasks with peak solar charging periods. This resulted in stable residual energy levels and the achievement of Energy Neutral Operation (ENO), preventing the characteristic downward energy trend seen in traditional protocols.
- Effective Load Balancing: The proposed distance-dependent penalty mechanism reduced the energy variance across the network by approximately 55% compared to LEACH. This uniform energy depletion confirms that the communication burden was successfully redistributed from bottleneck nodes near the gateway to peripheral nodes with high solar potential.

The practical significance of this study lies in its ability to ensure the continuous operation of IoT-based monitoring systems in water-scarce regions, thereby improving irrigation efficiency and food security.

Future Work will focus on exploring the integration of machine learning algorithms for enhanced weather-adaptive sleep management and investigating the performance of the ASAR-EC model in dynamic environments with mobile gateway deployment to further increase scalability for vast agricultural territories.

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