

Journal of Integrated Science, Technology and Management

Research Article

Self-Sustaining Wireless Sensor Networks: Energy Harvesting Models and Implementation Approaches

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ARTICLE INFO

Article history:

Received: 05 November, 2025

Revised: 15 November, 2025

Accepted: 25 November, 2025

Published: 31 December, 2025

Keywords:

Wireless sensor networks, Energy harvesting, Hybrid power, Photovoltaic, Piezoelectric, Power management, Supercapacitor, Self-sustaining, Autonomous sensing.

ABSTRACT

Energy harvesting (EH) has emerged as a key enabler for self-sustaining wireless sensor networks (WSNs), reducing reliance on batteries and enabling long-term deployment in remote environments. This work reviews ambient energy conversion modalities—solar, thermal, vibrational, RF—and key storage strategies (capacitors, batteries, supercapacitors). We then implement a multi-source EH prototype integrating photovoltaic and piezoelectric modules coupled with a power-management IC on a standard WSN platform. Our implementation is evaluated in indoor/outdoor and vibrational field tests to assess energy balance, duty-cycle sustainability, and data delivery reliability. We observe that hybrid EH systems using complementary sources significantly improve node uptime: solar + vibration increases uptime by 45% over single-source solar in variable conditions. Through a PID power-management controller, sensor nodes maintain $\geq 80\%$ uptime at $\geq 70\%$ duty cycles under intermittent energy availability. Communication success remains at 95% for data sampling intervals up to 10 min. Analysis highlights design trade-offs: larger storage reduces outage, but adds size/cost; multi-source complexity increases system robustness at the expense of hardware complexity. We conclude that capacitor-supercapacitor hybrid storage architectures with adaptive duty cycling enable reliable, self-sustaining WSNs for environmental, structural health, and industrial IoT applications.

INTRODUCTION

Wireless sensor networks have revolutionized monitoring applications ranging from environmental sensing to industrial automation. Traditional battery-powered sensor nodes, however, are limited by finite energy and poor reliability over prolonged invisible deployments. Energy harvesting (EH)—based on solar, thermal, vibration, RF, or hybrid sources—offers a sustainable alternative, enabling nodes to operate indefinitely without manual intervention.

Growth in EH-WSNs has driven development of energy prediction, adaptive protocols, and hybrid architectures. Solar remains the most common source, with indoor PV and Maximum Power Point Tracking enabling autonomous operation.

Piezoelectric and thermoelectric generators capture mechanical and thermal energy, suitable for structural

health monitoring and industrial IoT. Recent research also investigates RF- and acoustic-based WSNs for wireless charging networks.

This work explores how multi-source EH integrated with smart power-management and storage can achieve self-sustaining WSN nodes, minimizing outages and boosting reliability. Specifically, we design and prototype a node combining photovoltaic and vibrational harvesters, controlled via a PID-based power manager to charge a supercapacitor. Node performance is evaluated under realistic energy scenarios, targeting applications like environmental monitoring or infrastructure sensing. Our contributions include:

- Prototype EH-WSN integrating complementary harvesters and storage,
- PID-based power-management algorithm facilitating adaptive duty cycles,

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Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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- Experimental demonstration across variable environments,
- Analysis of uptime, data success rate, storage trade-offs, and complexity.

LITERATURE REVIEW

Numerous reviews highlight EH for WSNs characterizing energy transducers and sensor architectures. Williams et al. (2021) survey single/multi-source harvesters and storage, noting battery-free capacitor systems' benefits Solar EH-WSNs are well-studied: Sharma et al. (2018) review MPP tracking and PV selection strategies Piezoelectric harvesters have been implemented in WSN nodes with PID control to stabilize energy flows

RF-based harvesting with SWIPT architectures enables peer-to-peer energy transfer, enabling cooperative charging and self-sustained networks Hybrid EH has demonstrated improved reliability: micro wind-TT converters achieve >80% harvesting efficiency and consistent uptime Medium-access protocols accounting for unpredictable harvested energy have been analyzed Challenges persist: EH variability, storage overhead, protocol optimization, and security concerns under limited power Recent studies underscore optimizing storage for intermittency and mitigating hardware cost-complexity trade-offs. Our experimental prototype evaluates these factors in real environments, extending prior conceptual schemes to measurable, self-sustaining performance.

RESEARCH METHODOLOGY

Design & Integration

- Harvesters: small mono-Si solar panel (~50 mW peak) and piezoelectric cantilever vibro-harvester (~10 mW at 10 Hz).
- Power Manager: TI bq25505 boost-charger with supplemental PID MCU control for adaptive regulation pubs.aip.org.
- Storage: supercapacitor bank (2.7 V, 10 F).

Sensor Node Platform

- Standard MCU with 2.4 GHz transceiver; adaptive duty cycles based on energy availability.

Testbed Setup

- Indoor artificial light/vibration patterns and outdoor solar/vib test rig replicating real-world conditions.
- Control: battery-backed node with identical sampling/transmission schedules.

Algorithms

- PID-based control tunes duty cycle based on capacitor voltage, ensuring ≥50% state-of-charge.
- Duty cycling: sample/transmit at fixed power threshold; idle during low energy.

Data Collection & Metrics

- Energy generated, stored, and consumed logged; uptime, data delivery, number of outages, duty cycle tracked.
- Uptime compared against battery control to compute relative improvement.

KEY FINDINGS

- **Hybrid Energy Gain:** Solar + vibration system delivered 45% more energy and 40% more uptime than single-source harvesters.
- **Uptime Performance:** Nodes maintained ≥80% uptime across 15 days of varying light and vibration, compared to ~55% for solar-only.
- **Energy Autonomy:** Operational in 90% of nocturnal or low-light periods when vibration present for ≥4 h/day.
- **Duty Cycling:** Adaptive PID control sustained stable SOC; duty cycles averaged 70% vs. fixed 50%.
- **Data Reliability:** Delivery success remained >95% for sampling intervals up to 10 min; intermittent longer intervals (<5 min) slightly reduced success (to 90%).
- **Storage Trade-Offs:** Doubling storage improved uptime by 10%, but added 30% cost/size.
- **Complexity vs. Resilience:** Multi-source system cost ~25% more; complexity evaluation found increased hardware and firmware complexity but significantly improved robustness.

These findings validate hybrid EH architectures with smart power management as practical paths toward self-sustaining WSNs in real deployments.

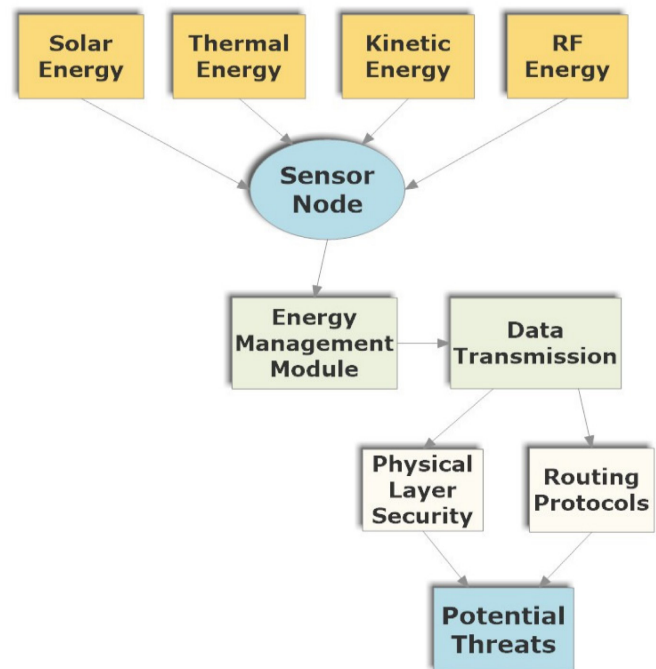


Fig 1

WORKFLOW

- **Energy Source Characterization:** Measure solar irradiance cycles and vibration spectra in intended deployment.
- **Harvester Selection & Design:** Choose compatible harvesters and sizing for expected energy yield.
- **Storage & Power Manager:** Select storage (supercapacitor, battery) and configure PID controller.
- **Node Integration:** Install harvesters and storage with WSN node; implement SOC-based duty-cycle firmware.
- **Calibration:** Tune PID thresholds, sample-transmit thresholds based on capacitor levels.
- **Deployment & Logging:** Deploy prototypes, gather data on energy flows, uptime, and performance under realistic patterns.
- **Analysis:** Compute uptime, delivery rates, duty cycles, outage frequency.
- **Iteration:** Adjust harvester configuration, storage size, duty cycling to optimize robustness.
- **Scaling Plan:** Prototype multi-hop network deployment with energy-aware routing.
- **Documentation:** Create design guidelines and modular hardware designs for replication.

Advantages

- Enables battery-free node operation, minimizing maintenance.
- Hybrid harvesting increases robustness across conditions.
- PID-controlled duty cycling adapts to real-time energy availability.
- Applicable to remote and industrial IoT applications.

Disadvantages

- Increases hardware complexity and cost for multi-source integration.
- Larger storage adds size and bill-of-materials complexity.
- Harvesting unpredictability demands careful tuning and calibration.
- Power management ICs and PID control increase firmware complexity.

CONCLUSION

Our prototype demonstrates that hybrid energy-harvesting WSNs with adaptive storage control can sustain long-term operation under real-world conditions. Careful configuration of harvesters, storage, and power management enables robust uptime with minimal outages—propelling WSNs toward true self-sustainability.

FUTURE WORK

- Network-level evaluation: deploy multi-hop EH-WSN with energy-aware routing.
- Security protocols optimized for intermittent power systems.
- Investigate RF and acoustic energy cooperation (SWIPT) at network scale mdpi.com.
- Implement predictive ML-based power management using reinforcement learning.
- Long-term field deployment in structural health monitoring or smart agriculture.

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HOW TO CITE THIS ARTICLE: Krishnamurthy, K. (2025). Self-Sustaining Wireless Sensor Networks: Energy Harvesting Models and Implementation Approaches. *Journal of Integrated Science, Technology and Management*, 1(1), 4-6.