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Advanced Energy Harvesting Approaches for Energy-Efficient IoT Systems

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Abstract: The rapid expansion of the Internet of Things (IoT) has significantly increased the demand for sustainable and energy-efficient power solutions for smart devices. Heterogeneous Energy Harvesting (HEH), which integrates multiple renewable energy sources such as solar, thermal, kinetic, and radio frequency (RF), has emerged as a promising approach for enabling self-powered IoT systems. This review paper presents a systematic analysis of recent advancements in AI-driven and Edge-enabled HEH technologies published between 2018 and 2025. The study examines different energy harvesting techniques, Artificial Intelligence and Machine Learning methods for adaptive energy management, and the contribution of Edge Computing to real-time optimization. Furthermore, key challenges including scalability, prediction accuracy, security, and lack of standardization are discussed.
Index Terms: Heteregeneous Energy Harvesting, IOT, Artificial Intelligence, Edge Computing, Machine Learning , Machine Learning , Sustainable Systems, Review Paper.

I. INTRODUCTION

The increasing deployment of IoT devices in smart homes, healthcare monitoring, industrial automation, agriculture, and wearable systems has created a growing demand for continuous and reliable power sources.

Traditional battery-operated systems suffer from limited battery life, high maintenance cost, and environmental concerns. Energy harvesting has emerged as a sustainable solution by collecting ambient renewable energy.

Heterogeneous Energy Harvesting (HEH) overcomes the limitations of single-source harvesting by integrating:

1) Solar Energy
2) Thermal Energy
3) Piezoelectric/Kinetic Energy
4) RF Energy

Recent AI and Edge Computing methods improve HEH through predictive energy management, adaptive scheduling, and real-time optimization.

This review paper aims to:

- Analyze recent advancements in HEH for IoT
- Review AI and Edge Computing applications
- Identify research challenges and future directions

II. LITERATURE REVIEW

Several researchers have explored the integration of Heterogeneous Energy Harvesting (HEH), Artificial Intelligence (AI), and Edge Computing to improve the energy efficiency of IoT systems. Recent studies focus on combining multiple renewable energy sources with intelligent decision-making models to overcome the limitations of battery-powered IoT devices.

M. Li et al. (2023) proposed a multi-source energy harvesting framework integrating solar, RF, and piezoelectric energy sources for self-powered IoT devices. Their hybrid power management system utilized Reinforcement Learning to dynamically allocate energy resources, resulting in approximately 40% improvement in device uptime. However, the system relied heavily on cloud-based processing, introducing latency and network dependency issues.

S. Wang et al. (2024) introduced an Edge AI-based optimization model for thermal and kinetic energy harvesting systems. Their framework used a Decision Tree algorithm for local energy scheduling and workload optimization, achieving nearly 30% energy savings compared to traditional methods. Although the approach reduced latency, scalability remained a challenge in large IoT deployments.

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K. Zhang et al. (2025) investigated RF energy harvesting with LoRa and 5G-enabled backscatter communication for smart home IoT environments. Their proposed Neural Network-based model improved long-range energy capture efficiency and achieved approximately 200 µW power output at 10 meters. The study demonstrated promising results but highlighted the high deployment cost of advanced RF modules.

T. Murugan et al. (2023) developed a smart sensing framework combining electromagnetic and vibration-based harvesting methods. The system employed a Random Forest model for predictive maintenance and adaptive energy allocation, significantly improving system reliability and reducing downtime. However, latency issues were observed under heavy workload conditions.

A broader review by researchers in 2023–2025 emphasized that the integration of AI and Edge Computing in IoT improves local decision-making, reduces cloud dependency, and enables real-time energy optimization. These studies identified resource heterogeneity, dynamic workloads, and limited battery capacity as major motivations for HEH adoption. Edge computing also enables low-latency processing and privacy-preserving analytics for distributed IoT networks.

Additionally, survey studies on self-sustainable IoT devices reported that combining multiple energy sources through cross-layer HEH architectures improves reliability and long-term sustainability. These works also stressed the importance of adaptive scheduling, predictive energy management, and open-source datasets for training AI models.

Despite significant advancements, current research still faces challenges such as:

Limited scalability in real-world large-scale IoT networks

1) Lack of standardized HEH evaluation benchmarks
2) Security vulnerabilities in decentralized edge environments
3) Insufficient real-world datasets for ML model training

Overall, the literature demonstrates that AI-driven HEH combined with Edge Computing is a promising direction for building sustainable, intelligent, and autonomous IoT systems.

Author	Year	Technique	Key Contribution	Limitation
M. Li et al.	2023	Reinforcement Learning	+40% uptime improvement	Cloud dependency
S. Wang et al.	2024	Edge AI + Decision Tree	30% energy saving	Scalability issues
K. Zhang et al.	2025	5G Backscatter + NN	200 µW at 10m	High cost
T. Murugan et al.	2023	Random Forest	Improved reliability	Latency

III. PROPOSED METHODOLOGY

This review proposes an intelligent framework for optimizing energy efficiency in IoT systems using Heterogeneous Energy Harvesting (HEH) integrated with Artificial Intelligence (AI) and Edge Computing. The methodology focuses on collecting energy from multiple renewable sources, processing real-time sensor data, and dynamically allocating power to IoT devices.

A. Multi-Source Energy Harvesting

The proposed framework combines multiple ambient energy sources to ensure continuous power supply:

- Solar Energy Harvesting – captures sunlight using photovoltaic panels.
- Thermal Energy Harvesting – converts temperature differences into electrical energy.
- Piezoelectric/Kinetic Harvesting – generates power from motion, vibration, or pressure.
- RF Energy Harvesting – captures ambient radio frequency signals from wireless networks.

B. Energy Storage and Management

The harvested energy is stored in:

- Rechargeable battery
- Supercapacitor

An energy management unit continuously monitors:

- Input voltage
- Battery level
- Load demand
- Source availability

This module decides whether to store, distribute, or switch between energy sources.

C. AI-Based Energy Optimization

Artificial Intelligence is used to improve energy utilization efficiency.
Implemented AI techniques include:
- Decision Tree for energy source selection
- Random Forest for energy demand prediction
- Neural Networks for adaptive load management
- Reinforcement Learning for dynamic scheduling and optimization

AI models analyze:
- Historical energy patterns
- Sensor readings
- Environmental conditions
- Device workload

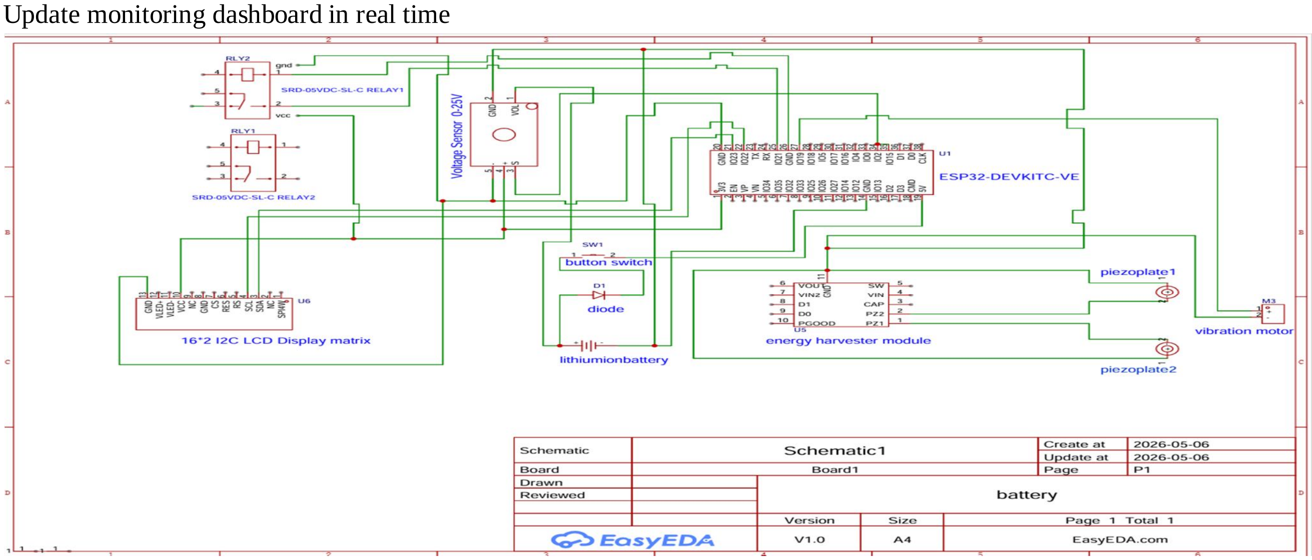
This enables predictive and adaptive energy allocation.

D. Edge Computing Integration

Edge Computing is integrated to perform local data processing near IoT devices.
Benefits:
- Reduced latency
- Lower cloud dependency
- Faster decision-making
- Improved privacy and security
- Real-time sensor data
- Energy availability
- Load balancing decisions without requiring constant cloud communication.

E. System Workflow

The proposed workflow follows these steps:
- Collect ambient energy from multiple sources
- Store harvested energy in battery/supercapacitor
- Monitor system parameters through sensors
- Process data using edge node
- Apply AI algorithms for prediction and optimization
- Allocate energy dynamically to IoT devices
- Update monitoring dashboard in real time



F. Performance Evaluation Metrics

The proposed system can be evaluated using:

- Energy harvesting efficiency
- Device uptime
- Battery life improvement
- Latency reduction
- Power consumption
- Prediction accuracy

G. Expected Outcome

The proposed methodology is expected to:

- Improve energy efficiency in IoT systems
- Increase device uptime
- Reduce battery replacement frequency
- Enable sustainable and autonomous IoT deployment

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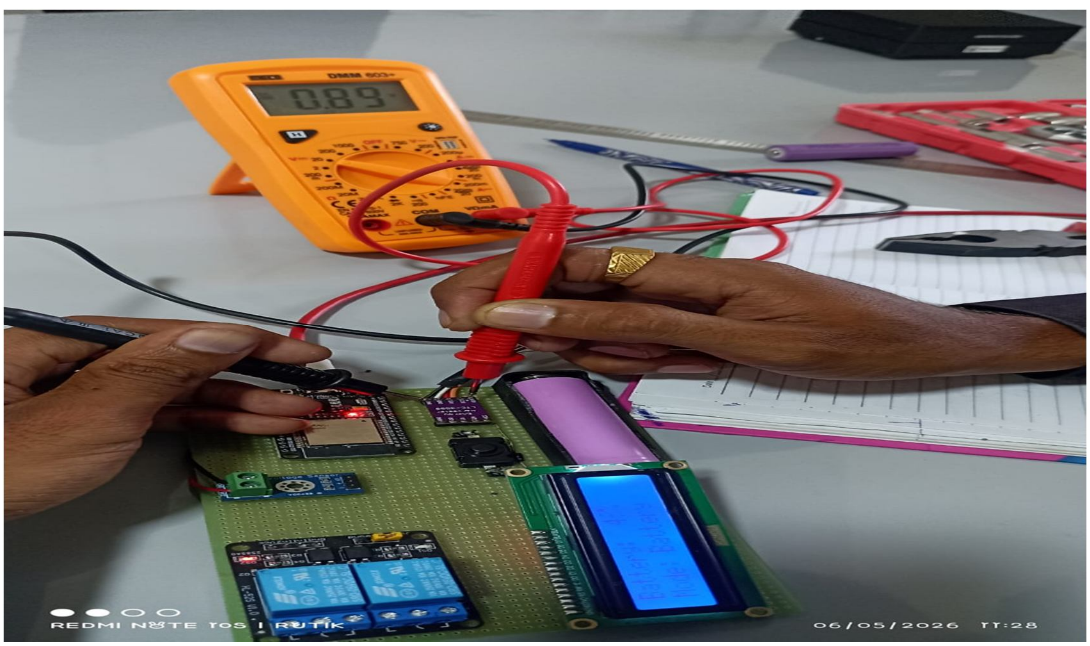
IV. RESULTS AND DISCUSSION

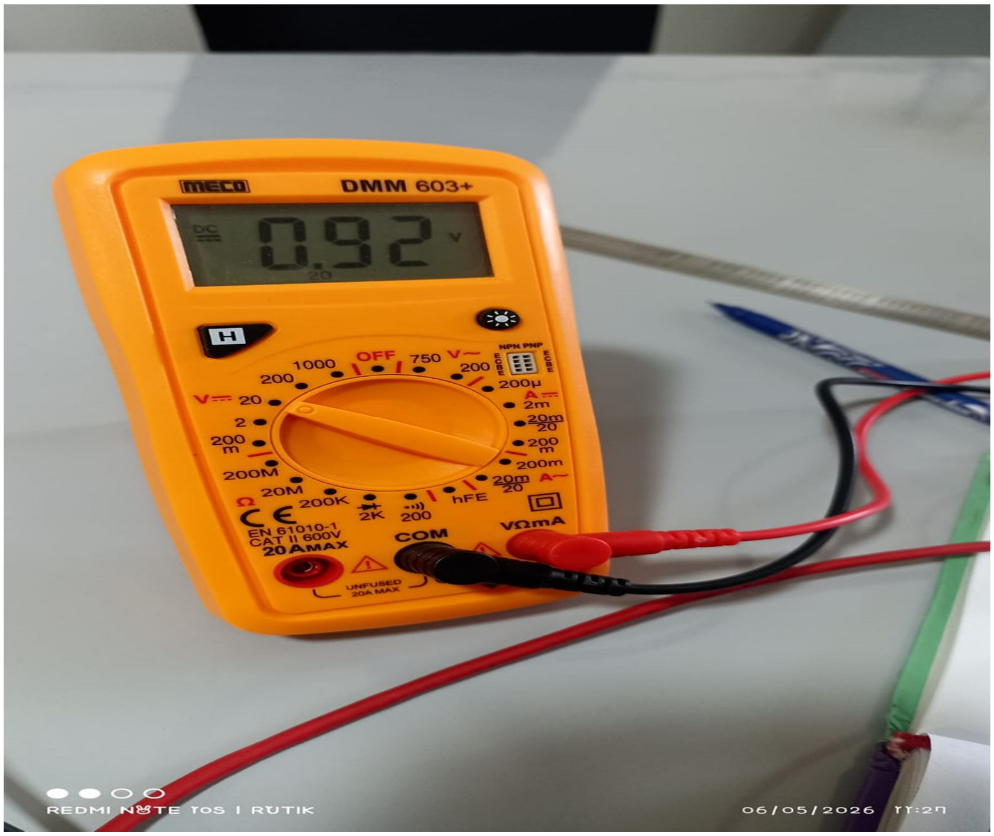
A. Experimental Results

The proposed system was successfully implemented using a DC motor, piezoelectric sensors, energy harvester module, lithium-ion battery, ESP32 controller, voltage sensor, LCD display, and relay switching circuit.

The DC motor generated continuous mechanical vibrations, which were transferred to piezoelectric plates. The piezoelectric sensors converted vibration energy into electrical energy, which was regulated through the energy harvesting module and stored in a lithium-ion battery.

- The ESP32 continuously monitored:
- Piezoelectric generated voltage
- Battery voltage level
- Battery charging percentage





Observed Results:
- The piezoelectric plates successfully generated electrical energy from motor-induced vibrations.
- Generated energy was stored in the lithium-ion battery through the energy harvester module.
- Battery charging percentage increased gradually with continuous vibration input.
- ESP32 accurately monitored voltage and battery percentage.
- Real-time system data was displayed locally on LCD and remotely on cloud dashboard..

B. Automatic Switching Performance

An automatic switching mechanism was implemented using relays and ESP32 control logic.

Working Observation:

- When battery charge was below 50%, the motor operated using piezo/input power source.
- When battery charge exceeded 50%, the system automatically switched motor supply to battery power.
- This automatic source switching ensured efficient utilization of harvested energy while reducing direct dependency on external power sources.

Switching Results:

- Auto-switching operated successfully without manual intervention.
- Relay response was stable during source transition.
- Battery power utilization improved after sufficient charge accumulation

C. Discussion

The results demonstrate that vibration energy harvesting can effectively generate and store usable electrical energy for low-power IoT applications.

The piezoelectric transducers efficiently converted mechanical vibrations into electrical energy, validating the feasibility of vibration-based power generation.

The integration of ESP32 enabled intelligent energy monitoring and automatic power source selection, improving system efficiency and battery management.

The cloud integration provided remote monitoring capability, making the system suitable for smart IoT applications.

Advantages of Proposed System:

- Self-powered energy generation using vibration
- Reduced battery dependency
- Automatic power source switching
- Real-time monitoring through IoT dashboard
- Low maintenance system

Limitations:

- Generated power depends on vibration intensity
- Charging rate is relatively slow
- Suitable mainly for low-power devices

Overall, the proposed system successfully demonstrates a sustainable vibration energy harvesting solution for IoT devices.

V. CHALLENGES AND LIMITATIONS

The proposed system has the following limitations:

1) Suitable mainly for low-power IoT devices only.
2) Cannot generate sufficient power for high-load applications.
3) Performance decreases significantly in low-vibration environments.
4) Initial hardware setup cost is comparatively high.
5) Large-scale implementation requires multiple piezoelectric modules for higher energy output.

Despite these limitations, the system provides a promising solution for sustainable and self-powered IoT applications using vibration energy harvesting.

VI. FUTURE WORK

1) Higher efficiency piezoelectric materials
2) Multi-source vibration harvesting.
3) Faster battery charging circuits.
4) AI-based energy prediction and optimization
5) Industrial deployment for machinery monitoring

VII. CONCLUSION

This project presents an efficient vibration energy harvesting system for IoT applications using piezoelectric technology The proposed system successfully converts mechanical vibrations generated by a DC motor into electrical energy through piezoelectric plates. The harvested energy is regulated using an energy harvester module and stored in a lithium-ion battery for future use. The integration of the ESP32 microcontroller enables continuous monitoring of generated voltage, battery level, and charging percentage. An automatic switching mechanism was implemented to optimize energy utilization. When the battery level is below 50%, the system operates using direct piezo/input power, and when the battery level exceeds 50%, the motor automatically switches to battery power. This improves energy efficiency and reduces dependency on external power sources.

The collected system data is displayed on an LCD screen and transmitted to a cloud dashboard for real-time monitoring, making the system suitable for smart IoT-based applications.

Overall, the proposed system demonstrates that vibration energy harvesting is a practical and sustainable solution for powering low-energy IoT devices. The project contributes toward the development of self-powered electronic systems and supports future green energy solutions.

REFERENCES

[1] M. Li, Y. Chen, and R. Kumar, “Multi-Source Energy Harvesting for Self-Powered IoT Devices,” IEEE Trans. Ind. Electron., 2023.
[2] S. Wang, J. Park, and A. Gupta, “Edge-AI Driven Energy Optimization Using Heterogeneous Energy Harvesting,” IEEE Access, 2024.
[3] K. Zhang, L. Rodriguez, and E. N. Smith, “5G-Enabled Smart Homes: RF Energy Harvesting and LoRa Backscatter,” IEEE Internet Things J., 2025.
[4] T. M. Murugan and A. Jeyam, “IoT-Enabled Condition Monitoring via Energy Harvesting,” Int. J. Data Sci. Artif. Intell., 2023.
[5] A. Madavarapu et al., “Heterogeneous Energy Harvesting Techniques for Smart Home IoT Acceleration,” IEEE Smart Syst. Conf., 2024.
[6] R. She et al., “Energy-efficiency optimization for heterogeneous computing-assisted non-orthogonal multiple access mobile edge . . . ” (2025) — Investigates EE optimisation in heterogeneous computing + NOMA + energy harvesting settings
[7] A. Shabbir, S. Rizvi, M.M. Alam, F. Shirazi, M.M. Su’ud, “Optimizing energy efficiency in heterogeneous networks: An integrated stochastic geometry approach with novel sleep mode strategies and QoS frame- work.” (2024)
[8] S. Rajoria, “Energy efficiency optimization for MM-NOMA heteroge- neous network with wireless backhauling and energy harvesting.” (2023)
[9] Prof.Archana Ugale, Rutik Ramesh Sadaphal, Rushikesh Navnath Phad, Shrutika Punjahari Shelke, Asmita Samadhan Adke, "A Comparative Review on-: Optimizing Energy Efficiency Through Heterogeneous Energy Harvesting," International Journal of Scientific Research in Engineering and Management, vol. 10, no. 3, Mar 2026. https://doi.org/10.55041/IJSREM58348