REVIEW ON : OPTIMIZING ENERGY EFFICIENCY THROUGH HETEROGENEOUS ENERGY HARVESTING

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ABSTRACT
The exponential growth of the Internet of Things (IoT) has accelerated research into sustainable and intelligent energy systems. Heterogeneous Energy Harvesting (HEH), which combines multiple renewable sources such as solar, thermal, kinetic, and RF, offers a promising path toward self-powered IoT devices. This paper provides a comprehensive review of recent advancements in HEH, emphasizing Artificial Intelligence (AI) and Edge Computing as enabling technologies for adaptive energy management. A systematic analysis of publications from 2018–2025 is presented, identifying major trends, methodologies, and limitations. Finally, this review highlights open research challenges and future directions for developing scalable, AI driven HEH architectures.

Keywords: —Heterogeneous Energy Harvesting, Internet of Things (IoT), Artificial Intelligence, Edge Computing, Machine Learning, Sustainable Systems, Review Paper.

Introduction
The proliferation of IoT devices in smart homes, healthcare, and industrial automation has led to increasing demand for energy-efficient and sustainable power solutions. Conventional battery-powered systems are limited by short lifespan and maintenance challenges. Heterogeneous Energy Harvesting (HEH) provides a viable alternative by combining multiple renewable sources to maintain a continuous energy supply.

However, HEH systems face issues such as unstable input power, source variability, and real-time decision-making constraints. Artificial Intelligence (AI) and Edge Computing are emerging solutions that enhance adaptability and efficiency by predicting energy demand, optimizing scheduling, and reducing latency.

This review paper contributes: • A comparative study of AI and Edge-based approaches in HEH for IoT systems. • Identification of research gaps and challenges in current HEH frameworks. • A set of future research recommendations for scalable and autonomous energy harvesting systems.

METHODOLOGY OF LITERATURE REVIEW:
The review follows a systematic methodology involving four key steps:
1) Database Selection: IEEE Xplore, ScienceDirect, SpringerLink, and MDPI Energies.
2) Keywords Used: “Heterogeneous Energy Harvesting”, “AI for IoT Energy”, “Edge Computing Optimization”, “Smart Energy Management”.
3) Selection Criteria: Papers published between 2018 2025 focusing on AI, ML, or Edge applications in HEH.
4) Analysis: Evaluation of energy sources, algorithms used, performance metrics, and limitations.

III. BACKGROUND AND FUNDAMENTALS:
A. Heterogeneous Energy Harvesting (HEH):
HEH combines multiple renewable energy sources—solar, thermal, piezoelectric, and RF—to ensure a consistent power supply. It is especially useful for remote IoT devices that operate autonomously without battery replacement.

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B. Role of Artificial Intelligence:
AI and ML algorithms (Decision Trees, Random Forests, Reinforcement Learning) enable predictive power management and adaptive energy allocation.
C.Edge Computing Integration :
Edge computing processes energy data locally, reducing latency and dependency on cloud servers. It enables real-time optimization and improves response time for IoT devices.

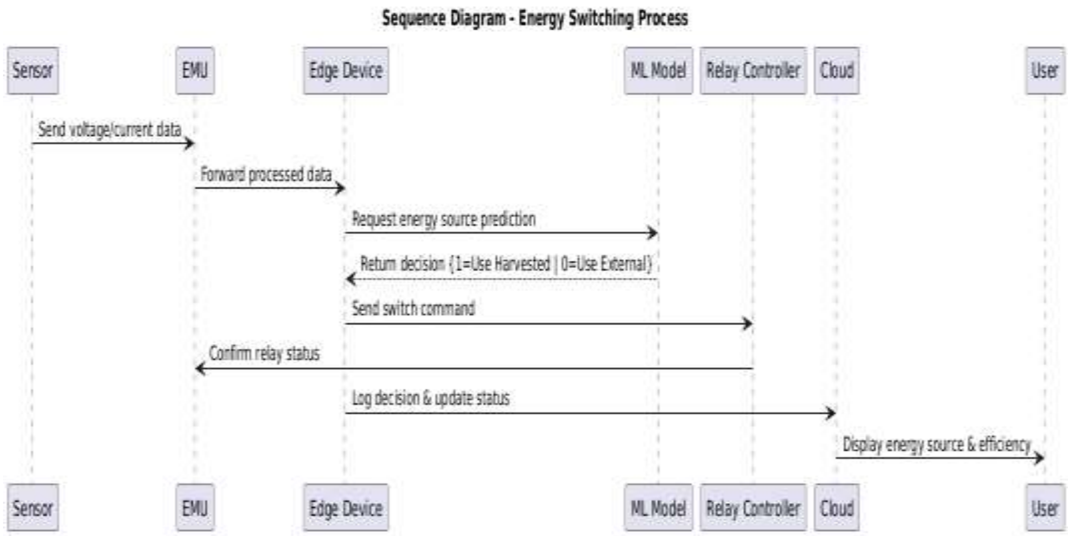
IV.REVIEW OF EXISTING RESEARCH:
Table I summarizes notable research in HEH, comparing methodologies, AI techniques, and performance.

V. KEY CHALLENGES AND RESEARCH GAPS:
Based on analysis, the major challenges include:
• Energy Prediction Accuracy: Limited training datasets affect ML model reliability.
• Scalability: Most HEH systems are not tested in large scale IoT environments.
• Security and Privacy: Edge devices may face cyber threats in decentralized systems.
• Standardization: Lack of unified HEH framework or performance benchmarks.

TABLE I COMPARATIVE ANALYSIS OF RELATED WORKS IN AI-DRIVEN HEH:

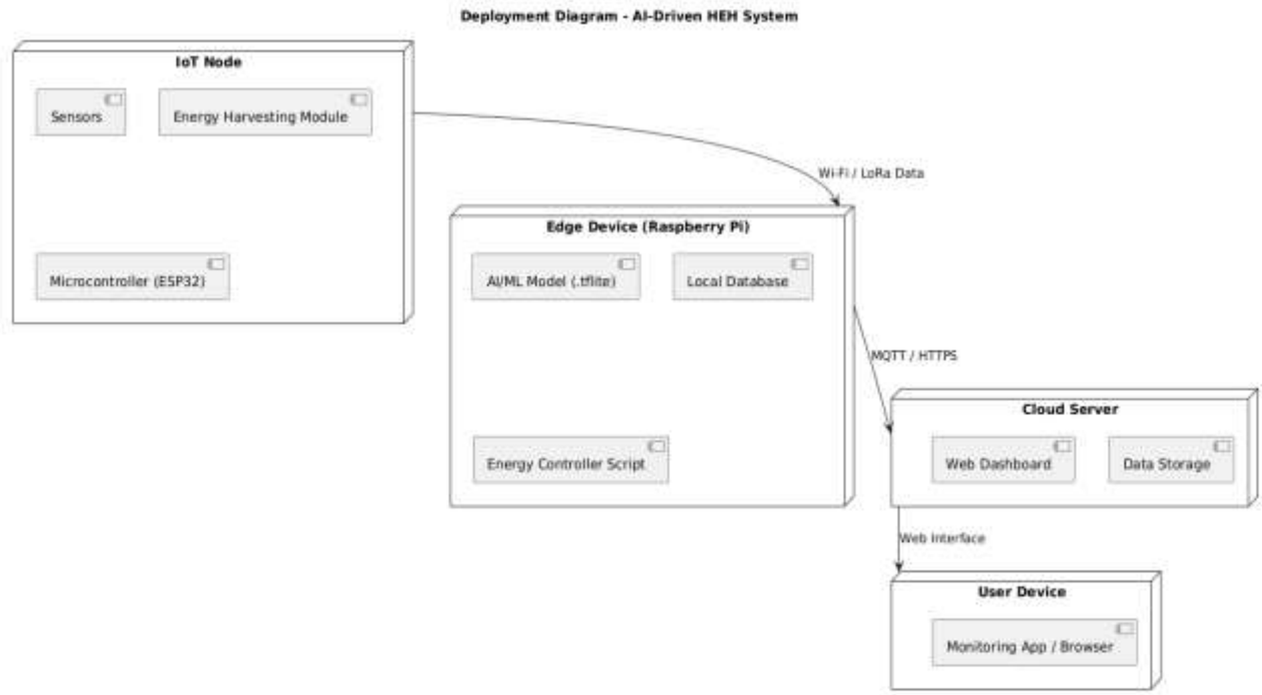
AUTHOR (YEAR)	ENERGY SOURCES	TECHNIQUE USED	AI/ML MODEL	KEY RESULTS	LIMITATIONS
M.Li et al.(2023)	Solar , RF,Piezo-electric	Hybrid Power Management	Reinforcement Learning	+40% Uptime	Cloud dependency
S.Wang et al.(2024)	Thermal, Kinetic	Federated Edge AI Optimization	Decision Tree Model	+30% Energy Saving	Limited scalability
K.Zhang et al.(2025)	RF, LoRa	5G-Enabled Backscatter	Neural Network	200mW at 10m range	High initial cost
T. Murugan et al.(2023)	Electromagnetic, Vibration	Smart Sensing Framework	Random Forcement	Improved Reliability	Latency under load
This Review(2025)	Solar , Thermal, RF, Kinetic	AI + Edge Integration	Comparative Analysis	Identifies Gap& Trends	NA

VI. SYSTEM MODELING USING UML DIAGRAMS
A . Use Case Diagram :



Use Case Diagram of AI-Driven HEH System.

B.



Component Diagram showing modular structure of HEH system

C. Sequence Diagram

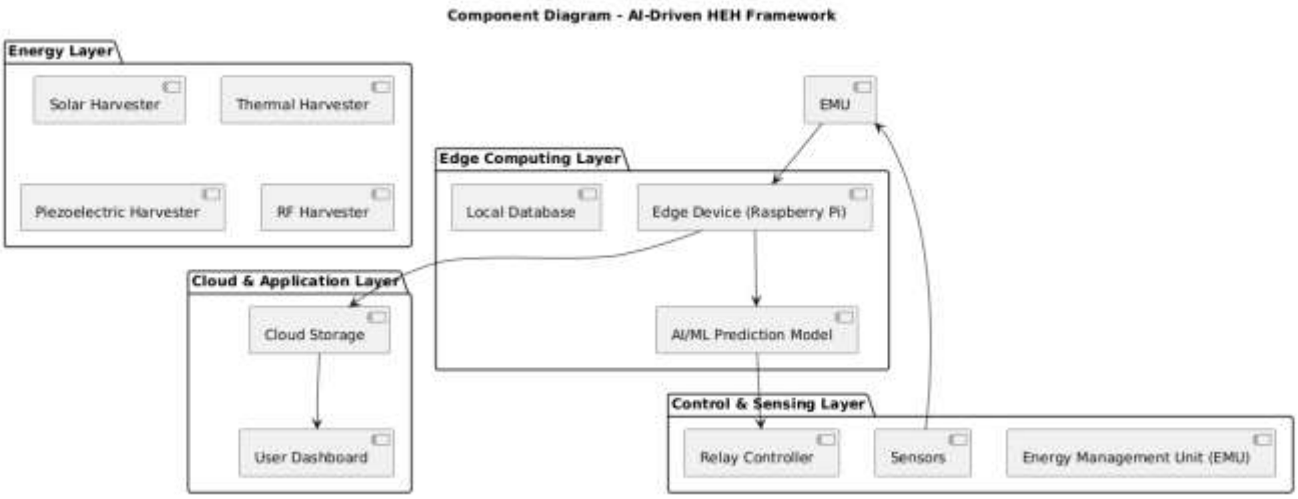


Fig .2. Sequence Diagram of energy – switching process

VII. FUTURE RESEARCH DIRECTIONS

Future advancements may focus on :

1) Integration of Reinforcement Learning for real-time energy control.
2) Hybrid Edge-Cloud collaboration for adaptive optimization.
3) Blockchain for secure, transparent energy transactions.
4) Creation of open-access HEH datasets for AI model training.

VIII. CONCLUSION:

This review analyzed state-of-the-art AI and edge computing approaches in heterogeneous energy harvesting. While significant progress has been achieved, key challenges such as real-time adaptability, scalability, and data security remain. Future systems integrating reinforcement learning and distributed edge frameworks can enable more intelligent, resilient, and sustainable IoT energy architectures.

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