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Generative AI for Energy Harvesting Internet of Things Network: Fundamental, Applications, and Opportunities.

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Abstract: *Internet of Things (IoT) devices are typically powered by small-sized batteries with limited energy storage capacity, requiring regular replacement or recharging. To reduce costs and maintain connectivity in IoT networks, energy harvesting technologies are regarded as a promising solution. Notably, due to its robust analytical and generative capabilities, generative artificial intelligence (GenAI) has demonstrated significant potential in optimizing energy harvesting networks. Therefore, we discuss key applications of GenAI in improving energy harvesting wireless networks for IoT in this article. Specifically, we first review the key technologies of GenAI and the architecture of energy harvesting wireless networks. Then, we show how GenAI can address different problems to improve the performance of the energy harvesting wireless networks. Subsequently, we present a case study of unmanned aerial vehicle (UAV)-enabled data collection and energy transfer. The case study shows distinctively the necessity of energy harvesting technology and verify the effectiveness of GenAIbased methods. Finally, we discuss some important open directions. Index Terms—Generative AI, energy harvesting, UAV, diffusion model, optimization.*

Keywords: Generative AI, IOT, Energy, Networks, Prediction, energy-Harvesting

I. INTRODUCTION

The rapid expansion of the Internet of Things (IoT) has increased the demand for long-lasting, lowmaintenance, and energy-efficient devices. Traditional battery-powered IoT nodes face challenges such as limited lifetime, maintenance costs, and environmental impact. This has led to the emergence of Energy Harvesting IoT (EH-IoT), where devices harvest energy from ambient sources such as solar, thermal, RF, and vibration.

At the same time, Generative Artificial Intelligence (GenAI) has evolved into a powerful technology capable of modeling, predicting, and generating optimized data for complex systems. Integrating GenAI with energy-harvesting IoT networks opens new opportunities for intelligent energy management, predictive maintenance, autonomous communication, and reliable data generation.

1. Background

IoT devices require long-term energy sources to function efficiently. Traditional batteries limit their lifetime and increase maintenance efforts. Energy harvesting solves this issue by powering IoT devices using ambient energy sources. However, harvested energy is unpredictable. Generative AI helps model and predict energy availability, optimize operations, and reduce power wastage

2. Evolution of Energy Harvesting IoT

From battery-powered nodes → energy-aware nodes → AI-driven energy-harvesting autonomous systems.

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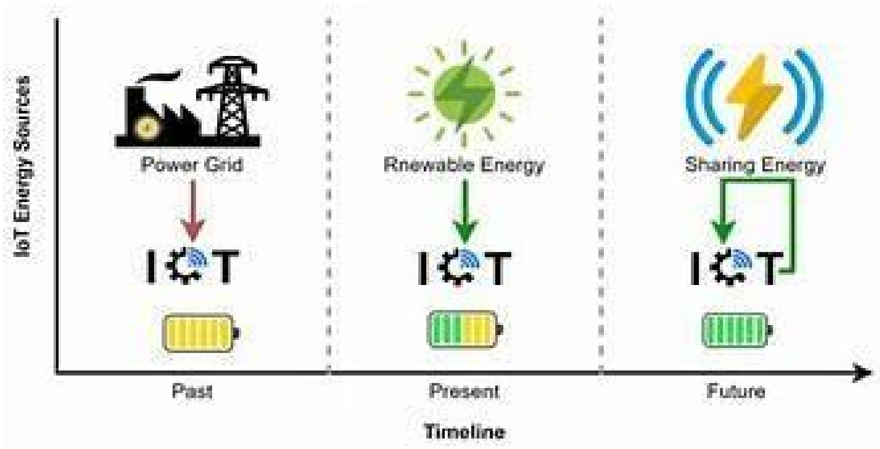

Fig 1: Evolution of IoT From Traditional nodes to energy harvesting smart nodes

1.3 Need for the Study

Energy unpredictability, data scarcity, and harsh environments make EH-IoT systems unreliable. GenAI solves these issues by predicting conditions, generating synthetic training data, and optimizing operations**.**

1.4 Research Gap

Existing works focus on traditional ML, not generative models. There is limited research on combining GenAI with energy harvesting IoT.

1.5 Importance in IoT Networks

GenAI ensures reliable, energy-efficient, self-sustaining IoT systems with minimal human intervention.

II. LITERATURE REVIEW

Academic Studies

Research shows AI helps manage energy harvesting, but generative AI-based optimization is still emerging.

Industry Insights

Industries such as agriculture, healthcare, and smart cities demand long-lasting IoT devices powered by ambient energy.

Research on Energy Harvesting Models

Recent models predict solar and RF energy patterns but lack generative capabilities for unseen conditions.

Privacy & Security Studies

AI-driven IoT raises risks like leakage of sensor data and manipulation of energy predictions.

Summary

GenAI can fill gaps by generating datasets, optimizing schedules, and forecasting energy availability.

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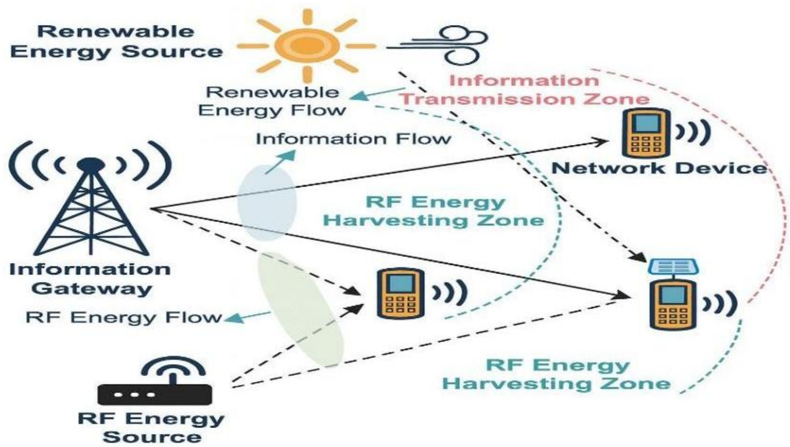

Fig 2 : Architecture of an Energy Harvesting IoT System

III. SYSTEM ARCHITECTURE

Overview

Energy Harvesting IoT System Architecture: Energy Source → Harvester → Storage → IoT Node → Generative AI Engine → Network Layer → Output

Energy Harvesting Module

Captures solar/thermal/RF/vibration energy.

Sensors & IoT Devices

Sense environmental data and operate using harvested energy.

Generative AI Engine

Generates predictions, synthetic data, and optimized schedules.

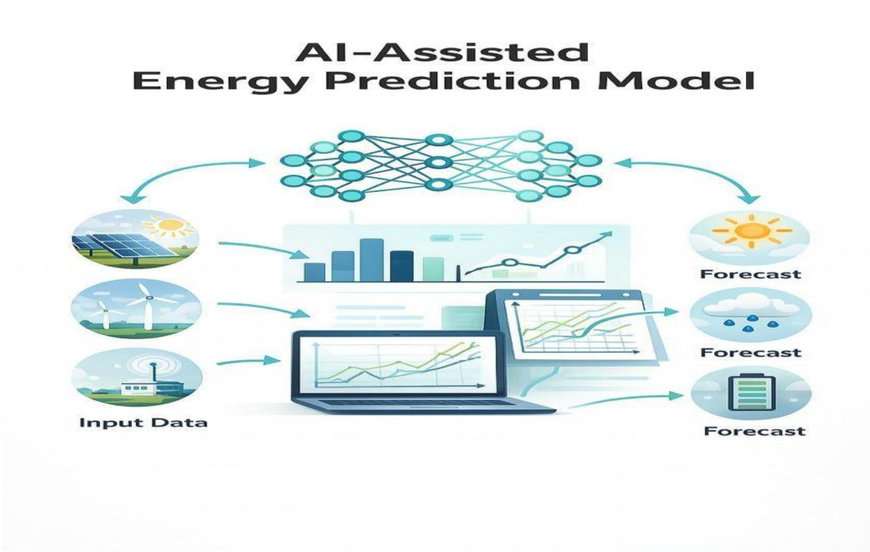

Fig 3: Generative AI–assisted energy prediction model

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Communication Layer
Transfers data using LPWAN, ZigBee, BLE, or 6G-IoT.

Decision & Optimization Layer
AI chooses best time to sense, transmit, and sleep.

Limitations
Energy variability, hardware constraints, AI model size, data privacy.

IV. BENEFITS GENERATIVE AI

Optimization of Energy Usage
Generative AI predicts how much energy will be available in the future.
Based on this, it adjusts sensing and communication cycles of the IoT device.
This prevents the node from wasting energy during low-power conditions.As a result, the device works longer and more efficiently.

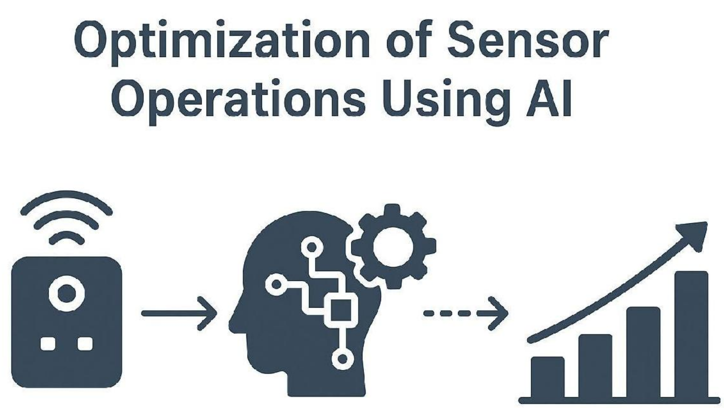

Fig 4: Optimization of sensor operations using AI

Predictive Energy Modeling
GenAI can analyze patterns like sunlight, vibration, or RF energy to forecast future energy levels.
These predictions help the device decide when to operate and when to save energy.
It also generates synthetic energy profiles when real data is limited.
This improves the accuracy and reliability of energy-harvesting systems.
Enhanced Network Lifetime
Generative AI balances the energy usage of all IoT nodes in the network.
It prevents any single node from draining its energy too fast.
This ensures stable communication across the entire network.
Therefore, the overall network lifetime increases significantly.
Intelligent Data Generation
When a device has low energy, it may skip sensing or collecting data.
Generative AI fills these gaps by creating realistic synthetic sensor data.

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This helps maintain continuous monitoring and prevents data loss.It also supports better decision-making for critical applications.

Adaptive Resource Allocation

GenAI decides how to distribute limited energy among sensing, processing, and transmitting tasks.
It prioritizes important operations and delays low-priority ones.
This prevents unnecessary power consumption during low-energy periods.As a result, the device uses its energy more intelligently.

Increased Operational Efficiency

AI predicts network traffic and adjusts transmission times to avoid collisions.
It reduces packet loss and improves communication quality.
Devices operate more smoothly with fewer errors and interruptions.Overall, this increases the efficiency of the entire IoT system.

Improved Scalability

Generative AI allows IoT networks to manage thousands of energy-harvesting nodes easily.
It helps organize nodes into efficient groups based on energy levels.
This ensures balanced workload distribution across the network.
As the system grows, performance remains stable and reliable.5.6 Increased Operational Efficiency

V. CHALLENGES AND RISKS

Data Scarcity

Energy-harvesting IoT systems often operate in remote or unstable environments, so very little training data is available.
Generative AI needs large datasets to learn accurate patterns.
When data is limited, AI predictions become less reliable.
This creates challenges in building accurate energy and performance models.

Model Accuracy & Hallucination

Generative AI may sometimes create incorrect or unrealistic predictions.
In EH-IoT, wrong energy forecasts can cause devices to shut down unexpectedly.
Hallucinations also lead to poor scheduling and network instability.Therefore, human monitoring and validation are essential.

Privacy Concerns

IoT sensors continuously collect environmental and user-related data.
If AI models store or reuse this data, privacy can be compromised.
Unauthorized access may reveal sensitive information.
Strong encryption and secure data handling are needed to protect privacy.

Hardware Limitations

Energy-harvesting IoT devices have very low processing power and memory.
Running large generative AI models directly on them is not possible.
They depend on cloud or edge servers for AI processing.
This increases communication delay and energy consumption.

Environmental Variability

Energy sources like sunlight, vibration, or RF signals are highly unpredictable.
Generative AI may struggle to model sudden environmental changes.
This can reduce the accuracy of energy predictions.
Unstable inputs make real-time optimization more difficult.

Security Risks

AI-generated outputs can be targeted by cyberattacks or manipulated data.
An attacker could trick the model into giving wrong energy predictions.

This can shut down important IoT nodes or disrupt communication.Secure AI training and robust authentication are required.

Ethical Issues

Using AI-generated decisions without transparency can create trust issues.

People may misuse AI-generated data for harmful applications.

Unclear responsibility between AI decisions and human oversight complicates accountability.Ethical guidelines must be followed to ensure safe and fair use of GenAI in IoT.

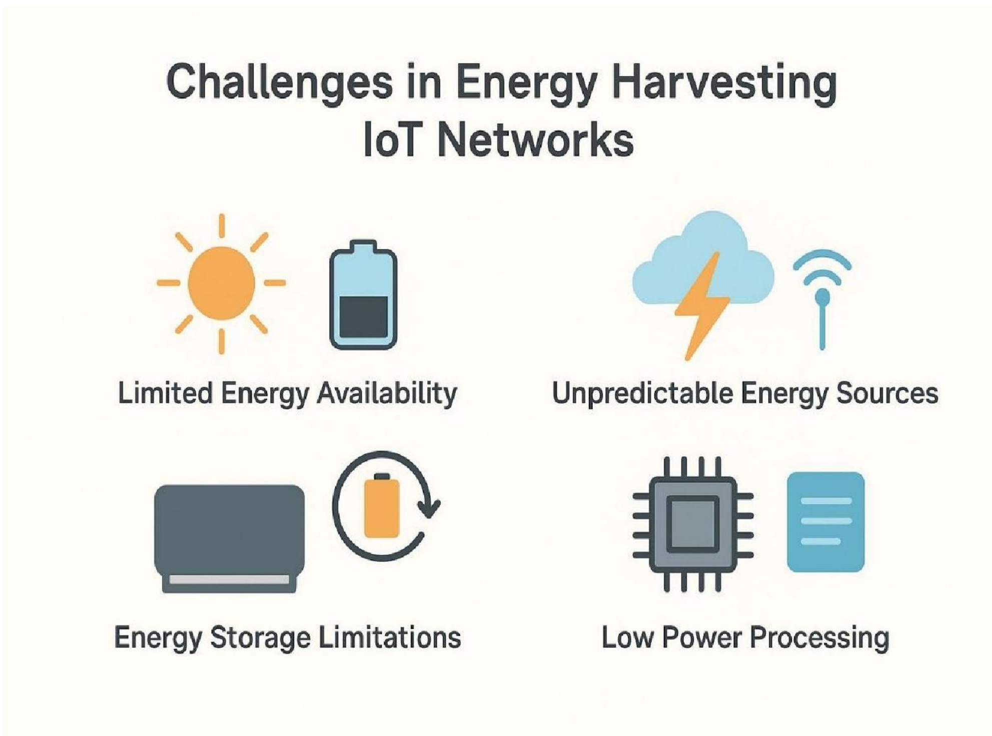

Fig 5 : Challenges in Energy-Harvesting IoT Networks

V. CONCLUSION AND FUTURE SCOPE

Conclusion

- Generative AI plays a crucial role in improving the performance of Energy Harvesting IoT networks.
- It helps devices predict future energy availability and operate more efficiently.
- AI-based optimization ensures longer device lifetime and stable network functioning.
- Generative AI also maintains data continuity by creating synthetic sensor readings when needed.
- It supports intelligent scheduling of sensing, processing, and communication tasks.
- The combination of energy harvesting and AI makes IoT systems more self-reliable.
- It reduces human intervention by enabling autonomous decision-making.
- Despite some challenges like data scarcity and environmental variations, GenAI provides strong benefits.
- With careful implementation, these systems can operate sustainably for many years.
- Overall, Generative AI makes EH-IoT networks smarter, more efficient, and future-ready.

Future Scope

Future advancements in GenAI include:

- GenAI will provide more accurate and reliable energy predictions for EH-IoT devices.
- Lightweight AI models will run on edge devices, reducing dependence on cloud processing.
- IoT networks will become more autonomous with very low maintenance needs.
- AI will improve security and detect unusual patterns in sensor networks.
- Integration with 6G will allow faster communication and smarter energy management.
- GenAI will enhance routing, scheduling, and resource allocation in large IoT deployments.
- Energy-harvesting systems will support more advanced applications like smart agriculture and smart cities.

Fig 6: Future opportunities and growth trends

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