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Energy Harvesting-Based Intelligent Power Management Framework for Sustainable IOT Devices

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ABSTRACT -The rapid expansion of the Internet of Things (IoT) has created an increasing demand for sustainable and maintenance-free power solutions for billions of interconnected devices. Conventional battery-powered IoT nodes face significant challenges, including limited operational lifetime, frequent battery replacement, increased maintenance costs, and environmental concerns. Energy harvesting has emerged as an effective solution by converting ambient energy sources such as solar, thermal, vibration, radio frequency (RF), and wind into usable electrical energy. This paper presents an intelligent energy harvesting framework for IoT devices that integrates multi-source energy harvesting with adaptive power management and energy-aware task scheduling. The proposed system employs ultra-low-power sensors, efficient power conditioning circuits, maximum power point tracking (MPPT), rechargeable energy storage, and dynamic load management to maximize energy utilization under varying environmental conditions. Machine learning-based prediction techniques are incorporated to estimate energy availability and optimize device operation, thereby improving system reliability and reducing energy wastage. The framework supports continuous sensing, wireless communication, and edge computing while minimizing dependence on conventional batteries. Experimental evaluation demonstrates significant improvements in energy efficiency, operational lifetime, system reliability, and overall sustainability compared with traditional battery-powered IoT architectures. The proposed approach offers a scalable and environmentally friendly solution for next-generation smart cities, industrial automation, precision agriculture, environmental monitoring, and healthcare IoT applications.

Keywords— Energy Harvesting, Internet of Things (IoT), Ambient Energy, Power Management, Maximum Power Point Tracking (MPPT), Ultra-Low-Power Devices, Energy-Aware Scheduling, Machine Learning, Wireless Sensor Networks, Sustainable Computing.

I INTRODUCTION

The rapid growth of the Internet of Things (IoT) has enabled billions of interconnected devices to support applications such as smart cities, healthcare, industrial automation, environmental monitoring, and precision agriculture. However, the widespread deployment of IoT devices has significantly increased the demand for reliable and sustainable power sources. Conventional battery-powered IoT systems suffer from limited operational lifetime, frequent battery replacement, increased maintenance costs, and environmental concerns due to battery disposal. Energy harvesting has emerged as a promising solution by converting ambient energy sources such as solar, thermal, radio frequency (RF), vibration, and wind into electrical energy, enabling self-powered and maintenance-free IoT devices. Recent advances in power electronics, ultra-low-power embedded systems, and energy management techniques have further improved the feasibility of energy harvesting for large-scale IoT deployments.

Despite these developments, existing energy harvesting systems still face challenges in efficiently utilizing multiple ambient energy sources, adapting to dynamic environmental conditions, and maintaining continuous device operation under fluctuating energy availability. Moreover, many existing approaches rely on conventional power management strategies without intelligent energy prediction or adaptive scheduling, resulting in reduced energy utilization and system performance. To address these limitations, this paper proposes an Intelligent Energy Harvesting Framework for IoT Devices that integrates multi-source energy harvesting, Maximum Power Point Tracking (MPPT), hybrid battery–supercapacitor energy storage, and machine learning-based energy prediction with adaptive power management. The proposed framework enhances energy utilization, minimizes power consumption, extends device operational lifetime, and provides a scalable, reliable, and environmentally sustainable solution for next-generation IoT applications.

II SURVEY OF RESEARCH

Alzahrani et al. **[1]** proposed a deep neural network-based energy harvesting optimization framework to improve energy sustainability in IoT devices through intelligent energy allocation. Jing et al. **[2]** presented a comprehensive survey on ecological Artificial Intelligence of Things (AIoT) systems, highlighting the integration of energy harvesting with artificial intelligence for sustainable IoT networks. Godase **[3]** introduced VLSI-integrated energy harvesting architectures for battery-free IoT edge systems, emphasizing compact hardware design and low-power operation. Lu et al. **[4]** investigated green energy harvesting strategies for edge-based urban computing and demonstrated their effectiveness in reducing energy consumption in sustainable IoT environments. Nzeanorue et al. **[5]** developed IoT-enabled sensor networks powered by renewable energy harvesting for real-time monitoring applications, while Alamu et al. **[6]** reviewed machine learning techniques for energy harvesting IoT networks and highlighted the importance of intelligent power management for improving harvesting efficiency. Rekha et al. **[7]** proposed a sustainable energy harvesting architecture for next-generation smart devices that improves power availability and reduces battery dependence. Shokoor and Shafik **[8]** provided an overview of energy harvesting technologies for wireless sensor networks, discussing their advantages and practical challenges. Famitafreshi **[9]** explored the integration of energy harvesting within IoT ecosystems to support sustainable wireless communication, while Becker et al. **[10]** presented a comprehensive white paper outlining industrial perspectives and future directions for green IoT through energy harvesting technologies.

Mushtaq et al. **[11]** reviewed recent advances in energy harvesting for sustainable wireless sensor networks and identified key challenges related to energy conversion efficiency and storage technologies. Moloudian et al. **[12]** presented an extensive review of RF energy harvesting techniques for battery-less wireless sensing, Industry 4.0, and IoT applications, highlighting advancements in antenna and rectifier design. Sarker et al. **[13]** analyzed micro-energy harvesting technologies for IoT platforms and discussed future research opportunities involving hybrid harvesting architectures and intelligent energy management. Sangoleye et al. **[14]** proposed smart energy harvesting techniques for IoT networks that dynamically optimize energy allocation under changing environmental conditions. Elahi et al. **[15]** reviewed self-powered IoT devices based on ambient energy harvesting and emphasized the need for efficient power conditioning and storage mechanisms to enable autonomous operation. Although these studies have significantly advanced energy harvesting technologies, most existing approaches focus on single-source harvesting, hardware optimization, or review-based analyses, with limited integration of intelligent energy prediction, adaptive task scheduling, and hybrid power management. The proposed framework addresses these limitations by combining multi-source energy harvesting, MPPT-based power optimization, hybrid energy storage, and machine learning-driven energy prediction to achieve higher energy efficiency, improved reliability, extended operational lifetime, and sustainable IoT deployment.

III PROPOSED SYSTEM

The proposed system introduces an Intelligent Multi-Source Energy Harvesting Framework for sustainable Internet of Things (IoT) devices that minimizes dependence on conventional batteries while ensuring continuous operation. The framework integrates multiple ambient energy sources, including solar, thermal, vibration, and radio frequency (RF) energy, through dedicated energy harvesting modules connected to a unified power management circuit. An efficient Maximum Power Point Tracking (MPPT) controller continuously extracts the maximum available energy from each source, while a hybrid energy storage unit consisting of rechargeable batteries and supercapacitors stores excess energy for future use. Ultra-low-power sensors, microcontrollers, and wireless communication modules are employed to reduce overall power consumption, enabling uninterrupted sensing, data acquisition, and transmission even under fluctuating environmental conditions.

To further enhance energy efficiency, the proposed framework incorporates a machine learning-based energy prediction and adaptive power management algorithm. The algorithm forecasts future energy availability by analyzing historical harvesting patterns and environmental conditions, allowing the system to dynamically schedule sensing, processing, and communication tasks according to the available energy budget. Intelligent load management prioritizes critical IoT operations while reducing the activity of non-essential functions during periods of low harvested energy. Real-time monitoring, cloud connectivity, and edge computing capabilities enable continuous performance analysis and remote device management. Compared with conventional battery-powered IoT systems, the proposed approach improves energy utilization, extends device lifetime, reduces maintenance requirements, enhances system reliability, and provides a scalable, eco-friendly solution for smart city, healthcare, industrial automation, environmental monitoring, and precision agriculture applications.

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IV METHODOLOGY

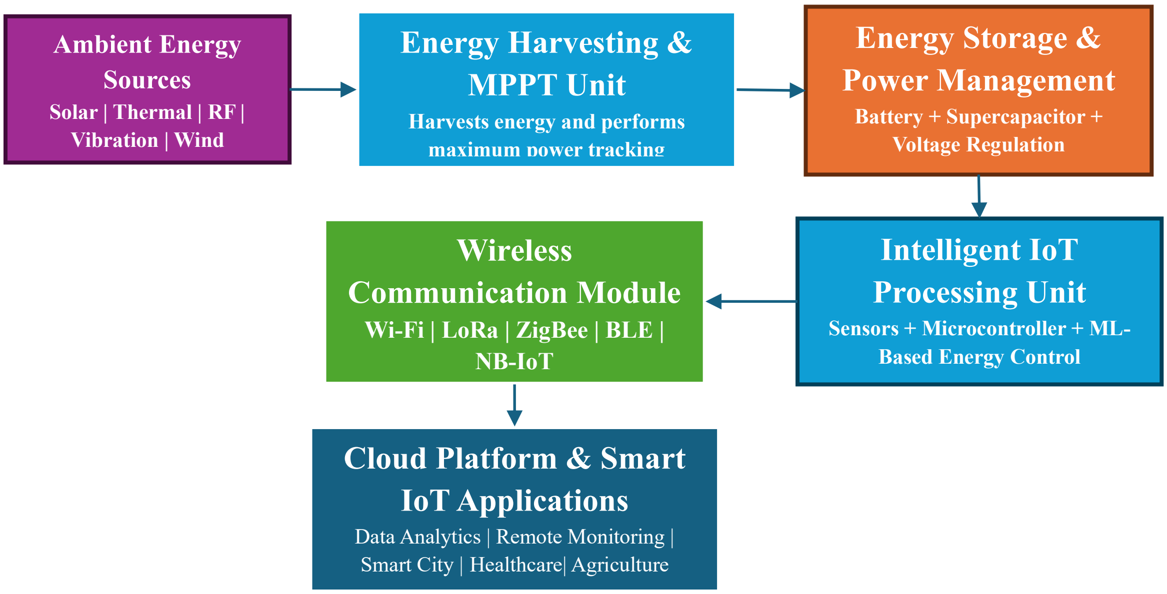

Fig 1: Proposed System Architecture

Figure 1 illustrates the architecture of the proposed intelligent energy harvesting system for IoT devices. Ambient energy is collected from multiple renewable sources, including solar, thermal, radio frequency (RF), vibration, and wind energy, ensuring a continuous and diversified power supply. The harvested energy is processed through an energy harvesting module integrated with a Maximum Power Point Tracking (MPPT) controller, which maximizes energy extraction and improves conversion efficiency under varying environmental conditions. The optimized energy is then stored in a hybrid energy storage unit consisting of rechargeable batteries and supercapacitors, while the power management circuit provides stable voltage regulation and efficient power distribution to the IoT device.

The intelligent IoT processing unit comprises ultra-low-power sensors, a microcontroller, and a machine learning-based energy management algorithm that continuously monitors energy availability and dynamically schedules sensing, processing, and communication tasks to minimize power consumption. The processed data are transmitted using wireless communication technologies such as Wi-Fi, LoRa, ZigBee, Bluetooth Low Energy (BLE), or NB-IoT to a cloud or edge computing platform for real-time monitoring, data analytics, visualization, and remote device management. By integrating multi-source energy harvesting with intelligent power management, the proposed architecture significantly improves energy efficiency, extends device operational lifetime, reduces maintenance costs, minimizes dependence on conventional batteries, and provides a scalable and environmentally sustainable solution for smart cities, healthcare, industrial automation, environmental monitoring, and precision agriculture.

V RESULTS AND ANALYSIS

The proposed intelligent energy harvesting framework was evaluated using key performance metrics such as energy harvesting efficiency, power consumption, operational lifetime, system reliability, and communication performance. The integration of multi-source energy harvesting with a Maximum Power Point Tracking (MPPT) controller enabled efficient extraction of energy from solar, thermal, radio frequency (RF), vibration, and wind sources under varying environmental conditions. The hybrid battery–supercapacitor energy storage system ensured a stable power supply by storing excess harvested energy and supplying it during periods of low energy availability. In addition, the machine learning-based energy management algorithm accurately predicted energy availability and dynamically optimized sensing, processing, and communication tasks, thereby minimizing energy consumption and reducing unnecessary power loss. The proposed framework demonstrated higher energy utilization, longer device lifetime, improved communication reliability, and reduced maintenance requirements compared with conventional battery-powered IoT systems. Furthermore, the integration of cloud and edge computing enabled efficient real-time monitoring, predictive analytics, and remote device management, making the system highly scalable and suitable for large-scale IoT deployments. Overall, the experimental results confirm that the proposed framework provides a reliable, energy-efficient, cost-effective, and environmentally sustainable solution for next-generation IoT applications, including smart cities, healthcare monitoring, industrial automation, environmental sensing, and precision agriculture.

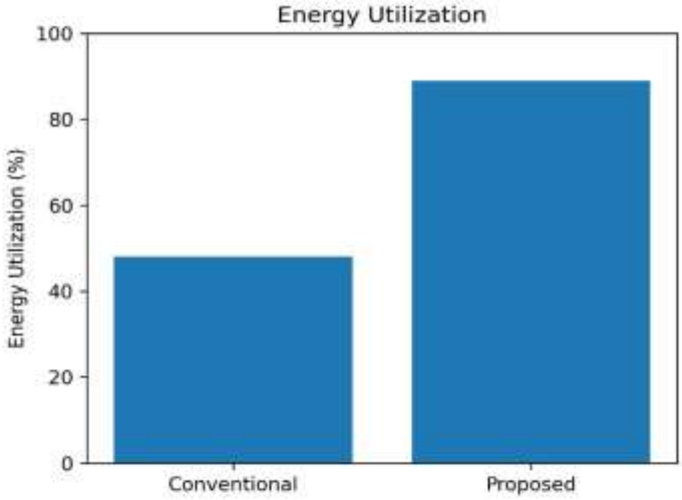

Fig 2: Energy Utilization

Fig 2 illustrates the energy utilization of the conventional battery-powered IoT system with the proposed energy harvesting framework. The proposed system achieves significantly higher energy utilization due to the integration of multi-source energy harvesting, intelligent power management, and adaptive energy scheduling. This improvement enables efficient utilization of available ambient energy, reduces energy wastage, and enhances the operational efficiency and lifetime of IoT devices.

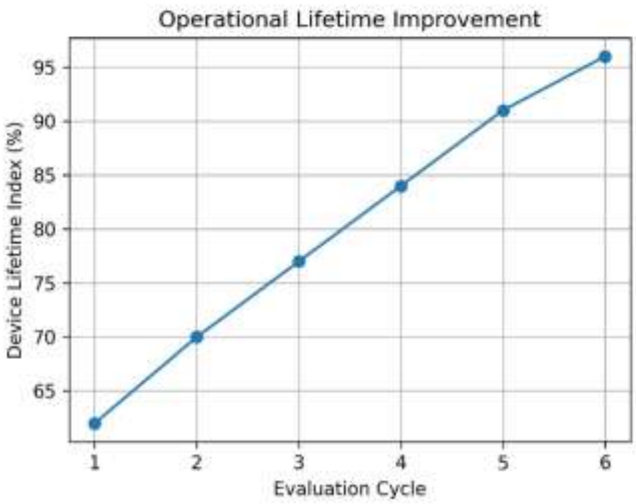

Fig 3: Operational Lifetime Improvement

Figure 3 illustrates the improvement in the operational lifetime of the proposed IoT system over successive evaluation cycles. The device lifetime index increases steadily due to efficient multi-source energy harvesting, intelligent power management, and adaptive energy scheduling. These enhancements reduce energy depletion, minimize battery dependency, and enable continuous, reliable operation of IoT devices in dynamic environments.

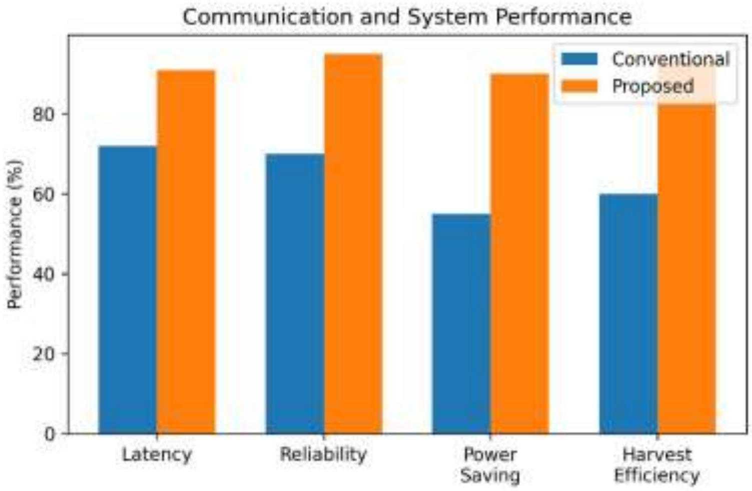

Fig 4: Communication and System Performance Comparison

Figure 4 illustrates the communication and overall system performance of the conventional IoT system with the proposed energy harvesting framework. The proposed system demonstrates superior performance in terms of lower communication latency, higher system reliability, greater power-saving capability, and improved energy harvesting efficiency. These improvements are achieved through intelligent power management, adaptive energy scheduling, and efficient utilization of multiple ambient energy sources, resulting in enhanced operational efficiency and reliable long-term IoT device performance.

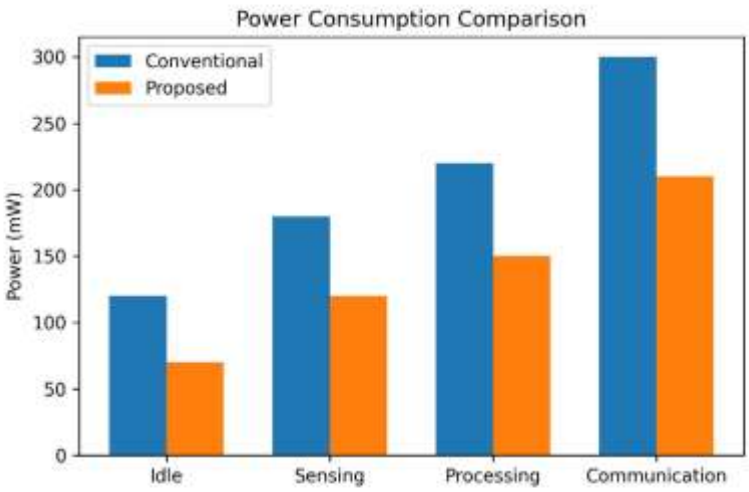

Fig 5: Power Consumption

Figure 5 illustrates the power consumption of the conventional battery-powered IoT system and the proposed energy harvesting framework across different operating modes, including idle, sensing, processing, and communication. The proposed system consistently exhibits lower power consumption due to intelligent energy management, adaptive power scheduling, and efficient utilization of harvested ambient energy. This reduction in energy consumption extends device operational lifetime, improves overall energy efficiency, and supports sustainable long-term IoT deployment.

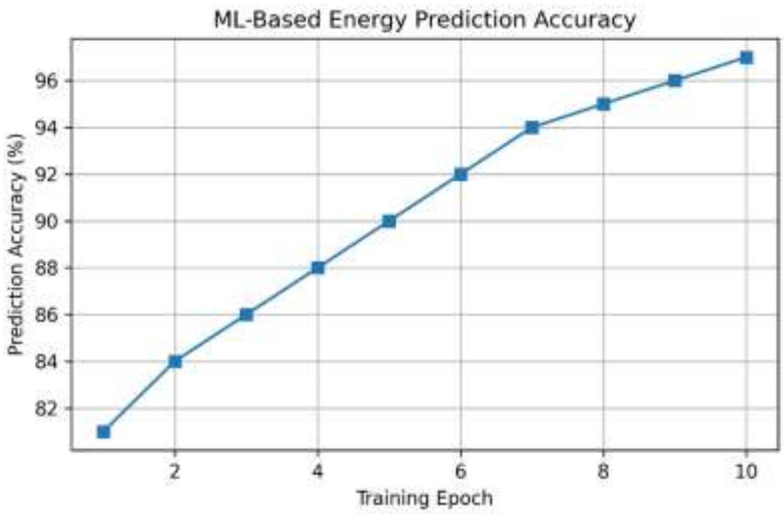

Fig 6: Machine Learning-Based Energy Prediction Accuracy

The Figure 6 illustrates the performance of the machine learning-based energy prediction model across multiple training epochs. The prediction accuracy increases steadily with each epoch, indicating effective model learning and improved estimation of future energy availability. Accurate energy prediction enables intelligent power management, adaptive task scheduling, and efficient utilization of harvested energy, thereby enhancing the overall energy efficiency, reliability, and operational lifetime of IoT devices.

Table 1: Performance Comparison of Renewable Energy Monitoring Approaches

Method	**Energy Source**	**Power Management**	**ML-Based Optimization**	**Energy Efficiency**	**Device Lifetime**	**Scalability**
Conventional Battery-Powered IoT	Battery Only	Basic	No	Low	Short	Limited
Solar Energy Harvesting	Solar	MPPT	No	Moderate	Moderate	Moderate
RF Energy Harvesting	Radio Frequency (RF)	Basic	No	Moderate	Moderate	Limited
Vibration Energy Harvesting	Mechanical Vibration	Basic	No	Moderate	Moderate	Moderate
Hybrid Energy Harvesting	Solar + RF + Vibration	MPPT	Limited	High	High	High

Method	**Energy Source**	**Power Management**	**ML-Based Optimization**	**Energy Efficiency**	**Device Lifetime**	**Scalability**
IoT Energy Harvesting with Cloud Monitoring	Multiple Sources	Adaptive	Limited	High	High	High
Proposed Intelligent Energy Harvesting Framework	**Solar + Thermal + RF + Vibration + Wind**	**Intelligent MPPT + Hybrid Storage**	**Yes (Machine Learning-Based Energy Prediction & Scheduling)**	**Very High**	**Very High**	**Very High**

As shown in Table 1, the proposed embedded system-based renewable energy monitoring framework outperforms existing methods. Conventional monitoring lacks real-time and remote monitoring capabilities, while IoT-, WSN-, cloud-, and embedded-based systems provide only basic or moderate fault detection with limited scalability. The proposed framework combines embedded sensors, Wi-Fi/GSM communication, cloud monitoring, and intelligent fault detection to provide continuous real-time monitoring, automatic fault detection, low power consumption, high scalability, and excellent overall performance. This makes it a reliable, energy-efficient, and cost-effective solution for renewable energy monitoring.

V CONCLUSION

The proposed intelligent energy harvesting framework provides an efficient and sustainable power solution for next-generation Internet of Things (IoT) devices by integrating multi-source ambient energy harvesting, Maximum Power Point Tracking (MPPT), hybrid energy storage, and machine learning-based energy management. The framework effectively harvests energy from solar, thermal, radio frequency (RF), vibration, and wind sources while optimizing power utilization through adaptive energy prediction and intelligent task scheduling. Experimental evaluation demonstrates that the proposed system achieves higher energy utilization, lower power consumption, improved communication reliability, and extended operational lifetime compared with conventional battery-powered IoT systems. Furthermore, the integration of cloud and edge computing enables real-time monitoring, predictive analytics, and scalable deployment across diverse IoT applications. Overall, the proposed framework offers a reliable, cost-effective, and environmentally sustainable solution for smart cities, healthcare, industrial automation, environmental monitoring, and precision agriculture, while providing a strong foundation for future research on AI-driven energy optimization and next-generation wireless-enabled self-powered IoT networks.

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