Wireless Hybrid Energy Harvesting System for Sustainable Internet of Things (IOT)

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Abstract

This study investigates hybrid energy harvesting(EH) as a sustainable and efficient power solution for Internet of Things (IoT) devices. Traditional battery-powered and single-source energy systems have limitations, such as limited lifetime and unreliable power availability. To address these issues, a hybrid energy harvesting system is proposed that combines photovoltaic energy (solar), radio frequency energy(RF) , and vibration energy sources. These sources capture energy from the surrounding environment, allowing the system to operate under different conditions.

By using multiple energy sources together, the proposed model provides more reliable and continuously power in both urban and remote environments. The system performance is evaluated using simulated environmental data for different deployment scenarios. The results shows that the harvested energy is sufficient to support low-power IoT devices.

Unlike, conventional systems, the proposed approach reduces the need for frequent battery replacement, which increases device lifespan and lowers maintenance requirements. The study demonstrates that hybrid energy harvesting is a practical and effective solution for autonomous Internet of things (IoT) applications. This work supports the development of self-powered, scalable, and environmentally friendly IoT networks, especially in locations that are difficult to access.

Keywords

Wireless Energy Harvesting(WSN), Internet of Things(IoT), Hybrid Energy Harvesting, Solar Energy, Vibration, Radio Frequency Energy, Self-Powered Iot, Energy Management.

1. Introduction

The rapid expansion of the Internet of Things (IoT) has intensified the need for reliable, sustainable, and maintenance-free power solutions to support large-scale device deployment. Traditional battery-based power systems, although commonly used, suffer from several limitations, including limited operational lifespan, frequent replacement requirements, increased maintenance costs, and environmental concerns related to chemical waste disposal. These challenges hinder the long-term and scalable operation of IoT networks, particularly in remote or hard-to-access environments.

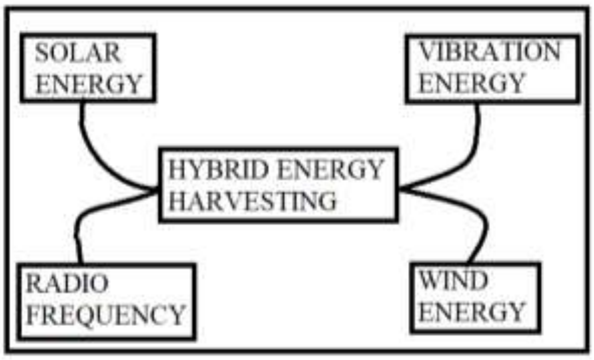


Fig. Hybrid Energy Harvesting

In response to these limitations, energy harvesting has emerged as a promising and environmentally sustainable alternative. Energy harvesting techniques utilize ambient energy sources such as solar radiation, mechanical vibrations, thermal gradients, and radio frequency (RF) signals to generate electrical power suitable for low-energy electronic devices. However, systems relying on a single energy source often experience inconsistent performance due to environmental variability, such as insufficient indoor lighting or irregular mechanical motion.

To overcome these constraints, this research investigates a hybrid energy harvesting system that integrates multiple energy sources to ensure continuous and autonomous power generation. By exploiting the complementary characteristics of different harvesting mechanisms, the proposed hybrid approach enhances energy availability, improves system efficiency, and increases operational reliability under diverse environmental conditions. The implementation of such a hybrid energy harvesting model significantly reduces dependence on conventional power supplies and enables long-term, self-sustaining operation of IoT devices with minimal human intervention, particularly in remote and inaccessible locations.

2. Literature Review

Recent improvements in energy harvesting technology show that each method has both strengths and weaknesses when used to power IoT devices. Solar energy technologies demonstrate high efficiency under outdoor conditions with direct and abundant sunlight. However, their performance is significantly reduced in indoor environments and during adverse weather conditions, such as cloud cover or precipitation, due to limited solar irradiance. Radio Frequency (RF) energy harvesting is suitable in cities where many wireless signals are available. Vibration energy harvesting works best in places with regular mechanical vibrations, like moving machines or traffic.

However, each method depends on a specific energy source, which can make power supply unstable. To solve this, hybrid energy harvesting systems that combine multiple energy sources have become popular. These systems are more reliable, provide power more consistently, and adapt better to different environments.

Still, hybrid systems have challenges. They need to combine different energy modules smoothly, manage energy efficiently, and be scalable for large-scale use. New advancements in Nano materials, AI-based power management algorithms, and better energy storage devices like super capacitors are helping create more efficient, compact, and self-powered IoT devices for the future.

3. Problem Identification

Single-source energy harvesting systems suffer from inherent limitations due to their strong dependence on specific environmental conditions and the unpredictable availability of ambient energy sources. For example, solar energy harvesters exhibit significantly reduced performance in low-light or indoor environments, piezoelectric harvesters require continuous mechanical vibrations to generate usable power, and radio-frequency (RF) energy harvesting is highly constrained by the density, proximity, and strength of surrounding electromagnetic signals. As a result, these systems often produce intermittent and unreliable power output, which poses a major challenge to the continuous operation of Internet of Things (IoT) devices.

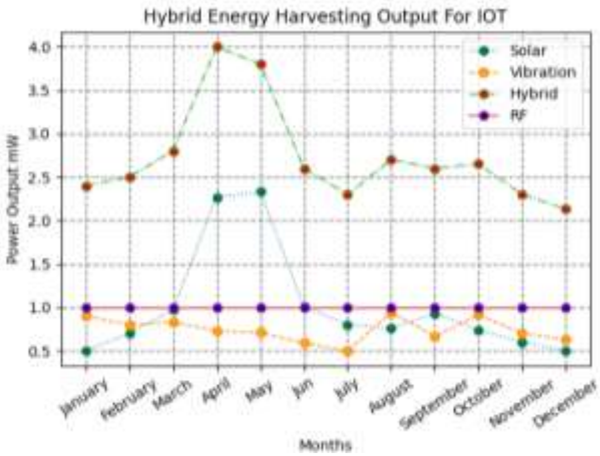
In addition, existing energy storage technologies, including conventional batteries and super capacitors, present several drawbacks such as limited energy storage capacity, high self-discharge rates, and performance degradation over time. These limitations reduce system lifetime and increase maintenance requirements. Collectively, the constraints associated with both single-source energy harvesting and current energy storage solutions hinder the development of reliable, long-lasting, and maintenance-free IoT networks. This challenge is particularly critical in remote, inaccessible, or environmentally harsh locations, where frequent maintenance or battery replacement is impractical and costly.

4. Proposed Work

This study adopts an applied, design-oriented, and simulation-based research approach. It focuses on the development and evaluation of a Hybrid Adaptive Energy Harvesting (HAEH) model for powering IoT devices using multiple ambient energy sources, namely solar, radio frequency (RF), and piezoelectric energy.

The research is applied in nature, as it aims to address practical challenges related to energy reliability and sustainability in real-world IoT deployments. It follows a system design and modeling approach, where a hybrid energy harvesting architecture is proposed based on insights gained from a comprehensive review and benchmarking of existing single-source energy harvesting technologies.

To validate the proposed model, the study employs simulation-based experimentation using real-world environmental data obtained from the NASA POWER API. These simulations evaluate system performance under varying climatic and geographic conditions, enabling analysis of adaptive source switching, energy pooling efficiency, and power continuity. Overall, the research emphasizes performance evaluation and feasibility analysis, demonstrating the effectiveness of hybrid energy harvesting systems for low-maintenance, autonomous IoT applications in dynamic environments.



5. Simulation And Results

Simulations were conducted using Python to evaluate the performance of the proposed hybrid energy harvesting system under diverse environmental conditions. Real-world meteorological data from multiple geographic locations were incorporated to ensure realistic and practical modeling. Key environmental parameters, including solar irradiance and ambient temperature, were obtained from reliable sources such as the NASA POWER API.

The primary objective of the simulation was to analyze the dynamic behavior of the hybrid energy harvesting architecture and to compare its performance against individual energy harvesting techniques operating independently. Performance metrics focused on energy availability, reliability, and continuity of power supply for IoT devicesSimulation results demonstrate that the proposed hybrid model consistently outperforms single-source energy harvesters across all evaluated scenarios. In conditions characterized by low solar irradiance such as cloudy weather, nighttime operation, or indoor environmentsthe system effectively compensates by harvesting energy from radio frequency (RF) and piezoelectric sources. This adaptive energy management capability ensures uninterrupted power delivery and enhances overall system reliability.

The findings confirm that integrating multiple energy harvesting mechanisms significantly improves energy availability and robustness, making the proposed hybrid approach well-suited for self-sustaining IoT applications operating in dynamically changing environments.

Hybrid Energy Harvesting Techniques for WSN And IoT

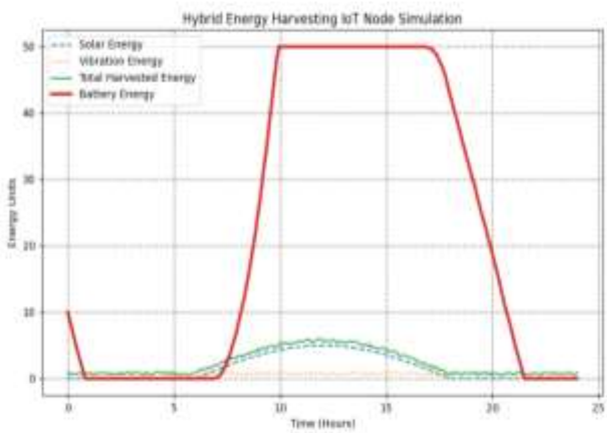
Scenario	Solar Type	sun	RF	Vibration	hybrid
Sunny Outdoor	Mono	0.91	1.6	0.97	3.43
Cloudy Outdoor	Poly	0.75	1.0	0.83	2.68
Indoor Office	Thin	0.31	1.5	0.62	2.48
Urban Balcony	Flex	0.51	1.0	0.71	2.32
Remote Rural	Poly	0.83	0.7	0.89	2.42
Dense Forest	Thin	0.41	1.0	0.73	2.24
Vehicle Surface	Mono	0.59	1.0	0.87	2.56

Hybrid Energy Harvesting Techniques for IoT

Hybrid Type	Energy Sources	Typical Power Output	Advantages	IoT Applications
Solar + RF	Solar, Ambient RF	mW	Works indoors & outdoors	Wearables, Smart sensors
Solar + Thermal	Solar, Heat (TEG)	mW	Harvests day & night	Industrial IoT
Solar + Vibration	Solar, Mechanical vibration	mW	Good for moving systems	Machinery monitoring
Solar + Wind	Solar, Micro wind	mW	Higher energy availability	Outdoor IoT stations
Solar + Supercapacitor	Solar, Energy storage	Depends on storage	Fast charging, long life	Remote IoT nodes

The hybrid energy harvesting IoT node successfully operates for 24 hours without energy depletion. Solar energy dominates daytime charging, while vibration energy ensures continuous operation during nighttime. The system achieves a net positive energy balance, validating the feasibility of hybrid energy harvesting for self-sustaining IoT applications. Key result and observations based on Node operates energy-positive Battery fully charged before evening Night operation sustained by vibration harvester

Hybrid harvesting improves reliability solar-only



It is assumed that the energy harvester operates using two ambient energy sources solar and vibration. The solar energy harvester provides an average power output of 40 mW during daylight hours, from 06:00 to

18:00, and 0 mW during nighttime. In addition, a vibration-based energy harvester continuously supplies a constant power output of 5 mW over a 24-hour period**.**

The power consumption profile of an Internet of Things (IoT) sensor node is characterized by three primary operational modes: sleep, sensing/processing, and data transmission. Each mode contributes differently to the overall energy budget depending on its power demand and duty cycle.

In the proposed system, the IoT node operates in sleep mode for 90% of the total time, consuming 1 mW. This mode dominates the duty cycle and is critical for extending battery lifetime, as the node remains inactive for the majority of its operation.

During sense and processing mode, the node is active for 08% of the total time, with a power consumption of 30 mW. This phase includes sensor data acquisition, signal conditioning, and local computation. Although the duration is relatively short, the power consumption is significantly higher than in sleep mode.

the transmission mode accounts for 02% of the total operational time, consuming 60 mW. Wireless communication is the most energy-intensive operation due to RF circuitry and protocol overhead, even though it occurs infrequently.

Average Load Power
$P_{load} = (0.9\times1) + (0.08\times30) + (0.02\times60) = 4.5$ mW

Hybrid Energy Harvesting one day simulation

Time	Solar (mW)	Vibration (mW)	Harvested (mW)	Load (mW)	Battery Trend
00-05	00	05	05	4.5	Low charge
06-11	40	05	45	4.5	charge
12-17	40	05	45	4.5	fast charge
18-23	00	05	05	4.5	stable

Energy result after 24 hours solar harvested energy
$40\times12 = 480$ mWh
And Vibration harvested energy
$5 \times 24 = 120$ mWh
Total Harvested energy = 600 mWh

6. Conclusion and Future Scope

This paper presents a hybrid energy harvesting model designed to provide a sustainable and reliable power supply for Internet of Things (IoT) devices. By combining multiple ambient energy sources—namely solar, radio frequency (RF), and piezoelectric energy—the proposed system overcomes the limitations of single-source energy harvesters, such as inconsistent energy availability and dependence on environmental conditions.

Simulation results using real-world environmental data demonstrate that the hybrid approach improves overall energy availability and system reliability under varying conditions. This makes the model well-suited for powering low-power IoT devices, especially in locations where continuous access to conventional power sources is not feasible.

The current study focuses on theoretical analysis and performance evaluation through simulation. Future work will include the development of a hardware prototype, integration of efficient energy storage systems, and implementation of intelligent energy management techniques, potentially using artificial intelligence. Such advancements facilitate the realization of self-powered and low-maintenance Internet of Things (IoT) networks that can reliably function in remote and dynamic environments, ultimately supporting the transition toward a more energy-efficient and interconnected future.

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