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Energy Harvesting in IoT Networks for Smart City Infrastructure

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Abstract

The integration of Energy Harvesting Technologies (EHTs) in Internet of Things (IoT) networks is pivotal for enhancing smart city infrastructure. This research addresses the pressing issue of energy sustainability in IoT applications, where traditional battery reliance poses significant maintenance and environmental challenges. Employing a comprehensive review of various energy harvesting methods—including solar, kinetic, and thermal energy—this study outlines their applicability in urban settings. The methodology involves analyzing existing literature and case studies to evaluate the efficiency and effectiveness of these technologies in real-world scenarios. Key findings indicate that energy harvesting can significantly reduce operational costs by eliminating the need for frequent battery replacements, thereby promoting a more sustainable urban environment. Furthermore, the results suggest that implementing these technologies can enhance the longevity and reliability of IoT devices, making them self-sufficient and reducing their carbon footprint. The implications for the field are profound, as adopting energy harvesting solutions could lead to smarter, more resilient cities capable of meeting future energy demands without compromising environmental integrity.

Keywords: Sustainability, IoT devices, Renewable energy, Urban environments, Energy efficiency, Battery replacement, Environmental impact, Smart cities.

1 | Introduction

The rapid urbanization seen across the globe has fostered the development of smart cities designed to offer high-quality services that align with the growing demands of urban populations [1]. The integration of advanced technologies in these cities has redefined urban life, improving sustainability, mobility, and the overall quality of life for citizens. Smart city infrastructure is built upon an ecosystem of devices connected through the Internet of Things (IoT) and supported by robust Information and Communication Technologies (ICTs). Over the past decade, the proliferation of digital devices has contributed to an increasingly connected

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world, with smart cities leveraging this connectivity to implement various services, including traffic surveillance and environmental monitoring [1].

The concept of a smart city revolves around real-time data collection from multiple IoT-enabled devices distributed throughout urban areas. This data facilitates real-time decision-making and enhances city operations, significantly benefiting urban inhabitants. However, as cities become smarter, the infrastructure supporting them must become more energy-efficient and sustainable. The increased deployment of IoT devices and sensors in urban environments, while improving connectivity and communication, also leads to higher energy demands and resource consumption [2].

Energy Harvesting Technologies (EHTs) have emerged as a solution to address these challenges by providing a sustainable energy source for IoT devices, as depicted in Fig.1, deployed in smart city ecosystems. These technologies convert ambient energy—such as solar, thermal, and vibration energy—into usable power for IoT systems, enabling them to operate continuously without relying heavily on batteries or the conventional power grid, as depicted in *Tables 1-3* [3]. Moreover, advancements in wireless communication, sensing, and computing have enabled the development of integrated systems capable of performing these tasks with minimal energy consumption, thereby promoting the sustainability of smart cities [3].

This paper aims to explore the role of energy harvesting in IoT networks for smart city infrastructure, highlighting key advancements, challenges, and potential solutions. It also discusses the integration of communication, sensing, and computing technologies in the context of energy-efficient smart cities. By analyzing current research trends and technologies, this work provides insights into the development of sustainable urban environments driven by IoT-enabled energy harvesting systems [4].

Table 1. Power density of various energy sources.

Energy Source	Power Density (mW/cm^2)
Solar panels	100-200
Piezoelectric	0.1-10
Thermoelectric	0.5-5
Wind turbines	50-150

Table 2. Challenges and solutions in energy harvesting for IoT.

Challenge	Proposed Solution
Low power output	Use of supercapacitors for storage
Environmental variability	Hybrid systems combining multiple sources
Maintenance costs	Self-sustaining designs with minimal upkeep

Table 3. Summary of energy harvesting Methods.

Method	Energy Source	Typical Applications	Advantages
Solar	Sunlight	Streetlights, sensors	High efficiency, widely available
Kinetic	Motion	Wearable devices, road sensors	Self-sustaining, low-maintenance
Thermal	Heat sources	Industrial monitoring	Utilizes waste heat
Radio Frequency	Electromagnetic	Wireless sensors	No physical connection needed

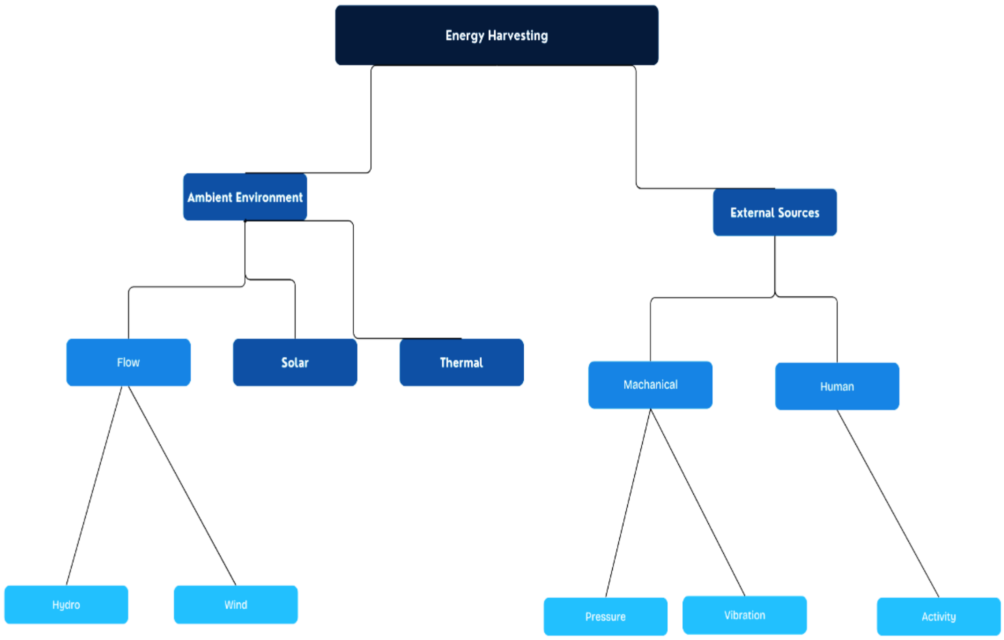

Fig. 1. Flowchart depicting the different sources of Energy harvesting.

2 | Literature Review

2.1 | Energy Harvesting Techniques for IoT

In recent years, energy harvesting has gained significant attention as a solution for powering IoT devices in smart city environments. Various energy sources can be exploited to supply energy to IoT devices, including ambient, mechanical, human, organic, and hybrid sources. Ambient sources, such as solar, Radio Frequency (RF), thermal, wind, and hydro-based energies, are naturally available in the environment and can be harnessed with minimal operational costs. Additionally, vibrations and pressure are mechanical energy sources that can be explicitly harvested from the environment. Solar energy harvesting is one of the most abundant energy sources, providing a continuous power supply to IoT devices. It has been shown that approximately 173×10^{12} kW of energy is continuously produced from solar sources, which is far more than the global energy demand. Photovoltaic (PV) cells, typically made from silicon, convert solar energy into electrical energy through the PV effect. Various types of PV cells, such as mono-crystalline, polycrystalline, and thin-film cells, offer varying efficiency levels. Mono-crystalline cells, with efficiency rates ranging from 15% to 24%, are the most efficient but also the most expensive. While outdoor applications of PV cells dominate, advancements have enabled the deployment of solar energy harvesting in indoor environments as well [5].

2.2 | Cognitive Radio and Energy

The increased use of wireless devices has caused spectrum scarcity issues in unlicensed bands, leading to the development of Cognitive Radio (CR) technology. CR enables dynamic access to licensed spectrum bands by allowing wireless devices to adapt their operating frequencies based on spectrum availability. CR can coexist with licensed users, such as primary users of the spectrum, by identifying vacant bands through techniques like spectrum sensing, spectrum decision, and spectrum handoff. CR-enabled wireless devices can detect unused spectrum bands and opportunistically access them, improving overall spectrum utilization while ensuring minimal interference with primary users. In the context of Cognitive Radio Sensor Networks (CRSNs), dynamic spectrum access allows sensor nodes to transmit data over underutilized licensed bands, significantly improving the efficiency and performance of Wireless Sensor Networks (WSNs).

The cognitive capability of sensor nodes enables spectrum-aware communication, reducing transmission errors and latency while also optimizing energy usage. The integration of energy harvesting techniques with CRSNs further enhances the sustainability of the network by powering CR-enabled sensor nodes autonomously, utilizing ambient energy sources such as solar or RF. This approach is particularly relevant in smart cities, where sensor nodes are deployed over large areas and require long-term, energy-efficient operation [6].

2.3 | Energy Harvesting in Smart Cities

Smart cities rely on advanced sensing and communication es to optimize resource management, infrastructure operation, and service delivery. In such cities, sensors deployed across different systems, including transportation, waste management, and healthcare, require a reliable and continuous power supply. Energy harvesting techniques, particularly those leveraging ambient energy sources, provide a sustainable powering of these sensors. By utilizing energy harvesting, sensors can operate autonomously for extended periods without needing battery replacement or maintenance, which is critical in large-scale deployments.

The holistic planning and operation of smart city infrastructures involve the strategic management of various owes to enhance efficiency, sustainability, and resilience. In this context, energy harvesting plays a crucial role in ensuring the continuous operation of IoT devices that monitor and control city infrastructures. For example, waste management systems in smart cities can use electric trucks powered by energy harvested from the environmentalism overall efficiency by integrating energy, transportation, and waste collection systems. This interoperability between different infrastructures is essential for the seamless operation of smart city services, ensuring that rows are optimized and sustainable. Smart cities rely on advanced sensing and communication technologies to optimize resource management, infrastructure operation, and service delivery. In such cities, sensors deployed across different systems, including transportation, waste management, and healthcare, require a reliable and continuous power supply. Energy harvesting techniques, particularly those leveraging ambient energy sources, provide a sustainable solution for powering these sensors. By utilizing energy harvesting, sensors can operate autonomously for extended periods without needing battery replacement or maintenance, which is critical in large-scale deployments.

The holistic planning and operation of smart city infrastructures involve the strategic management of various resource flows to enhance efficiency, sustainability, and resilience. In this context, energy harvesting plays a crucial role in ensuring the continuous operation of IoT devices that monitor and control city infrastructures. For example, waste management systems in smart cities can use electric trucks powered by energy harvested from the environment, thus improving overall efficiency by integrating energy, transportation, and waste collection systems. This interoperability between different infrastructures is essential for the seamless operation of smart city services, ensuring that resource flows are optimized and sustainable [4].

2.4 | Transportation Sector

The transportation sector is a significant consumer of energy, having consumed 40 million tonnes of oil-equivalent energy in 2020, with projections indicating a rise of 8% to 16% in congested traffic by 2050. This anticipated increase in traffic density is expected to lead to greater energy waste, particularly through thermal and mechanical forms, such as friction and vibration. Addressing this issue is crucial for promoting sustainability within the sector, primarily by focusing on strategies that minimize energy loss and enhance energy reclamation [7].

2.5 | Piezoelectric Materials for Energy Harvesting

Among the promising technologies for energy reclamation are piezoelectric and electromagnetic road energy harvesters. These devices are designed to capture vibrations and compressive forces generated by moving vehicles. Additionally, alternative energy sources, such as thermoelectric systems and solar panels, can be utilized to harness unused solar and thermal energy from road surfaces. Various studies have concentrated on the development and optimization of piezoelectric road energy harvesters, employing both numerical simulations and laboratory tests to analyze their performance under dynamic loads that replicate real-world driving conditions. These harvesters are typically composed of interconnected piezoelectric elements arranged in various configurations, including cylinders, bridges, stacks, cantilever beams, and cymbals. Experimental testing has shown that certain designs of piezoelectric harvesters can produce voltage outputs ranging significantly based on their structure and the mechanical conditions they endure. While these devices demonstrate an increase in output power with higher applied stress and frequency, their energy yield often remains limited to milliwatt and microwatt ranges. The primary challenges associated with piezoelectric harvesters include their relatively low power output and high maintenance costs, which hinder their widespread applicability [7].

2.6 | Electromagnetic Road Harvester

Electromagnetic road harvesters represent another avenue for energy collection. These devices, typically integrated into traffic-calming infrastructures like speed bumps and road rumble strips, convert surface displacements into electrical energy through mechanisms such as rack and pinion systems, hydraulics, and linear electromagnetic generators. Comprehensive evaluations through theoretical simulations, laboratory experiments, and field tests have indicated varying levels of power output, with some configurations achieving peak power outputs significantly higher than those of piezoelectric systems.

2.7 | Solar Energy

Solar energy also presents a viable source for road energy harvesting, encompassing technologies such as solar panel roads and solar collectors. Solar panel roads integrate engineered solar panels that meet the mechanical requirements of roadway surfaces. However, despite advancements in this area, these solar pavements have exhibited limitations, including brittleness and the necessity for frequent repairs, which significantly impact their durability and energy generation capacity. Conversely, solar collectors, which involve circulating water or air through pipelines embedded in the pavement, provide another means of harnessing solar energy, albeit with different operational dynamics [7].

2.7 | Thermoelectric Energy

Thermoelectric energy harvesters utilize the temperature gradient between the road surface and its subsurface to generate electricity. These systems capitalize on temperature differentials to produce electrical voltage, making them adaptable in various configurations. When comparing the power outputs of different road EHTs, it becomes evident that while piezoelectric and thermoelectric systems generate energy within the microwatt to milliwatt range, solar pavements and electromagnetic harvesters can yield watt-level power outputs. Nonetheless, the challenges faced by solar panel roads, particularly regarding cost, fragility, and weather dependence, remain a concern for their deployment in smart city infrastructure [7].

3 | Challenges Associated with the Energy Harvesting Using IoT

The integration of EHTs within IoT networks for smart city infrastructure presents several challenges that must be addressed to ensure effective implementation and operation. These challenges include:

3.1 | Energy Output Limitations

Many EHTs, such as piezoelectric and thermoelectric systems, typically produce low power outputs, often in the microwatt to milliwatt range. This limited energy generation may not be sufficient to meet the demands of high-performance IoT devices, particularly those requiring continuous power for real-time data processing and communication.

3.2 | Environmental Variability

The efficiency of energy harvesting systems is highly dependent on environmental conditions. For example, solar energy harvesters are affected by factors such as weather, seasonal changes, and time of day. Similarly, piezoelectric harvesters rely on consistent mechanical stress, which can vary significantly based on traffic patterns or human activity.

3.3 | Maintenance and Durability

Many energy harvesting devices face challenges related to durability and maintenance. For instance, solar panel roads have been reported to suffer from brittleness and require frequent repairs due to mechanical stress from traffic. This raises concerns about the long-term viability and cost-effectiveness of deploying such technologies on a large scale.

3.4 | Integration Complexity

Integrating multiple EHTs into a cohesive system poses significant technical challenges. Each technology may require different infrastructure, control systems, and data management protocols, complicating the overall design and operation of smart city applications.

3.5 | Interference with Traffic Flow

Certain energy harvesting solutions, particularly those that involve physical modifications to roadways (like speed bumps or other electromagnetic harvesters), can disrupt traffic flow if not designed carefully. This can lead to increased congestion and frustration among drivers.

3.6 | Spectrum Scarcity

The increasing number of wireless devices in urban areas has led to spectrum scarcity issues, complicating the communication needs of IoT networks. Efficiently managing spectrum access while ensuring minimal interference with licensed users remains a significant challenge.

3.7 | Cost Considerations

The initial investment required for deploying EHTs can be substantial. Budget constraints in urban planning may limit the adoption of these solutions despite their potential long-term benefits.

3.9 | Scalability

As smart cities expand and the number of connected devices increases, ensuring that energy harvesting systems can scale effectively becomes critical. Solutions must be adaptable to accommodate growing energy demands without compromising performance.

3.10 | Regulatory and Standardization Issues

The lack of standardized regulations for deploying EHTs can hinder their widespread adoption. Clear guidelines are needed to ensure safety, interoperability, and compatibility with existing infrastructure.

3.11 | Data Management and Processing

The integration of EHTs with IoT networks generates vast amounts of data that require efficient processing and management solutions. Developing robust data analytics frameworks that can handle this influx while ensuring timely decision-making is essential for optimizing smart city operations.

4 | Proposed Work

4.1 | Development of Energy-Harvesting CR Networks

The first step in this proposed work involves designing a robust architecture for Energy-Harvesting Cognitive Radio Sensor Networks (EH-CRSNs). This architecture will incorporate CR capabilities, allowing sensor nodes to access underutilized licensed spectrum bands dynamically. By employing advanced spectrum sensing techniques, the network will identify available channels and adaptively switch frequencies to optimize communication while minimizing interference with primary users. The design will focus on enhancing the network's resilience against environmental challenges, ensuring reliable data transmission across various urban settings.

4.2 | Integration of EHTs

To address the power constraints of traditional sensor nodes, the proposed framework will integrate multiple EHTs, including solar, piezoelectric, and thermoelectric systems. Each node will be equipped with a hybrid energy harvesting module capable of capturing energy from various ambient sources such as sunlight, vibrations from traffic, and temperature gradients. This approach not only extends the operational lifetime of sensor nodes but also reduces dependency on conventional battery systems, thereby promoting sustainability.

4.3 | Implementation of a Dynamic Spectrum Access Protocol

A critical component of this work is the development of a dynamic spectrum access protocol tailored for EH-CRSNs. This protocol will facilitate efficient communication by enabling nodes to share spectrum sensing results while minimizing control overhead. The protocol will employ distributed decision-making mechanisms to allow nodes to collaboratively determine the best available channels for transmission based on real-time environmental conditions and traffic demands. By optimizing channel selection and reducing transmission errors, this protocol aims to enhance overall network performance and reliability.

4.4 | Performance Evaluation and Optimization

To assess the effectiveness of the proposed EH-CRSN framework, a series of simulations and real-world experiments will be conducted. These evaluations will focus on key performance metrics such as energy efficiency, data throughput, latency, and reliability under varying traffic conditions. The results will provide insights into the operational dynamics of the network and inform further optimization strategies. Additionally, machine learning algorithms may be employed to predict traffic patterns and optimize resource allocation dynamically.

4.5 | Scalability and Deployment Considerations

Scalability is essential for the success of any smart city application. Therefore, the proposed work will include an analysis of scalability challenges associated with deploying EH-CRSNs in urban environments. Strategies for scaling up the network while maintaining performance levels will be explored, including hierarchical network architectures and adaptive resource management techniques.

4.6 | Addressing Security and Privacy Concerns

As with any IoT deployment, security and privacy are paramount considerations. The proposed work will incorporate security measures to protect data integrity and user privacy within EH-CRSNs. Techniques such as encryption, secure authentication protocols, and intrusion detection systems will be integrated into the network design to safeguard against potential threats.

5 | Conclusion

The discussions surrounding energy harvesting in IoT networks for smart city infrastructure highlight a critical intersection of technology, sustainability, and urban development. As urbanization progresses, the demand for efficient energy solutions becomes increasingly urgent, particularly in the transportation sector, which consumed a staggering 40 million tonnes of oil-equivalent energy in 2020. Projections indicate that this figure will rise significantly due to anticipated increases in traffic congestion. This scenario not only exacerbates energy consumption but also leads to considerable waste, primarily in thermal and mechanical forms such as friction and vibration. Therefore, addressing these challenges through innovative energy harvesting techniques is essential for promoting sustainability within urban environments.

EHTs, including piezoelectric systems, electromagnetic harvesters, and solar panels, present viable solutions for capturing wasted energy from various sources. For instance, piezoelectric road energy harvesters can convert vibrations from vehicle traffic into usable electrical energy. Similarly, electromagnetic harvesters can be integrated into traffic calming measures like speed bumps to harness energy from road surface displacements. Solar energy remains a promising avenue as well, with solar panel roads and collectors capable of generating power from sunlight. However, each of these technologies comes with its own set of challenges, including low power output, environmental variability, durability issues, and integration complexities. The literature emphasizes the importance of CR technology in enhancing the efficiency of energy harvesting systems in smart cities.

CRs enable dynamic spectrum access by allowing devices to opportunistically use underutilized licensed spectrum bands without interfering with primary users. This capability not only improves overall spectrum utilization but also enhances the reliability and performance of communication networks within urban environments. By integrating CR capabilities into sensor networks, known as CR CRSNs, it becomes possible to optimize data transmission while minimizing energy consumption. One significant advantage of employing energy-harvesting CRs is their ability to create self-sustaining communication systems. By utilizing ambient energy sources such as sunlight, vibrations from traffic, and temperature gradients, these systems can operate autonomously without the need for frequent battery replacements or recharges. This is particularly beneficial for sensor nodes deployed in remote or hard-to-access areas where maintenance is challenging. The integration of energy harvesting with CR technology not only extends the operational lifetime of sensor networks but also enhances their overall efficiency and effectiveness. Despite the promising potential of these technologies, several challenges must be addressed to realize their full benefits in smart city applications. The low output power generated by many harvesting methods limits their applicability for high-demand devices.

Additionally, environmental factors such as weather conditions can significantly impact the performance of solar-based systems. Moreover, integrating multiple EHTs into a cohesive framework poses technical challenges that require careful consideration during the design phase. To overcome these challenges, future work should focus on developing hybrid energy harvesting systems that combine various sources to optimize power generation. Furthermore, implementing advanced machine learning algorithms can enhance the predictive capabilities of these systems, allowing them to adapt dynamically to changing environmental conditions and user demands. Thus, the integration of EHTs within IoT networks represents a crucial step toward achieving sustainable smart city infrastructures.

By leveraging CR capabilities alongside innovative energy harvesting methods, urban environments can transition toward more efficient and resilient systems. Addressing the challenges associated with these technologies will be essential for unlocking their full potential and ensuring that cities can meet the growing demands of their populations while minimizing their environmental impact. As research continues to advance in this field, stakeholders must collaborate to develop practical solutions that enhance both the quality of life for urban residents and the sustainability of city operations. The future of smart cities hinges on our ability to harness available resources effectively while fostering innovation that supports long-term growth and resilience.

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Data Availability

The data used and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

These sections should be tailored to reflect the specific details and contributions if necessary.

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