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SWOT Analysis of the Application of Battery-Free Sensor Systems for Smart Infrastructure: A Literature Review on Micro Energy Technology

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ABSTRACT

The development of smart infrastructure requires sensor systems that can operate autonomously without relying on conventional batteries. This study analyzes the strengths, weaknesses, opportunities, and challenges (SWOT) of implementing battery-free sensor systems based on energy harvesting technology for smart infrastructure through a systematic literature study. The research methodology uses a literature review approach by analyzing 85 indexed international journal articles from the IEEE Xplore, ScienceDirect, SpringerLink, and MDPI databases for the period 2019-2024. The results of the SWOT analysis show that battery-free sensor systems have the main advantages of continuous operation, reduced maintenance costs by up to 60%, and are environmentally friendly. The main disadvantages include the limited energy that can be harvested (0.1-100 μW), dependence on environmental conditions, and the complexity of energy management. The greatest opportunities lie in the growth of the smart city market, which will reach $2.5 trillion by 2025, and the development of low-power communication technologies. Key challenges include fluctuations in environmental energy sources, electromagnetic interference, and data security regulations. This study provides strategic guidance for the development and implementation of battery-free sensor systems in smart infrastructure with energy harvesting efficiency that can be increased up to 85% through design optimization and adaptive energy management algorithms.

Keywords: Battery-Free Sensors, Energy Harvesting, Smart Infrastructure, SWOT Analysis, IoT, Smart City

INTRODUCTION

The digital revolution and rapid advances in the Internet of Things (IoT) have increased the need for efficient, autonomous, and sustainable infrastructure monitoring systems. This transformation is driving the development of sensor technologies that can operate autonomously without relying on external resources, particularly in smart infrastructure applications that require continuous, long-term monitoring (Cai et al., 2023; Takacs et al., 2024). Modern smart infrastructure, such as bridges, high-rise buildings, and transportation systems, requires monitoring solutions that can integrate various physical and environmental parameters in real time to ensure operational safety and maintenance efficiency.

Conventional battery-dependent wireless sensor systems face significant challenges in terms of sustainability and maintainability, particularly in large-scale infrastructure applications. Reliance on conventional batteries results in the need for regular replacement, which incurs high operational costs and creates a substantial environmental impact (La Rosa et al., 2024; Loubet et al., 2019). These issues are further complicated when sensors are installed in difficult-to-reach or hazardous locations, such as bridge structures at extreme heights, offshore installations, or underground infrastructure that requires special access.

Battery waste from IoT applications and wireless sensors has reached alarming levels, with an estimated 15 billion batteries discarded annually globally, creating a serious environmental challenge (Rosa et al., 2019; La Rosa et al., 2020). Batteries' chemical composition, which contains heavy metals and toxic materials, has the potential to pollute the environment if not managed with a proper waste management system. Furthermore, the battery production process requires intensive mineral extraction and contributes to a significant carbon footprint in the lifecycle assessment of sensor systems.

Battery-free sensor technology based on energy harvesting offers a new paradigm in the development of sustainable and economically viable infrastructure monitoring systems. This technology utilizes various ambient energy sources available in the surrounding environment, including photovoltaic energy from solar radiation, kinetic energy from structural vibrations, electromagnetic energy from radio waves, and thermal energy from environmental temperature gradients (Park et al., 2021; Allagui & Elrouby, 2022). This diversification of energy sources enables the development of more resilient and adaptable systems to varying operational environmental conditions.

Global market projections for energy harvesting technology show very promising growth, estimated to reach $1.2 billion by 2027 with a compound annual growth rate (CAGR) of 11.2% (Zhou et al., 2023). This growth is driven by increasing demand for autonomous systems in various application sectors, from smart city infrastructure to industrial automation. This technology enables the realization of the concept of truly autonomous monitoring systems that can operate for decades without human intervention, with an operational lifespan of up to 20 years or more depending on environmental conditions and system design.

The implementation of energy harvesting technology in sensor systems faces various complex technical challenges and requires a multidisciplinary approach to address them. The fundamental limitation in the power density that can be harvested from ambient energy sources, which typically ranges from 0.1 to 100 μW, necessitates the development of extremely power-efficient electronic circuitry (Sun et al., 2020; Huang et al., 2024). This challenge requires innovation in the design of power management systems, the development of ultra-low-power microcontrollers, and the implementation of energy-efficient communication protocols.

The architecture of a battery-free sensor system requires careful consideration of the trade-offs between functionality, reliability, and energy efficiency. The development of sophisticated energy management algorithms is a critical success factor for optimizing power consumption and scheduling operations based on energy availability predictions (Alam et al., 2019; Gupta & Garg, 2022). This complexity is further compounded by the need to integrate multiple energy harvesting sources within a single device, which requires advanced power conditioning circuits and intelligent switching mechanisms.

Miniaturizing energy harvesting devices while maintaining acceptable energy conversion efficiency is a significant engineering challenge in the development of battery-free sensor systems. The stringent dimensional constraints of many infrastructure applications require careful design optimization to maximize power output per unit volume or area (Gupta & Garg, 2022). The integration of MEMS (Micro-Electro-Mechanical Systems) technology and advanced materials is key to achieving compact form factors without significantly sacrificing performance.

The context of smart infrastructure applications presents unique requirements and challenges that differ from conventional IoT applications. Infrastructure monitoring requires long-term reliability, resistance to harsh environmental conditions, and the capability to measure parameters critical for structural health assessment (Cai et al., 2023; La Rosa et al., 2024). Sensor systems must be able to operate in a wide temperature range, high humidity, exposure to UV radiation, and significant potential mechanical stress.

A systematic literature review is essential for identifying and analyzing critical factors influencing the successful implementation of battery-free sensor systems in the context of smart infrastructure. A SWOT analysis approach provides a comprehensive framework for evaluating the technology's internal strengths and weaknesses, as well as external opportunities and threats that can impact adoption rates and commercial viability (Mohammadi & Noor, 2023). This analysis provides a crucial foundation for developing a strategic roadmap and identifying research priorities that will determine the future development trajectory of battery-free sensor technology.

METHOD

Research Design

This study adopted a systematic literature review approach following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure the quality and consistency of the analysis process. The methodology used was designed to identify, evaluate, and synthesize empirical evidence related to the implementation of battery-free sensor systems in the context of smart infrastructure. This systematic approach enabled the identification of research gaps, assessment of the current state-of-the-art, and development of a comprehensive SWOT analysis based on consolidated findings from multiple studies.

Search Strategy and Data Sources

The literature search strategy was conducted through four major internationally recognized academic databases: IEEE Xplore Digital Library, ScienceDirect (Elsevier), SpringerLink, and MDPI. These databases were selected based on their comprehensive coverage of publications in engineering, computer science, and environmental technology. The search period was set between 2019 and 2024 to ensure relevance to the latest technological developments, given the rapid advancements in energy harvesting and IoT technology over the past five years.

The search strategy was developed using a combination of keywords categorized into three main domains. The first category includes technology terms such as "battery-free sensor," "energy harvesting," "self-powered sensor," "autonomous wireless sensor," and "ambient energy harvesting." The second category focuses on application domains with keywords such as "smart infrastructure," "structural health monitoring," "IoT applications," "smart city," and "intelligent infrastructure." The third category targets analysis aspects with terms such as "SWOT analysis," "challenges and opportunities," "performance evaluation," and "feasibility study."

Selection Criteria and Screening Process

The literature selection process was conducted using clearly defined inclusion and exclusion criteria to ensure the quality of the selected publications. Inclusion criteria included peer-reviewed journal articles published in English, focusing on battery-free sensor technology and energy harvesting, and discussing applications in smart infrastructure or monitoring systems. Publications must be available in full-text format and accessible through institutional subscriptions or open access repositories.

Exclusion criteria were applied to filter out publications irrelevant to the research focus, including conference proceedings and grey literature that had not undergone a rigorous peer-review process. Review articles that did not present primary data or original research findings were also eliminated, as were publications with unclear methodology or insufficient detail for evaluation. Duplicate publications from various databases were identified and removed to avoid bias in the analysis.

The screening process was conducted in three sequential stages to ensure systematic evaluation. The first stage involved screening based on titles and abstracts to identify relevant publications, resulting in 450 articles from the initial search results. The second stage conducted a full-text assessment of 150 articles that met the initial criteria, with an in-depth evaluation of methodology, findings, and relevance to the research questions. The final stage yielded 85 high-quality articles that met all criteria and were used as the basis for a comprehensive SWOT analysis.

SWOT Analysis

The SWOT analysis used in this study was designed to identify and categorize factors influencing the implementation of battery-free sensor systems in the context of smart infrastructure. The analysis was conducted by grouping findings from the selected literature into four main, interrelated categories, providing a comprehensive picture of the current state and future prospects of this technology.

The Strengths category covers positive internal factors that provide a competitive advantage for battery-free sensor technology, including technical capabilities, economic benefits, and environmental advantages. The Weaknesses category identifies internal factors that hinder implementation, such as technical limitations, cost constraints, and system complexity. The Opportunities category covers external factors that can be leveraged to accelerate adoption, including market trends, policy support, and technological developments. The Threats category identifies external factors that could hinder successful implementation, such as competition, regulatory barriers, and market uncertainties.

Data Extraction and Validation

The data extraction process was conducted using a data extraction standard developed specifically for this study. The form included bibliographic information, research methodology, energy harvesting technology used, specific infrastructure applications, performance metrics, and identification of SWOT factors. Data extraction was conducted systematically by reviewers trained in energy harvesting and IoT technology, with cross-validation to ensure accuracy and consistency.

Validation of findings was conducted through data triangulation from multiple sources and cross-referencing with expert knowledge in the fields of energy harvesting, sensor technology, and infrastructure monitoring. A quality assessment was conducted on each selected publication using established criteria to evaluate methodological rigor, data quality, and relevance of findings. This validation process ensured that the conclusions drawn from the SWOT analysis were supported by high-quality empirical evidence and representative of the current state-of-the-art in battery-free sensor technology.

RESULTS AND DISCUSSION

Publication Profile and Research Trends

An analysis of 85 selected articles shows a significant upward trend in research publications on battery-free sensor systems for smart infrastructure during the period 2019-2024. The distribution of publications shows exponential growth with an average increase of 23% per year, reflecting the growing interest of the research community in this technology. The largest number of publications came from IEEE journals (34%), followed by ScienceDirect (28%), MDPI (24%), and SpringerLink (14%), indicating a predominance of publications in engineering and computer science.

Geographic distribution analysis shows that research in this area is dominated by developing countries, with a strong emphasis on smart city development. The United States leads with 24% of publications, followed by China (18%), European Union countries (22%), and emerging economies such as India and Brazil (16%). This distribution reflects the global nature of infrastructure monitoring challenges and the widespread interest in sustainable technology solutions.

Operational Excellence and Sustainability

Battery-free sensor systems demonstrate significant operational advantages in terms of autonomous operation and long-term sustainability. The ability to operate continuously without manual intervention is a key advantage that is invaluable for infrastructure monitoring applications. Studies have shown that these systems can maintain operational status for 5–20 years without maintenance requirements, a stark contrast to battery-powered systems that require replacement every 6–24 months (Hsu et al., 2020; La Rosa et al., 2024).

Sustainability is becoming increasingly important in the context of environmental awareness and regulatory pressure to reduce e-waste. Eliminating the need for battery replacement not only reduces operational costs but also significantly contributes to environmental protection by reducing hazardous waste. This system has the potential to reduce the carbon footprint of infrastructure monitoring by up to 40% compared to conventional battery-powered systems (Zhou et al., 2023).

Economic Efficiency and Cost Reduction

The economic benefits of battery-free sensor systems are substantial from a long-term operational perspective. Cost-benefit analyses indicate that implementation can reduce the total cost of ownership by up to 60% over the system's operational lifecycle. These savings primarily come from eliminating battery replacement costs, reducing maintenance visits, and minimizing system downtime that can lead to operational disruptions (Park et al., 2021; Kumar & Kumar, 2021).

A case study of the implementation of monitoring 500 sensor nodes for bridge infrastructure demonstrated potential savings of up to $2.5 million over 10 years of operation (Karray & Belghith, 2021). These savings include direct costs such as battery procurement and replacement labor, as well as indirect costs such as traffic disruption during maintenance activities and potential liability issues from sensor failures.

Technology Flexibility and Adaptability

Energy harvesting technologies demonstrate remarkable flexibility in terms of energy source diversification and adaptability to various environmental conditions. The ability to integrate multiple energy sources such as photovoltaic, piezoelectric, electromagnetic, and thermoelectric within a single system provides resilience to environmental variations (Sun et al., 2020; Allagui & Elrouby, 2022). A multimodal energy harvesting approach can increase system reliability by up to 95% with a stable power output in the range of 50–150 μW.

Advanced energy storage technologies such as supercapacitors and hybrid energy storage systems provide additional flexibility in energy management, enabling systems to operate efficiently even during periods of low energy availability. Integration with advanced power management algorithms can optimize energy utilization and significantly extend operational life (Mohammadi & Noor, 2023).

Weaknesses

Fundamental Limitations of Energy

The limitation in the power density that can be harvested from environmental energy sources is a fundamental weakness that significantly impacts system capabilities. Typical power levels that can be obtained from energy harvesting range from 0.1–100 μW, which is substantially lower than the power consumption requirements for complex sensing and communication operations (Sun et al., 2020; Gupta & Garg, 2022). This limitation necessitates careful consideration of functionality, performance, and energy efficiency in system design.

These energy constraints result in limitations in the sensing frequency, data transmission rate, and computational capabilities that can be implemented in the system. Typical operation only allows sensing and data transmission every 10–60 minutes to maintain energy balance, which can be inadequate for applications requiring high-frequency monitoring or real-time response capabilities (Loubet et al., 2019).

Dependence on Environmental Conditions

Environmental dependency is an inherent weakness that significantly impacts system reliability and predictability. Variations in environmental conditions such as light intensity, vibration levels, temperature gradients, and electromagnetic field strength can cause substantial fluctuations in power generation. Research shows that efficiency can decrease by up to 70% during adverse environmental conditions such as prolonged cloudy periods, low-vibration environments, or extreme temperatures (Kumar & Kumar, 2021).

Seasonal variations also significantly impact system performance, with potential power output reductions of up to 80% during winter months or severe weather conditions. This unpredictability requires the implementation of sophisticated energy management strategies and potentially backup power systems to maintain operational continuity (Alam et al., 2019).

Technical Complexity and Integration

The technical complexity of developing efficient energy harvesting systems is a significant barrier to widespread adoption. Integrating multiple energy sources, developing efficient power conditioning circuits, and implementing intelligent energy management algorithms require sophisticated engineering expertise and advanced design capabilities. This complexity translates into higher development costs and longer time-to-market (Cai et al., 2023).

Miniaturization challenges are also a significant concern, particularly for applications requiring compact form factors. Achieving efficient energy harvesting within small device dimensions requires careful optimization of the harvesting elements, power electronics, and energy storage components. Tradeoffs between device size and power output can result in compromises in system performance or dimensional requirements (Zhou et al., 2023).

Opportunities

Smart City and IoT Market Expansion

The exponential growth in smart city initiatives and IoT deployments presents a tremendous opportunity for the adoption of battery-free sensor systems. The global smart city market is projected to reach $2.5 trillion by 2025, with infrastructure monitoring being a key application area. Demand for autonomous sensor systems in smart city applications is growing at a 15% annual rate, driven by increasing urbanization and the need for efficient infrastructure management (La Rosa et al., 2024; Takacs et al., 2024).

Government initiatives and policy support for smart city development create a favorable environment for technology adoption. Many countries have announced significant investments in smart infrastructure projects, including the implementation of advanced monitoring systems. Regulatory frameworks that support the adoption of sustainable technologies also provide additional impetus for the adoption of battery-free sensor systems (Mohammadi & Noor, 2023).

Low Power Communication Technology

Rapid advances in low-power communication technologies provide significant opportunities for optimizing battery-free sensor systems. Technologies such as LoRaWAN, NB-IoT, and massive 5G IoT enable long-distance data transmission with very low power consumption (<50 mW). Integration with energy harvesting systems can achieve communication ranges of up to 15 km with a power budget of <100 μW, which is highly compatible with typical energy harvesting capabilities (Alam et al., 2019; Karray & Belghith, 2021).

The development of edge computing capabilities and distributed processing architectures also enables more efficient data processing and reduced communication requirements. Local processing can minimize data transmission requirements and optimize energy utilization, further enhancing the feasibility of battery-free sensor systems for complex infrastructure monitoring applications (Kumar & Kumar, 2021).

Innovation in Materials and Storage Technologies

Breakthroughs in advanced materials and energy storage technologies offer opportunities for significant improvements in system performance. The development of high-efficiency photovoltaic materials, advanced piezoelectric materials, and improved thermoelectric materials could substantially increase power generation capabilities. Similarly, innovations in energy storage technologies such as solid-state supercapacitors and hybrid energy storage systems could improve energy buffering capabilities and system reliability (Huang et al., 2024).

Nanotechnology developments also enable miniaturization without significant performance degradation, potentially enabling applications previously considered impractical due to size constraints. Advanced manufacturing techniques can reduce production costs and increase scalability for mass deployment (Hsu et al., 2020).

Threats

Energy Source Instability

The inherent variability and unpredictability of environmental energy sources constitute a fundamental threat that can significantly impact system reliability. The effects of climate change can result in increasingly unpredictable weather patterns, directly impacting energy availability for harvesting systems. Extreme weather events can cause prolonged periods of low energy availability, potentially resulting in system failures or critical data gaps for infrastructure monitoring applications (Rosa et al., 2019; Gupta & Garg, 2022).

Seasonal variations can result in system downtime of up to 30% without adequate backup systems, which can be unacceptable for critical infrastructure monitoring applications. Long-term climate trends can also affect the feasibility of certain energy harvesting approaches in specific geographic areas, requiring adaptive system design or alternative energy sources (Alam et al., 2019).

Electromagnetic Interference and Compatibility

Electromagnetic interference from various sources in urban environments can significantly impact system performance, especially for RF energy harvesting systems. A dense electromagnetic environment can reduce harvesting efficiency by up to 50% and potentially cause false readings or system malfunctions. The increasing adoption of wireless technology and electronic devices in urban areas can exacerbate this interference problem (Kang & Lee, 2020; Mohammadi & Noor, 2023).

Compatibility issues with existing infrastructure and communication systems can also pose significant challenges. Integration with legacy monitoring systems can require expensive modifications or complete system replacement, which can hinder adoption by infrastructure owners with limited budgets for technology upgrades (Kumar & Kumar, 2021).

Regulation and Standardization

Regulatory uncertainty and a lack of standardization can significantly hinder the widespread adoption of battery-free sensor systems. Different countries and regions have varying regulations regarding RF spectrum usage, data privacy, and cybersecurity requirements, which can complicate system design and deployment. Compliance with multiple regulatory frameworks can increase development costs by up to 25% and delay time-to-market (Cai et al., 2023; Hsu et al., 2020).

Cybersecurity concerns are also becoming increasingly important with the increasing adoption of connected infrastructure monitoring systems. Potential vulnerabilities in wireless communication systems can pose significant risks, especially for critical infrastructure applications. Regulatory requirements for cybersecurity compliance can add substantial complexity and cost to system development (Karray & Belghith, 2021).

SWOT Analysis Synthesis

A comprehensive SWOT analysis shows that battery-free sensor systems have substantial potential to revolutionize infrastructure monitoring, with significant advantages in terms of sustainability, cost-effectiveness, and operational autonomy. However, successful implementation requires careful consideration of technical limitations and a strategic approach to mitigate identified weaknesses and threats.

Opportunities significantly outweigh threats in the current market environment, with strong growth projections for smart city initiatives and favorable technological developments. A strategic focus on high-value applications such as critical infrastructure monitoring can maximize the benefits of technology while minimizing exposure to identified risks. Integration with emerging technologies and the development of hybrid approaches can address many of the identified weaknesses while capitalizing on the opportunities available.

Based on the synthesis of 85 indexed journal articles analyzed, several key energy harvesting technologies are used in battery-free sensor systems for smart infrastructure. Each technology has distinct characteristics in terms of power density, energy efficiency, optimal application context, and its own advantages and disadvantages. Understanding these characteristics is crucial for determining appropriate implementation strategies, particularly in the context of varying operational environments and limited environmental energy resources.

Table 1 below presents a brief comparison between the most widely used energy harvesting technologies, namely photovoltaic, piezoelectric, electromagnetic, and thermoelectric, which have been discussed in the previous section.

Table 1. Comparison of Energy Harvesting Technologies for Battery-Free Sensor Systems

Technology	Power Density ($\mu W/cm^2$)	Efficiency (%)	Optimal Application	Excess	Lack
Photovoltaic	10-15,000	15-22	Outdoor monitoring	Mature technology, high power	Depends on the weather
Piezoelectric	50-300	25-35	Vibration monitoring	Mechanical durability	Low power output
Electromagnetic	0.1-100	40-80	RF environment	Consistent power	Depends on distance
Thermoelectric	10-100	5-15	Temperature gradient	24/7 Operation	Low efficiency

The table makes it clear that no single technology is completely superior in all aspects, but rather that the choice of solution must consider the trade-offs between energy efficiency, resource stability, integration complexity, and the specific needs of the monitoring system being implemented. In the context of highly diverse smart infrastructures—both in terms of geographic location, structure type, and monitored parameters—a hybrid approach or a combination of several harvesting types is often the most flexible and optimal solution.

Therefore, the results of this analysis reinforce the urgency of developing adaptive and modular system designs, as well as integrating them with intelligent energy management algorithms, to achieve maximum performance. This understanding will form the basis for developing strategic conclusions and further research directions in the following sections.

CONCLUSION

A comprehensive SWOT analysis of battery-free sensor systems for smart infrastructure demonstrates that this technology has significant transformative potential for revolutionizing infrastructure monitoring practices. Its fundamental advantages in sustainability, cost-effectiveness, and operational autonomy provide a compelling value proposition for a wide range of infrastructure applications, particularly in the context of growing environmental awareness and economic pressures for efficient infrastructure management.

The main weaknesses related to energy limitations and environmental dependency, while significant, can be overcome through strategic technology development and careful application selection. Rapid advancements in energy harvesting technologies, power management systems, and communication technologies provide an optimistic outlook for addressing current limitations and expanding application possibilities.

Substantial market opportunities, driven by smart city growth and IoT expansion, provide a favorable environment for technology adoption and commercial success. A strategic focus on high-value applications, combined with continued investment in technology development, can position battery-free sensor systems as the dominant technology for infrastructure monitoring applications.

The identified threats, particularly environmental variability and regulatory uncertainties, require proactive management approaches and strategic risk mitigation. However, these threats are not fundamental barriers to technology adoption and can be effectively managed through appropriate strategic approaches.

Strategic recommendations for successful implementation include a focus on high-value applications, investment in hybrid technology approaches, development of strategic partnerships, and proactive engagement with regulatory bodies. Continued investment in research and development, particularly in energy harvesting efficiency, power management, and system integration, will be critical to maintaining competitive advantage and addressing evolving market requirements.

Future research priorities must focus on the development of more efficient energy harvesting technologies, advanced energy storage systems, and intelligent energy management algorithms. Integration with emerging technologies such as artificial intelligence and machine learning can provide additional opportunities for system optimization and performance improvements.

With an appropriate strategic approach and continued technology development, battery-free sensor systems can become crucial technology enablers for the realization of truly sustainable and autonomous infrastructure monitoring systems, contributing significantly to the development of smart, efficient, and environmentally responsible infrastructure management practices.

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