

A review of energy harvesting techniques for low-power IoT and wireless sensor networks

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Article Info

Article history:

Received Feb 26, 2026

Revised Apr 23, 2026

Accepted May 12, 2026

Keywords:

Energy harvesting

Internet of things

Low-power systems

Self-powered sensors

Wireless sensor networks

ABSTRACT

Limited battery life remains a major challenge in deploying the internet of things (IoT) and wireless sensor networks (WSN), particularly for long-term, low-maintenance applications. Energy harvesting has emerged as a promising approach that utilizes ambient energy sources to enable the autonomous operation of sensor nodes. This paper presents a comprehensive review of energy harvesting techniques for low-power IoT and WSN systems, including solar, mechanical vibration, thermal, and radio frequency (RF) energy harvesting. The review covers the working principles, performance characteristics, advantages, and limitations of each technique, and provides a quantitative comparative analysis based on key parameters such as power density, conversion efficiency, environmental dependence, and application suitability. The results indicate that no single energy harvesting technique is universally optimal, as performance strongly depends on environmental conditions and application-specific power requirements. This study contributes by providing a structured comparative framework and a systematic analysis of performance limitations and design considerations to support the selection of appropriate energy harvesting methods. Furthermore, hybrid energy-harvesting systems and the integration of efficient power-management strategies are identified as key enablers for improving energy reliability, extending system lifetime, achieving sustainable, maintenance-free IoT, and WSN deployments.

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1. INTRODUCTION

The rapid development of the internet of things (IoT) and wireless sensor networks (WSN) has driven the adoption of intelligent monitoring and control systems across various fields, including environmental monitoring, smart agriculture, industrial automation, smart cities, and healthcare [1], [2]. The implementation of these systems generally relies on low-power sensor nodes that operate in a distributed manner and are often located in hard-to-reach locations [3]. Although low-power electronics technology and communication protocols continue to advance, limited battery life remains a major issue, especially in long-term applications that require maintenance-free operation [4], [5]. In addition to increasing operational costs, regular battery replacement also has an environmental impact by increasing e-waste [6], [7].

As a sustainable solution, energy harvesting, a technique for converting energy from the surrounding environment into electrical energy, has emerged as a promising approach to reduce dependence

on batteries and support the development of self-powered IoT and WSN systems [8]. Various energy harvesting techniques have been extensively studied, including solar energy, which offers relatively high power density and mature technology, especially for outdoor applications [7]. In addition, mechanical vibration-based energy harvesting, such as piezoelectric, electromagnetic, and electrostatic, is widely applied in industrial and infrastructure environments with continuous vibration sources [9]. Other techniques, such as thermal energy harvesting using thermoelectric generators, are also explored in systems with stable temperature differences [10]. While radio frequency (RF)-based energy harvesting is attracting attention for ultra-low-power IoT applications by leveraging ambient electromagnetic signals or dedicated RF transmitters [11], [12].

However, most existing research still focuses on one type of energy harvesting technique or a specific application [13]. The available literature reviews generally do not provide a systematic and comprehensive comparison that accounts for the typical limitations of low-power IoT and WSN systems, such as power availability, dependence on environmental conditions, integration complexity, and system-level implementation [8], [14]. In addition, discussions on energy storage integration, power management strategies, and implementation challenges in the field remain relatively limited, making it difficult for system designers to select the most suitable energy harvesting solution [15]–[17].

This paper presents a comprehensive review of energy harvesting techniques for low-power IoT and WSN systems. The main contributions of this review include a systematic classification of various energy harvesting techniques, a quantitative comparative analysis based on key performance parameters, and a discussion on the integration of energy storage and power management. Furthermore, this paper identifies open research challenges and future development directions. With its holistic approach, this review is expected to be a useful reference for researchers and practitioners in designing efficient, reliable, and sustainable IoT and WSN systems.

2. ENERGY HARVESTING TECHNIQUES

Energy harvesting for IoT and WSN systems uses various environmental energy sources to generate electrical power at micro- to milliwatt scales [18]. The selection of an appropriate energy harvesting technique depends heavily on environmental conditions, application characteristics, and the power requirements of the sensor nodes [19]. This section discusses some of the most commonly used energy harvesting techniques for low-power IoT and WSN systems. The main energy harvesting techniques that can be applied to low-power IoT and WSN systems are as shown in Figure 1.

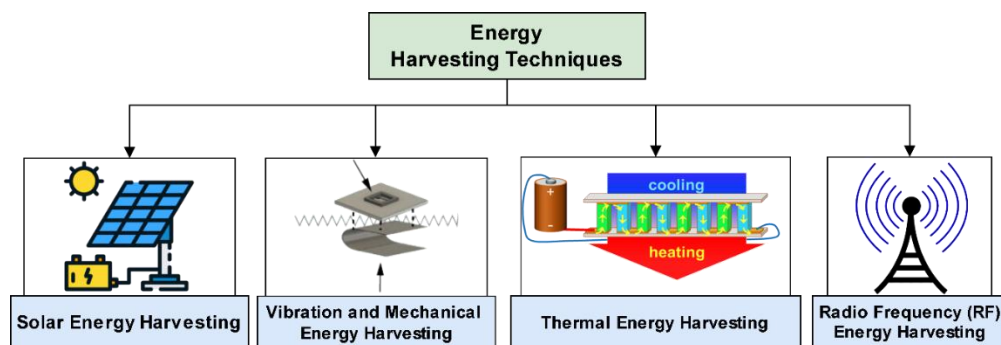


Figure 1. Classification of energy harvesting techniques for IoT and WSN applications

2.1. Solar energy harvesting

Solar energy harvesting is the most mature and widely used energy harvesting technique in IoT and WSN systems [20]. This method utilizes the photovoltaic effect, in which light incident on a semiconductor material in a solar cell produces electron-hole pairs [21]. These charge pairs are then separated by an internal electric field at the semiconductor junction, thus producing an electric current that can be used as a power source for sensor nodes [22]. Advances in semiconductor materials, such as amorphous and crystalline silicon and thin-film materials, have increased the efficiency and flexibility of solar cells for low-power systems [23].

In the context of IoT and WSN applications, solar energy harvesting is generally classified into indoor and outdoor systems, which have very different performance characteristics [24]. Quantitatively, the

power density generated by solar energy harvesting is highly dependent on lighting conditions and the type of application [24]. In outdoor environments, sunlight intensity can reach approximately 1000 W/m², allowing solar cells to produce electrical power densities of 10–100 mW/cm², depending on material efficiency and operational conditions [25]. This value is sufficient to continuously supply the power needs of IoT and WSN nodes, while also charging energy storage media [26].

In contrast, in indoor environments, the intensity of artificial light is much lower, typically 100–1000 lux. Under these conditions, the power density generated by indoor solar cells typically ranges from 1 to 100 μW/cm², requiring the design of sensor nodes with ultra-low power consumption and the implementation of aggressive duty cycles [27]. The significant difference in power density between indoor and outdoor systems makes outdoor solar energy harvesting a more dominant solution, while indoor applications require more complex system optimization [28]. The power density characteristics of solar energy harvesting under various lighting conditions differ significantly between outdoor and indoor environments, as reported in previous literature [25], [29].

2.2. Vibration and mechanical energy harvesting

Vibration and mechanical energy harvesting is a technique that uses kinetic energy from vibrations or mechanical movements in the environment to generate electrical energy [30]. Vibration sources can come from industrial machines, vehicles, building structures, bridges, or other infrastructure [31]. Therefore, this technique is highly relevant for IoT and WSN applications in industrial environments and smart infrastructure, where vibrations are generally continuous and relatively predictable [32], [33].

The most commonly used approach in vibration energy harvesting is the piezoelectric method, which uses materials such as lead zirconate titanate (PZT) or piezoelectric polymers to generate an electric charge from mechanical deformation [34], [35]. This technique offers a simple structure, a compact size, and a relatively high output voltage, making it suitable for low-power sensor applications [36]. However, the generated current tends to be small and is highly dependent on the amplitude and frequency of the environmental vibrations [37].

Besides piezoelectricity, electromagnetic, and electrostatic techniques are also widely researched. Electromagnetic energy harvesters operate on the principle of electromagnetic induction and are generally capable of producing higher currents but are larger and more mechanically complex [32]. Meanwhile, electrostatic techniques exploit changes in capacitance due to mechanical movement between electrodes and offer good integration potential with micro-electro-mechanical systems (MEMS) technology, although they usually require an initial voltage source and produce relatively low power [38], [39].

In general, the main advantage of vibration and mechanical energy harvesting is its suitability for industrial and infrastructure environments with natural vibration sources, enabling IoT, and WSN nodes to operate autonomously in the long term [40], [41]. However, the main limitation of this technique is its dependence on a specific resonance frequency, which can degrade performance when vibration conditions vary [42], [43]. Various case studies have shown that vibration energy harvesting, especially piezoelectric-based, can provide significant power density to support periodic sensor and wireless communication operations [44]. Thus, it can be a promising solution for applications with stable, repetitive vibration characteristics.

2.3. Thermal energy harvesting

Thermal energy harvesting is a technique that uses the temperature difference between two points to generate electrical energy, typically via a thermoelectric generator (TEG) that operates on the Seebeck effect [45]. The temperature difference between the hot and cold sides of the thermoelectric material produces an electrical voltage that is proportional to the temperature gradient, with materials such as bismuth telluride (Bi₂Te₃) widely used for their good performance in the low-to-medium temperature range [46].

In the context of IoT and WSN, thermal energy harvesting has attracted attention for its ability to continuously generate power as long as a temperature difference is available [47]. This technique is well-suited to applications with a relatively stable temperature gradient, such as industrial process monitoring, hot piping systems, continuously operating machines, and several wearable applications that exploit the temperature difference between the human body and the surrounding environment [48].

The main advantage of thermal energy harvesting is the absence of moving components, which results in high reliability and a long service life [49]. However, TEG performance is highly dependent on the available temperature difference, and in many ambient conditions and wearable applications, the ΔT value is generally small, limiting output power to the microwatt-milliwatt range [50], [51]. This condition requires integration with an efficient power management circuit and a low-power operation strategy [52], [53].

In practical implementations, this is typically achieved using DC–DC boost converters to increase the low output voltage of TEGs, which is often in the range of tens to hundreds of millivolts, to a usable level for

electronic systems [54]. In addition, maximum power point tracking (MPPT) techniques are employed to optimize energy extraction under varying temperature gradients [55]. Therefore, implementing thermal energy harvesting in IoT and WSN systems requires a holistic design approach that includes optimizing temperature gradients, selecting thermoelectric materials, and integrating energy storage and power management [56], [57].

Energy storage components play a critical role in this integration. Supercapacitors are widely used to buffer short-term energy fluctuations due to their high power density and fast charging characteristics, while rechargeable micro-batteries provide longer-term energy storage to support continuous operation during periods of low or zero temperature gradient [58].

To overcome the limitations of individual storage technologies, hybrid energy storage systems that combine supercapacitors and batteries have been increasingly adopted to balance power density and energy capacity [8]. Furthermore, efficient power management circuits are required to regulate energy flow between the TEG, storage elements, and the load [4]. These circuits typically incorporate voltage regulation, cold-start mechanisms, and load management strategies to ensure reliable system startup and stable operation under low-power conditions [29]. With this approach, thermal energy harvesting remains a promising solution for applications with stable heat sources, although it has limitations in environments with small temperature differences [59].

2.4. Radio frequency energy harvesting

RF energy harvesting is a technique that converts electromagnetic energy from radio waves in the environment into electrical energy. RF energy sources can come from ambient signals such as cellular networks, Wi-Fi, and television and radio broadcasts, or from special RF transmitters designed for deliberate power transmission [14], [60], [61]. This approach offers a sustainable solution for powering electronic devices with very low energy consumption, especially IoT nodes and WSN sensors in remote or hard-to-reach locations [62].

The main component of an RF energy harvesting system is the rectenna, a combination of a receiving antenna and a rectifier circuit that captures RF signals and converts them into DC voltage [63]–[65]. This circuit generally consists of an antenna, an impedance-matching network, a rectifier diode, and a DC filter, with impedance matching playing an important role in maximizing power transfer [66], [67]. The performance of the rectenna is strongly influenced by the RF signal intensity and frequency, the antenna orientation, the propagation conditions, and the efficiency of the electronic components [68].

The main advantage of RF energy harvesting is the absence of moving mechanical components, which results in high reliability, a long service life, and low maintenance requirements [69]. In addition, this technique supports wireless power transfer and is well-suited for ultra-low-power applications such as radio frequency identification (RFID), passive sensors, and event-driven IoT nodes [70]. However, the main limitation of this method is the very low output power, especially from ambient RF sources, which is typically only in the nanowatt to several microwatt range [71], [72]. This condition limits its applicability to low-power loads and requires integrating efficient power management and energy storage systems [73].

Recent developments in RF energy harvesting focus on optimizing rectenna designs, using multiband systems, and integrating with techniques such as simultaneous wireless information and power transfer (SWIPT) and hybrid energy-harvesting approaches to improve system reliability [74]. With these advances, RF energy harvesting continues to emerge as a promising complementary solution to support autonomous and sustainable IoT and WSN systems, especially in applications with very low power requirements [75].

3. COMPARATIVE ANALYSIS OF ENERGY HARVESTING TECHNIQUES

A comparison of energy harvesting techniques is crucial for understanding the advantages, limitations, and responsiveness of each energy source to environmental conditions and the needs of IoT and WSN applications. This section presents a comparative analysis based on key parameters such as power density, conversion efficiency, environmental dependency, and typical applications for each technique discussed previously.

3.1. Quantitative comparison

A quantitative comparison between energy harvesting techniques shows significant variations in performance characteristics and application suitability. Techniques such as solar energy harvesting tend to have high power densities but are highly dependent on light, while thermal, vibration, and RF energy harvesting exhibit lower power densities but can operate in specific environments with their own advantages. A comparison of the quantitative characteristics of each technique is presented in Table 1.

In quantitative comparisons of energy harvesting techniques, the main parameters commonly used include power density, conversion efficiency, environmental dependency, and application suitability. Solar

energy harvesting generally offers the highest power density and efficiency, especially under outdoor conditions, while RF energy harvesting from ambient sources produces the lowest power output. Vibration and thermal techniques fall in the middle, with performance heavily influenced by vibration characteristics and ambient temperature differences. These differences directly determine application suitability: solar is more effective for outdoor applications, vibration and thermal are suitable for industrial and wearable environments, and RF energy harvesting is aimed at ultra-low-power IoT applications with a low duty cycle.

3.2. Case study

A recent real-world implementation of energy harvesting in IoT systems can be observed in battery-less WSNs designed for environmental and industrial monitoring. A study in the [76] demonstrated the feasibility of battery-free IoT devices powered by solar, kinetic, and RF energy sources using supercapacitors for energy storage. These systems can operate autonomously by harvesting ambient energy and adapting their duty cycles based on energy availability. Similarly, recent research [70] highlights the application of RF energy harvesting in IoT networks. This enables wireless sensors to operate without batteries in smart environments and industrial systems, significantly reducing maintenance requirements and increasing sustainability. In agriculture, solar energy harvesting has been successfully applied to power distributed sensor nodes. This is used to monitor environmental parameters, eliminating the need for frequent battery replacement and enabling long-term operation in remote areas [22]. These case studies confirm that energy harvesting technologies are not only theoretically viable but have been practically implemented to achieve self-sustaining, low-maintenance IoT and WSN systems.

Table 1. Comparison of energy harvesting techniques for IoT and WSN applications [24], [32], [36], [39], [52], [65], [69], [77], [78]

Technique	Power density (typical)	Conversion efficiency (typical) (%)	Typical applications	Environmental dependence	Cost	Lifetime
Solar energy (PV)	10–100 mW/cm ² (outdoor); 1–100 μW/cm ² (indoor)	10–25 (commercial)	Smart agriculture, outdoor WSN, and environmental monitoring	Strongly dependent on light intensity	Low–medium (low maintenance, but initial cost depends on panel size, and storage)	Long (≈20–25 years for PV modules; system-level depends on storage)
Vibration (piezoelectric)	~10–10,000 μW/cm ³ depending on resonance	5–15	Industrial monitoring and structural health sensing	Requires operation at a specific vibration frequency	Medium (material and mechanical packaging required)	Medium (5–15 years, affected by mechanical fatigue)
Vibration (electromagnetic)	<1–~1,000 μW/cm ³	5–15	Mechanical health monitoring	Dependent on vibration frequency and amplitude	Medium (material and mechanical packaging required)	Long (10–20 years, robust mechanical structure)
Vibration (electrostatic)	~10–200 μW/cm ³	5–15	Micro-scale sensing	Requires an initial bias voltage	Medium (requires coil and magnet components with higher complexity)	Medium (5–10 years, sensitive to environmental conditions)
Thermal (TEG)	~10–50 μW/cm ³ (low ΔT), up to milliwatts at high ΔT	2–8	Industrial, wearable, heat recovery	Dependent on a stable temperature gradient (ΔT)	Medium–high (thermoelectric materials are relatively expensive)	Long (10–20 years, no moving parts, needs high reliability)
RF (ambient)	nW–μW	Very low	Ultra-low power RFID and event-driven IoT	Requires a strong ambient RF source	Low (simple antenna and rectifier circuit)	Long (10–20 years, minimal degradation)
RF (dedicated)	μW–mW depending on amplifier	Relatively low	Wireless power transfer and smart tags	Dependent on transmitter design and configuration	Medium–high (requires external RF transmitter infrastructure)	Long (depends on transmitter, receiver can be long-lasting)

3.3. Performance limitations and design considerations

While various energy harvesting techniques offer the potential to support autonomous operation in IoT and WSN systems, no single approach is optimal for all applications. Each technique has trade-offs among power density, conversion efficiency, sensitivity to environmental conditions, and system complexity, so the choice must be tailored to the environmental conditions and the node's power requirements.

The comparative performance of different energy harvesting techniques can be effectively visualized using a radar chart, as shown in Figure 2. This visualization highlights the relative strengths and limitations of each technique across multiple parameters, including power density, conversion efficiency, environmental dependency, cost, and lifetime. Solar energy harvesting exhibits superior performance in terms of power density, efficiency, and lifetime; however, it is highly dependent on environmental conditions. In contrast, RF-based energy harvesting demonstrates lower power density and efficiency but offers relatively stable operation and longer lifetime. Vibration- and thermal-based energy harvesting techniques exhibit moderate performance across most parameters, with their effectiveness strongly influenced by environmental conditions and system design. The values presented in Figure 2 are normalized based on the data in Table 1 to provide a qualitative comparison among the different techniques.

Solar energy harvesting offers the highest power density and is highly effective for outdoor applications, but its performance depends heavily on light intensity and duration. Vibration energy harvesting is suitable for industrial environments with stable vibrations, but its performance degrades significantly when the vibration frequency does not match the harvester's resonance characteristics. Thermal energy harvesting can continuously generate power as long as a temperature difference is available, but its efficiency is relatively low under the small temperature differences commonly encountered in ambient environments. Meanwhile, RF energy harvesting offers high reliability because it has no moving mechanical components, but the power harvested from ambient RF sources is very limited and suitable only for ultra-low-power applications with a low duty cycle.

Overall, the trade-off among energy availability, power stability, and system complexity is a key factor in selecting an energy harvesting technique. These limitations highlight the need for more adaptive and reliable solutions, prompting the development of hybrid energy-harvesting systems, which are discussed in the following subsection.

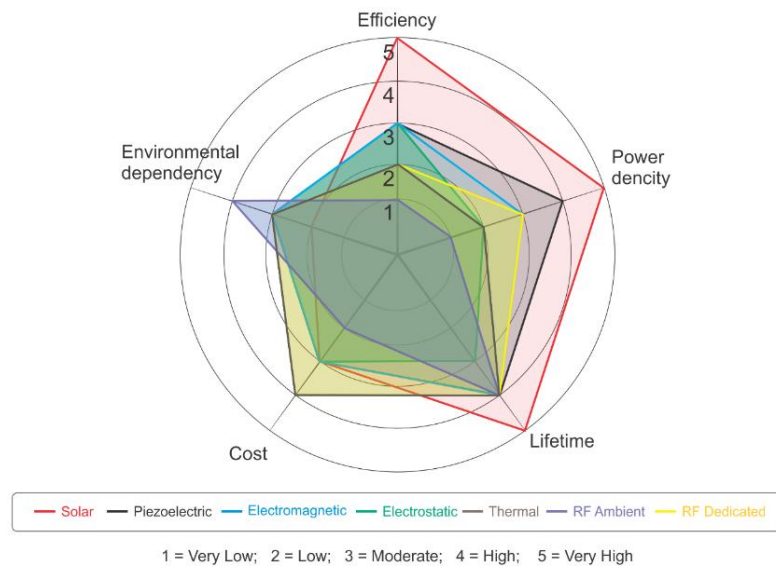


Figure 2. Performance comparison diagram of energy harvesting techniques

3.4. Hybrid energy harvesting systems

To overcome the limitations of single-source energy harvesting, recent studies have increasingly focused on hybrid energy harvesting systems that combine multiple energy sources to improve reliability and energy availability. In practical IoT deployments, the energy generated from a single source is often intermittent and insufficient to ensure continuous operation. Therefore, hybrid approaches, such as integrating solar and vibration energy or thermal and electromagnetic energy, have been proposed to enhance system performance and achieve energy-neutral operation. A study demonstrated a hybrid system that

combines TEG and electromagnetic energy harvesting for industrial motor monitoring, enabling a stable power supply under fluctuating environmental conditions [79].

In work [80], a piezoelectric–electromagnetic hybrid energy harvester was proposed for sustainable smart agriculture systems. The system integrates electromagnetic and piezoelectric mechanisms through magnetic coupling, enabling efficient energy conversion and stable power generation. Experimental results demonstrate that the hybrid harvester can provide a continuous and reliable energy supply for low-power sensors, such as soil monitoring systems, highlighting its effectiveness in real-world IoT applications. Recent studies further reinforce the advantages of hybrid energy harvesting systems. For instance, triboelectric–electromagnetic hybrid systems have demonstrated effective wind-based energy harvesting for smart agriculture monitoring, enabling continuous sensing capabilities under variable environmental conditions [81].

Furthermore, comprehensive reviews indicate that multi-source hybridization significantly enhances overall energy output and system reliability, although it introduces additional design complexity and control challenges [82]. Furthermore, advances in smart materials and adaptive mechanical structures enable improved energy harvesting performance in vibration-based systems, particularly through tunable mechanical responses [83].

In the literature [84], the proposed architecture combines RF, electromagnetic, solar, and triboelectric energy sources to form an efficient energy-harvesting system. An integrated system of energy harvesting and storage technologies. In an integrated system that uses power management circuits, such as DC-DC converters and MPPT techniques, the flow of energy is efficiently regulated from multiple sources to the storage elements. The harvested-energy hybrid PV-thermal system is managed via a boost converter and a controlled charging strategy to optimize energy utilization and maintain stable output for low-power IoT devices. These hybrid configurations not only improve energy reliability but also reduce battery degradation and maintenance requirements. However, such systems introduce additional challenges, including increased system complexity, higher implementation cost, and the need for advanced energy management strategies to coordinate multiple energy sources and storage components. Overall, hybrid energy-harvesting systems, combined with advanced energy-storage strategies, represent a promising. However, a design-intensive solution for achieving sustainable, maintenance-free, and long-lifetime IoT and WSN deployments. The comparison of real-world implementations in Table 2 summarizes representative hybrid energy-harvesting case studies.

Table 2. Case-based comparison of hybrid energy harvesting systems for IoT and WSN

Ref	Application	Hybrid techniques	Energy availability	Cost	Maintenance	Key advantages	Key limitations
[79]	Industrial motor monitoring	TEG + electromagnetic	High (continuous under fluctuating conditions)	Medium–high	Medium	Stable power from combined thermal and EM sources	Requires thermal gradient and vibration
[80]	Smart agriculture (soil monitoring)	Piezoelectric + electromagnetic	Medium–high	Medium	Low–medium	Efficient magnetic coupling; reliable for low-power sensors	Depends on environmental excitation
[84]	Multi-source IoT/smart environment	RF + electromagnetic + solar + triboelectric	High	High	Low–medium	Multi-source redundancy; optimized via MPPT	High complexity
[81]	Smart agriculture (wind-based)	Triboelectric + electromagnetic	Medium–high	Medium	Low	Suitable for environmental sensing	Wind dependency
[82]	General hybrid EH systems	Multi-source (thermal, vibration, RF, and solar)	High	Medium–high	Low–medium	Improved system efficiency and reliability	Design complexity
[83]	Smart material-based energy harvesting/adaptive structures	Mechanical / vibration-based systems	Medium	Medium	Medium	Tunable mechanical response for optimized energy harvesting	Requires advanced material design

4. CONCLUSION

This review paper comprehensively discusses various energy harvesting techniques with the potential to support autonomous operation in IoT and WSN systems, including solar, vibration, thermal, and

RF energy harvesting. Quantitative comparisons show that solar energy harvesting offers the highest power density, especially for outdoor applications. In contrast, vibration, and thermal energy harvesting are better suited for industrial environments or applications with stable mechanical and thermal conditions. On the other hand, RF energy harvesting is primarily intended for ultra-low-power applications with low duty cycles, although the harvested power is relatively limited.

The main contribution of this review is to present a structured comparative analysis, including quantitative evaluation and a discussion of performance limitations and design considerations among different energy harvesting techniques. This analysis provides clear guidance for researchers and practitioners in selecting the most appropriate technique based on environmental conditions, power requirements, and application characteristics, particularly for long-term IoT and WSN systems with minimal maintenance requirements.

Furthermore, this review highlights the growing importance of hybrid energy harvesting systems as an effective approach to overcome the limitations of single-source energy harvesting. By combining multiple energy sources and integrating advanced energy storage solutions, hybrid systems can significantly improve energy availability, reliability, and system lifetime. However, these benefits come with additional challenges, including increased system complexity, higher implementation cost, and the need for efficient multi-source energy management strategies.

Despite its significant potential, energy harvesting still faces several challenges, including limited output power, dependence on dynamic environmental conditions, and the need for more efficient power management and energy storage systems. In the future, the development of hybrid energy harvesting systems, the integration of intelligent power management, and the application of artificial intelligence-based algorithms are expected to play a crucial role in enabling more autonomous, reliable, and sustainable IoT and WSN systems.

In particular, machine learning techniques can be utilized to predict energy availability based on environmental conditions, enabling more efficient energy scheduling and improved system reliability. In addition, AI-driven duty cycling strategies can dynamically adjust sensing and communication activities to minimize energy consumption. For hybrid energy-harvesting systems, intelligent control algorithms can further enable adaptive switching among multiple energy sources, optimizing overall energy utilization under varying conditions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Universitas Ahmad Dahlan (UAD), and the Embedded Systems and Power Electronics Research Group (ESPERG) for their invaluable support and contributions to this research. The facilities, guidance, and collaborative environment provided by these institutions were instrumental in the successful completion and publication of this work.

FUNDING INFORMATION

The research was funded by PT. Intelektual Pustaka Media Utama (IPMU) under contract number 01/RST-E/IPMU/I/2026, which supported the facilitation of this work.

AUTHOR CONTRIBUTIONS STATEMENT

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study

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