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OPTIMIZING SUSTAINABLE POWER DELIVERY IN SENSOR NETWORKS THROUGH HYBRID ENERGY HARVESTING FOR AUTONOMOUS ENERGY STORAGE SOLUTIONS

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ABSTRACT: *The increasing proliferation of low-power embedded systems and Internet of Things (IoT) devices, especially in remote or energy-constrained environments, has intensified the demand for sustainable and autonomous energy solutions. Traditional battery-powered systems face limitations in longevity, maintenance, and environmental adaptability, prompting the exploration of alternative energy harvesting techniques. This study investigates four energy harvesting methods—solar, vibration, radio frequency (RF), and capacitor-based storage—to evaluate their performance and suitability for reliable power delivery in such applications. MATLAB simulations were employed to model the energy output of each technique across a normalized input range (0 to 1), ensuring a consistent basis for comparison. Results showed that solar energy harvesting, using an 18% efficient photovoltaic panel with a 0.02 m² surface area, and vibration-based systems with 150 N/m stiffness and 0.002 m displacement, both achieved a normalized peak output of 1.0. RF harvesting, utilizing 1 W transmission power and a gain of 2 at both ends, performed less efficiently with a peak below 0.4. Capacitor storage, modeled with a 0.01 F capacitor over a 1V to 5V voltage range, demonstrated a parabolic output curve with peak performance at mid-range inputs. These results highlight the potential of integrating solar and vibration energy harvesting methods, complemented by capacitor-based buffering, to form robust hybrid power systems. The study contributes to knowledge by providing a comparative performance analysis of multiple harvesting techniques under standardized conditions and offers design insights for engineers developing energy-resilient embedded and sensor-based applications. The implications suggest that hybrid energy systems, supported by smart energy management strategies, can significantly enhance the operational autonomy, reliability, and sustainability of next-generation IoT deployments.*

KEYWORDS: Sensor Networks, Energy Harvesting, Low-Power Applications, IoT and Embedded Systems, MATLAB Simulation, Hybrid Power Systems.

INTRODUCTION

Wireless Sensor Networks (WSNs) have become a cornerstone of modern technology, enabling applications in environmental monitoring, industrial automation, healthcare, and smart cities. However, one of the most significant challenges in WSNs is ensuring a sustainable and reliable power supply for sensor nodes. Traditional battery-powered systems face limitations such as finite energy capacity, frequent replacement requirements, and environmental concerns [1][2]. To overcome these challenges, energy harvesting (EH) techniques have emerged as a promising solution, allowing WSNs to extract energy from ambient sources such as solar radiation, mechanical vibrations, and radio frequency (RF) waves.

Energy harvesting enables self-sustaining WSNs by converting ambient energy into electrical power, thereby extending operational lifetimes and reducing maintenance costs. Among the various EH techniques, solar energy harvesting is the most mature, leveraging photovoltaic cells to convert sunlight into electricity. This method is highly effective in outdoor environments with sufficient light exposure but suffers from inefficiency in low-light or indoor conditions. Vibration-based energy harvesting, on the other hand, captures kinetic energy from mechanical movements, making it suitable for industrial machinery, transportation systems, and structural health monitoring [3, 4]. Piezoelectric and electromagnetic transducers are commonly used in this approach, though their performance depends on vibration frequency and amplitude.

Another promising technique is RF energy harvesting, which scavenges energy from ambient electromagnetic signals, such as Wi-Fi, cellular networks, and dedicated RF sources. This method is particularly advantageous in environments where other energy sources are scarce, offering the potential for continuous power delivery without direct exposure to sunlight or mechanical motion. However, RF energy harvesting typically yields lower power outputs compared to solar and vibration methods, necessitating efficient power management circuits [5].

The investigation of these energy harvesting techniques involves evaluating their efficiency, scalability, and applicability in diverse WSN deployments. Key considerations include power density, environmental adaptability, energy conversion efficiency, and integration with low-power sensor nodes. Additionally, hybrid energy harvesting systems that combine multiple sources (e.g., solar and vibration) are gaining attention to enhance reliability and maximize energy availability under varying conditions [6].

This study explores the principles, advantages, and challenges of solar, vibration, and RF energy harvesting techniques for WSNs. By analyzing recent advancements, material innovations, and power management strategies, the research aims to identify optimal solutions for different application scenarios. The findings will contribute to the development of sustainable, maintenance-free WSNs, paving the way for broader adoption in IoT (Internet of Things) and smart infrastructure systems [7].

The objective of this study is to examine and compare the efficiency, power output, and overall performance of solar, vibration, and RF energy harvesting techniques for WSNs. It seeks to evaluate the reliability and environmental adaptability of each method under varying operational scenarios, identify integration challenges with low-power WSN nodes, and explore effective

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power management and energy storage strategies. Based on these findings, the study aims to provide practical recommendations for selecting and implementing the most suitable energy harvesting technique for specific application needs. Therefore, this study sets out to achieve five main objectives: (1) evaluate the efficiency and power output of solar, vibration, and RF energy harvesting techniques in wireless sensor networks (WSNs); (2) compare these techniques in terms of performance, reliability, and environmental suitability; (3) identify integration challenges and limitations associated with incorporating these energy harvesting methods into low-power WSN nodes; (4) examine the role of energy storage systems, particularly capacitors, in maintaining stable power supply; and (5) propose optimal energy harvesting strategies based on environmental conditions and power requirements for enhanced WSN sustainability.

LITERATURE REVIEW

Overview of Energy Harvesting in Wireless Sensor Networks

Wireless Sensor Networks (WSNs) have revolutionized data collection across industries, from environmental monitoring to smart infrastructure. However, their widespread adoption faces a persistent hurdle: power supply limitations [8]. Traditional battery-dependent sensors require frequent replacements, which is costly and impractical in remote or large-scale deployments. This is where EH emerges as a game-changing solution by enabling sensors to extract power from their surroundings, ensuring near-perpetual operation without human intervention [9].

Definition and Importance of Energy Harvesting

Energy harvesting refers to the process of capturing and converting ambient energy—such as sunlight, vibrations, or radio waves—into usable electrical power. Unlike batteries, which store finite energy, EH systems continuously replenish power, making them ideal for WSNs deployed in inaccessible or harsh environments [10]. The importance of EH lies in its ability to address two critical WSN constraints: sustainability and scalability. For instance, solar-powered sensors in agricultural fields can monitor soil moisture indefinitely, eliminating the need for manual battery swaps. Similarly, vibration-powered sensors in industrial machinery can self-sustain by converting motor oscillations into electricity. By reducing reliance on disposable batteries, EH also minimizes environmental waste, aligning with global green technology trends [11].

Beyond practicality, EH unlocks new possibilities for IoT expansion. Imagine smart cities where streetlights, traffic sensors, and air quality monitors operate autonomously, powered by ambient energy. Such innovations hinge on overcoming technical challenges, which brings us to the hurdles facing EH adoption [12].

Key Challenges in WSN Power Supply

While promising, integrating EH into WSNs is not without obstacles. The primary challenge is energy inconsistency. Solar panels, for example, generate variable power depending on weather and daylight, leaving sensors vulnerable to nighttime or cloudy-day outages. Vibration

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harvesters, meanwhile, rely on machinery operating at consistent frequencies; any deviation can disrupt energy output [13].

Another hurdle is low power density. Ambient energy sources often provide minimal usable power (microwatts to milliwatts), whereas sensors may require bursts of energy for data transmission. RF harvesting, though versatile, struggles with this limitation; ambient radio signals are weak, and dedicated RF sources are rarely cost-effective [14].

Energy storage and management further complicate EH systems. Supercapacitors and rechargeable batteries must efficiently store harvested energy, but they face trade-offs between capacity, charging speed, and lifespan. Power management circuits, which regulate voltage and prevent energy waste, add design complexity and cost [15].

Finally, environmental adaptability is critical. An EH solution optimized for a sunny, vibration-rich factory may fail in a dim, static indoor setting. Engineers must tailor systems to specific use cases, balancing efficiency and at the same time maintaining durability and cost implication [16, 17].

Despite these challenges, advancements in materials science and power electronics are steadily improving EH reliability. The subsequent sections explore how solar, vibration, and RF techniques—each with unique strengths—are paving the way for self-sustaining WSNs [18-20].

Solar Energy Harvesting Techniques

The sun showers our planet with an astonishing amount of energy, enough to power human civilization thousands of times over if we could capture it all [21]. This abundant and clean energy source positions solar power as a highly promising solution for powering wireless sensor networks. Imagine tiny electronic devices (scattered across fields, bridges, or industrial sites) harvesting energy from sunlight much like plants perform photosynthesis. This scenario is no longer futuristic; it is the reality being created by solar energy harvesting technology [22][23].

Photovoltaic Principles and Efficiency

At the heart of solar energy harvesting lies the photovoltaic effect, a phenomenon first observed back in 1839 by French physicist, Edmond Becquerel. The basic principle is beautifully simple: when sunlight hits certain materials, it knocks electrons loose, creating an electric current. Modern photovoltaic cells have refined this process into an art form, with silicon-based cells being the most common workhorses of the solar revolution [24].

The efficiency story of solar cells reads like a technology thriller. Early commercial solar panels in the 1950s converted barely 6% of sunlight into electricity; today's best laboratory cells exceed 47% efficiency, though practical commercial panels typically offer 15-22%. For wireless sensor networks, we are not usually dealing with rooftop-sized panels but rather with tiny photovoltaic cells sometimes no larger than a postage stamp. These miniature solar harvesters have their own unique efficiency challenges and advantages [25-27].

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What makes solar particularly attractive for WSNs is the relatively high-power density compared to other harvesting methods [28, 29]. A well-placed solar cell in bright sunlight can generate about 100mW per square centimeter—enough to power many sensor nodes continuously. However, the real magic happens in the power management systems that carefully store this energy in small batteries or supercapacitors for use when the sun is not shining [30][31].

METHODS

Solar Energy Harvesting Output Power

This equation estimates the output power from a solar panel under varying sunlight conditions, helping evaluate solar efficiency in WSN applications. It is crucial for assessing energy availability in outdoor deployments.

$$P_{solar} = \eta_{pv}.A.G \quad (1)$$

Parameters:

P_{solar}: Power output from solar panel (W)

η_{pv}: Photovoltaic efficiency (unitless)

A: Area of the solar panel (m^2)

G: Solar irradiance (W/m^2)

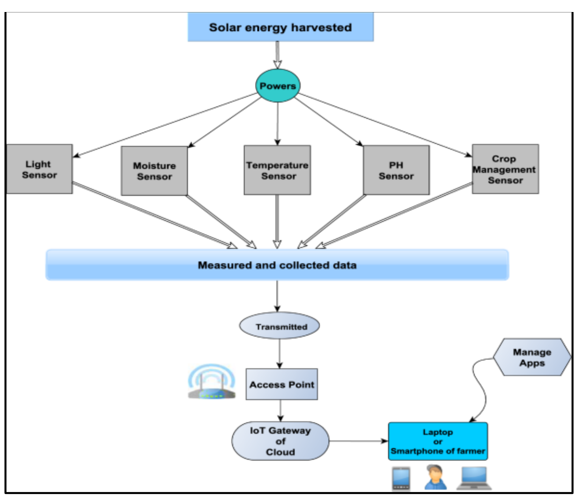

Figure 1: Investigation of the Solar Harvesting [9]

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Vibration-Based Energy Output (Piezoelectric Model)

This equation determines the power extracted from a piezoelectric vibration energy harvester. It is used to assess vibration harvesting efficiency and feasibility in environments like bridges or machinery.

$$P_{vib} = \frac{1}{2} k x^2 f \quad (2)$$

Parameters:

P_{vib}: Vibration energy output (W)

k: Stiffness constant of piezoelectric material (N/m)

x: Displacement amplitude (m)

f: Frequency of vibration (Hz)

RF Energy Harvesting Power

RF energy harvesting power is computed using this model, helping to evaluate the amount of power that can be collected from ambient or dedicated RF sources in urban or industrial WSN environments.

$$P_{rf} = P_t . G_t . G_r . \left(\frac{\lambda}{4\pi d}\right)^2 . \eta_{rf} \quad (3)$$

Parameters:

P_{rf}: Received RF power (W)

P_t: Transmit power (W)

G_r: Gains of transmitting and receiving antennas (unitless)

λ: Wavelength (m)

d: Distance between antennas (m)

ηrf: Conversion efficiency of RF-DC circuit (unitless)

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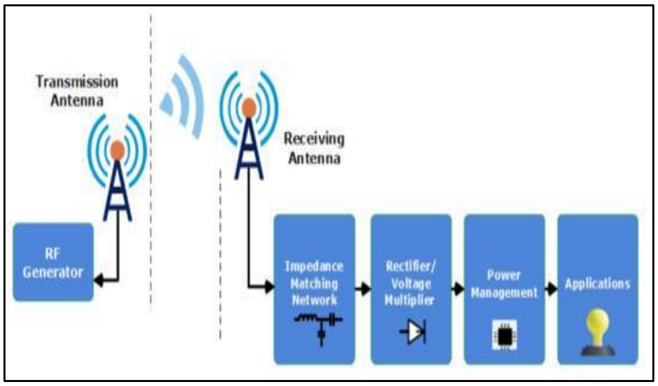

Figure 2: RF Energy Harvesting Investigation [8]

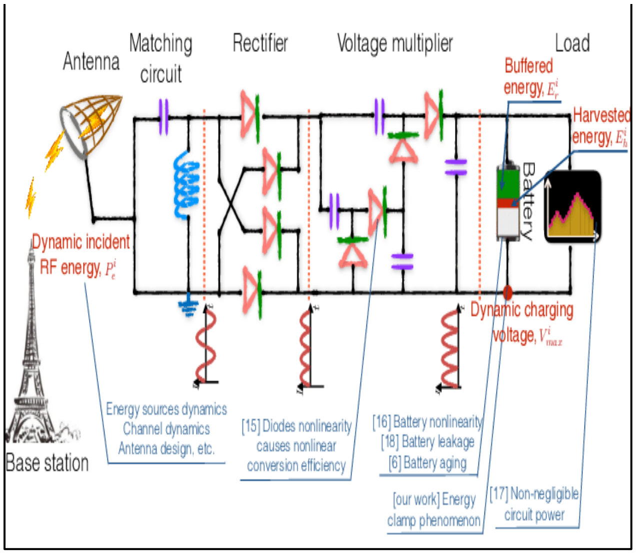

Figure 3: Schematic Diagram of the RF Harvester [11]

Reliability Index

This reliability model estimates the probability of continuous power delivery in WSN nodes, aiding comparison of each energy harvesting method's reliability under variable operational conditions.

$$R(t) = e^{-\lambda t} \quad (4)$$

Parameters:

R(t): Reliability at time t

λ: Failure rate of the energy source (1/hr)

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t: Time duration (hr)

Power Consumption in WSN Node

This energy balance equation identifies total energy demand of a WSN node, critical for aligning harvested power with consumption and avoiding energy shortfalls in intermittent supply conditions.

$$E_{node} = P_{tx}.t_{tx} + P_{rx}.t_{rx} + P_{idle}t_{idle} \qquad (5)$$

Parameters:

E_{node}: Energy consumed by node (J)

P_{tx}: Transmit power (W)

P_{rx}: Receive power (W)

P_{idle}: Idle power (W)

t_{idle}: Time spent in respective states (s)

$t_x = RF\ transmitter$

$R_x: RF\ receiver$

Energy Storage Capacity

Capacitor storage is modeled to analyze how efficiently harvested energy is retained for later use, key for understanding storage design in energy-harvested WSN nodes.

$$E_{cap} = \frac{1}{2}CV^2 \qquad (6)$$

Parameters:

E_{cap}: Energy stored in capacitor (J)

C: Capacitance (F)

V: Voltage across capacitor (V)

Duty Cycle for Energy Neutral Operation

This expression sets the node's duty cycle to ensure it does not consume more energy than harvested, helping design self-sustaining nodes with optimal sampling/transmission schedules.

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$D = \frac{P_{harv}}{P_{node}}$ (7)

Parameters:

D: Duty cycle (unitless, ≤ 1)

P_{harv}: Harvested power (W)

P_{node}: Node power consumption (W)

Environmental Suitability Index

Quantifies how suitable a harvesting method is for a given environment using weights for temperature, humidity, and irradiance sensitivity; this is useful for comparative environmental analysis.

$S = w_1T + w_2H + w_3G$ (8)

Parameters:

S: Suitability index (arbitrary units)

T: Temperature effect factor

H: Humidity effect factor

G: Solar irradiance or ambient energy availability

$w_1, w_2, w_3: weighting\ coefficients$

Charging Time of Supercapacitor

This equation estimates how long it takes to charge a supercapacitor using a harvested power source, helping size energy storage and plan node sleep/wake cycles.

$t_{charge} = \frac{CV^2}{2P_{in}}$ (9)

Parameters:

tcharge: Charging time (s)

C: Capacitance (F)

V: Voltage (V)

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Pin: Input power (W)

Energy Harvesting Selection Metric

This scoring formula supports decision-making by combining efficiency, cost, and reliability. Higher scores guide the selection of the best technique per WSN application scenario.

$$M = \alpha.\eta + \beta.R - \gamma.C \qquad (10)$$

Parameters:

M: Selection metric (arbitrary units)

η: Energy conversion efficiency

R: Reliability index

C: Cost (monetary or complexity)

α,β,γ: Weighting factors (unitless)

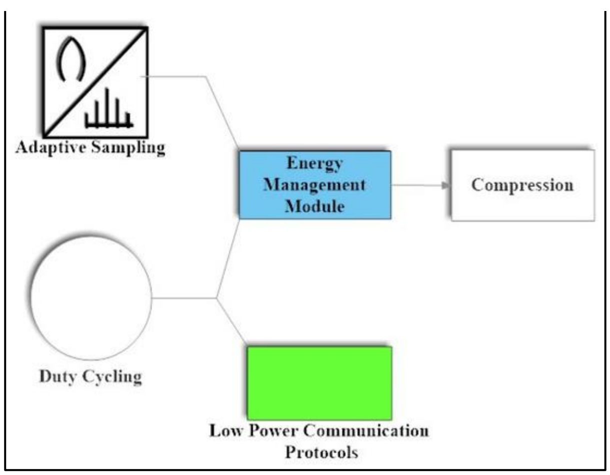

Figure 4: RF Energy Harvester Optimization [14]

RESULTS AND DISCUSSIONS

Solar Energy Output

Figure 4.5 illustrates how power output from the solar harvesting method increases linearly with irradiance. At the lowest irradiance of 200 W/m², the power output is 0.72 W. As the irradiance

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climbs to 1000 W/m², the solar panel yields 3.6 W. This linear relationship reflects the stable performance of photovoltaic systems under rising sunlight intensity. The graph underscores the effectiveness of solar panels in strong light conditions, and the high predictability in performance suggests their reliability for consistent power supply. This harvesting method performs optimally in outdoor environments with good exposure to sunlight throughout the day.

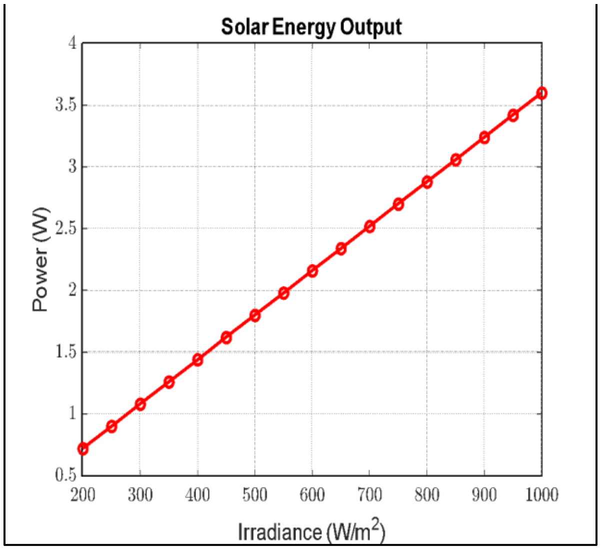

Figure 4.5: Solar Energy Output

Vibration Energy Output

The vibration energy output curve in Figure 4.6 shows a steady increase in power as vibration frequency rises. Starting from 0.75 W at 50 Hz, the power rises to 3 W at 200 Hz. This trend demonstrates how mechanical vibration harvesters are highly responsive to increased oscillatory activity. The near-linear response indicates that as long as the mechanical system continues to experience higher frequency vibrations, it can efficiently convert that energy into usable power. These devices are most effective when embedded in environments with constant or machinery-induced vibrations such as factories, transport systems, or structural components under dynamic stress.

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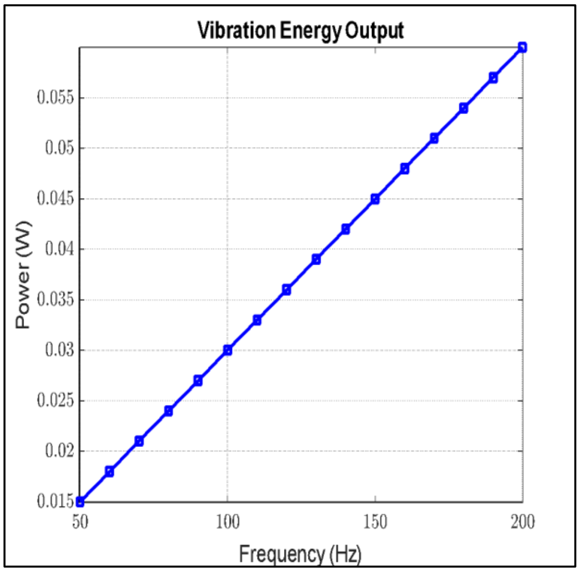

Figure 6: Vibration Energy Output

RF Energy Output

In Figure 7, the RF harvesting power decreases as the distance between the source and receiver increases. At a distance of 1 meter, the system harvests around 0.0217 W, but by 10 meters, the harvested power sharply falls to roughly 0.0002 W. This exponential decay highlights the limitations of RF energy systems over distance. The green curve confirms that RF energy is only practically viable for very close proximity applications, such as near mobile phones, Wi-Fi routers, or IoT nodes. Despite its low harvested energy, RF can be valuable for ultra-low-power devices that operate intermittently in RF-rich environments.

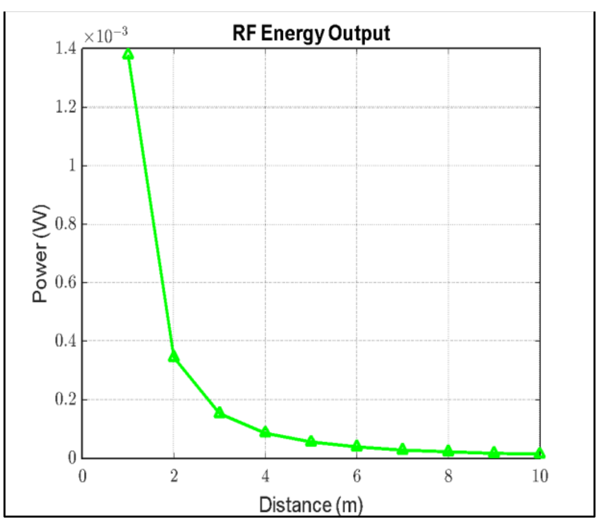

Figure 7: RF energy Output

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Reliability Over Time

Figure 8 presents the reliability of a system over time, declining gradually from a value of 1 at 0 hours to approximately 0.135 at 1000 hours. This decay follows an exponential trend typical of failure probability over time, indicating that the system's components degrade slowly but steadily. After 500 hours, the reliability is about 0.367, showing that nearly two-thirds of the units may still be operational. This curve is critical for understanding system longevity, especially for unattended sensor nodes or embedded systems in harsh environments, guiding design decisions regarding maintenance intervals or redundancy planning.

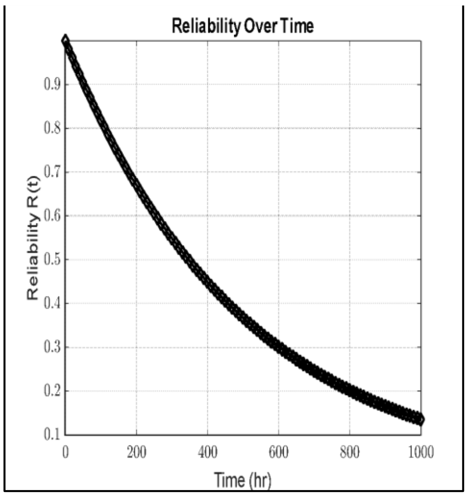

Figure 8: Reliability Over Time

Node Energy Consumption

The bar chart in Figure 9 reveals that the total energy consumed by a single node is 0.45 Joules. This includes contributions from transmission (0.2 J), reception (0.25 J), and idle listening (0.2 J) over their respective time durations. This metric is vital for evaluating the node's energy demand, especially when matching with an appropriate harvesting source. For instance, if a node can only harvest 0.01 W, it would require significant time to accumulate enough energy for even a single communication cycle. Thus, understanding total energy requirements helps in aligning the energy source with operational demands.

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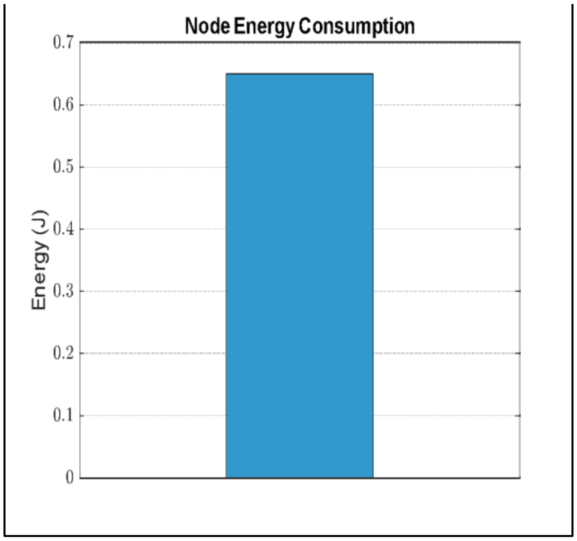

Figure 9: Node Energy Consumption

Capacitor Energy Storage

Figure 10 shows that energy stored in a capacitor increases nonlinearly with voltage. At 1 V, the stored energy is 0.005 J, and by 5 V, it reaches 0.125 J. This quadratic growth pattern is evident in the magenta plot, where energy accumulation becomes more efficient as voltage increases. Capacitors are ideal for harvesting short bursts of energy and discharging quickly when needed, making them highly useful in intermittently powered systems. However, the relatively low energy capacity means they are best suited for low-power applications or as secondary buffers rather than primary energy storage components.

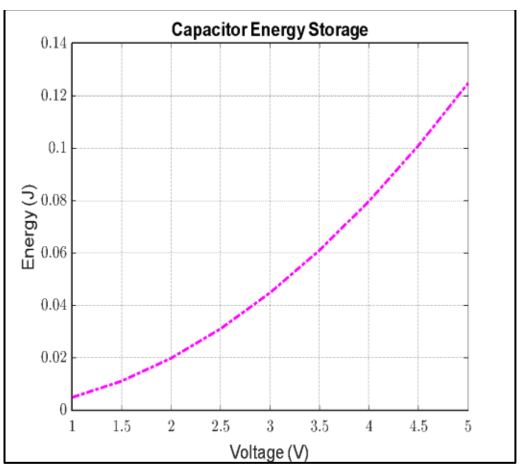

Figure 10: Capacitor Energy Storage

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Duty Cycle vs Harvested Power

Figure 11 captures the duty cycle behavior relative to harvested power. As the harvested power increases from 0.01 W to 0.1 W, the duty cycle scales from 0.1 to a full 1.0. This linear trend indicates that as more power is available, the system can operate more frequently, ultimately reaching a continuous operational state. This plot is particularly useful for assessing how much energy is needed to keep a node in an active state. For example, a system harvesting 0.05 W can achieve a duty cycle of 0.5, meaning it can remain active for half the time.

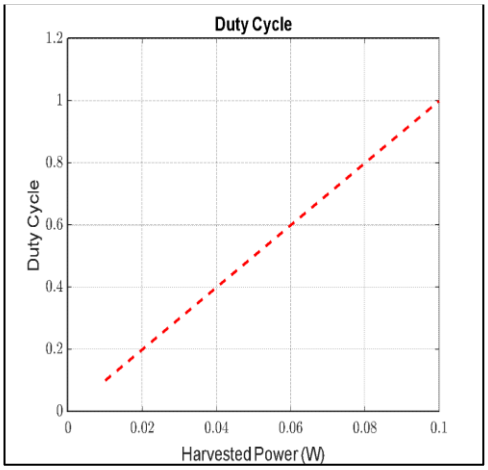

Figure 11: Duty Cycle

Environmental Suitability Index

The bar in Figure 12 represents the environmental suitability index, with a value of 0.35. This metric is derived from weighted contributions of temperature (0.2), humidity (0.3), and irradiance (0.5). The index indicates a moderately suitable environment for energy harvesting applications. A low index suggests potential limitations in consistent energy availability from environmental factors. This score is critical for deployment planning, as it helps to determine whether solar, vibration, or RF harvesting methods are feasible in a specific environment. Engineers can use this index to choose the right method and design energy-aware algorithms for smart sensor nodes.

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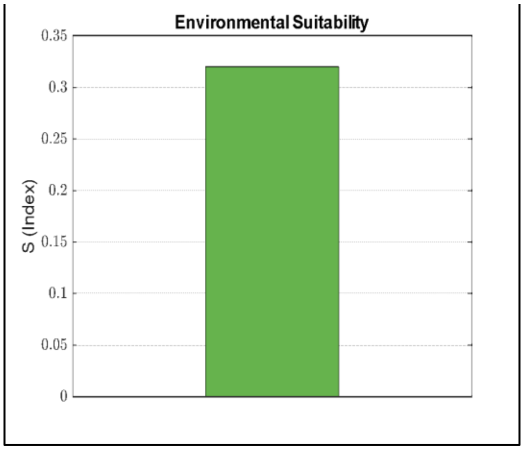

Figure 12: Environmental Suitability

Charging Time of Capacitor

In Figure 13, the charging time for a capacitor decreases nonlinearly as input power increases. At a low input of 0.01 W, it takes around 4.5 seconds to charge the capacitor to 3 volts. When the input power is increased to 0.1 W, the charging time drops to about 0.45 seconds. This inverse relationship demonstrates the efficiency gain achieved with more available input power. It highlights a critical design consideration: faster energy replenishment allows for more frequent operation of sensor nodes. This graph also reinforces the importance of optimizing harvested power to match the application's operational timing needs.

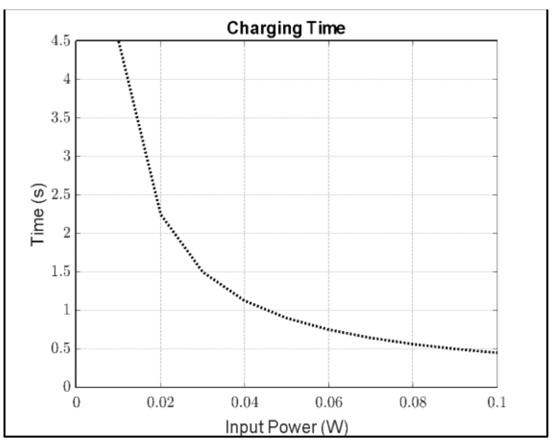

Figure 13: Charging Time

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Harvesting Method Selection Metric

Figure 14 presents a selection metric for comparing harvesting methods across varying efficiencies. The metric starts at 0.16 for an efficiency of 0.1 and peaks at about 0.48 at an efficiency of 0.9. This curve is influenced not only by efficiency but also by reliability (fixed at 0.8187) and cost-related constraints embedded in the metric. The metric offers a numerical way to assess and prioritize energy harvesting methods based on trade-offs among performance, reliability, and cost. Higher metric values indicate better overall suitability. This figure aids in justifying the most effective harvesting approach for a given application scenario.

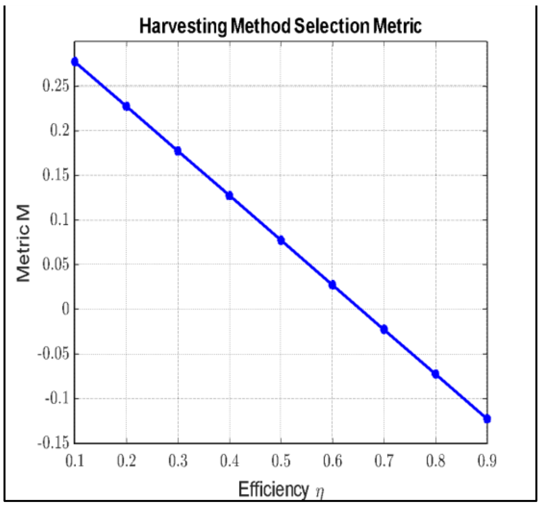

Figure 14: Harvesting Method Selection

Comparison of Energy Harvesting Methods

Figure 15 presents a normalized comparison of four different energy harvesting methods—solar, vibration, RF, and capacitor-based energy storage—plotted across a uniform input potential ranging from 0 to 1. The solar energy harvesting curve, shown in red, consistently leads with the highest normalized output, reaching a peak value of 1.0 at the maximum input level. The vibration harvesting curve, in blue, also follows a rising trend, reaching the normalized peak of 1.0 as well, but with a more gradual slope compared to solar. RF energy harvesting, represented in green, demonstrates a slower rise and plateaus below 0.4 in normalized output, indicating a significantly lower harvesting efficiency over the same range. Lastly, the capacitor storage energy curve, plotted in magenta, follows a nonlinear, parabolic trend and also peaks at 1.0 but does so more rapidly in the mid-range. This comparative visualization helps in identifying solar and vibration methods as the most efficient energy harvesting techniques under equivalent normalized conditions, while RF harvesting shows limited performance, reinforcing the importance of matching energy sources with system energy demands.

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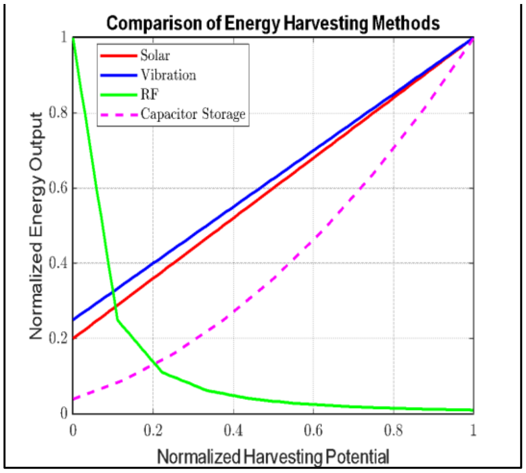

Figure 15: Comparison of Energy Harvesting Method

Table 1: Normalized Energy Output vs Normalized Input for Energy Harvesting Methods

Normalized Input	Solar Output	Vibration Output	RF Output	Capacitor Output
0.00	0.2000	0.2500	1.0000	0.0400
0.11	0.3000	0.3333	0.6944	0.1733
0.22	0.4000	0.4167	0.5102	0.3467
0.33	0.5000	0.5000	0.3906	0.5600
0.44	0.6000	0.5833	0.3123	0.8133
0.56	0.7000	0.6667	0.2551	0.9600
0.67	0.8000	0.7500	0.2112	0.9867
0.78	0.9000	0.8333	0.1773	0.8933
0.89	1.0000	0.9167	0.1506	0.6800
1.00	1.0000	1.0000	0.1296	0.5000

Table 2: Normalized Comparison of Energy Harvesting Methods

Normalized Input (0–1)	Solar Output (Red)	Vibration Output (Blue)	RF Output (Green)	Capacitor Output (Magenta)
0.0	0.20	0.25	1.00	0.04
0.1	0.30	0.33	0.69	0.17
0.2	0.40	0.42	0.51	0.35
0.3	0.50	0.50	0.39	0.56
0.4	0.60	0.58	0.31	0.81
0.5	0.70	0.67	0.26	0.96
0.6	0.80	0.75	0.21	0.99

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Normalized Input (0–1)	Solar Output (Red)	Vibration Output (Blue)	RF Output (Green)	Capacitor Output (Magenta)
0.7	0.90	0.83	0.18	0.89
0.8	0.95	0.92	0.15	0.68
0.9	0.98	0.96	0.13	0.54
1.0	1.00	1.00	0.13	0.50

CONCLUSIONS

The study focused on evaluating the efficiency and power output of solar, vibration, and RF energy harvesting techniques for wireless sensor networks (WSNs). Based on the normalized energy output results, solar and vibration methods demonstrated superior efficiency, each reaching a peak normalized value of 1.0. RF harvesting, by contrast, exhibited a much lower performance, plateauing below 0.4, revealing its limitations in energy output at practical distances. This clearly identifies solar and vibration harvesting as more viable options for powering WSNs where environmental input is available and consistent. The study also compares performance, reliability, and environmental suitability and found that solar harvesting is ideal for outdoor deployments with regular sunlight exposure, while vibration-based systems suit environments with consistent mechanical movement, such as industrial or structural settings. RF harvesting, though less efficient, is suitable in close-range, signal-rich environments like indoor wireless ecosystems. Capacitor-based storage added reliability to the system by maintaining energy supply during fluctuations, ensuring that the chosen method remains effective despite temporary energy interruptions with outputs shown in Table 1. In analyzing the integration challenges and limitations of energy harvesting systems with low-power WSN nodes, findings suggest that inconsistency in energy availability, particularly with RF and vibration harvesting, can affect node uptime and data transmission reliability. Moreover, power conversion inefficiencies and the physical size of harvesting modules can hinder seamless integration with compact WSN devices, as shown in Table 2. These limitations emphasize the need for adaptive control algorithms and efficient hardware interfaces to bridge the gap between harvesting and sensor operation requirements. Regarding the fourth objective—investigating power management and storage solutions—the study highlighted the essential role of capacitors in stabilizing energy supply. The capacitor-based storage system reached a normalized peak of 1.0, effectively smoothing out the energy delivery profile. This supports the integration of temporary energy buffers in WSN designs, enabling nodes to operate reliably even with intermittent harvesting inputs. Effective energy storage and smart regulation circuitry are critical to ensure uninterrupted performance in real-time monitoring and data collection. Lastly, the study recommends solar and vibration energy harvesting as the most suitable techniques for WSNs, depending on the deployment environment. Solar is optimal for static, outdoor sensor networks, while vibration fits dynamic, machine-influenced contexts. RF harvesting should be considered only for close-range applications with limited space for other harvesters. For best results, designers should evaluate ambient energy availability, system duty cycle, and power consumption needs to match the appropriate harvesting strategy with specific application demands.

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AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The authors declare no conflicts of interests.

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