International Journal of Machine Learning, AI & Data Science Evolution

Volume 2, Issue 9 – September 2026 • E-ISSN: 3067-5073 P-ISSN: 3067-6932

Advanced Materials for Energy Harvesting: Emerging Solutions for Self-Powered Intelligent Devices

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Abstract

The expansion of wearable electronics, distributed sensor networks, implantable technologies, and intelligent Internet of Things devices has increased demand for compact and reliable power sources. Conventional batteries provide comparatively stable energy, but their finite lifetime, physical rigidity, maintenance requirements, and disposal impacts can restrict long-duration and inaccessible applications. Energy-harvesting materials offer a complementary pathway by converting mechanical motion, vibration, heat, light, radio-frequency radiation, and interfacial charge transfer into usable electrical energy. Progress in nanostructured piezoelectrics, triboelectric polymers, flexible thermoelectrics, thin-film photovoltaics, conductive composites, and multifunctional textiles is enabling energy generators that can be integrated directly with intelligent devices.

This simulation-based study evaluates material platforms and system architectures for self-powered intelligent devices. A hypothetical hybrid harvester integrating triboelectric, piezoelectric, photovoltaic, thermoelectric, and radio-frequency mechanisms was examined under mixed ambient conditions. The simulated usable-energy contribution was distributed as 32% triboelectric, 27% piezoelectric, 21% photovoltaic, 12% thermoelectric, and 8% radio-frequency or electromagnetic harvesting. These percentages illustrate system-level complementarity and do not represent measured device outputs.

The analysis indicates that no individual material mechanism is universally optimal. Mechanical harvesters provide intermittent but potentially substantial outputs during movement, photovoltaic materials are productive under adequate illumination, and thermoelectric materials require sustained temperature gradients. Hybrid systems can reduce dependence on a single environmental source, but they introduce challenges in impedance matching, rectification, energy management, storage integration, mechanical durability, and lifecycle sustainability. The study concludes that self-powered intelligence requires coordinated design across materials, device architecture, power electronics, energy storage, sensing, computation, and communication. Future research should evaluate net usable energy, reliability, environmental impact, and task completion rather than emphasizing peak laboratory output alone.

Keywords: advanced materials, energy harvesting, self-powered devices, triboelectric nanogenerators, piezoelectric materials, thermoelectric materials, flexible electronics, intelligent sensors

1. Introduction

Intelligent devices are becoming smaller, more distributed, and more deeply integrated into physical environments. Wearable monitors, implantable sensors, structural-health systems, industrial sensor nodes, environmental monitors, smart textiles, and autonomous edge devices require dependable electrical power. Many of these devices are expected to operate in locations where frequent battery replacement is inconvenient, expensive, hazardous, or technically impossible.

Batteries remain essential because they provide controlled energy storage and comparatively stable output. However, a battery-powered device has a finite operating period unless it can be recharged or replaced. Large networks containing thousands of sensor nodes can create substantial maintenance requirements. Discarded batteries also contribute to material consumption and waste-management concerns.

Energy harvesting addresses this limitation by converting ambient energy into electrical power. Potential sources include mechanical deformation, vibration, human movement, temperature differences, sunlight, indoor illumination, flowing water, wind, acoustic waves, and electromagnetic radiation. The resulting power is generally lower and more variable than that supplied by conventional batteries, but it may be sufficient for low-power sensing, intermittent communication, data logging, or edge computation.

Advanced materials are central to this transition because energy conversion occurs through interactions among mechanical, electrical, thermal, optical, and interfacial properties. A material suitable for energy harvesting must not only generate charge. It may also require mechanical flexibility, fatigue resistance, environmental stability, biocompatibility, scalable processing, and compatibility with storage and electronic components.

Nanostructuring can enhance active surface area, strain distribution, charge separation, optical absorption, and thermal transport. Polymer composites can combine flexibility with functional ceramic or conductive fillers. Textiles can incorporate energy-harvesting fibers without eliminating comfort or breathability. Two-dimensional materials and conductive nanostructures can serve as lightweight electrodes and interfacial layers.

Self-powered does not necessarily mean that a device operates continuously without storage or external energy under every condition. A realistic self-powered system may harvest energy intermittently, store it locally, activate sensors at scheduled intervals, conduct limited computation, and transmit information only when sufficient energy is available. The design objective is therefore energy autonomy appropriate to a defined task.

2. Review of Literature

2.1 Mechanical Energy-Harvesting Materials

Mechanical energy is widely available through human movement, machinery vibration, structural deformation, fluid motion, and contact between surfaces. Piezoelectric materials generate electrical polarization when subjected to mechanical stress. Traditional piezoelectric ceramics can provide strong electromechanical response but may be brittle, dense, and unsuitable for repeated large deformation.

Piezoelectric polymers such as polyvinylidene fluoride provide greater flexibility and processability. Their piezoelectric response is often lower than that of high-performance ceramics, but their compatibility with films, fibers, and flexible substrates makes them suitable for wearable and

Volume 2, Issue 9 – September 2026 ● E-ISSN: 3067-5073 P-ISSN: 3067-6932

conformable devices. Ceramic–polymer composites attempt to combine strong polarization with mechanical flexibility.

Triboelectric nanogenerators use contact electrification and electrostatic induction to convert relative motion into electrical energy. Wang and colleagues explained that triboelectric systems can be constructed using diverse material pairs and structural configurations. Their relatively high voltage, flexible design, and suitability for low-frequency motion make them attractive for self-powered sensing. Triboelectric systems may operate through vertical contact separation, lateral sliding, single-electrode, or freestanding-layer configurations. Their output depends on surface-charge density, contact area, material affinity, motion frequency, humidity, wear, and environmental contamination. Surface microstructuring and nanostructuring can increase effective contact area, although repeated friction may reduce long-term durability.

2.2 Thermal, Optical, and Electromagnetic Harvesting

Thermoelectric materials convert temperature gradients directly into electrical voltage through the Seebeck effect.

Their performance is commonly discussed using the dimensionless figure of merit:

ZT=κS2σT

where S represents the Seebeck coefficient, σ represents electrical conductivity, T represents absolute temperature, and κ represents thermal conductivity. Effective thermoelectric materials require a difficult combination of high electrical conductivity and low thermal conductivity.

Rigid inorganic thermoelectric materials can perform effectively under stable thermal gradients but may be unsuitable for flexible devices. Conducting polymers, carbon-based composites, nanostructured alloys, and flexible thermoelectric films offer alternative routes. For wearables, the available temperature difference between skin and the environment may be small and variable, requiring careful thermal-interface design.

Photovoltaic materials convert light into electricity and can provide relatively sustained output under sufficient illumination. Crystalline silicon remains widely used, but thin-film, organic, dye-sensitized, and perovskite photovoltaic materials enable lighter and more flexible forms. Indoor environments create different spectral and intensity conditions from outdoor sunlight, so material selection should reflect the actual operating environment.

Radio-frequency and electromagnetic harvesting can capture energy from ambient communication signals, inductive coupling, or deliberate power transmitters. Ambient radio-frequency energy is often weak and spatially variable. Its practical value therefore depends on antenna design, frequency matching, rectification efficiency, and proximity to suitable sources.

2.3 Hybrid Harvesting and Integrated Storage

A single ambient source may be intermittent or unavailable. Hybrid systems combine several mechanisms to improve energy availability across changing conditions. Pu and colleagues reviewed the integration of energy-harvesting and storage devices, emphasizing that effective autonomous systems must coordinate generation, storage, and delivery.

A wearable device may combine mechanical energy from walking, thermal energy from body heat, and photovoltaic energy from ambient light. An industrial sensor may combine vibration and thermal gradients. Such configurations provide source diversity but increase structural and electrical complexity.

Energy storage is required when harvested power and device demand do not occur simultaneously. Micro-supercapacitors can provide rapid charging and high cycle life, while microbatteries offer greater energy density. Hybrid storage can balance short power bursts with longer-duration supply.

The literature demonstrates rapid material innovation but also reveals a persistent gap between material-level output and complete system autonomy. Peak voltage or power density does not by itself show whether a device can sense, compute, store data, and communicate reliably over its intended lifetime.

3. Objectives of the Study

The principal objective of this study is to evaluate how advanced functional materials can support energy autonomy in intelligent devices. The study considers energy harvesting as a complete materials-to-system problem rather than an isolated electrical-output challenge.

A second objective is to examine hybridization. Because ambient energy conditions vary across applications, the study evaluates whether combining several conversion mechanisms can provide a more stable usable-energy profile than dependence on one source.

The specific objectives are:

- To examine the properties of piezoelectric, triboelectric, thermoelectric, photovoltaic, and electromagnetic energy-harvesting materials.
- To compare the suitability of these materials for wearable, environmental, industrial, structural, and embedded intelligent devices.
- To develop a simulated hybrid energy-contribution model under mixed ambient conditions.
- To evaluate the relationship among harvested energy, storage, sensing, computation, and communication.
- To identify challenges involving conversion efficiency, mechanical durability, power conditioning, scalability, and lifecycle sustainability.
- To propose material and system-design principles for reliable self-powered intelligent devices.

The study addresses five research questions:

- Which advanced-material properties are most important for self-powered intelligent devices?
- Under what operating conditions does each energy-harvesting mechanism provide the greatest value?
- Can hybrid harvesting reduce dependence on a single variable energy source?
- How do power-management and storage losses affect usable energy?
- Which evaluation criteria are necessary beyond peak material output?

4. Research Methodology

4.1 Simulation Design and Device Context

The study uses an analytical simulation and does not report experimental measurements from a fabricated energy harvester. A hypothetical low-power intelligent device was assumed to contain environmental sensors, local processing, intermittent data storage, and short-range wireless communication.

Volume 2, Issue 9 – September 2026 • E-ISSN: 3067-5073 P-ISSN: 3067-6932

The device was evaluated under mixed ambient conditions involving periodic movement, mechanical vibration, changing illumination, a modest temperature gradient, and low-intensity radio-frequency exposure. These conditions were selected to represent a generalized device rather than a specific wearable, industrial, or environmental application.

Five energy-harvesting mechanisms were integrated conceptually. The simulation estimated their relative contribution to usable stored energy after simplified power-conditioning losses. The percentages were normalized to 100 for compositional interpretation.

4.2 Material Platforms and Functional Variables

Each harvesting mechanism was associated with a representative material platform and operational condition.

Table 1: Material platforms considered in the simulated hybrid harvester

Harvesting mechanism	Representative advanced material	Ambient source	Principal design requirement
Triboelectric	Microstructured fluoropolymer and conductive textile	Contact and sliding motion	Surface durability and humidity control
Piezoelectric	Lead-free ceramic–polymer composite	Strain and vibration	Mechanical coupling and fatigue resistance
Photovoltaic	Flexible thin-film photovoltaic layer	Outdoor or indoor light	Spectral response and encapsulation
Thermoelectric	Flexible nanostructured thermoelectric composite	Temperature gradient	Low thermal leakage
RF/electromagnetic	Conductive antenna and rectifying interface	Ambient or directed radiation	Frequency and impedance matching

4.3 Analytical Model and Assumptions

Usable energy from harvesting mechanism i was represented as:

$E_{u,i}=E_{a,i}\eta_{m,i}\eta_{c,i}\eta_{s,i}$

where $E_{u,i}$ represents usable stored energy, $E_{a,i}$ represents ambient energy available to the harvester, $\eta_{m,i}$ represents material-conversion efficiency, $\eta_{c,i}$ represents conditioning efficiency, and $\eta_{s,i}$ represents storage efficiency.

The total usable energy was estimated as:

$E_{total} = \sum_{i=1}^{n} E_{u,i} - E_{control}$

where Econtrol represents energy consumed by monitoring, switching, source selection, and power-management electronics. This term is important because complex hybrid control can consume part of the energy gained through source diversification.

5. Analysis and Results

The simulated hybrid harvester produced a diversified energy portfolio. Triboelectric harvesting made the largest contribution because the assumed device experienced regular contact and low-frequency movement. Piezoelectric harvesting provided the second-largest contribution through strain and vibration.

Photovoltaic energy contributed meaningfully but remained below the two mechanical mechanisms because illumination was intermittent. Thermoelectric harvesting provided a smaller contribution because the temperature gradient was modest. Radio-frequency and electromagnetic harvesting provided the lowest contribution under the assumed ambient conditions.

Table 2: Simulated energy contribution and operational interpretation

Energy source	Contribution	Availability pattern	Principal role
Triboelectric	32%	Intermittent during contact and motion	High-voltage mechanical harvesting
Piezoelectric	27%	Repeated strain and vibration	Mechanically coupled generation
Photovoltaic	21%	Dependent on illumination	Sustained daytime or indoor-light contribution
Thermoelectric	12%	Dependent on temperature gradient	Background thermal generation
RF/electromagnetic	8%	Low but potentially continuous	Supplementary energy collection

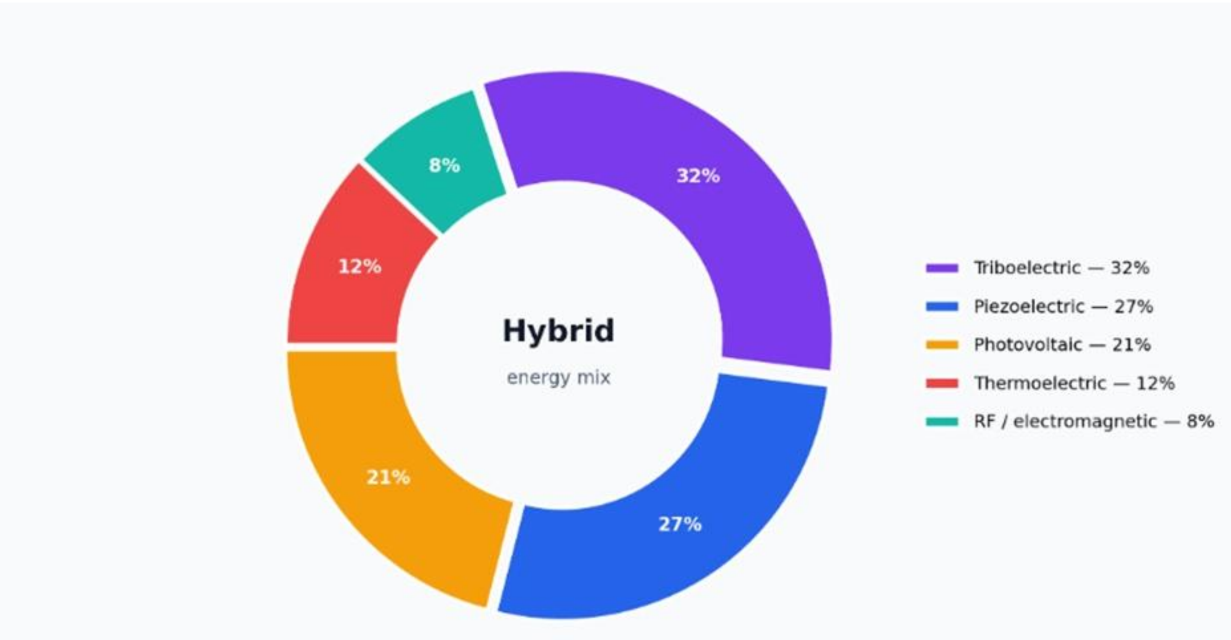
Note: Values are author-developed simulated shares and are not measured device outputs.

Mechanical harvesting collectively contributed 59% of usable energy. This outcome does not establish a universal advantage for mechanical systems. It reflects the simulated availability of motion and vibration. A stationary outdoor sensor could obtain a substantially larger photovoltaic share, while an industrial sensor positioned near a hot process could receive a larger thermoelectric contribution.

The hybrid configuration provided energy-source diversity. When light availability decreased, mechanical and thermal mechanisms continued contributing. When the device remained stationary, photovoltaic and radio-frequency mechanisms maintained partial generation. This complementarity reduced complete energy interruption.

Hybridization also introduced conversion losses. The five mechanisms produced different voltage, current, frequency, and impedance characteristics. Separate conditioning pathways were therefore required before energy could be combined within a shared storage system.

Graph 1. Simulated Energy Contribution in a Hybrid Self-Powered Device



Graph caption: Simulated percentage distribution of usable harvested energy from triboelectric, piezoelectric, photovoltaic, thermoelectric, and radio-frequency or electromagnetic sources under mixed ambient conditions.

Supporting data: Triboelectric harvesting contributed 32%, piezoelectric harvesting 27%, photovoltaic harvesting 21%, thermoelectric harvesting 12%, and radio-frequency or electromagnetic harvesting 8%. The five values total 100%.

Interpretation: No single mechanism provided the complete energy supply. Mechanical sources dominated under the assumed operating conditions, while optical, thermal, and electromagnetic sources improved diversity and continuity.

Key finding: Hybrid energy harvesting can reduce dependence on a single environmental source, but its practical value depends on whether additional conversion channels produce more usable energy than the control and conditioning architecture consumes.

A system-level assessment showed that communication remained the most demanding intermittent operation in the hypothetical device. Local feature extraction reduced transmission frequency and allowed the device to accumulate energy between communication events. Energy-aware task scheduling therefore improved autonomy without changing the harvesting material.

The analysis indicates that a material producing high peak voltage may still provide limited usable energy if its current is low, the mechanical event is infrequent, or rectification losses are large. Energy-harvesting studies should report load-matched power, operating duration, environmental conditions, conditioning losses, and completed device functions.

6. Challenges and Limitations

Mechanical durability is a central challenge. Wearable and structural harvesters may undergo bending, stretching, compression, friction, and repeated loading. Microcracks, delamination, electrode failure, and surface wear can gradually reduce output. Laboratory demonstrations conducted over short periods may not represent operational lifetime.

Environmental stability is equally important. Humidity can influence triboelectric charge retention, while oxygen, moisture, ultraviolet radiation, and heat can degrade photovoltaic and polymeric materials. Encapsulation improves protection but may reduce flexibility, thermal transfer, optical transmission, or mechanical coupling.

Material toxicity and resource availability must be considered. Some high-performance piezoelectric and thermoelectric materials contain lead, tellurium, or other elements associated with supply and environmental concerns. Lead-free and abundant-material alternatives may provide lower performance but better lifecycle suitability.

Power management creates another barrier. Mechanical nanogenerators may produce irregular high-voltage pulses, thermoelectric generators may provide low voltage, and photovoltaic outputs vary with illumination. Efficient rectifiers, converters, maximum-power-point tracking, and storage interfaces are required to combine these outputs.

Device miniaturization creates trade-offs between active area, mechanical compliance, output, and durability. Increasing surface area can improve harvesting but conflict with compactness. Thicker active layers may generate more energy but reduce flexibility.

The simulation has important limitations. It does not model a specific material composition, geometry, frequency, thermal gradient, illumination level, antenna environment, storage device, or electronic load. Its percentage contributions were constructed for conceptual comparison and cannot predict real device performance.

7. Discussion

7.1 Materials Selection as an Application-Specific Decision

The findings reinforce that there is no universally superior energy-harvesting material. Material selection must begin with the energy environment and operational task. A wearable device experiences low-frequency movement and body heat, while an industrial machine may provide continuous vibration and stronger thermal gradients.

Piezoelectric and triboelectric systems are appropriate when mechanical energy is available. Piezoelectric materials can provide stable conversion under repeated deformation, while triboelectric generators offer material diversity and high voltage. Their output characteristics and durability requirements remain different.

Photovoltaics may dominate where light is reliable, while thermoelectrics require a maintained temperature gradient. Radio-frequency harvesting is attractive because it does not require direct mechanical contact, but ambient power density can be insufficient for continuous high-demand operation.

7.2 Hybridization and Energy-Aware Intelligence

Hybridization improves source diversity but should not be adopted automatically. Every additional harvester adds mass, volume, manufacturing steps, wiring, conditioning electronics, and potential failure points. The system should therefore be optimized for net lifecycle value rather than the number of mechanisms.

Intelligent energy management can help coordinate hybrid sources. A controller may prioritize the most productive source, adjust sensing frequency, defer communication, or place the processor in a low-power state. Prediction of source availability can improve scheduling; for example, a wearable may learn when movement or light is normally available.

The intelligent device can also adapt its workload to stored energy. High-priority measurements may continue under low-energy conditions, while optional sensing and communication are delayed. This approach connects materials engineering with adaptive computing.

7.3 Sustainability and Translation Beyond Laboratory Output

Energy harvesters are frequently described as sustainable because they reduce battery dependence. This claim requires lifecycle evidence. Fabrication may involve solvents, high-temperature processing, scarce elements, difficult-to-recycle composites, or short-lived interfaces.

A sustainable harvester should generate enough useful energy during its life to justify its material and manufacturing burden. Durability, repairability, recyclability, and compatibility with device disassembly should therefore be included in evaluation.

Commercial translation also requires reproducibility at scale. Materials that perform well in small laboratory samples may experience reduced uniformity when manufactured over large areas. Printing, coating, roll-to-roll processing, fiber integration, and additive manufacturing offer scalable pathways, but process control remains essential.

8. Conclusion

Advanced materials are enabling energy-harvesting devices that convert mechanical, thermal, optical, and electromagnetic energy into electrical power. Piezoelectric composites, triboelectric interfaces, flexible thermoelectrics, thin-film photovoltaics, conductive textiles, and nanostructured electrodes provide different combinations of output, flexibility, durability, and environmental compatibility.

The simulation demonstrates how hybrid harvesting can provide a diversified energy supply. Under the assumed conditions, triboelectric and piezoelectric mechanisms supplied the largest shares, while photovoltaic, thermoelectric, and radio-frequency sources improved continuity. These values are illustrative and should not be interpreted as experimental performance claims.

Self-powered intelligence requires more than a high-output material. Harvested energy must be rectified, conditioned, stored, and delivered according to device demand. Energy-aware sensing, local computation, and intermittent communication can be as important as conversion efficiency in achieving practical autonomy.

Future research should report complete energy pathways and realistic operating conditions. Material performance should be evaluated alongside mechanical lifetime, storage integration, task completion, scalability, toxicity, and recyclability. The strongest solutions will emerge from coordinated design across materials science, electronics, data processing, and sustainability engineering.

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