

# Self-Sufficient Systems: Integrating Energy Harvesting with Smart Structures and Soft Robotics

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## Abstract

The burgeoning fields of smart structures and soft robotics promise a future of adaptive, compliant, and intelligent systems for applications ranging from biomedical implants to remote environmental monitoring. However, a critical bottleneck constraining their long-term deployment and autonomy is the reliance on conventional, rigid batteries, which necessitate frequent recharging or replacement, thereby limiting operational lifespan and increasing maintenance complexity. This review article posits that the integration of energy harvesting technologies directly into the fabric of smart structures and the constitutive materials of soft robots is the pivotal step towards realizing truly self-sufficient systems. We present a comprehensive analysis of the synergy between three core domains: advanced energy harvesting mechanisms (piezoelectric, triboelectric, pyroelectric, and bio-chemical), multifunctional smart materials (shape memory alloys, electroactive polymers, hydrogels), and the architectural principles of soft robotics. The article systematically reviews recent breakthroughs in material science that enable dual-functionality, where a material can simultaneously act as a sensor, an actuator, and an energy harvester. We explore innovative system-level designs that transform structural deformations, ambient thermal fluctuations, and even biochemical energy from the environment into usable electrical power to sustain onboard computation, sensing, and actuation. Furthermore, the paper addresses the significant challenges of power management, energy storage at the micro-scale, and system-level integration efficiency. By synthesizing the current state-of-the-art and projecting future research trajectories, this work aims to provide a foundational framework for the next generation of autonomous, maintenance-free intelligent systems capable of perpetual operation in unpredictable and inaccessible environments.

## Keywords

Energy Harvesting, Soft Robotics, Self-Powered Systems, Piezoelectricity, Triboelectric Nanogenerators, Intelligent Structures, Bio-Inspired Design

## 1. Introduction

The 21st century has witnessed an unprecedented convergence of materials science, robotics, and electronics, giving rise to two transformative technological paradigms: smart structures and soft robotics. Smart structures, embedded with sensors, actuators, and control systems, can perceive their environment and adapt their properties or configuration accordingly, finding applications in aerospace (adaptive wings), civil engineering (structural health monitoring), and wearable technology [1]. In parallel, soft robotics, constructed from compliant, deformable materials, has emerged to overcome the limitations of traditional rigid robots, enabling safe human-robot interaction, complex manipulation of delicate objects, and locomotion in confined, unstructured environments.

Despite their revolutionary potential, both domains share a common, critical dependency: the need for a continuous and reliable power supply. The current reliance on lithium-ion batteries and wired power sources imposes severe constraints. For implantable biomedical devices, surgical replacement of batteries is invasive and risky [2]. For environmental sensors deployed in remote locations or large-scale distributed sensor networks, manual battery replacement is logistically prohibitive and costly. In soft robotics, the incorporation of heavy, rigid batteries compromises the very principle of softness and compliance, leading to a performance trade-off. This energy constraint is the primary impediment to the vision of long-term, autonomous, and maintenance-free systems.

Energy harvesting—the process of capturing and converting ambient, otherwise wasted energy from the environment into usable electrical energy—presents a compelling solution. Ambient energy sources are abundant and ubiquitous, including mechanical vibrations, human motion, temperature gradients, light, and even biochemical energy from the human body or surrounding media. The integration of energy harvesting mechanisms directly into the structural elements and soft bodies of these systems can pave the way for self-sufficiency. This paradigm shift involves moving from a design philosophy of "design, then power" to one of "power through design," where energy generation is an inherent, multifunctional property of the system's material composition and mechanical architecture [3].

This article comprehensively explores the integration of energy harvesting technologies with smart structures and soft robotics to create self-sufficient systems. We will first delineate the fundamental principles of the most relevant energy harvesting mechanisms. Subsequently, we will delve into how these mechanisms are being embedded within smart structural systems, enabling them to power their own sensing and diagnostic capabilities. The core of our discussion will focus on the nascent but rapidly advancing field of energetically autonomous soft robots, where actuation, sensing, and power generation are synergistically combined. We will present illustrative case studies, supported by conceptual figures, and critically examine the persistent challenges in power management, storage, and system integration. Finally, we will outline future research directions and the broader implications of this technology.

## 2. Fundamentals of Energy Harvesting Mechanisms

To effectively integrate energy harvesting into smart systems, a deep understanding of the underlying physical principles is essential. The choice of harvesting mechanism is dictated by the dominant ambient energy source in the target application.

### 2.1 Piezoelectric Harvesting

The piezoelectric effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress. This direct conversion of mechanical energy to electrical energy is highly effective for harvesting energy from vibrations, impacts, and repetitive strains. Materials such as lead zirconate titanate (PZT) ceramics and polyvinylidene fluoride (PVDF) polymers are widely used. PZT offers a high energy density and coupling coefficient but is brittle, whereas PVDF is flexible, making it more suitable for integration into soft and deformable systems. Recent research focuses on developing lead-free and biocompatible piezoelectric materials, such as barium titanate (BTO) and zinc oxide (ZnO) nanowires, for sustainable and biomedical applications [4].

### 2.2 Triboelectric Harvesting

The triboelectric nanogenerator (TENG) operates on the coupled effects of triboelectrification and electrostatic induction. When two dissimilar materials come into contact, surface charges are transferred. Subsequent separation or sliding motion between the charged surfaces generates a potential difference that drives electrons in an external circuit. TENGs are exceptionally versatile, capable of harvesting energy from a wide range of mechanical motions, including low-frequency and irregular movements like walking, wind, and water waves. Their advantages include high output voltage, a vast choice of materials (from polymers to fabrics), simple fabrication, and high efficiency at low frequencies, making them ideal for wearable and soft robotic applications [5].

### 2.3 Pyroelectric and Thermoelectric Harvesting

These mechanisms convert thermal energy into electricity. Pyroelectric materials, which are often also piezoelectric, generate a temporary voltage when they experience a time-dependent temperature change ( $dT/dt$ ). This is suitable for environments with fluctuating temperatures. Thermoelectric generators (TEGs), based on the Seebeck effect, generate a continuous voltage from a steady-state spatial temperature gradient ( $\Delta T$ ) [6]. While TEGs are more established for waste heat recovery in industrial settings, pyroelectric harvesting is gaining traction for powering wearable sensors that experience temperature cycles from the environment or the human body.

### 2.4 Bio-Chemical Energy Harvesting

For implantable devices and bio-integrated robots, the most relevant energy source is the host itself. Bio-fuel cells can generate electricity by oxidizing biofuels (e.g., glucose in blood or interstitial fluid) at the anode and reducing oxygen at the cathode. This provides a direct, continuous, and biologically compatible power source, potentially enabling lifelong operation of medical implants without the need for surgery.

**Table 1.** Comparison of Primary Energy Harvesting Mechanisms

Mechanism	Principle	Typical Materials	Advantages	Limitations	Best Suited For
Piezoelectric	Mechanical stress → Charge	PZT, PVDF, BTO	High power density, Direct conversion, Fast response	Brittle (ceramics), Sensitive to fatigue	Vibrations, Impacts, Repetitive strain
Triboelectric (TENG)	Contact-Separation → Induction	PDMS, PET, FEP, Fabrics	High voltage, Flexible, Low-cost, Low-frequency	Surface wear, Humidity sensitivity	Human motion, Wind, Low-freq. oscillations
Thermoelectric	Temperature gradient → Voltage (Seebeck)	$\text{Bi}_2\text{Te}_3$ , $\text{Sb}_2\text{Te}_3$	Continuous DC power, Robust, No moving parts	Low efficiency, Requires large $\Delta T$	Industrial waste heat, Body heat (with large $\Delta T$ )
Pyroelectric	Temp. change → Charge	PZT, PVDF, $\text{LiTaO}_3$	Responds to temp. fluctuations, Can be combined with piezo	Requires $dT/dt$ , Not for steady-state	Cyclic thermal environments
Bio-Chemical	Glucose/ $\text{O}_2$ reaction → Current	Enzymes, Carbon nanotubes	Biocompatible, Continuous (in vivo)	Low power output, Bio-fouling, Stability	Implantable devices, Bio-robots

Table 1 compares several major energy harvesting mechanisms, examining their principles, materials, advantages, disadvantages, and the most suitable application scenarios, provides an overview and comparison to help you choose the appropriate energy harvesting mechanism based on different energy sources (mechanical, thermal, chemical) and application requirements.

### 3. Energy Harvesting in Smart Structures

Smart structures are designed to sense and react to their operational environment. Integrating energy harvesting transforms them from merely "smart" to "self-sufficient," allowing them to power their own sensory and processing units [7].

#### 3.1 Structural Health Monitoring (SHM)

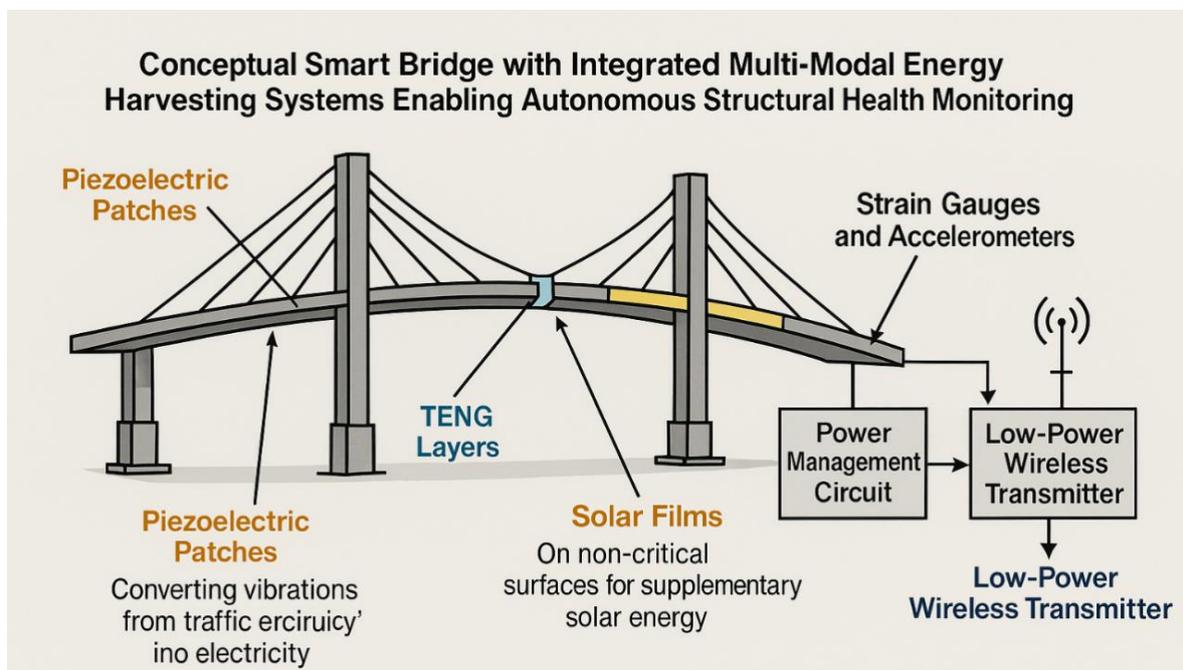
Large-scale civil structures like bridges, buildings, and wind turbine blades are subject to continuous vibrations and wind loads. Embedding or attaching piezoelectric patches or TENGs onto these structures can harness this ambient mechanical energy. The generated power can operate micro-sensors that monitor critical parameters such as strain, crack formation, and corrosion, wirelessly transmitting data to a central hub. This creates a perpetually powered, distributed sensor network that provides real-time health assessment without the need for external power infrastructure or battery maintenance. For example, a TENG integrated into a bridge's bearing or cable can harvest energy from both traffic-induced vibrations and wind, powering a strain gauge and a wireless transmitter.

#### 3.2 Aerospace Applications

In aircraft, vibration energy from the airframe and wings is a significant and constant energy source. Piezoelectric elements can be integrated into the composite skin of wings or the fuselage to power sensors monitoring stress, temperature, and damage. Furthermore, the concept of "morphing wings"-wings that change shape for optimal performance-can be enhanced by using the energy harvested during the morphing process itself to partially power the shape-memory alloy or piezoelectric actuators responsible for the deformation [8]. This creates a synergistic loop where the actuation process contributes to its own energy needs.

#### 3.3 Wearable and Textile-Integrated Systems

Smart textiles represent a major class of smart structures. Here, energy harvesting is crucial for powering embedded physiological sensors (ECG, EMG, temperature). Fiber-based TENGs and piezoelectric polymers (e.g., PVDF nanofibers) can be woven directly into fabrics. These "e-textiles" can harvest energy from the wearer's body movements-walking, arm swinging, or even the pulse-to power the sensors and a low-power Bluetooth module for data transmission. This enables continuous, long-term health monitoring without the user ever needing to charge the device [9].



**Figure 1.** Conceptual Diagram of a Self-Powered Smart Structure (e.g., a Bridge)

Figure 1 illustrates a concept of a "smart bridge + multiple energy harvesting systems + autonomous structural health monitoring". A conceptual smart bridge that achieves autonomous structural health monitoring by integrating a multimodal energy harvesting system.

**Energy Harvesters on Bridges:** Piezoelectric Patches: Attached to the bridge deck and piers, these patches convert mechanical vibrations caused by vehicle movement and wind into electrical energy. Triboelectric Nanogenerators (TENG Layers): Placed at expansion joints, these layers generate electricity when relative displacement occurs between sections of the bridge structure. Solar Films: Attached to non-critical surfaces to provide additional solar power.

**Electricity Management and Storage:** The electricity generated by all energy harvesting devices is collected into the Power Management Circuit and then stored in a Micro-Supercapacitor or similar energy storage device.

**Power Supply and Monitoring System:** Stored electricity powers the bridge's strain gauges and accelerometers, enabling real-time monitoring of the bridge's structural health, including stress and vibration. Monitoring data is transmitted via a Low-Power Wireless Transmitter (e.g., to a monitoring center).

**Overall Significance:** This bridge does not require an external power source; instead, it generates and manages its own electrical energy through its environment (vehicles, wind, displacement, sunlight), thus achieving a "self-sufficient" structural health monitoring system.

#### 4. Energy-Autonomous Soft Robotics

The integration of energy harvesting in soft robotics is arguably more profound, as it addresses the core challenge of untethered, autonomous operation. The compliant nature of soft robots provides a perfect platform for harvesting energy from their own interaction with the environment [10].

##### 4.1 Harvesting from Actuation and Locomotion

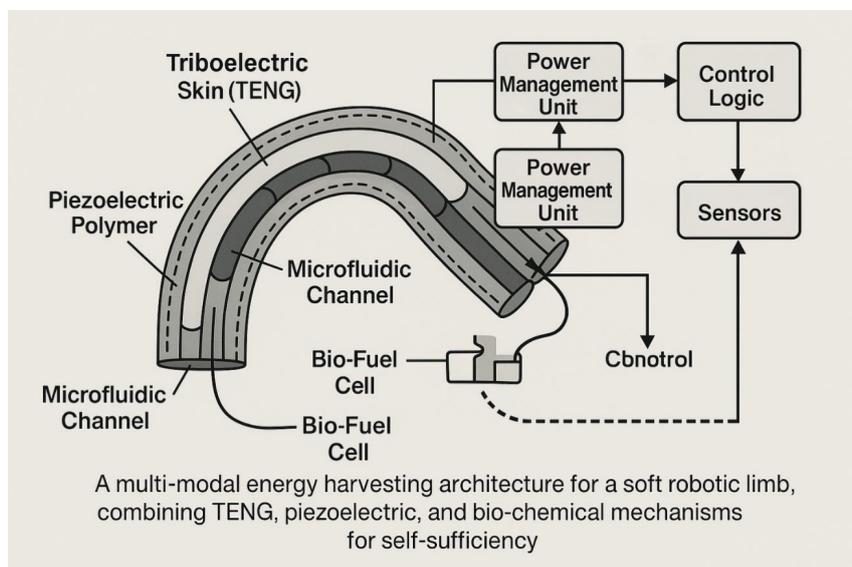
The very motion of a soft robot can be a source of power. For instance, a pneumatically actuated soft robot's gait often involves cyclic contact and release with the ground. By lining the robot's feet or body with TENGs, each step can generate an electrical pulse. Similarly, the internal fluid flow within a soft hydraulic or pneumatic actuator can be used to drive a miniature rotary TENG or a piezoelectric flapper, converting a portion of the actuation energy back into electricity. This "regenerative" approach, analogous to regenerative braking in electric vehicles, can recapture energy that would otherwise be dissipated as heat, improving overall system efficiency.

##### 4.2 Bio-Hybrid and Chemically Powered Robots

At the intersection of soft robotics and biomimicry lie bio-hybrid systems. These robots use living biological cells as integral components. A groundbreaking approach is the use of engineered muscle tissue, powered by nutrients in the environment, as both the actuator and the energy harvester. The metabolic processes of the muscle cells not only generate force for contraction but also create biochemical gradients that can, in principle, be tapped by bio-fuel cells to power control electronics. While still in its infancy, this concept points towards a future where soft robots can "feed" off their environment for energy, much like biological organisms [11].

##### 4.3 Environmental Scavenging for Exploration

Soft robots are ideal for exploration in delicate environments like coral reefs, disaster rubble, or other planets. In these scenarios, energy harvesting is not just convenient but essential. A soft robot could use a TENG-based "skin" to harvest energy from wind or rain [12]. In aquatic environments, a soft, flapping-fin robot could use embedded piezoelectric composites to harvest energy from water currents and vortex shedding, simultaneously using the harvested energy to power its navigation sensors and communication systems, enabling indefinite mission duration limited only by hardware wear-and-tear.



**Figure 2.** Architecture of an Energetically Autonomous Soft Robotic Limb

Figure 2 illustrates the conceptual structure of how a soft robotic arm (or gripper) can generate its own power in various ways to achieve self-sufficient operation.

**The soft limb itself:** The outer layer is labeled Triboelectric Skin (TENG): This is equivalent to "triboelectric skin," generating electricity when it comes into contact with or rubs against external objects. The inner ring is Piezoelectric Polymer (such as PVDF): When the soft arm is bent, inflated, or compressed, changes in internal pressure and strain generate electrical energy in this material. In the middle is a Microfluidic Channel: This channel can hold reactants to drive a miniature Bio-Fuel Cell, converting chemical energy into electrical energy.

**Energy Management and Storage:** All these power generation methods (TENG, piezoelectric layer, biofuel cell) are connected to a miniature Power Management Unit (PMU). The PMU charges a **flexible Micro-Supercapacitor** and distributes the electricity as needed.

**Control and Sensing + Feedback Loop:** Power is supplied to the Control Logic and various sensors. Data collected by the sensors (such as pressure, bending, and tactile sensors) is fed back to the Control Logic, which then adjusts the soft limb's movements—forming a closed-loop control system. Because the energy is harvested from the environment, the soft limb can operate autonomously for extended periods without an external power source.

This is a multimodal energy harvesting architecture designed for soft robot limbs, combining TENG, piezoelectric and biochemical mechanisms to achieve system self-sufficiency.

## 5. Materials and System Integration Challenges

The seamless integration of energy harvesting into functional systems presents a multi-faceted challenge at the material, component, and system levels.

### 5.1 Multifunctional Materials

The ultimate goal is to develop materials that are not just substrates for attaching harvesters but are themselves multifunctional. Research is focused on composites where piezoelectric nanoparticles (e.g., BTO) are dispersed within a soft silicone or hydrogel matrix, creating a material that is simultaneously stretchable, actuatable, and energy-harvesting. Similarly, ionic hydrogels can be used to create "soft power sources" that generate electricity from salinity gradients or mechanical deformation, blurring the line between battery, sensor, and structure.

### 5.2 Power Management and Storage

The electrical output from most harvesters is AC (piezoelectric, TENG) or pulsed DC, with variable voltage and current characteristics that are poorly matched to the needs of standard electronics. Efficient power management circuits (PMCs) are therefore critical. These circuits must perform AC-DC conversion, voltage regulation, and impedance matching to maximize power transfer. Furthermore, the intermittent nature of ambient energy necessitates on-board energy storage. Traditional batteries are often incompatible with soft systems. Instead, flexible micro-supercapacitors are emerging as the preferred solution due to their high power density, long lifecycle, rapid charging, and mechanical flexibility. Integrating these storage elements without compromising system compliance is a key area of research.

### 5.3 Efficiency and Durability

The overall system efficiency—from captured ambient energy to useful work performed—is currently low. Losses occur at every stage: coupling with the energy source, transduction efficiency, power conditioning, storage, and final actuation/sensing. Improving the coupling coefficient of piezoelectric materials and the surface charge density of TENGs is a primary materials challenge. Furthermore, the long-term durability of these systems, especially under cyclic mechanical loading, is a concern. Issues like fatigue in piezoelectric ceramics, wear of triboelectric surfaces, and delamination of composite layers must be addressed for real-world deployment.

## 6. Future Perspectives and Conclusion

The integration of energy harvesting with smart structures and soft robotics is poised to redefine the boundaries of autonomous systems. The trajectory points towards several exciting future directions:

- **Hybrid Harvesting:** Systems will not rely on a single mechanism but will incorporate multiple, complementary harvesters (e.g., piezoelectric + TENG + solar) to ensure a more consistent power output across diverse and changing environmental conditions.
- **AI-Driven Power Management:** Machine learning algorithms can be employed to predict energy availability and dynamically manage power budgets. For example, a soft robot could learn to modify its gait to move to a sunnier spot or a more vibration-rich area when its energy reserves are low.
- **Complete Bio-Integration:** The ultimate self-sufficient system may be a bio-hybrid robot that harvests energy, senses, and actuates using entirely biological or bio-compatible materials, operating seamlessly within a biological host or ecosystem.

• **4D-Printed Harvesting Systems:** Using advanced additive manufacturing to create structures that can change shape over time (the 4th dimension) in response to stimuli, with energy harvesting functionality directly printed into the complex 3D geometry.

In conclusion, the path towards self-sufficient intelligent systems is being paved by the deep integration of energy harvesting technologies. By transforming the structural and material components of smart structures and soft robots from passive, energy-consuming elements into active, energy-generating entities, we can overcome the critical limitation of power autonomy. While significant challenges in materials science, power electronics, and system integration remain, the rapid progress in this interdisciplinary field promises a future where our machines can operate independently, sustainably, and perpetually, unlocking new possibilities in healthcare, environmental science, exploration, and beyond. The vision of machines that live off their environment, much like living organisms, is steadily transitioning from science fiction to an engineering reality.

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