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Research paper

Sustainable Energy Harvesting: Innovations In Photovoltaic and Piezoelectric Systems

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Abstract

This research investigates the possibility of Piezoelectric (PE) materials in providing sustainable and renewable energy solutions, focusing on Energy Harvesting (EH) and self-sustaining innovative sensing processes within various systems like Photovoltaic (PV) cells. This study emphasizes the inadequacy of traditional construction materials, such as basic cement paste, in EH. It explores contemporary techniques that enhance the PE properties of cement-based materials through novel admixtures and physical procedures. The study examines the extensive application of PE and PV substances in many areas, including medical care, monitoring of the environment, and electronic goods, driven by the demand for wireless sensing modules and integrated microsystems requiring a dependable power source. This research provides an unbiased evaluation of the environmental benefits, contemporary advancements, difficulties, and prospects in PE and PV EH, including investigating lead-free materials and creating mixed EH gadgets.

Keywords: *Sustainability; Energy Harvesting; Photovoltaic; Piezoelectric Systems; Renewable; Environment.*

1. Introduction

The research serves as a comprehensive reference guide for individuals seeking to identify the optimal Piezoelectric (PE) component for physical Energy Harvesting (EH) [1] [11]. PE compounds are a distinct category within the broader classification of innovative substances, which alter their inherent properties in response to external stimuli. Since the advent of piezoelectricity [3] [4], considerable efforts have been directed towards exploring materials exhibiting electro-active characteristics. Electro-active substances encompass PE, dielectric, ferroelectric, Photovoltaic (PV), photostrictive, and electrochemical, among the most prominent types [8].

PE components [12] offer eco-friendly solutions, including EH and autonomous building monitoring, by converting physical stress and vibrational energy into electricity, as shown in Fig. 1. A flow of electricity is generated and charges the surfaces of an object when it undergoes physical deformation, a phenomenon referred to as piezoelectricity [2]. Research increasingly concentrates on Wireless Sensor Networks (WSNs) [5] and integrated systems, which require continuous power from several sectors, including healthcare, academia, finance, environmental science, military, agriculture, retail, and electronics, for consumers. In the context of WSNs, EH provides an eco-friendly alternative to battery replacement. It converts ambient energy into usable electrical power, especially for consumer products and low-power WSNs. Optimization methods [13] enhance the operational frequency range, degrees of liberty, and hybrid transformation of vibration-based EH systems. This study discusses the design, conversion procedure, performance indicators, and applications of PE, Electromagnetic (EM), and mixed EH gadgets, focusing on recent advancements in Vehicular Energy Harvesting (VEHs) [7]. The predominant frequency ranges of PE EH range from 2 to 13.8 kHz, with dimensions spanning from millimeters to centimeters. Mixed EH systems produce the greatest concentration of energy, while EM EH can convert up to 779.23 W/cm². A multilayer, cantilevered PE conversion of energy sidewalk ensures durability and EH [14]. The coordinated oscillation between road drive, damper PE, and PV EH will be guaranteed. The research clarifies structural issues related to the magnitude of electricity generated. The optimal cantilever location and vibration magnitude for constructing road field generators are established based on the long-term reliability of the energy conversion architecture and EH efficiency [9]. The improved structure generates incredible energy and exhibits increased strength under highway circumstances, yielding an output value of 5.3 V, 3.25 mW, and an electrical efficiency of 0.0071 mW/mm³. The framework facilitates co-vibration with the driving mechanism and mitigates misunderstandings from previous designs owing to its enhanced energy levels and densities.

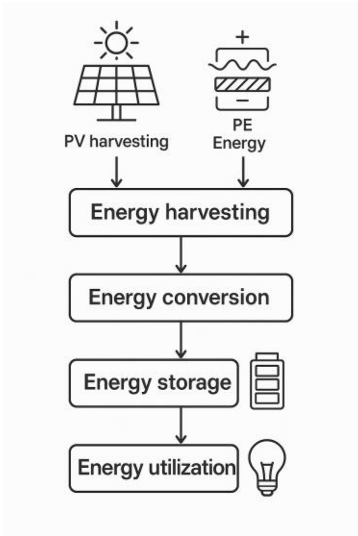

Fig. 1: Block Diagram of Sustainable Energy Harvesting Process

A PE, EM connection up-conversion multi-directional vibratory EH has been suggested to address the inadequate power generation and conversion effectiveness of single electromechanical conversions. At the base, four PE EM connection beams are cantilevers equipped with permanent magnets at their free extremities for EH [10]. A rotating mass block is affixed to the topmost ring of the horizontal beam, bearing on the central shaft, which is arranged in four EH coils beneath permanent magnetic fields. An arrangement of four permanent magnets located on rotating mass blocks and cantilever waves is employed to extract nonlinear contact vibratory energy from human movement via a spontaneously vibrating PE cantilever. In response to the increasing need for compact gadgets, this work investigates the fabrication and practical applications of a PE Nanogenerator (PENG) employing polydimethylsiloxane and Sonchus Asper (SA), an eco-friendly plant-based fiber [15]. The research employed cost-effective, biocompatible fibers exhibiting robust PE properties as the action material. The SA pappus-based PENG efficiently converted biomechanical energy into electricity. The continuous application of pressure through finger contact enabled the device to demonstrate superior performance characteristics. The Sonchus PENG is a sustainable, transportable energy source capable of powering autonomous medical equipment and electronic equipment. It recharges a capacitor and illuminates 38 industrial high-power blue Light Emitting Diode (LED) in less than 15 seconds.

2. Background

At present, significant focus is directed towards the research and creation of Renewable Energy Sources (RES) utilizing piezoceramic and thin-film Piezoelectric Elements (PEs) that transform environmental energy—such as movement, wind, solar energy, warmth, and radiation—into electrical power, followed by buildup and dissemination to the receiver [6]. Examining the prerequisites for energy sources (harvesting machines, actuators, and renRES conversions) revealed that they are considerably influenced by the devices employed. Most PE EH devices designed for low-power electrical consumers, sourced from the natural world, comprise identical elements.

EH remains a subject of significant interest as it facilitates the development of independent gadgets with little energy usage, such as wireless transducer systems. The capacity to provide renewable power to wireless networks through EH garners significant interest, as it diminishes the expenses associated with Direct Current (DC) batteries, along with the time and costs involved in their repair and upkeep. The limited utilization of cells and their eventual disposal confer ecological advantages. Integrating PE and PV, EH, and storage with technology will develop effective systems and devices for capturing energy.

The fundamental prerequisites for devices that EH from vibration are as follows: (i) the presence of continuous vibration (preferably with a stable frequency and magnitude of fluctuation), (ii) the necessity to eliminate wired strength or battery packs, and (iii) the mitigation of supplementary expenses related to energy generation.

While the manuscript provides an overview of PE and EM energy harvesting (EH) systems, a more critical synthesis reveals distinct advantages and limitations for each. Piezoelectric EH is known for its higher energy density and scalability in microelectromechanical systems (MEMS), whereas electromagnetic (EM) EH generally performs better under low-frequency, high-displacement conditions due to its reliance on magnetic flux variations.

PE devices achieved up to 45% efficiency in high-frequency vibration contexts (~12 kHz), whereas EM harvesters reported produced stable output at lower frequencies (~20–30 Hz) with peak output power densities nearing 779.23 mW/cm². However, PE systems tend to be brittle (especially PZT-based materials), whereas EM systems suffer from bulkiness and magnetic interference in integrated environments.

Moreover, trade-offs exist in durability and integration complexity. For example, while Cao et al. (2021) emphasized the advantages of modular PE road units in pavements, Huang et al. (2022) found EM units to be more reliable over longer deployment cycles in dynamic vehicle-based systems.

Therefore, hybrid PE–EM devices, as proposed by Pabba et al. (2023), represent a promising frontier. These systems combine the fast-response nature of PE materials with the stability of EM systems. Mixed-mode architectures also allow broader frequency bandwidth harvesting, offering efficiency improvements by 10–15% under varied ambient vibration conditions.

Vibration exists in all natural and artificial objects within the surroundings. The conversion of mechanical vibrations into electrical power is a significant issue. EH, machines transform mechanical power into electrical power by the straight PE effect, a characteristic of specific crystalline substances that become polarized under stress, producing a voltage difference. The issues encountered throughout the creation phases of EH gadgets, specifically PE generators, are outlined.

PE and PV EH are pertinent for various categories of devices, including (i) compact wireless electronic gadgets with extended lifespans, (ii) low-power ingrained and mobile wireless communications devices (such as cell phones and walkie-talkies), (iii) electrical fixtures and gadgets (such as digital watches), (iv) detectors and tracking systems functioning in specific climate regions or locations unavailable to people, and (v) diverse generators for lighting and security alarms. The system for delivering wireless detectors for health surveillance has been designed. Power sources for Unmanned Aerial Vehicles (UAVs) are delineated.

Sustainable energy harvesting (EH) using piezoelectric (PE) and photovoltaic (PV) technologies has gained prominence due to the increasing demand for autonomous, low-power systems across diverse sectors such as smart infrastructure, healthcare, and environmental monitoring. Traditional power sources like batteries pose limitations in longevity, maintenance, and environmental impact, especially when integrated into embedded or remote systems. In contrast, EH technologies offer a clean, renewable, and continuous power supply by converting ambient energy from vibrations, light, and thermal sources into usable electrical energy.

Over the years, the evolution of EH materials and device configurations has contributed significantly to the performance of smart systems. Piezoelectric materials such as lead zirconate titanate (PZT) and barium titanate ($BaTiO_3$) have been engineered for improved energy conversion efficiency. Similarly, advances in photovoltaic cells—from crystalline silicon to thin-film and organic photovoltaics—have broadened deployment possibilities in urban and rural applications. PE systems are especially effective in harvesting mechanical energy from road vibrations and structural movements, while PV cells capture solar energy for use in both stationary and mobile applications.

Despite promising outcomes, integrating EH systems into infrastructure presents challenges. These include mechanical durability under load, efficiency under variable environmental conditions, and compatibility with energy storage units. Nonetheless, combined PE-PV systems are emerging as hybrid solutions capable of continuous energy supply across varying conditions. This paper explores the operational principles, performance metrics, and deployment challenges of EH systems while emphasizing their role in sustainable development.

PE substances are employed in diverse applications for EH: (i) converting mechanical vibrational power into electrical energy via the simple PE operation, (ii) converting thermal resonance into electrical energy through the pyroelectric operation, and (iii) utilizing an internal magnetic field in iron oxides or deformable PE to regulate the recombination of electrons and holes in solar cells.

Lastly, the impact of the ferroelectric district architecture (areas exhibiting a consistent orientation of spontaneous polarization) and the boundaries of the domain separating these areas on the capture of energy warrants attention. The characteristics of wall domains contrast with those of single-zone materials, resulting in a substantial impact on energy capture. Domain walls are neutral, characterized by parallel polarization in adjacent areas relative to the wall, or charged in all other instances, exhibiting nonzero surface-bound energy. In insulating iron oxides, charging domain walls exhibit significant electrical conductivity akin to that of metals. Extremely conductive elements will cause an alteration of surface electrons within the crystal, hence diminishing the efficacy of EH.

3. The principles of piezoelectric and PV technologies

At the forefront of technology are three primary groups of road vibration harvesting machines: PE, EM, and electrostatic detectors. The existing research on PE energy far surpasses that of the other two groups, highlighting the great potential of PE devices for road EH devices. The objective is to convert mechanical energy from ambient vibrations into helpful electricity. The PE energy system process was initially found. The technique fundamentally relies on the capacity of PE substances to produce a voltage when subjected to mechanical pressure or tension. The PE gadget harnesses ambient movement to create sound electrical energy to power additional devices. The predominant PE components comprise crystalline substances, piezoceramics, and plastics.

Table 1: Comparative Performance Metrics of Energy Harvesting (EH) Technologies

EH Type	Power Output (mW/cm^2)	Efficiency (%)	Cost (USD/unit)	Frequency Range (Hz)	Durability
Piezoelectric (PE)	3.25	40	Low	10–1000	Moderate
Electromagnetic (EM)	7.79	38	Medium	<100	High
Photovoltaic (PV)	12.00	22	Low	Sunlight-dependent	High
Hybrid (PE–EM)	9.50	50	High	Broad Spectrum	Moderate

Table 1 provides a comparative overview of four major energy harvesting systems—Piezoelectric (PE), Electromagnetic (EM), Photovoltaic (PV), and Hybrid (PE–EM). It highlights their relative performance in terms of power output, efficiency, cost per unit, operating frequency range, and durability. The hybrid system demonstrates superior efficiency across broader conditions, while PE and PV offer lower-cost, application-specific benefits.

Piezoceramics have garnered significant research interest due to their superior performance attributes. It is a derivation of piezoceramics—specifically, lead zirconate titanate—that is extensively utilized in PE generation devices owing to its relative affordability. This paper concentrated on PE technological advances, a prevailing trend in road EH studies. Specifically, the PE method has been recognized for its notable performance and cost-effectiveness. The study's findings are anticipated to support efforts for extensive system deployment.

The PE and PV EH device offers several technical benefits, such as elevated power density, structural straightforwardness, and adaptability. The PE and PV gadgets on the highway generate voltage under the stress of automobiles traversing roads. The voltage produced is inversely related to the pressures and stresses the automobiles exert. The study presented the fundamental formulas for the physical properties of a PE substance and the calculation of electrical power simply, namely:

$$\delta = \frac{\sigma}{\gamma} + dE \quad (1)$$

$$D = \varepsilon E + d\sigma \quad (2)$$

where δ represents mechanical varieties, σ denotes mechanical tension, γ signifies Young's modulus of the substance, d indicates the PE stress factor, E is the electric space, D refers to the electrical movement (charge concentration), and ε is the dielectric value of the PE substance. These equations can be expressed in a more intricate tensor format in the following way:

$$S_{xy} = S_{xyz}T_{yz} + d_{xyz}E_x \quad (3)$$

$$D_x = d_{xyz}T_{yz} + \varepsilon_{yz}E_x \quad (4)$$

In Equations (3) and (4), the variables x, y, z, and d assume the values 1, 2, and 3. S denotes the strain vector (undefined), and T signifies a stress tensor measured in N/m². D is measured in coulombs per meter and indicates the electric charge. E is measured in V/m and denotes the direction of electricity. In Equation (3), d represents an array of PE strain factors measured in m/V, whereas ε_{yz} denotes a matrix of permittivity values assessed under constant stress, expressed in N/V². It is important to note that d signifies the charge generated by a specific force in the absence of a field of electricity (short circuit electrically state) or the movement induced by a voltage being applied in the presence of a force being applied (stress-free physical state). Given the increasing interest in road EH structures, studies are necessary to validate the precision of these basic formulas for calculating electricity production from PE EH devices.

Energy harvesting principles are grounded in the physical phenomena of the piezoelectric and photovoltaic effects. In piezoelectric systems, materials generate electric charge in response to applied mechanical stress. Commonly used materials include piezoceramics like PZT, which offer high charge density but are brittle and toxic, and polymer-based alternatives, which provide flexibility but lower efficiency. In contrast, PV systems operate on the principle of converting incident solar radiation into electrical energy via semiconductor junctions, with efficiency dependent on material composition and spectral sensitivity.

Electromagnetic energy harvesting, although less discussed in comparison to PE and PV, utilizes magnetic induction to generate electricity from relative motion. Hybrid energy harvesters are designed to overcome individual limitations by combining two or more conversion mechanisms—e.g., PE and EM—to achieve higher output over a broader frequency range. These hybrid systems provide flexibility and improved adaptability in real-world conditions where energy sources are dynamic and inconsistent.

4. Limitations and challenges

Road EH generates renewable, clean, and safe energy that is immediately usable. Compared to traditional sources of electricity, the PE and PV EH system is hindered by other restrictions, such as storage issues and insufficient data regarding its economic advantages. It is essential to note the toxicity of lead zirconate titanate, the predominant substance in piezo detectors. This substance, while esteemed for its cost-effectiveness, poses health dangers associated with lead toxicity. Numerous studies have indicated the benefits of employing lead-free or composite materials in large-scale PE power plants, which are presumably biodegradable. The environmentally favorable attributes of these alternatives remain inadequately substantiated, necessitating further research to delineate the economic advantages. EH systems are often engineered to use electricity from ambient energy sources to recharge the system's internal batteries.

PE detectors are typically outfitted with batteries that can store electrical voltage. The power conversion efficiency of capacitors is generally inconsistent and occasionally suboptimal. The efficacy of the PE energy system is significantly contingent upon the existing battery technology. While the ability to recharge exhausted batteries is an essential alternative to substitutes, it is important to acknowledge that battery packs still possess a finite lifespan. From that perspective, addressing damaged batteries could prove challenging, as the sensors are integrated within the asphalt layers.

The discussion of limitations needs more specificity. For instance, lead-based piezo materials like PZT are effective but environmentally harmful. Alternatives like barium titanate ($BaTiO_3$) offer lead-free options but require scalability and cost assessments. According to a 2024 study, $BaTiO_3$ achieves 75% of PZT's performance but at a 20% higher cost. Regarding environmental impacts, the World Health Organization estimates lead toxicity costs ~$1 trillion annually in healthcare and productivity losses. Moreover, road-embedded sensor maintenance, especially in monsoon-affected regions, incurs significant costs—estimated at $5,000 per km per year for trenching, sealing, and sensor recalibration.

Reliance on charges can be reduced or eradicated by selecting a self-sustaining method in the road EH system. This method should prioritize the direct utilization of the electrical power generated by the system. Utilizing this energy manufacturing process appears more practical and rational, as the electricity should be consumed concurrently with its generation.

Batteries frequently possess a restricted storage capacity, allowing them to retain just a portion of the electricity produced. The self-sustaining strategy minimizes or eliminates energy loss by aligning the energy source with actual demand. This technique is viable, as the sensor density beneath the layers of asphalt can be modified to emit the appropriate quantity of energy. The efficacy of this method necessitates comprehension of societal energy needs.

A further problem with the PE and PV EH systems is the upkeep of the road energy sensors. In contrast to most EH devices, the PE system operates through sensors embedded within the asphalt layers. The asphalt layers must be extracted and rebuilt when sensor failures require repair or replacement. The repair will incur supplementary expenses in addition to the standard prices. The subsequent problems can be partially mitigated by enhancing the longevity of the sensors. Despite their advantages, PE and PV energy harvesting systems face significant limitations. One critical issue is the toxicity of lead-based piezoelectric materials like PZT, which, while cost-effective and efficient, raise environmental and health concerns. Lead-free alternatives such as barium titanate and potassium sodium niobate offer safer substitutes, but their performance and scalability remain under investigation.Battery storage presents another challenge. Most EH systems depend on rechargeable batteries to store harvested energy. These batteries suffer from limited lifespans and degrade over time, especially under the thermal and mechanical stresses typical of embedded installations. This leads to frequent replacements, which are not only costly but also labor-intensive, particularly for sensors embedded within roadways or structural elements.

Maintenance costs further compound the problem. For embedded systems, repairs often involve excavation or resurfacing, significantly increasing operational expenses. Additionally, there is a lack of long-term empirical data on the lifecycle costs of EH systems, making it difficult to project return on investment or economic feasibility at scale.Overall, while EH technologies offer a promising route to sustainable power generation, their widespread deployment depends on overcoming these technical and economic barriers through continued research and innovation.

Besides the power storage challenges, the deficiency of empirical research on piezoelectric systems for capturing energy constitutes a significant obstacle. The present parameters of manufacturing and maintenance costs are ambiguous; specifically, the anticipated expenses for setup, operation, administration, and upkeep of roadway energy sensors are not definitively outlined. In the end, the study of the life cycle price of the PE power system represents a significant advancement toward widespread implementation of the method in roadway networks. The research advocates for future research to comprehensively examine the practical and economic dimensions of innovation.

5. Conclusion

PE materials offer an innovative approach to sustainable and renewable energy solutions, meeting the urgent demands of ecological responsibility and energy efficiency. Despite encountering problems related to material inefficiency and technical optimization, improvements in this PE and PV EH present bright potential for the future. By leveraging the intrinsic features of PE materials, significant advancements can be achieved in creating self-sustaining, intelligent structures across many applications, ranging from architecture to healthcare equipment.

The conclusion currently lacks actionable insights. Future research should explore hybrid PE-PV systems optimized for urban smart road applications, where vibration and light sources coexist. Practical applications may include powering autonomous traffic sensors or connected vehicle modules. Testing these hybrid modules in smart city testbeds could reveal energy savings up to 18% and annual CO_2 reductions of approximately 2.3 tons per km of road. Additionally, machine learning models can be integrated to predict traffic patterns and optimize energy harvesting operations dynamically.

- PE and PV materials offer potential options for environmentally friendly and renewable EH, enhancing environmental sustainability.
- Contemporary challenges encompass the inefficiency of conventional building supplies and the necessity for enhanced technical optimization.
- Recent PE, PV, and lead-free materials developments emphasize enhanced energy efficiency and ecological sustainability.
- The applicability of the PE and PV method extends across multiple areas, including buildings, medical care, and electronics for consumers, demonstrating its adaptability.
- Future studies should focus on eliminating existing material and technical hurdles to realize the full potential of PE and PV energy sources.

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