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Piezoelectric Energy Harvesting: Properties, Applications, and Evaluation

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Abstract. The advancement of small form-factor electronics, including wearable devices and health monitors, is increasingly constrained by battery limitations. Piezoelectric Energy Harvesters (PEHs) present a groundbreaking solution by converting otherwise wasted mechanical energy into electrical energy. This paper explains the concept of energy harvesting and provides a foundational overview of PEH technology. Fundamental mechanisms of piezoelectric materials are explored with a focus on crystal structures. The significance of various coefficients that characterize these materials is also discussed. Furthermore, three typical PEH structures—cantilever, cymbal, and stack configurations—are analyzed and compared in terms of efficiency, advantages, and limitations. The practical applications of PEHs, including biomedical implants, wearable sensors, and power harvesting systems for infrastructures are explored in detail. Moreover, a brief review of three other electromechanical energy harvesters—electrostatic, electromagnetic, and triboelectric—is included and compared to PEHs with respect to power density. All four approaches are critically evaluated in terms of their merits and limitations. Further, prospects of PEH technology, including possible applications, material advancements, and future research on hybrid energy harvesters are explored.

Keywords: Piezoelectric Energy Harvester, Piezoelectric Materials, Electromechanical Energy Harvesters, MEMS technology, Wearable Electronics, Implantable Devices

1. Introduction

The proliferation of small form-factor electronics, including wearable and portable electronics, has revolutionized the way we interact with our environment. However, the rapid development of these small electronic devices is significantly hindered by a persistent and critical challenge: energy supply [1-3]. Batteries, which power the majority of these devices, suffer from limitations in size, weight, energy density, and performance due to environmental impact [4]. Frequent recharging and eventual disposal of batteries contribute to inconvenience for users and pollution. Moreover, the

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reliance on batteries limits the potential for continuous, long-term operation of these electronic devices, posing a significant barrier to their widespread adoption and effectiveness [2,3]. As a result, though the battery technology is constantly improving, it cannot fully meet the requirements of size and weight for small form-factor electronics. Thus, there is a pressing need for innovative energy solutions that can provide sustainable, reliable, and long-lasting power to meet the demands of modern electronics.

As the search for alternative energy sources intensifies, energy harvesting technology offers a promising solution by obtaining the existing energy that naturally dissipated from ambient power sources during the human activities and cycles of nature [5]. Although the energy harvested from nature, such as wind and solar, is renewable and the process is almost free of pollution, for the purpose of portable electronics, those energy sources are not able to provide a continuous power supply due to their dependence on natural environment and size limitations.

The innovation in material science enables a new type of energy harvester: Piezoelectric Energy Harvester (PEH). By leveraging the inherent properties of piezoelectric materials, PEHs harness mechanical energy from various sources, such as vibrations, movements, and mechanical stresses, to power electronic devices. PEHs can harvest mechanical energy from everyday activities with a high-power density, providing a continuous and sustainable power source for portable electronics. Unlike batteries, PEHs do not require frequent replacement or recharging, and they also have the potential to significantly reduce pollution by minimizing electronic waste.

Recent research on piezoelectric energy harvesters (PEHs) highlights their growing potential in various applications, driven by the need for sustainable energy solutions. PEHs have found significant use in powering small electronic devices, particularly in wearable technology and IoT sensors. Their ability to convert mechanical energy from human movement or environmental vibrations into electrical energy has led to innovations in self-powered systems, such as smartwatches and health monitoring devices. Additionally, PEHs are being integrated into infrastructure monitoring systems, where they harness vibrations from bridges, buildings, and railways to power wireless sensors. This application not only extends the lifespan of sensor networks but also reduces maintenance costs. In automotive industries, PEHs are employed in tire pressure monitoring systems and energy recovery systems in vehicles, contributing to more efficient energy use. Moreover, research is exploring PEHs in biomedical applications, where they could power implantable medical devices, reducing the need for battery replacements. Overall, the versatility of PEHs across diverse fields underscores their importance in the future of energy harvesting technologies [1].

This paper aims to explore the potential of PEHs as a solution to the energy challenges faced by small form-factor electronics. Working mechanisms and operation modes of piezoelectric materials are explained in detail with reference to crystal structures and polarization. An in-depth examination of the basic characteristics and three common structures of PEHs is conducted to demonstrate its merits and drawbacks. The paper focuses on the low-voltage applications of PEHs, specifically self-powered implantable biomedical electronics, and the discussion is extended to high-voltage infrastructure applications.

A comparative analysis is conducted to compare PEHs with other electromechanical energy harvesting systems. Those harvesting systems are introduced, and working mechanisms and applications are briefly described. Then this paper quantitively compared the typical power densities of these energy harvesters and qualitatively discussed their merits and limitations. The findings illustrate the distinctive attributes of PEHs in comparison to their counterparts, substantiating their suitability for the next generation of sustainable and self-powered electronic devices. Lastly, the

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future prospective of PEH is discussed, with suggestions of further improvements to PEH and its material. The concept of one solution, hybrid energy harvester, is introduced to address certain limitations of these electromechanical energy harvesters. Nevertheless, this new technology still needs to overcome the challenges of size and complexity. A summary of future applications and research area is presented to demonstrate various possibilities of PEHs.

2. Piezoelectric energy harvester properties

2.1. Significance of energy harvesting

Energy harvesting technology plays an important role in the advancement of small electronic devices and sustainable development. This technology offers a way to collect otherwise wasted ambient energy and convert those energies into useable forms, thereby reducing dependency on conventional energy systems and promoting greener, self-powered solutions.

Among the various methods of energy harvesting for small electronics, electromechanical systems are widely utilized due to their ability to connect human movements with electrical energy. Among these, in terms of power density, PEH stands out from electrostatic, electromagnetic, and triboelectric harvesters. As calculated by Priya et al, PEH's power density can be three to five times greater than that of their counterparts, making PEHs particularly advantageous [6].

The following paragraphs briefly introduce three other types of electromechanical harvesters with specific attention to their working mechanism, development, and typical applications. Then, these electromechanical harvesters are compared with piezoelectric energy harvesters in terms of their power density, an important metric for energy harvesters.

2.2. Piezoelectric effect mechanism

2.2.1. Background

Piezoelectric materials are integral to many everyday technologies, due to the unique properties that they possess. In gas lighters, the generation of a high-voltage spark that ignites the gas is achieved by striking on piezoelectric crystals. Microphones employ piezoelectric elements to convert sound waves into electrical signals, facilitating audio capture and amplification. Quartz watches rely on the stable vibrations of a piezoelectric quartz crystal to maintain timekeeping with remarkable accuracy. These applications illustrate the versatility of piezoelectric materials. Understanding how piezoelectricity is utilized in our everyday life provides an intuitive foundation for a more in-depth investigation of piezoelectric energy harvesters (PEHs). They convert mechanical energy into electrical energy through three primary steps as Figure 1 shows:

1. Transfer of external excitation to mechanical energy,
2. Conversion of mechanical energy to electrical energy using piezoelectric materials
3. Transfer of electrical energy to an energy storage system via a circuit [6,7].

The most crucial step in PEH systems is the conversion of mechanical energy to electrical energy, known as the piezoelectric effect. This effect was first demonstrated on the natural crystal quartz by French physicists Jacques and Pierre Curie in 1880 [1,8]. Since then, numerous synthetic piezoelectric materials have been developed, including the barium titanate (BTO) family and lead zirconate titanate (PZT). These materials can be poled by applying high temperature and a strong electric field to enhance their piezoelectric effect [7]. Further advancements in material science have

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enabled doping these materials with metallic impurities, optimizing their properties for specific applications [9].

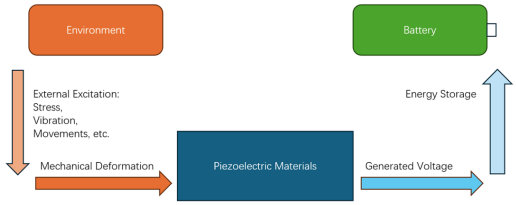

Figure 1. Demonstration of energy transfer process

2.2.2. Piezoelectric effect

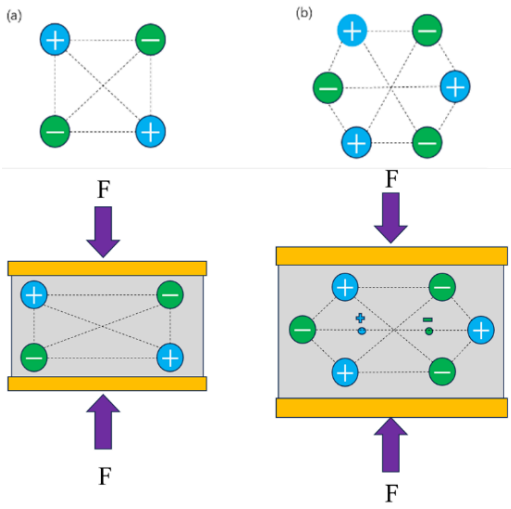

Figure 2. Schematic of 2D crystal structures: (a) Non piezoelectric square (b) Piezoelectric Hexagon

When an external mechanical force is exerted on a piezoelectric material, electrostatic polarization occurs within the crystal structure due to the separation of charges. This phenomenon is deeply rooted in the crystals' structural symmetry. For example, a symmetric square structure is shown in Figure 2(a), when stress is applied to the material, the symmetrical square arrangement of the atoms is not disturbed. As a result, the centers of charges don't separate, and no piezoelectricity is exhibited. However, quartz, a common natural piezoelectric crystal, has a crystal structure consisting of a tetrahedral arrangement of silicon and oxygen atoms, and at a certain 2D cross section, quartz has a hexagon crystal structure made of silicon and oxygen atoms as Figure 2(b) shows [10]. Under mechanical stress, the arrangement of the atoms is disturbed, causing a separation of positive and negative charge centers within the unit cells of the crystal. This separation creates an electric dipole moment, resulting in a potential difference across the material, demonstrating the direct piezoelectric effect [11].

Conversely, when an electric field is applied across a piezoelectric crystal, the positive and negative charge centers are attracted or repelled by the electric field, deforming the crystal. This process of electrical energy converting into mechanical energy is known as the inverse piezoelectric effect [5].

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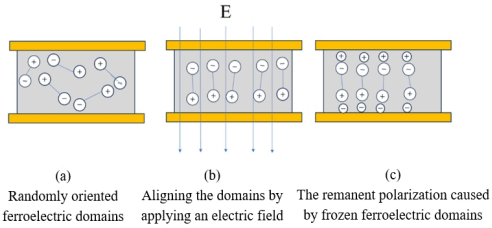

Figure 3. Demonstration of polling process of piezoelectric ceramics

While natural crystals like quartz exhibit piezoelectricity due to their specific crystal structure, synthetic ceramics such as lead zirconate titanate (PZT) need to be poled to impart piezoelectricity due to their perovskite structure [1,12]. PZT, in its raw state, consists of randomly oriented ferroelectric domains, which are regions of uniform polarization, as illustrated in Figure 3(a). These ferroelectric domains create small electric dipoles within the material. Due to this random orientation, the net polarization of the ceramic is approximately zero, meaning that it exhibits very little or no piezoelectric effect in its unpoled state. During the poling process, PZT ceramic is heated to just below its Curie temperature while a strong electric field is applied. This electric field aligns the domains in the direction of the field. This process is demonstrated in Figure 3(b). The high poling temperature allows the domains to reorient more easily because the thermal energy helps them overcome the energy barriers associated with their initial random orientations. However, the poling temperature must be lower than PZT's Curie temperature. At the Curie temperature, the ferroelectric domains become neutral due to changes in PZT's crystal structure, and the material loses its piezoelectricity. As PZT cools while maintaining the electric field, the domains become frozen in their new orientation (Figure 3 (c)), resulting in remanent polarization, where a significant number of domains remain aligned even after the external electric field is removed [5]. After poling, the PZT material exhibits a much stronger piezoelectric effect. The aligned ferroelectric domains now collectively contribute to the material's piezoelectric response, creating a higher potential difference under mechanical stress and increased mechanical deformation under an electric field compared to the raw sample.

2.2.3. Energy conservation in piezoelectric material

Piezoelectricity is a dynamic process, meaning that once the stress on the piezoelectric material is held constant, the PEH system reaches an equilibrium where no further potential difference or current is produced. According to the conservation of energy, energy can neither be created nor destroyed. When piezoelectric energy harvesters are connected to a circuit, mechanical work done by the environment causes deformation of the piezoelectric material and the collection of electrical energy. As the environment stops applying stress, no further work is done, and charges in the circuit respond to the separation of charge in piezoelectric materials leading to an equilibrium. Thus, no more energy is collected.

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2.3. Operation modes

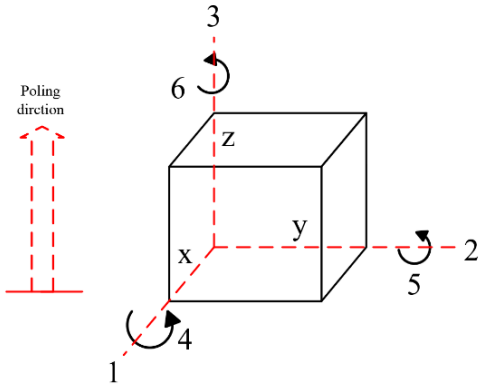

Figure 4. 3D view of a material with labelling on axes for explanation of operation modes [13]

Piezoelectric materials operate in different modes depending on the direction of the applied mechanical stress and the resulting electric potential difference. The notations d33 and d31 stand for piezoelectric charge coefficients of a material working under 33 and 31 modes. This coefficient connects a piezoelectric material's electrical and mechanical behavior. Detailed explanations of this specific coefficient will be provided in the following section.

The numbers represent operation modes defined by the orientation of stress and axis of potential difference relative to material's polarization axis, or poling direction [1]. When mechanical stress is applied to the material, potential differences will generate along with the polarization axis. This potential difference is then used for power harvesting.

As Figure 4 shows, the primary axes that describe the operation modes of piezoelectric materials are labeled 1, 2, and 3, which respectively correspond to the x, y, and z in Cartesian coordinates. When examining a piece of piezoelectric material, its polarization axis is arbitrarily aligned with the z axis, or direction "3." [11,13]

The axis of the material that is perpendicular to the polarization axis is denoted with "1" or "2" direction. Additionally, number 4, 5, and 6 corresponds to shear/rotation along 1, 2, and 3 axes [13]. The notation of piezoelectric material operation modes consists of letter d and two number subscripts. The first number stands for axis of polarization and has values from 1 to 3. The second number stands for axis of applied stress or shear, and hence it has values from 1 to 6. Modes d33 and d31 are the two most used operation modes of the material, and shear mode d14 is less used [11].

In the d33 mode, both the applied mechanical stress and the generated electric field are aligned along the same axis, which is also the direction of the material's polarization. The notation "33" indicates that the stress and electric displacement are parallel with the "3" direction. This mode yields higher voltage output and is often used in stack structure harvesters [1,7].

In the d31 mode, the applied mechanical stress and the generated electric field are perpendicular to each other. Here "3" indicates the axis of polarization and potential difference, and "1" represents the plane of applied stress that is perpendicular to the polarization axis. Since direction "1" and "2" are both in the same plane, direction "1" is often used to represent the plane. The d31 mode has a superior current output, and the mode is widely used in cymbal, unmorphed, and bimorph harvester structures [1,7].

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2.4. Explanation of material characteristics with coefficients

2.4.1. Piezoelectric charge coefficient d

2.4.1.1. Definition

Piezoelectric coefficient is one of the most determinative parameters to the performance of piezoelectric material. It represents the charges density per unit stress applied to the material for direct effect. Conversely, it also illustrates the strain generated under unit electric field for inverse effect [5]. This coefficient indicates the coupling between mechanical and electrical response and directly determines the power density and energy conversion efficiency.

2.4.1.2. Derivation

The derivation starts with two fundamental equations to describe the electrical and mechanical behavior of the piezoelectric material respectively:

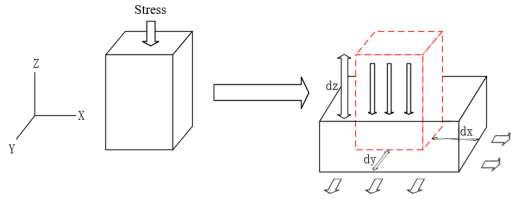

Figure 5. Visualization of 3D deformation under external uniaxial stress

The electrical behavior is explained by the definition of electrical displacement in the field of electrodynamic:

$$D = \varepsilon E \tag{2.4.1}$$

Where D is the electrical displacement, ε is the permittivity, E is the applied electric field strength.

Mechanical behavior is explained by Hooke's Law in 3-dimensional material science. The basic equation, $F = kx$ or $\sigma = Y\epsilon$, describes the relationship between the extension of the material and the isotropic force in one dimension, which is not sufficient for the material in 3D. This is because when stress is applied on the surface of the material, the deformation not only occurs in the direction of the stress, but also the plane that is perpendicular to the stress. This relationship is measured by Poisson's Ratio, the ratio of the transverse strain to the axial strain with a uniaxial stress applied on the material [14]. Figure 5 below visualizes the phenomenon and the generalized Hooke's Law is calculated by 3D tensors in Eq 2.3.2:

$$S = sT \tag{2.4.2}$$

Where S is strain, s is compliance and T is stress. However, due to the complexity of tensor analysis, further explanation of Hooke's Law will not be discussed in this paper, and additional document are provided [15].

The interplay of electrical and mechanical behavior is the key in piezoelectric material analysis. The electrical displacement is caused not only by the electric field but also the stress due to the

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direct piezoelectric effect. The same is true for the mechanical strain due to the inverse piezoelectric effect [16]. Thus, to calculate these quantities comprehensively, piezoelectric coefficient d is introduced to connect electrical and mechanical behaviors:

Direct Effect

$$D = dT + \varepsilon^T E \tag{2.4.3}$$

Inverse Effect

$$S = s^E T + d^t E \tag{2.4.4}$$

Where the upper superscript E refers to the condition under the constant electric field E and upper superscript T refers to condition under the constant stress T. d describes the direct piezoelectric effect and d^t describe the inverse piezoelectric effect [7,17].

2.4.2. Piezoelectric voltage coefficient g

The piezoelectric voltage coefficient is the electric field generated per unit stress, or alternatively the voltage generated per unit strain. This parameter, with the unit of Volt Meter per Newton (Vm/N), indicates the voltage output capability of the material [5,17].

The relationship between the piezoelectric voltage coefficient and piezoelectric charge coefficient is linked by the relative permittivity of the material ε_{ij}.

$$g_{ij} = \frac{d_{ij}}{\varepsilon_{ij}} \tag{2.4.5}$$

The product of piezoelectric charge coefficient and voltage coefficient, the transduction coefficient, is proportional to the output power of the piezoelectric energy harvester. By substituting the relationship between d_{ij} and g_{ij}, a simplified equation can be derived [4]:

$$d_{ij} \times g_{ij} = d_{ij} \times \frac{d_{ij}}{\varepsilon_{ij}^T} = \frac{{d_{ij}}^2}{\varepsilon_{ij}^T} \tag{2.4.6}$$

2.4.3. Electromechanical coupling factor k

The coupling factor k defines the ratio of electrical energy to mechanical energy [5,18].

$$k^2 = \frac{E_e}{E_m} \tag{2.4.7}$$

This equation implies the energy conversion efficiency of PEHs.

2.4.4. Dielectric loss δ

The dielectric loss indicates the heat dissipation when an alternating electric field is applied to a dielectric material. This coefficient represents the energy storing capability of the piezoelectric material with respect to its electrical behavior [19,20].

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$$tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{2.4.8}$$

Where δ is the dielectric loss, ε'' is the imaginary part of the permittivity (associated with energy loss) and ε' is the real part of the permittivity (associated with energy storage) [21]

2.4.5. Mechanical quality factor qm

The mechanical quality factor is defined as the ratio of stored mechanical energy in the system to the mechanical energy loss per cycle, which is the dissipated power. This factor represents the energy storing capability of the piezoelectric material with respect to its mechanical behavior.

$$Q_m = 2\pi f \frac{U_e}{P_d} \tag{2.4.9}$$

Where Q_m is the mechanical quality factor, f is the frequency of the oscillation, U_e is the stored energy and P_d is dissipation power [22].

2.5. Typical equivalent circuits

2.5.1. Butterworth model

The equivalent model for vibrators was first proposed by Butterworth in 1914 and verified by Van Dyke in 1928 through experiments. This model is called Butterworth-Van Dyke (BVD) circuit and still being used nowadays [7, 23, 24]. This model maps the mechanical components, including damper, spring and mass, to the electrical components and form LCR circuit as shown in Figure 6 [20].

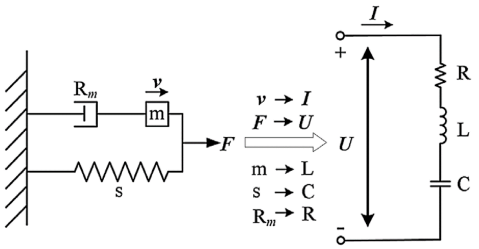

Figure 6. Mapping of mechanical system to Butterworth model of piezoelectric material equivalent circuit [20]

2.5.2. Dielectric model

On the other hand, the piezoelectric material has a working mechanism analogous to that of capacitor, since they both involve high dielectric properties and polarization. In a capacitor, the applied potential difference across the dielectric plates controls the electric charge and electric field, while in a piezoelectric material, the mechanical stress serves the same control function. Capacitor is polarized due to the external electric field to store and release electrical energy. For piezoelectric material, the polarization induced by mechanical stress generates electrical energy from mechanical energy. Thus, the piezoelectric material can be simplified into a variable capacitor with internal impedance with respect to its equivalent circuit [20,23].

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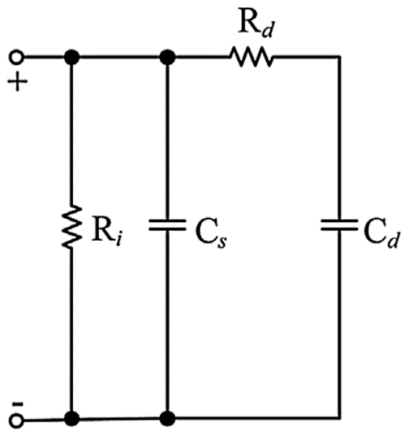

Figure 7. Dielectric model of piezoelectric material equivalent circuit [20]

This approach represents the characteristics of dielectrics when the operating frequency is away from the resonances. As shown in Figure 7, the equivalent circuit consists of two resistors and two capacitors [20]. R_i denotes the insulation resistance, which measures the material's ability to prevent leakage current. C_s represents the geometric capacitance, referring to the capacitance formed by non-polarized dielectric materials situated between the electrodes. C_d and R_d signify the polarization capacitance and the equivalent polarization loss resistance, respectively. These components characterize the capacitance and resistance arising from the dielectric dipole rotation phenomenon [20].

2.6. Common structures of PEH

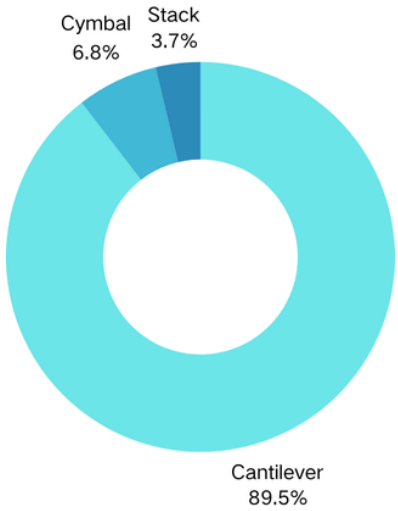

Figure 8. Proportion of research about cantilever, cymbal and stack structures from 2000 to 2016

In previous sections, this paper has provided the knowledge of fundamental mechanism behind the piezoelectric effect. With this knowledge, this paper will continue to explore various structural designs employed to improve the performance and feasibility of piezoelectric materials in energy harvesters. According to research on the number of papers discussing different structures of PEHs, currently researchers focus more on cantilever structures compared to other structures, as shown in Figure 8 [6]. The following table, Table 1, displays a general summary of the three common PEH

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structures, including their general description, advantages, and disadvantages. A more detailed examination of these structures is included in the following section.

Table 1. Summary for three PEH structures

Structure	Description	Advantages	Disadvantages
Cantilever	This structure absorbs energy from a vibration system by inducing dynamic strain in piezoelectric layers	1. Simple structure with low cost 2. lower resonance frequency in bimorph structure 3. High quality factor and adjustable power output through proofing mass 4. Higher power output by changing shapes	1. narrow band of resonance frequency, which limit its power output 2. Can not defense high load due to brittleness of piezoelectric materials
Cymbal	This structure converts the direction of applied stress from perpendicular to the piezoelectric disk to radial direction of the disk	1. greater power output and higher piezoelectric coefficient 2. favorable for micro energy harvesting 3. higher capacity of high load	1. mechanical energy loss due to the end caps deformation limits the efficiency 2. relatively high resonant frequency
Stack	Multiple piezoelectric layers with the same polarization direction are stacked together	1. high load capacity, piezoelectric coefficient, capacitance, electrical power, and power density 2. Can be combined with other PEH structures to improve power output	1. high complexity and stiffness of the piezoelectric material

2.6.1. Cantilever

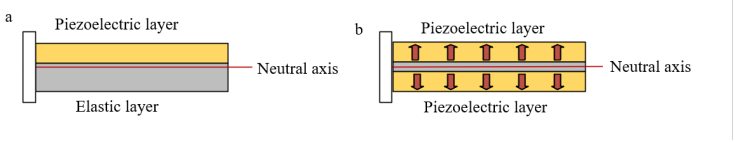

Figure 9. Schematic of cantilever: (a) unimorph (b) bimorph

PEH cantilever structure is a simple harvester structure with low cost. This structure absorbs energy from a vibration system by inducing dynamic strain in piezoelectric layers, resulting in an alternating voltage [1]. This type of structure usually includes two configurations: unimorph and bimorph. Unimorph structure consists of one piezoelectric layer, while bimorph structure has two piezoelectric layers bonded together (Figure 9(a) and (b)).

Compared to unimorph structure, bimorph structure has lower resonance frequency and can harvest power in low frequency applications. Bimorph structure outputs more electrical power with less deformation. However, compared to unimorph, bimorph structure is intrinsically more complex and more costly to produce [2,25,26].

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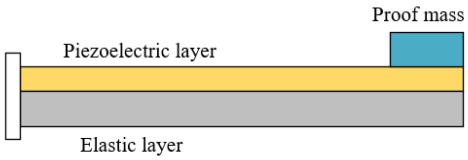

Figure 10. Schematic of a bimorph cantilever structure with proof mass [6]

Generally, cantilever structure has a narrow band of resonance frequency, which limits its power output. To solve this problem, the design of a proof mass on the cantilever structure shown in Figure 10 can provide a flexible resonance frequency by adjusting the inertia effect of the cantilever. This design yields a higher quality factor and power output for practical applications. However, due to the brittleness of piezoelectric material and proof mass, protective equipment is necessary [6,7].

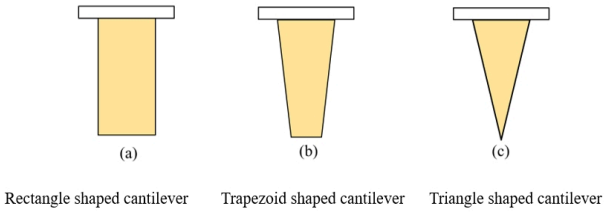

Figure 11. Three different shapes of piezoelectric cantilever vibrators

Additionally, when piezoelectric layers are bent in a cantilever structure, stress concentration effect will occur. This effect means that stress will be concentrated in the fixed end, and there will be almost zero stress in the free end of the cantilever. To further optimize the cantilever structure, changing the shape of cantilever structures into trapezoid or triangle instead of rectangle can improve cantilever PEH's energy conversion efficiency. Experiments underscore that triangular cantilever beams can optimize the strain distribution and provide the highest power output among the three shapes under the same conditions (Figure 11) [27].

2.6.2. Cymbal

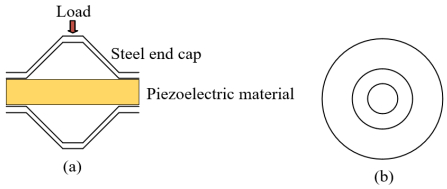

Figure 12. Cymbal structure schematic: (a) cross-section view (b) top view

PEH Cymbal structure consists of two steel end caps which are at the top and bottom of the piezoelectric disk, as shown in Figure 12(a). This structure is able to withstand a higher load compared to cantilever structure. A top view of the cymbal structure is illustrated in Figure 12(b). When the external stress is applied to the end caps, they will convert the direction of applied stress from perpendicular to the piezoelectric disk to radial direction of the disk. This structure has a greater power output and higher piezoelectric coefficient than cantilever structures [1,6,7]. Additionally, the thickness to radius ratio of the metal end caps and the thickness ratio of

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piezoelectric material and substrate are two important parameters that describe the energy harvesting performance of this structure [28].

Cymbal structure is favorable for micro energy harvesting, because the metal end caps will generate a greater in-plane strain under a lateral external force compared to other structures when the volume is limited [8]. However, the mechanical energy loss due to the end caps deformation limits the efficiency of this PEH structure, and the relatively high resonant frequency limits the applications of cymbal structures to high frequency vibration situations [1,2].

2.6.3. Stack

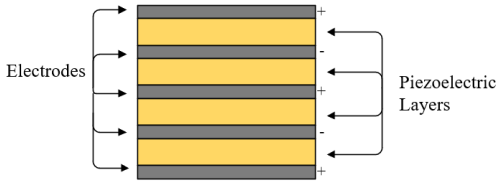

Figure 13. Schematic for stack structure

When multiple piezoelectric layers with the same polarization direction are stacked together, they form a stack structure of energy harvester, as shown in Figure 13 [1,7]. This structure shows advantages in high load capacity, piezoelectric constant, capacitance, electrical power, and power density [6,29]. Additionally, the stacked piezoelectric layers can be connected in series or in parallel. When the layers are connected in series, stack structure exhibits high open circuit voltage, and when connected in parallel, higher electric current can be produced [6]. Further, stack structure can also be combined with other PEH structures such as cantilever and cymbal to improve power output. However, the main disadvantage of the stack structure includes high complexity and stiffness of the piezoelectric material, causing this structure to be relatively fragile and limited in applications [6,7].

3. Other electromechanical energy harvesters

3.1. Introduction to electrostatic, electromagnetic and triboelectric energy harvester

3.1.1. Electrostatic energy harvester

3.1.1.1. Description of working mechanism

The nature of electrostatic energy harvester is a variable capacitor, which consists of two conductive plates and separated by dielectrics. The fundamental property of capacitor is that the width between two plates is proportional to the capacitance. The mechanical vibration of two plates causes the displacement thus the change in capacitance, which leads to the change of voltage if the plates are pre-charged [30]. One of the typical methods of pre-charging is through electret, which contains permanent electrical polarization through charged dielectric materials [31]. A typical implementation and charge-voltage characteristics of electrostatic energy harvester is shown in Figure 14.

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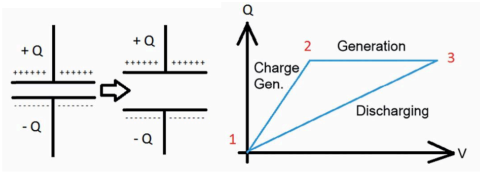

Figure 14. Principle of operation of electrostatic energy harvester and QV characteristics [32]

3.1.1.2. Development and application

The electrostatic energy harvester was originally derived from capacitive systems and now incorporates MEMS technology to integrate with electronics circuits. The significant development of electrostatic energy harvester is its electret material, which allows continuous operation without the need for external charging, enhancing the practicality of these systems. The use of electret material was promoted by West and Sessler in the 1960s, when they discovered the electret-based microphone. The advances of this high voltage material improved its power performance and frequency range of energy harvesting [31].

The application area of this harvester is quite similar to PEH, focusing on powering small electronics devices. However, due to the scalability and sensitivity to low frequency vibration, electrostatic energy harvester is particularly used in MEMS technology and wireless sensor network [33, 34].

3.1.2. Electromagnetic energy harvester

3.1.2.1. Description of working mechanism

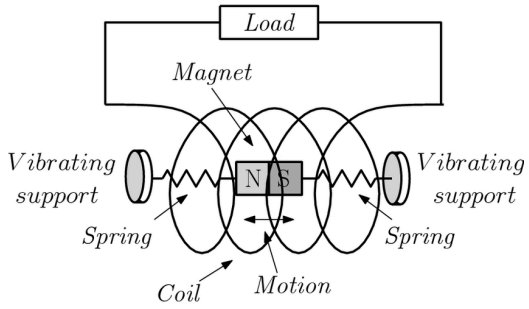

Figure 15. Simple structure of electromagnetic energy harvester [35]

Since early 1930s, close to time when Faraday's Principal breakthrough, the electromagnetic conversion method was used to produce electricity [36]. Electromagnetic harvesters are compelling due to its simple configuration and sound power generation at low frequences conditions. The mechanism is mainly based on Faraday's Law of induction, where magnetic flux is changed when it passes through the closed loop, leading to induction electromotive force generation. According to this law, coil can absorb ambient vibration which result in magnet vibrating align with the axial direction of the coil and provide induced voltage. Given that the load can be connected to closed loop, generating current in the circuit [37,38]. A simple schematic, Figure 15, provides a visual understanding of the mechanism.

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3.1.2.2. Application

Due to the challenges of fabricating micro coils and magnets, electromagnetic energy harvesters are more commonly used in automotive sensors and monitoring systems. The vibration and rotational motion caused by cars can be harvested through tires, and power the tire pressure sensors [39]. A similar approach was widely applied in railroad, where the strong vibration on the rail track generated by passing trains is captured and the energy is used for trackside equipment to monitor and detect any defects or rail wear [40].

3.1.3. Triboelectric energy harvester

3.1.3.1. Introduction of triboelectric energy harvester

Triboelectric effect, based on the process of contact electrification and electrostatic induction, happens when two objects contact or slide against each other [41,42]. The energy originates from the contact between two different materials with different triboelectric polarity, yielding surface charges transfer [42]. Triboelectric harvesters can harvest energy from not only frictions, but also contact between liquid and gas. For example, as water flows through a pipe, triboelectric energy harvesters can collect the electrostatic energy from the contact between water and pipe [41].

It has two basic operation modes which differ in direction of movement: vertical contact-separation mode (CS) and lateral sliding mode (LS) [42,43]. CS mode has higher open-circuit peak-to-peak voltage, and LS mode is used to enhance current output [43]. A simple chart of working principle of a triboelectric energy harvester is shown below by Figure 16.

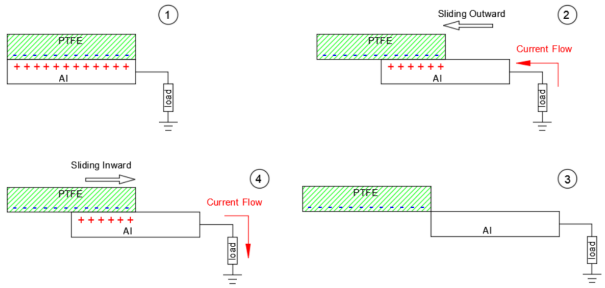

Figure 16. Operation mechanism of triboelectric energy harvester [42]

3.1.3.2. Application of triboelectric energy harvester

Triboelectric effect can be applied in many areas. It is mainly used to collect wasted energy generated from friction. For example, Mao et al. designed a triboelectric device installed on tires of vehicles to harvest the energy of friction between tires and the ground, which accounts for 5% to 7% of all energy consumed when driving, according to the US Department of Energy [42]. Besides, it is also applied into smart agriculture, smart home, various sensors, ocean energy conversion and other fields [42,44].

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4. Comparison

4.1. Metric for electromechanical energy harvester

4.1.1. Power density

4.1.1.1. Definition

Power density and energy conversional energy are the common metrics to access different energy harvesters. For power density, its fundamentally definition is the power harvested per unit area of the energy harvester [45,46]:

$$\rho = \frac{P}{A} \tag{4.1.1}$$

The higher the power density, the smaller the size of the energy harvester is required to produce the same amount of energy.

4.1.1.2. Metric comparison

The power density of piezoelectric, electromagnetic and electrostatic energy harvesters is compared in terms of bandwidth. An analytical derivation is provided by Hu Y et al [47], however, in our paper, we focus on the several representative numerical values to four energy harvesters. Figure 17 below shows a normalized comparison between several materials of the three harvesters and author's own result, which is excluded in our consideration. In the extremely low bandwidth region, the PEH has a higher average power density compared to the other two harvesters. The average power density of electromagnetic harvester is almost same as that of electrostatic harvester [48]. The other plot (Figure 18) gives comparison between PEH and triboelectric energy harvester (TEH). The power density of PEH is 5 to 10 times higher than that of TEH depending on the gap width. The table gives specific data on different examples of PEH and THE. From a broad perspective, the power density range associated with piezoelectric, electromagnetic and electrostatic has been studied and estimated: 0.76 μW cm^{-3} to 5.5 μW cm^{-3}, 190.5 nW to 8.24 μW cm^{-3}, and 4.9 nW cm^{-3} to 42.9 μW cm^{-3} respectively [33]. All these data and figures has proved that PEH has the highest average power density among electromechanical energy harvesters.

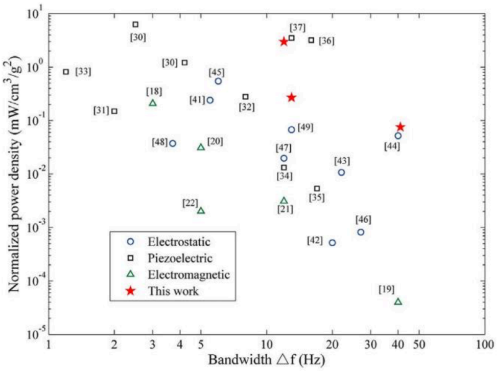

Figure 17. Comparison of energy harvesters regarding to the normalized power density and bandwidth [49]

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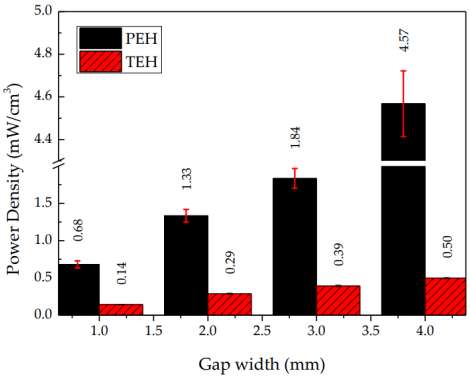

Figure 18. Comparison between piezoelectric and triboelectric energy harvesters in terms of their power density and operating bandwidth [50]

4.1.2. Energy conversion efficiency

For energy conversional efficiency, it is the ratio of converted useful energy divided by the total energy input [51]. An increase in energy conversion efficiency results in a reduction in the amount of energy lost as heat.

$$\eta = \frac{E_{load}}{E_{total}} \tag{4.1.2}$$

However, all energy harvesters obtain a wide range of efficiency depending on specific design optimizations and application environments. There are many factors that determine the overall energy conversion efficiency of the harvester, such as vibration frequency, device scale, material, etc. It is not a reasonable proposition to undertake an objective assessment of the relative efficiency of these energy harvesters without first specifying the intended applications. Thus, the paper will not expand the comparison of energy conversion efficiency with respect to four electromechanical energy harvesters.

4.2. Comparative analysis of energy harvesting technologies

Table 2. Advantages and disadvantages of piezoelectric, electromagnetic, electrostatic and triboelectric energy harvesters [33, 50]

	Advantages	Disadvantages
Common Characteristics	1. High Voltage Outputs: All harvesters can produce high voltage, useful for powering small electronic devices. 2. Environmental-Friendly: These harvesters offer a sustainable alternative to batteries, reducing environmental impact. 3. Versatility Across Applications: These harvesters can be adaptable to a wide range of environments, from wearable technology to industrial machinery.	1. Dependency on Vibration: All these systems require continuous mechanical vibrations to generate energy, limiting their use to specific environments. 2. Sensitivity to Environmental Factors: Their performance can be affected by environmental conditions such as temperature and humidity. 3. Low Power Output: These harvesters generally produce low power, which may not be enough for high-energy applications.

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Table 2. (continued)

Piezoelectric	1. High Energy Density: Capable of converting a high amount of mechanical energy into electrical energy. 2. Ease of Voltage Rectification: High output voltage facilitates easy rectification for use in electronic circuits. 3. Low Internal Resistance: This characteristic allows small-scale electronic device applications.	1. Brittle Material: Piezoelectric materials are often brittle, making them vulnerable to damage in high-impact or high-vibration environments. 2. Self-Discharge at Low Frequencies: They tend to lose charge when operated at low frequencies, reducing efficiency in such conditions. 3. Limited Bandwidth: PEHs are less effective in environments with varying or wideband frequency vibrations as they are often tuned to specific resonant frequencies to fit certain application.
Electromagnetic	1. No Need for Mechanical Contacts Between Parts: Reduces wear and tear, leading to lower maintenance and longer life. 2. High Current Output: Generates a significant amount of current due to low internal resistance. 3. Robust Design: Electromagnetic harvesters are durable and capable of withstanding harsh conditions, making them suitable for long-term use.	1. Low Efficiency at Micro Scale: They are difficult to fabricate at the micro-scale, and efficiency drops significantly when miniaturized. 2. Ohmic Losses in Coils: These losses can reduce overall efficiency, particularly in applications requiring high resistance. 3. Low Voltage Output: Typically produces low voltage, necessitating specialized rectification circuits to convert the output into usable power.
Electrostatic	1. Miniaturization Capabilities: Ideal for integration into MEMS technology, making them highly suitable for small-scale applications. 2. Low Maintenance: Due to their simple structure, they have a long-life span with minimal maintenance. 3. High Electrical Damping: This allows for better energy conversion efficiency, especially in environments with steady vibrations.	1. Requires External Power Source to Initiate: Needs an initial charge or external voltage source to start energy harvesting. 2. Dielectric Breakdown: The risk of dielectric material breaking down under high voltage, leading to potential failure. 3. Low Capacitance: This limits the amount of energy that can be stored and converted, reducing overall efficiency.
Triboelectric	1. Simple Construction: The straightforward design of triboelectric harvesters makes them easy and cost-effective to fabricate. 2. Scalable for Various Applications: They can be easily scaled down or up, depending on the specific energy harvesting needs. 3. Low Cost: Materials and fabrication processes are generally inexpensive compared to other types of energy harvesters.	1. High Internal Resistance: This limits the current output and overall power, making them less efficient in some applications. 2. Environmental Sensitivity: Their output can be significantly affected by environmental factors such as humidity, temperature, and surface contamination. 3. Low Power Density: Typically harvests less energy compared to other technologies, which might not be sufficient for high-energy demands.

The above table summarizes and compares the advantages and disadvantages of piezoelectric, electromagnetic, electrostatic, and triboelectric energy harvesters, highlighting that under varying conditions and restrictions regarding application, different types of electromagnetic energy harvesters should be considered.

5. Applications

Having explored the fundamental structures of piezoelectric energy harvesters and their adaptation to various mechanical inputs, the next section delves into the practical applications of PEHs. By examining how these structures are employed in real-world scenarios, this section highlights the

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versatility and effectiveness of PEHs across diverse fields. Specific applications in wearable technology, biomedical implants, and infrastructure are discussed. A detailed examination of those applications in working mechanism, device structure, and power output is provided, demonstrating the broad potential of PEH systems to provide sustainable and efficient power solutions in these critical areas.

5.1. Low voltage applications

5.1.1. Wearable devices

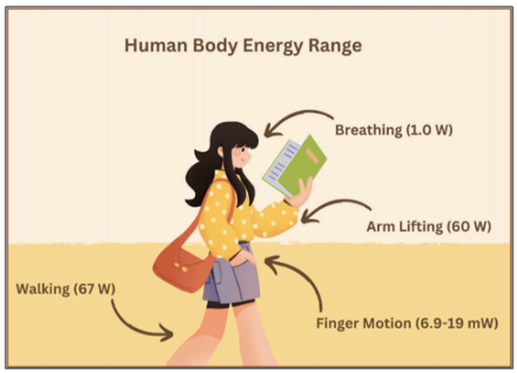

Figure 19. Human body energy range [52]

The main energy source of PEH for wearable devices is human body movement, including arm lifting, walking, breathing etc. The collectable power range of movement is illustrated in Figure 19 [52].

One way to harvest such energy from the human body is through a belt-integrated PEH. This device is designed by Mustafa İlker Beyaz & Naveed Ahmed, aiming to charge batteries of wearable devices by leveraging waist movements during breathing and walking. The belt energy harvester mainly consists of piezoelectric components, a rectifying circuit, and a battery.

Illustrated in Figure 20, the piezoelectric components are integrated on the inner side, while the circuits and batteries are on the outer side. As shown in Figure 21(a), the piezoelectric component of this device is made by combining a piezoelectric layer on top of a metal disk. Due to the constraints of a belt, the radius of the piezoelectric material is limited to be 27 mm, and its thickness is limited to 200μm. The material used is PZT-5J with a piezoelectric coefficient at 550pC/N operating at d33 mode.



Figure 20. Piezoelectric belt simple schematic [53]

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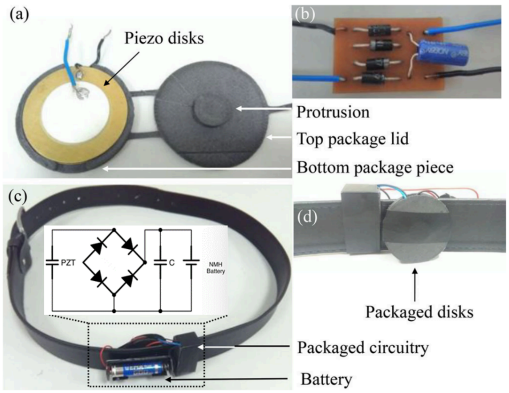

Figure 21. Prototype and detailed schematic of piezoelectric belt [53]

As illustrated on the schematic in Figure 21(c), a full bridge rectifier is used to convert AC inputs of the piezoelectric material to DC voltage output, and a capacitor is used to smooth out the peaks in the output. Figure 21(b) shows how circuit components are integrated. An overview of the packaged circuit, battery, and piezoelectric components is shown in Figure 21(c) and 21(d).

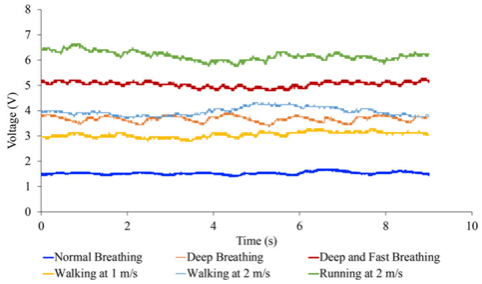

Figure 22. Graph of generated voltage against time under different conditions [53]

Experiments of the prototype belt energy harvester are conducted, and a graph of generated open circuit voltage against time is plotted as in Figure 22. Despite that a rectifier is added to the circuit, the voltage output fluctuates, since the amplitude of the raw AC output is unstable due to the nature of human movements. This fluctuation in output voltage could present a serious problem for certain electronics.

Further, this belt is then used to power an on-skin temperature sensor. The blue curve in Figure 23 shows that when energy harvester is disconnected from the circuit, the battery voltage drops due to the power draw of the sensor from the battery. However, when the energy harvester is connected to the circuit, the battery voltage is stable with a negligible voltage drop. This experiment effectively demonstrates the benefits of energy harvesting. With current technology, the unoptimized prototype energy harvesting belt is able to support the continuous operation of an on-skin sensor. With further development in piezoelectric energy harvesters, it is very promising that PEH will become a crucial part of our wearable electronics industry.

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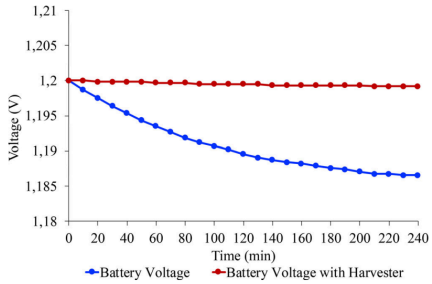

Figure 23. Graph of voltage of the battery when the belt is powering a sensor [53]

5.1.2. Implantable devices

Compared to wearable devices, powering implantable devices is a more challenging problem [2]. Size and weight of PEH systems must be limited to minimize burden on human body. The strict conditions require more effort in making small but efficient PEHs. However, solving this difficult engineering problem comes with great rewards. The lifespan of biomedical implants could be extended, leading to less demand for surgeries to replace/recharge the batteries and less risk for the patient [54]. One popular application of implantable PEH is powering cardiac pacemakers.

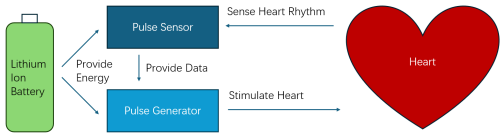

Figure 24. Simplified schematic of current pacemaker models

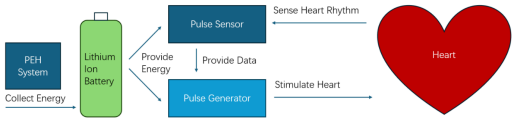

Figure 25. Simplified schematic of new pacemaker models

Currently, pacemakers utilize a fully charged, non-rechargeable battery to supply electrical pulses to the heart. A simplified schematic of current pacemakers is shown in Figure 24. The battery powers pulse generator and sensor. The sensor detects heart rhythm and provides data for the generator. Then, when needed, the pulse generator delivers pulses through wires and electrodes to the heart [55].

In contrast, the new generation pacemakers make use of a piezoelectric energy harvesting system and a rechargeable battery. As Figure 25 demonstrates, the PEH system collects energy from muscle movements to recharge the battery and power the pacemaker.

These types of new cardiac pacemakers adopt a flexible piezoelectric material called “PMN-PT” [55]. This novel piezoelectric material has high dielectric permittivity and piezoelectric coefficient. These characteristics of the material make it suitable for stack configuration in energy harvesters, enabling the PEH systems to have a high power output and density [55]. The following figure, Figure 26, explains the fabrication and structure of the piezoelectric energy harvester with PMN-PT material.

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The deposited Au bottom electrode PMN-PT plate is completely bonded to the silicon wafer by means of an epoxy resin binder. Then put it under electric fields to achieve polarization.

The top piezoelectric portion of the PMN-PT metal-insulator-metal (MIM) layer was stripped from the silicon substrate using an electroplated stretch Ni stressor using a mechanical stripping process.

The free-standing thin PMN-PT film on a thin plastic substrate provides enough flexibility to achieve conformal contact on the curved subcutaneous layer and on the corrugated organs of the human body to collect energy effectively under slight mechanical movements.

Finally, two electrodes are installed on the surface of the heart, capturing and converting the mechanical energy through vibration into electricity [54].

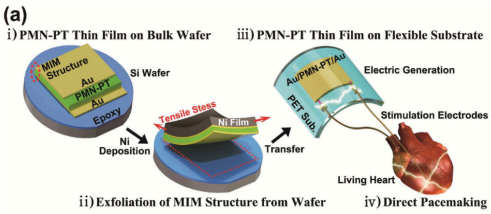

Figure 26. Fabrication process and structure of a PMN-PT energy harvester used for pacemaker [54]

In surgeries, energy harvester should be placed on the heart's left ventricle at an angle for PEH's best performance. This choice of placement is due to the thickness of the muscle at the location and the large surface area in contact. With this configuration, PMN-PT based PEH system is able to fully power a pacemaker [54]. According to tests and theoretical simulations of FlexPacer, a pacemaker model with integrated PEH system, when considering a 10% loss in the battery, the PEH system in FlexPacer is able to keep an output of 15.8w per year. Furthermore, FlexPacer only needs 0.081w per year to maintain its operation [55]. This demonstrates that the PEH system is able to harvest energy enough for sustained operation for 20 years with only less than two months of heart activity, providing solid evidence for the claim that PEH systems have a great potential in solving challenges posed by batteries in current implantable devices.

5.2. High voltage

5.2.1. Piezoelectric roadway

Previous sections explain how piezoelectric energy harvesters' unique characteristics, especially their high power density, make them suitable for solving energy problems caused by battery limitations in small form-factor electronics. However, applications of PEH systems are not limited to only these types of devices. PEHs can also be integrated into infrastructure designs. PEH systems in this area are often used to collect mechanical energy, usually in the form of vibration and stress, induced by large scale human activity, such as people walking on pedestrians, cars/trucks driving on the roadway, trains traveling on the railway, etc. [1].

Piezoelectric roadway, or smart road, is the current focus of PEH system infrastructure research, and in certain areas, piezoelectric roadways are under experiment investigations and road tests [56,57]. On a typical highway, heavy weight vehicles cause vibration and exert stress on the asphalt as they pass. Mechanical energy in these forms is often ignored. However, PEH is able to collect these otherwise wasted energy by implementing the system underneath the road surface, and then use them to power road infrastructures, including road lights, sensors, weighting stations, etc [1,56].

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To integrate piezoelectric energy harvesters into roadways, two engineering challenges must be addressed. First, a PEH unit needs to be developed to effectively withstand potential high loads on the roadways. Specific structures are required to effectively collect the energy. Second, stacked piezoelectric materials need to be protected from withstanding stress on their sides, because if stress is applied along the unexpected direction, piezoelectric materials could shatter due to their brittleness, especially when stacked. Further, integrated with roadways, PEH systems need to be shielded from environmental factors, since piezoelectric roadways are required to function even with the worst weather [57].

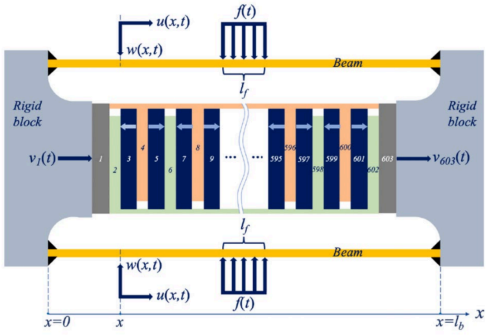

Figure 27. Schematic of roadway piezoelectric energy harvester [57]

Figure 27 shows the schematic of one PEH unit design. It features a stacked PZT material working in d33 mode, sandwiched between two metal blocks. Two elastic beams on the top and bottom connect the two metal blocks. The notation $f(t)$ stands for the direction of applied stress, and $v_n(t)$ shows the direction of road traffic. When vehicles drive over the energy harvesting unit, it is assumed that the wheels exert a triangular compressional force on the piezoelectric energy harvester (PEH). This force acts over the time it takes for the vehicle to pass over the PEH, with the peak force being influenced by both the vehicle's weight and the dynamic response of its suspension system [57].

Furthermore, several PEH units are connected in parallel electrically and contained in a holding tower structure. This structure is named piezoelectric energy harvesting tower (PEHT). A PEHT structure protects the PEH units within from mechanical damage, water, dust, and gravel, making the PEH system more robust when encountering harsh roadway environments [57]. Then, many PEHT structures are implemented in road tests with a configuration shown in Figure 28. The towers are placed on the ground base of the road, along the direction of vehicle traffic, labelled by Row 1, Row 2, and Row 3 PEH towers. This configuration ensures that the mechanical energy from the vehicles is collected as much as possible, and the traffic interruption is minimized [57]. Experimental data shows that, as a Nissan Altima drives pass the PEH system at a speed of 40 km/h, each PEH module is activated twice, by the front and rear wheels. The open circuit energy collected by the system is 20.29J, and the maximum open circuit voltage observed was 484V. These results demonstrate the potential of piezoelectric roadway systems to effectively capture and convert mechanical energy from vehicular movement into usable electrical power, paving the way for sustainable infrastructure solutions.

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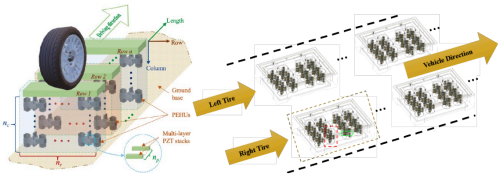

Figure 28. PEH system road test layout [57]

6. Prospects

6.1. Improvement on piezoelectric material

6.1.1. Material

The extensive variety of piezoelectric materials, including nanostructured materials, polymers, polymer nanocomposites, and piezoelectric films, represents the significant advancements made over the decades [11]. Nanostructured materials such as PMN-PT NWs and BaTiO3 are highlighted for their high piezoelectric coefficient. Polymers and nanocomposites have the unique advantages of flexibility, stability, and biocompatibility. The thinness and high sensitivity of piezoelectric films make it suitable for micro-scale electronic devices. Figure 29 compares various piezoelectric materials in terms of their piezoelectric coefficient. To meet the requirements of future applications, d_{33} needs to exceed 600 pC/N. Other challenges to the conventional piezoelectric materials include their rigidity, brittleness and toxicity, driving the development of Pb-free ceramics and flexible polymers as alternative materials.

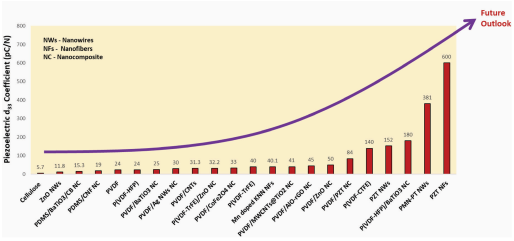

Figure 29. The piezoelectric charge coefficient d_{33} of continuously evolving piezoelectric material [11]

6.1.2. Solutions to current challenges

1. Relying on the transverse mode restricts the efficiency of piezoelectric energy harvesters. It is possible to enhance their energy harvesting capabilities by designing these devices to operate in multiple modes. This can be achieved by transmitting compressive loads through simultaneous compression, shear, and bending.

2. To address the suboptimal power density of piezoelectric materials, it is possible to activate multiple dormant piezoelectric modes by adjusting the poling direction. This can be achieved through modified electrode configurations or by cutting the material at specific angles, thereby enhancing the overall power output.

3. The adoption of innovative materials, including piezoelectric-polymer composites and auxetic structures, can enhance both flexibility and energy performance, compared to traditional piezoelectric materials. This innovation expands the suitability of these materials for a broader range of applications [58].

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6.2. Hybrid energy harvester

6.2.1. Description

A hybrid energy harvester (HEH) is a system that integrates multiple energy conversion techniques. This approach may be either a single system that integrates with various energy harvesting systems, or a combination of multiple energy harvesting sources. With a concentration on electromechanical conversion, the combination of piezoelectric, electrostatic, electromagnetic, and triboelectric materials has been investigated and developed for specific applications. The advantages of a hybrid system have been demonstrated in several instances, including an increase in power density, efficiency, bandwidth, reliability, and a reduction in environmental dependency [31].

6.2.2. Example

A HEH commonly includes two systems due to the significant growth of complexity. An example to demonstrate the merits of HEH compared to a single system is provided below. A piezoelectric and electromagnetic systems based HSH operating at a low frequency has been developed by Zhang et al. As illustrated in Figure 30, the harvester comprises a double-sided piezoelectric trapezoidal beam, which supports three printed planar coils that are enclosed in a proof mass and magnet. As previously discussed in section 2.6.1 Cantilever, the trapezoidal beam is capable of generating a more uniform strain than the conventional rectangular beam in PEH. Consequently, this HEH can produce 637 μW power under the condition of 0.2 g base excitation. This value represents an overall increase of 52.4% in comparison to the power produced by a single piezoelectric or electromagnetic energy harvester [40].

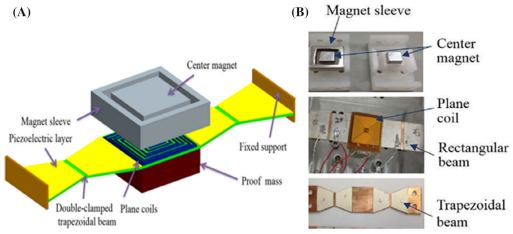

Figure 30. A hybrid energy harvester consists of piezoelectric and electromagnetic systems [40]

6.2.3. Challenges

Nevertheless, despite the hybrid system's capacity to supplant the battery more efficiently, its compactness regarding miniature electronic components, particularly those based on MEMS and nanotechnology, remains suboptimal. First, this is because the integration of two harvesting systems unavoidably increases the complexity, volume and mass of the whole harvester. As the power source of sensors and actuators, the increase of size results in an issue in the assembly of implantable or nano devices. Second, multiple energy conversion process requires more sophisticated design of power conditioning circuit and rectifier, to effectively combine two outputs without the loss of stability and dropdown of voltage [40].

6.3. Future applications and research area

In the field of biomedical devices, the category of PEH applications generally includes biosensors, human body energy harvesting, tissue regeneration, cell stimulation, implantable devices, as shown

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in Figure 31. The bio-MEMS health monitoring systems have been achieved and future research will potentially explore the possibility of PEH in cancer cell therapy, cell therapeutics and soft surgical robots. In order to realize these applications, the advantages of three types of PEH materials, mentioned in section 6.1.1 Material, must be combined, which include high power density, minimized size, high sensitivity, flexibility, long-term stability, biodegradability and biocompatibility [11].

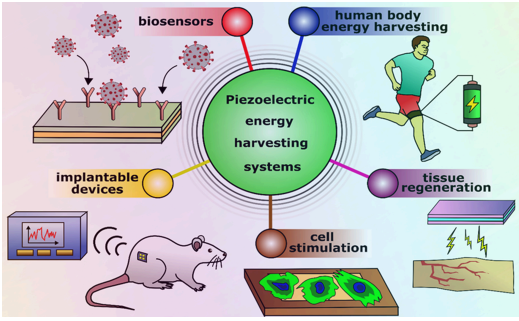

Figure 31. Category of PEH applications in biomedical devices [59]

Piezoelectric technology has a wide range of applications beyond the biomedical field, including the harvesting of acoustic energy and the powering of wireless sensors, Internet of Things (IoT) systems, environmental monitoring, and intelligent transportation [11]. In these fields, fewer restrictions are typically considered in comparison to those that apply to biomedical devices. The cost-effeteness and electrical outputs of PEH represent a significant criterion for future implementation. In addition to generating energy, piezoelectric modules can be utilized for data collection in commercial and industrial indoor spaces, tracking metrics such as the number of visitors, their movement patterns, and the duration of occupancy in specific areas, thereby optimizing the usage of other appliances [58].

The form of mechanical energy is not limited to vibrations in human activities; it can also be found in nature. In contrast to wind or hydro energy generators, which rely on electrical motors, the potential and kinetic energy of wind [60], water current, and wave motion [61] can be captured by piezoelectric material through various configurations. The predictable and reliable behavior of the oceans can drive PEH to power the Internet of Underwater Things, sensors, and other monitoring devices in oceans [61].

7. Conclusion

This paper has investigated the potential of piezoelectric energy harvesters (PEHs) as a viable solution to the energy challenges faced by small form-factor electronics. PEHs transform mechanical energy from ambient source into electrical energy, providing a continuous and sustainable power supply that mitigates the reliance for frequent battery replacements. This paper provides a comprehensive overview of piezoelectric materials' working mechanisms, providing a foundation for understanding PEH systems. The analysis of different PEH structures, including cantilever, cymbal, and stack configurations, reveals how raw materials are integrated into specific device applications. Additionally, strengths and limitations of each structure design are explored. Specific applications including belt integrated PEH system for wearable devices, implantable PEH systems for heart peacemakers, and PEH systems in road infrastructure are investigated with respect to mechanism, structure, and power output. These applications illustrate that, in the field of portable electronics, PEH systems are able to reduce the reliance on batteries or replace them completely and

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are even able to serve as part of our infrastructure and national grid. These applications demonstrate that PEH systems are versatile, efficient, and sustainable energy solutions.

Subsequently, a comparative analysis of piezoelectric energy harvesting systems with other electromechanical energy harvesters, including electrostatic, electromagnetic, and triboelectric harvesters, reveals that while each technology possesses distinctive advantages and limitations, piezoelectric energy harvesters (PEHs) exhibit superior performance in terms of power density. The findings indicate that piezoelectric energy harvesters have the potential to become a significant contributor to future applications, particularly in scenarios where compactness and reliability are essential. It is anticipated that the technological advancements in material and hybrid systems will facilitate PEH use in sophisticated applications across a diverse range of domains. The future objective is to enhance the cost-effectiveness, power density, miniaturization, compatibility and long-term stability of PEH.

In conclusion, the development and optimization of PEHs represent a crucial step towards achieving more sustainable and self-powered electronic devices, addressing the growing demand for energy-efficient solutions in a world that is increasingly reliant on portable electronics.

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Jiuyi Liu and Jialiang Chang contributed equally to this work and should be considered co-first authors.

References

[1] N. Sezer and M. Koç, “A comprehensive review on the state-of-the-art of piezoelectric energy harvesting, ” Nano Energy, vol. 80, no. 105567, p. 105567, Feb. 2021, doi: https: //doi.org/10.1016/j.nanoen.2020.105567.

[2] H. Zhou et al., “Stretchable piezoelectric energy harvesters and self-powered sensors for wearable and implantable devices, ” Biosensors and Bioelectronics, vol. 168, p. 112569, Nov. 2020, doi: https: //doi.org/10.1016/j.bios.2020.112569.

[3] M. Carminati, “Trends and paradigms in the development of miniaturized sensors for environmental monitoring, ” Mar. 2018, doi: https: //doi.org/10.1109/ee1.2018.8385259.

[4] Y. Liang et al., “A review of rechargeable batteries for portable electronic devices, ” InfoMat, vol. 1, no. 1, pp. 6–32, Mar. 2019, doi: https: //doi.org/10.1002/inf2.12000.

[5] E. L. Pradeesh, S. Udhayakumar, M. G. Vasundhara, and G. K. Kalavathi, “A review on piezoelectric energy harvesting, ” Microsystem Technologies, vol. 28, no. 8, pp. 1797–1830, Jun. 2022, doi: https: //doi.org/10.1007/s00542-022-05334-4.

[6] L. Li, J. Xu, J. Liu, and F. Gao, “Recent progress on piezoelectric energy harvesting: structures and materials, ” Advanced Composites and Hybrid Materials, vol. 1, no. 3, pp. 478–505, Aug. 2018, doi: https: //doi.org/10.1007/s42114-018-0046-1.

[7] C. Covaci and A. Gontean, “Piezoelectric Energy Harvesting Solutions: A Review, ” Sensors, vol. 20, no. 12, p. 3512, Jun. 2020, doi: https: //doi.org/10.3390/s20123512.

[8] K. Uchino, “The development of piezoelectric materials and the new perspective, ” ResearchGate, Dec. 31, 2010. https: //www.researchgate.net/publication/284511126_The_development_of_piezoelectric_materials_and_the_new_perspective (accessed Aug. 01, 2024).

[9] “History of Piezoelectricity, ” PIEZO.COM. https: //piezo.com/pages/history-of-piezoelectricity

[10] J. Götze, Y. Pan, and A. Müller, “Mineralogy and mineral chemistry of quartz: A review, ” Mineralogical Magazine, vol. 85, no. 5, pp. 639–664, Oct. 2021, doi: https: //doi.org/10.1180/mgm.2021.72.

[11] S. D. Mahapatra et al., “Piezoelectric Materials for Energy Harvesting and Sensing Applications: Roadmap for Future Smart Materials, ” Advanced Science, vol. 8, no. 17, p. 2100864, Jul. 2021, doi: https: //doi.org/10.1002/advs.202100864.

DOI: 10.54254/2755-2721/2025.29454

[12] S. Priya et al., “A Review on Piezoelectric Energy Harvesting: Materials, Methods, and Circuits, ” Energy Harvesting and Systems, vol. 4, no. 1, pp. 3–39, Aug. 2019, doi: https: //doi.org/10.1515/ehs-2016-0028.
[13] Z. Wang, S. Liu, Z. Yang, and S. Dong, “Perspective on Development of Piezoelectric Micro-Power Generators, ” Nanoenergy advances, vol. 3, no. 2, pp. 73–100, Apr. 2023, doi: https: //doi.org/10.3390/nanoenergyadv3020005.
[14] A. N. Norris, “Poisson’s ratio in cubic materials, ” Proceedings of the Royal Society A Mathematical Physical and Engineering Sciences, vol. 462, no. 2075, pp. 3385–3405, May 2006, doi: https: //doi.org/10.1098/rspa.2006.1726.
[15] J. Rychlewski, “On Hooke’s law, ” Journal of Applied Mathematics and Mechanics, vol. 48, no. 3, pp. 303–314, Jan. 1984, doi: https: //doi.org/10.1016/0021-8928(84)90137-0.
[16] A. Sharma, Mohd. Z. Ansari, and C. Cho, “Ultrasensitive flexible wearable pressure/strain sensors: Parameters, materials, mechanisms and applications, ” Sensors and Actuators A: Physical, vol. 347, p. 113934, Nov. 2022, doi: https: //doi.org/10.1016/j.sna.2022.113934.
[17] X. Pan, Y. Wu, Y. Wang, G. Zhou, and H. Cai, “Mechanical energy harvesting based on the piezoelectric materials: Recent advances and future perspectives, ” Chemical Engineering Journal, vol. 497, p. 154249, Oct. 2024, doi: https: //doi.org/10.1016/j.cej.2024.154249.
[18] S. H. Chang, N.N. Rogacheva, and C. C. Chou, “Analysis of methods for determining electromechanical coupling coefficients of piezoelectric elements, ” IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control, vol. 42, no. 4, pp. 630–640, Jul. 1995, doi: https: //doi.org/10.1109/58.393106.
[19] A. Morel, G. Pillonnet, Y. Wanderoild, and A. Badel, “Dielectric Losses Considerations for Piezoelectric Energy Harvesting, ” Journal of Low Power Electronics, vol. 14, no. 2, pp. 244–254, Jun. 2018, doi: https: //doi.org/10.1166/jolpe.2018.1562.
[20] T. Yang, Y. Zhu, S. Li, D. An, M. Yang, and W. Cao, “Dielectric loss and thermal effect in high power piezoelectric systems, ” Sensors and Actuators A: Physical, vol. 303, pp. 111724–111724, Mar. 2020, doi: https: //doi.org/10.1016/j.sna.2019.111724.
[21] J. Liang, H. Shu-Hung Chung, and W.-H. Liao, “Dielectric loss against piezoelectric power harvesting, ” Smart Materials and Structures, vol. 23, no. 9, p. 092001, Jul. 2014, doi: https: //doi.org/10.1088/0964-1726/23/9/092001.
[22] H.N. Shekhani and K. Uchino, “Evaluation of the mechanical quality factor under high power conditions in piezoelectric ceramics from electrical power, ” Journal of the European Ceramic Society, vol. 35, no. 2, pp. 541–544, Feb. 2015, doi: https: //doi.org/10.1016/j.jeurceramsoc.2014.08.038.
[23] I. C. Lien and Y. C. Shu, “Array of piezoelectric energy harvesting by the equivalent impedance approach, ” Smart Materials and Structures, vol. 21, no. 8, p. 082001, Jul. 2012, doi: https: //doi.org/10.1088/0964-1726/21/8/082001.
[24] A. Ballato, “Modeling piezoelectric and piezomagnetic devices and structures via equivalent networks, ” IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control, vol. 48, no. 5, pp. 1189–1240, Sep. 2001, doi: https: //doi.org/10.1109/58.949732.
[25] S. Mishra, Lakshmi Unnikrishnan, Sanjay Kumar Nayak, and S. Mohanty, “Advances in Piezoelectric Polymer Composites for Energy Harvesting Applications: A Systematic Review, ” Macromolecular Materials and Engineering, vol. 304, no. 1, Nov. 2018, doi: https: //doi.org/10.1002/mame.201800463.
[26] E. S. Leland and P. K. Wright, “Resonance tuning of piezoelectric vibration energy scavenging generators using compressive axial preload, ” Smart Materials and Structures, vol. 15, no. 5, pp. 1413–1420, Sep. 2006, doi: https: //doi.org/10.1088/0964-1726/15/5/030.
[27] Z. S. Chen, Y. M. Yang, and G. Q. Deng, “Analytical and experimental study on vibration energy harvesting behaviors of piezoelectric cantilevers with different geometries, ” Apr. 2009, doi: https: //doi.org/10.1109/supergen.2009.5348290.
[28] C. Mo, D. Arnold, W. C. Kinsel, and W. W. Clark, “Unimorph PZT Cymbal Design in Energy Harvesting, ” Jan. 2011, doi: https: //doi.org/10.1115/smasis2011-5005.
[29] T.-B. Xu et al., “Energy harvesting using a PZT ceramic multilayer stack, ” Smart Materials and Structures, vol. 22, no. 6, pp. 065015–065015, Apr. 2013, doi: https: //doi.org/10.1088/0964-1726/22/6/065015.
[30] U. Erturun, A. Eisape, and J. E. West, “Design and analysis of a vibration energy harvester using push-pull electrostatic conversion, ” Smart Materials and Structures, vol. 29, no. 10, p. 105018, Sep. 2020, doi: https: //doi.org/10.1088/1361-665x/aba5e2.
[31] U. Erturun, A. A. Eisape, S. H. Kang, and J. E. West, “Energy harvester using piezoelectric nanogenerator and electrostatic generator, ” Applied Physics Letters, vol. 118, no. 6, p. 063902, Feb. 2021, doi: https: //doi.org/10.1063/5.0030302.
[32] J. Formanek, V. Janicek, J. Jakovenko, and M. Husak, “Design and Fabrication of 3D Electrostatic Energy Harvester, ” DOAJ (DOAJ: Directory of Open Access Journals), Apr. 2012.
[33] F. U. Khan and M. U. Qadir, “State-of-the-art in vibration-based electrostatic energy harvesting, ” Journal of Micromechanics and Microengineering, vol. 26, no. 10, p. 103001, Sep. 2016, doi: https: //doi.org/10.1088/0960-

DOI: 10.54254/2755-2721/2025.29454

1317/26/10/103001.
[34] E. M. Yeatman, “Energy scavenging for wireless sensor nodes, ” Jan. 2007, doi: https: //doi.org/10.1109/iwasi.2007.4420014.
[35] M. Bonnin, F. L. Traversa, and F. Bonani, “Leveraging circuit theory and nonlinear dynamics for the efficiency improvement of energy harvesting, ” Nonlinear Dynamics, vol. 104, no. 1, pp. 367–382, Feb. 2021, doi: https: //doi.org/10.1007/s11071-021-06297-3
[36] S. P. Beeby and T. O’Donnell, “Electromagnetic Energy Harvesting, ” Energy Harvesting Technologies, pp. 129–161, doi: https: //doi.org/10.1007/978-0-387-76464-1_5.
[37] A. Muscat, S. Bhattacharya, and Y. Zhu, “Electromagnetic Vibrational Energy Harvesters: A Review, ” Sensors, vol. 22, no. 15, p. 5555, Jul. 2022, doi: https: //doi.org/10.3390/s22155555.
[38] Y. Tan, Y. Dong, and X. Wang, “Review of MEMS Electromagnetic Vibration Energy Harvester, ” Journal of Microelectromechanical Systems, vol. 26, no. 1, pp. 1–16, Feb. 2017, doi: https: //doi.org/10.1109/JMEMS.2016.2611677.
[39] J. Wang, L. Teng, and L. Zuo, “High Efficiency Electromagnetic Energy Harvester for Railroad Application, ” Volume 4: 18th Design for Manufacturing and the Life Cycle Conference; 2013 ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications, Aug. 2013, doi: https: //doi.org/10.1115/detc2013-12770.
[40] M. Iqbal et al., “Vibration-based piezoelectric, electromagnetic, and hybrid energy harvesters for microsystems applications: A contributed review, ” International Journal of Energy Research, Jul. 2020, doi: https: //doi.org/10.1002/er.5643.
[41] “Triboelectricity, ” MRSEC Education Group. https: //education.mrsec.wisc.edu/triboelectricity/
[42] D. A. Barkas, C. S. Psomopoulos, P. Papageorgas, K. Kalkanis, D. Piromalis, and A. Mouratidis, “Sustainable Energy Harvesting through Triboelectric Nano – Generators: A Review of current status and applications, ” Energy Procedia, vol. 157, pp. 999–1010, Jan. 2019, doi: https: //doi.org/10.1016/j.egypro.2018.11.267.
[43] Z. Xu, D. Zhang, H. Cai, Y. Yang, H. Zhang, and C. Du, “Performance enhancement of triboelectric nanogenerators using contact-separation mode in conjunction with the sliding mode and multifunctional application for motion monitoring, ” Nano Energy, vol. 102, p. 107719, Nov. 2022, doi: https: //doi.org/10.1016/j.nanoen.2022.107719.
[44] X. Cao, Y. Xiong, J. Sun, X. Xie, Q. Sun, and Zhong Lin Wang, “Multidiscipline Applications of Triboelectric Nanogenerators for the Intelligent Era of Internet of Things, ” vol. 15, no. 1, Dec. 2022, doi: https: //doi.org/10.1007/s40820-022-00981-8.
[45] S. Radfar, R. Panahi, Teymour Javaherchi, Siyavash Filom, and Ahmad Rezaee Mazyaki, “A comprehensive insight into tidal stream energy farms in Iran, ” Renewable and Sustainable Energy Reviews, vol. 79, pp. 323–338, Nov. 2017, doi: https: //doi.org/10.1016/j.rser.2017.05.037.
[46] L. Frenzel, “Power Density: What All EEs Need to Know, ” Electronicdesign.com, Sep. 2020. https: //www.electronicdesign.com/technologies/power/whitepaper/21140137/power-density-what-all-ees-need-to-know (accessed Aug. 02, 2024).
[47] Y. Hu et al., “High power density energy harvester with non-uniform cantilever structure due to high average strain distribution, ” Energy, vol. 169, pp. 294–304, Feb. 2019, doi: https: //doi.org/10.1016/j.energy.2018.11.085.
[48] S.-W. Kim et al., “Determination of the appropriate piezoelectric materials for various types of piezoelectric energy harvesters with high output power, ” Nano Energy, vol. 57, pp. 581–591, Mar. 2019, doi: https: //doi.org/10.1016/j.nanoen.2018.12.082.
[49] S. P. Beeby et al., “A micro electromagnetic generator for vibration energy harvesting, ” Journal of Micromechanics and Microengineering, vol. 17, no. 7, pp. 1257–1265, Jun. 2007, doi: https: //doi.org/10.1088/0960-1317/17/7/007
[50] P. Thainiramit, P. Yingyong, and D. Isarakorn, “Impact-Driven Energy Harvesting: Piezoelectric Versus Triboelectric Energy Harvesters, ” Sensors, vol. 20, no. 20, p. 5828, Oct. 2020, doi: https: //doi.org/10.3390/s20205828.
[51] S. Mitsushima, B. Gollas, and V. Hacker, “Chapter 1 - Introduction, ” ScienceDirect, Jan. 01, 2018. https: //www.sciencedirect.com/science/article/abs/pii/B9780128114599000013
[52] A. Ali, S. Iqbal, and X. Chen, “Recent advances in piezoelectric wearable energy harvesting based on human motion: Materials, design, and applications, ” Energy Strategy Reviews, vol. 53, p. 101422, May 2024, doi: https: //doi.org/10.1016/j.esr.2024.101422.
[53] M. İ. Beyaz and N. Ahmed, “A belt-integrated piezoelectric energy harvester for wearable electronic devices, ” Ferroelectrics, vol. 585, no. 1, pp. 187–197, Dec. 2021, doi: https: //doi.org/10.1080/00150193.2021.1991217.
[54] G.-T. Hwang et al., “Self-Powered Cardiac Pacemaker Enabled by Flexible Single Crystalline PMN-PT Piezoelectric Energy Harvester, ” Advanced Materials, vol. 26, no. 28, pp. 4880–4887, Apr. 2014, doi: https: //doi.org/10.1002/adma.201400562.

DOI: 10.54254/2755-2721/2025.29454

[55] Sanjana Gururaj, A. Applequist, S. Bhattarai, A. M. Appaji, and Pooja Kadambi, “Self-Powered Cardiac Pacemaker: The Viability of a Piezoelectric Energy Harvester, ” Jan. 2020, doi: https: //doi.org/10.1109/comsnets48256.2020.9027333.
[56] R. Li, Y. Yu, B. Zhou, Q. Guo, M. Li, and J. Pei, “Harvesting energy from pavement based on piezoelectric effects: Fabrication and electric properties of piezoelectric vibrator, ” Journal of Renewable and Sustainable Energy, vol. 10, no. 5, Sep. 2018, doi: https: //doi.org/10.1063/1.5002731.
[57] California Energy Commission, “Ultra-High Power Density Roadway Piezoelectric Energy Harvesting System, ” California Energy Commission, 2023. https: //www.energy.ca.gov/publications/2023/ultra-high-power-density-roadway-piezoelectric-energy-harvesting-system (accessed Aug. 28, 2024).
[58] S. Sharma, R. Kiran, P. Azad, and R. Vaish, “A review of piezoelectric energy harvesting tiles: Available designs and future perspective, ” Energy Conversion and Management, vol. 254, p. 115272, Feb. 2022, doi: https: //doi.org/10.1016/j.enconman.2022.115272.
[59] S. Panda et al., “Piezoelectric energy harvesting systems for biomedical applications, ” Nano Energy, vol. 100, p. 107514, Sep. 2022, doi: https: //doi.org/10.1016/j.nanoen.2022.107514.
[60] S. K. Karan, S. Maiti, J. H. Lee, Y. K. Mishra, B. B. Khatua, and J. K. Kim, “Recent Advances in Self-Powered Tribo-/Piezoelectric Energy Harvesters: All-In-One Package for Future Smart Technologies, ” Advanced Functional Materials, vol. 30, no. 48, p. 2004446, Sep. 2020, doi: https: //doi.org/10.1002/adfm.202004446.
[61] S. M. Kargar and G. Hao, “An Atlas of Piezoelectric Energy Harvesters in Oceanic Applications, ” Sensors, vol. 22, no. 5, p. 1949, Mar. 2022, doi: https: //doi.org/10.3390/s22051949.