electronics

Review

Optimizing Piezoelectric Energy Harvesting from Mechanical Vibration for Electrical Efficiency: A Comprehensive Review

Demeke Girma Wakshume * and Marek Łukasz Płaczek *

Department of Engineering Processes Automation and Integrated Manufacturing Systems, Silesian University of Technology, Konarskiego 18a Street, 44-100 Gliwice, Poland
* Correspondence: demeke.wakshume@polsl.pl (D.G.W.); marek.placzek@polsl.pl (M.Ł.P.)

Abstract: In the current era, energy resources from the environment via piezoelectric materials are not only used for self-powered electronic devices, but also play a significant role in creating a pleasant living environment. Piezoelectric materials have the potential to produce energy from micro to milliwatts of power depending on the ambient conditions. The energy obtained from these materials is used for powering small electronic devices such as sensors, health monitoring devices, and various smart electronic gadgets like watches, personal computers, and cameras. These reviews explain the comprehensive concepts related to piezoelectric (classical and non-classical) materials, energy harvesting from the mechanical vibration of piezoelectric materials, structural modelling, and their optimization. Non-conventional smart materials, such as polyceramics, polymers, or composite piezoelectric materials, stand out due to their slender actuator and sensor profiles, offering superior performance, flexibility, and reliability at competitive costs despite their susceptibility to performance fluctuations caused by temperature variations. Accurate modeling and performance optimization, employing analytical, numerical, and experimental methodologies are imperative. This review also furthers research and development in optimizing piezoelectric energy utilization, suggesting the need for continued experimentation to select optimal materials and structures for various energy applications.

Keywords: energy optimizing; modelling; performance enhancement; piezoelectric materials; energy harvesting

check for updates

Citation: Wakshume, D.G.; Płaczek, M.Ł. Optimizing Piezoelectric Energy Harvesting from Mechanical Vibration for Electrical Efficiency: A Comprehensive Review. *Electronics* **2024**, *13*, 987. https://doi.org/10.3390/electronics13050987

Academic Editor: Antonio J. Marques Cardoso

Received: 25 December 2023
Revised: 22 January 2024
Accepted: 21 February 2024
Published: 5 March 2024

1. Introduction

Clean and renewable energy harvesting from ambient environments is a technology that reduces the energy crisis, global warming, and environmental pollution. This technology is used to sustain self-power systems as feasible and economical alternatives to conventional energy-harvesting systems. Energy security, energy value, and the environment are necessary components for the energy sector to consider achieving sustainable development. Today, piezoelectric energy harvesters can be used to power small electronic devices, such as measurement equipment, in remote or hostile environments where batteries are not a viable option, and the power consumption of these small electronic devices can be reduced by tens of mW, as shown in Table 1. Energy-harvesting systems accommodate three main sources from which electrical energy is scavenged (such as sunlight, wind, human heat, or vibration), a harvesting mechanism (to convert ambient energy to electrical), and the load (where output electrical energy is stored) [1–6]. Due to the limitations of batteries, in the future, vibrational energy-harvesting technology will be used, which converts vibration energy into electrical energy to power small electronic devices, such as measuring instruments in remote or hostile environments where batteries are not an available option, and this is the only solution [7–9].

Table 1. Some electronic materials and their electrical power consumption.

Device	Voltage	Current	Power
Heart Pacemaker	2.5 V	13 µA	33 µW
GPS Tracker	3 V	Medium	Medium
Analog Watch	2.8 V	1 µA	2.8 µW average
ZigBee	3.0 V	20 mA	60 mW peak
Timer	2.5 V	35 nA	88 nW
Bluetooth 4.0	2–3.6 V	15 mA	45 mW max.
Apple Watch	3.76 V	13.8 mA	52 mW Average

Research is being conducted on the modelling, application, and testing of piezoelectric transducers used in systems for damping mechanical vibrations, their excitation, as well as application in systems for recovering electrical energy from mechanical vibrations with the use of both classical and non-classical composite piezoelectric transducers. This research is due to their properties increasing the effectiveness of the designed systems and the number of potential possibilities of their application in modern technical means. The enhancement of the overall performance of PEHs in the scientific domain is essential for promoting the development of self-powered microelectronics [4]. Previous work has been published in numerous scientific studies. In general, this work reviews the comprehensive points of some existing works and research reports on the possibility of using classical and non-classical piezoelectric transducers in systems for energy harvesting and performance optimization. The introduction includes piezoelectric energy harvesting and optimization and mechanical energy harvesting. The second section discusses piezoelectric materials, and the third section describes the methods of modeling piezoelectric energy harvesters. The fourth section covers the performance improvements in piezoelectric energy harvesters, and the final part reports the conclusions, future perspectives, and reference. It also provides an overview of the various strategies employed to optimize the performance of electrical energy systems derived from mechanical vibrations using piezoelectric transducers within geometric configurations, materials, and performance-enhancement mechanisms.

The concept behind vibrational energy harvesting is to convert vibrations into electrical energy through sequential conversion steps: initially, the kinetic energy of the vibrations is transformed into relative motion between components using mechanical-to-mechanical converters like the mass-spring mechanism. Subsequently, this relative motion is converted into power through mechanical-to-electrical converters, such as piezoelectric materials or variable capacitors [10–12].

Based on [13,14], it can be assumed that piezoelectric power harvesting involves three primary stages of energy flow. The first stage is a mechanical-to-mechanical energy transfer based on environmental excitation energy, ensuring the mechanical balance of the piezoelectric transducer under significant stresses and considering the damping factor. The second phase includes mechanical-to-electrical power transduction, involving the electromechanical coupling aspect in piezoelectric transducer structures and piezoelectric coefficient influence. The last phase is an electrical-to-electrical energy transfer, encompassing electrical impedance matching and circuit loss. The aim of scientific research in the field of obtaining electrical energy from mechanical vibrations is therefore to optimize this process to minimize energy conversion losses and obtain maximum efficiency. Limited research has comprehensively outlined the entire power flow or precise efficiency from the initial mechanical input power to the final electrical energy stored in a rechargeable battery through piezoelectric transducers.

One of the key requirements for the use of piezoelectric material is the potential to generate enough voltage or power even from small mechanical or biomechanical excitations at exceptionally low and out-of-resonance frequencies. Continuous progress in low-power electronics and energy harvesting is opening new opportunity ties for the realization of power sources replacing classical batteries for the sustainable, maintenance-free, and continuous running of small electronics. Table 1 summarizes the power consumption of small electronics [15].

The concept of harvesting energy from ambient resources has been extensively researched for over two decades and is extremely promising, not only because it is eco-friendly and cost-efficient, but also because this technology breaks the limitations posed by traditional batteries. Energy harvesting from piezoelectric materials is not only an essential component of self-sustaining systems, but it also presents a potentially viable and economically feasible alternative to batteries [1,2,16,17]. Small-scale energy sources commonly include solar energy, electromagnetic radiation, environmental mechanical energy, human body heat, and mechanical energy from the motion of the human body. Unlike solar and electromagnetic energy, which heavily relies on environmental conditions, energy harvesting from the motion of a human body can seamlessly integrate into daily activities to power a variety of wearable electronic devices. In addressing the challenge of energy resource scarcity, energy harvesting emerges as an attractive approach for extracting ambient energy in the form of electricity from renewable environmental sources such as solar, wind, geothermal, and tidal energy [17–19].

Another important challenge arises when an electric circuit is connected to the transducer, causing an interaction between the electrical and mechanical systems [20]. To improve the effectiveness of transforming mechanical energy into electrical power, several techniques have been designed. Automatic design and optimization methodologies that require minimal human intervention have been proposed to improve their performance. Two primary avenues of exploration emerge: firstly, optimizing the mechanical structure to enhance its resonant response or broaden the maximum stress bandwidth, and secondly, focusing on the electrical optimization of the energy harvesting circuit itself. The prospect of employing composite piezoelectric transducers in systems that recover electrical energy from mechanical vibrations is particularly intriguing for researchers [21,22].

In the realm of electric energy conversion, humanity has long utilized energy harvesting technologies such as windmills, watermills, geothermal, and solar power. There are increasing concerns about energy depletion and the need for reductions in carbon emissions. Hence, interest in replacing fossil fuel energies with alternative sources has emerged. Secondly, the environmental issue calls for clean, green, sustainable, and reusable energy [16,17,23]. Clean energy not only saves costs on public services but also maintains public health and enhances the prospects for future generations. Piezoelectric harvesting materials have the capacity to accumulate the clean energy and to transform it into electrical energy which is cost-effective, scalable, and easy to utilize [24,25]. However, despite these benefits, piezoelectric transducers cannot independently harvest mechanical energy due to their primary limitations, such as low harvested energy levels, necessitating rectification, optimal power extraction, and output voltage regulation [16]. Typically, a piezoelectric vibration energy-harvesting system comprises a mechanical oscillating structure, a piezoelectric electric harvester (PEH), an electrical interface circuit for converting output electrical energy in the form of AC current into DC, and an energy storage unit for accumulating and storing intermittent energy. Besides optimizing piezoelectric systems, the electrical interface circuits play a pivotal role in enhancing the harvested energy of the system, with optimization criteria varying based on the relative power coupling [26,27].

An essential component of an energy harvester is its energy conversion efficiency, which is vital for design optimization and comparative assessments. Power conversion efficiency denotes the ratio of the output electrical energy to the input energy of the system. For piezoelectric energy harvesters (PEHs), this ratio, called electromechanical coupling, represents the output electrical energy against the input mechanical energy [27,28]. A piezoelectric transducer has two effects, either direct or indirect. The direct effect occurs when stress is applied to piezoelectric materials, which produces charges on the surface of piezoelectric materials. The converse piezoelectric effect occurs when an electrical field is applied across the surface of piezoelectric materials and induces stress across the surface. Figure 1 shows the direct and converse piezoelectric effect [29,30].

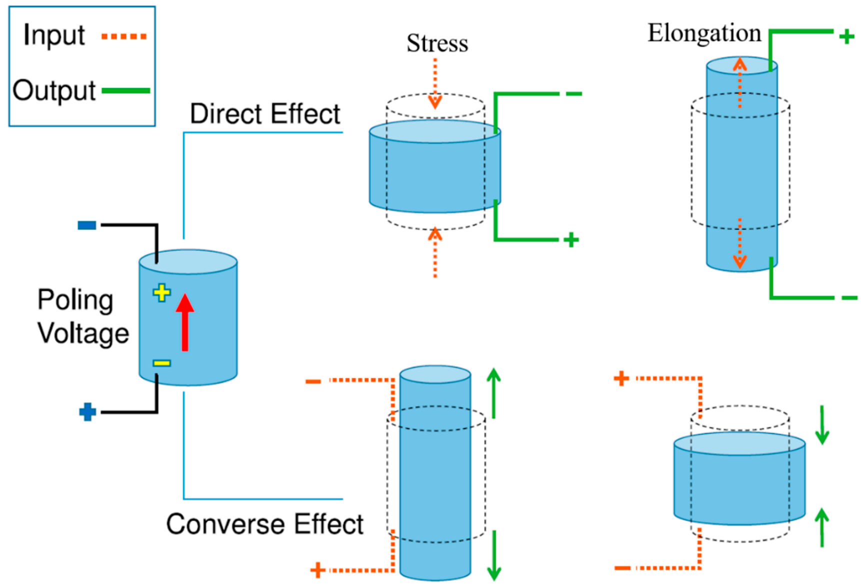


Figure 1. Direct and converse piezoelectric effect [30].

2. Piezoelectric Materials

Piezoelectric materials employed in energy harvesting typically exhibit an anisotropic nature, meaning their properties vary upon a force direction and a polarization/electrode orientation. Mostly, piezoelectric materials are brittle in nature. These materials are available in four types, single crystals, ceramics, polymers, and thin films. The dynamic compression force creates energy on the surface of piezoelectric materials in the form of electrical energy. The choice of a piezoelectric material significantly impacts the capability and performance of a harvesting system. Piezoelectric energy harvesting (PEH) systems have garnered attention due to their straightforward setup, high conversion efficiency, and adaptability for integration into complex systems [31]. Ceramic piezoelectric materials have been the cornerstone of energy harvesting for many years. The discovery of materials capable of generating an electric field under strain (the direct piezoelectric effect) dates to Pierre and Jacques Curie in 1880 [32]. These materials, termed 'smart' due to their ability to convert mechanical pressure into electrical signals, operate via the direct piezoelectric effect, polarizing when subjected to tensile or compressive stress, and generating voltage. Conversely, under the inverse effect, the application of electric potential induces mechanical displacement in the material [33]. Piezoelectric materials have evolved into various forms, including ceramics, polymers, and composites [34]. Researchers have continuously aimed to enhance energy harvesting performance by developing novel piezoelectric materials and composites [34,35]. The selection of smart materials for energy harvesting does not depend only on their piezoelectric properties and application capabilities but also on factors such as operating frequency, design flexibility, and available shape [16,36]. There are over two hundred piezoelectric materials commonly used in energy harvesting applications [27]. These materials generally fall into four categories: single crystals (e.g., Rochelle salt, lithium niobite, quartz crystals), ceramics (e.g., barium titanate ($BaTiO_3$), lead-zirconate-titanate (PZT)), polymers (e.g., polylactic acid (PLA), polyvinylidene fluoride (PVDF), co-polymers, cellulose and derivatives), and polymer composites or nanocomposites (e.g., polyvinylidene fluoride-zinc oxide (PVDF-ZnO), cellulose $BaTiO_3$, polyimides-PZT) [36,37].

Each of the PE materials have its own description and characterization [38].

1. Single Crystal Materials: with a highly ordered orientation of positive and negative ions.

Description: monocrystals grown vertically on a substrate using methods such as the Bridgeman or Flux method [39].

Characteristics: Exceptional piezoelectric properties making them suitable for sensor and actuator applications. Various nanostructure forms depending on the growth technique [40].

2. Lead zirconate titanate (lead-based piezoceramics):

Description: polycrystalline materials featuring a perovskite crystal structure [40].
Characteristics: Exhibits high piezoelectric effect and low dielectric loss.
Simple fabrication process and compatibility with (microelectromechanical systems (MEMS) manufacturing techniques. However, these materials pose high toxicity risks due to the presence of lead.

3. Lead-free Piezoceramics: cheap piezoelectric material [8].

Description: non-toxic alternatives to lead-based piezoceramics, such as $BaTiO_3$.
Characteristics: Lower transduction efficiency compared to lead-based counterparts like bismuth sodium titanate (BNT-BKT) [41,42].
Competitive alternatives with a perovskite crystal structure, including potassium sodium niobate (KNN)-based materials such as LS45 [43,44] and KNLNTS [44].

4. Piezo-Electroactive Polymers (Piezopolymers):

Polymer-based piezoelectric composites (PPCs) exhibit intrinsic advantages owing to their high damping properties and dynamic mechanical energy-harvesting abilities.
Description: a type of electroactive polymer (EAP) used in piezo-MEMS fabrication.
Characteristics: Flexible, non-toxic, and lightweight. Exhibits smaller electromechanical coupling compared to piezoceramics. Offers low fabrication costs and rapid processing [36].
Polymers derived from polyvinylidene fluoride (PVDF) are biocompatible, biodegradable, and require less power than other piezoelectric materials when applied as actuators [45–47].
These distinct characteristics and applications make each category of piezoelectric materials suitable for specific purposes, offering a range of benefits and limitations in various fields such as sensors, actuators, MEMS devices, and other applications requiring piezoelectric properties.

Classical transducers are the most widely used piezoelectric energy-harvesting transducers. Lead-zirconate-titanate (Pb (Zr, Ti) O_3, PZT) is well known for energy harvesting. Even if these PZT-based piezoelectric materials are nonetheless the most versatile and universally used piezoceramics, they are lead-based piezoelectric energy-harvesting materials.. However, the evaporation of poisonous lead and its compounds throughout the excessive-temperature sintering of PZT incurs environmental pollution and danger to health. Therefore, despite its excellent piezoelectric properties, the environmental and health implications of lead-based piezoelectric materials like PZT have prompted a search for alternative materials that offer a comparable performance without the use of toxic elements. This quest has led to significant research into lead-free alternatives to address environmental concerns while maintaining or approaching the performance characteristics of traditional lead-based materials [48–50].

Piezoelectric materials have seen several stages of development, from piezoelectric ceramic to piezoelectric fiber composite (PFC) and active fiber composite (AFC) to macro fiber composite (MFC), in order to attain better parameters such as electromechanical coupling, large blocking force, and quick response time [51–53]. Efforts to enhance piezoceramic properties have expanded beyond traditional compositional control to encompass innovative structural arrangements. Piezo composite, consisting of piezoceramics and polymers, has emerged as a promising material due to its highly customizable properties [34]. These composite piezoelectric materials offer an alternative to overcome limitations seen in practical applications of conventional monolithic piezoelectric transducers [54,55]. The development of composite piezoelectric materials involves embedding piezoceramic fibers within a polymer matrix, resulting in active fiber composites and macro fiber composites [37,56,57].

These materials present advantages such as flexibility, thinness, and lightweight characteristics, making them easily applicable in various mechanical systems. They can also be easily incorporated into various structures, including composite elements [58,59]. However, the limited piezoelectric effect considerably hampers the performance of macro fiber composite PE transducers in applications [60]. Although PZT is widely used as an energy-harvesting piezoelectric material, its notably brittle nature poses challenges in effectively absorbing pressure without fracturing [61]. The choice of a piezoelectric material depends on factors such as external excitation, material lifespan, operating temperature, and frequency. Based on their structural characteristics, piezoelectric materials are divided into four categories: ceramics, single crystals, polymers, and composites (the composite material is a combination of piezoelectric ceramics or single crystals with polymers) (see Table 2). Piezoceramics have a higher fundamental frequency with the same vibration mode, when compared to polymers and composites of the same size and geometry. When the frequency of vibration is higher (100 Hz or higher), the design of piezoelectric materials is simple. However, as the frequency of the vibration host decreases, designing the energy harvesting unit becomes more complex. This is because dimension and weight constraints limit the use of ceramics to achieve the desired fundamental frequency [60]. Lead zirconate titanate has the property of brittleness which limits its application in flexible devices, and despite the satisfactory flexibility of polymers, their poor piezoelectric properties restrict their use in high-energy-density applications [2]. In this case, composite piezoelectric materials (macro fiber composites (MFCs) and active fiber composites (AFCs)) can often be the candidate material. This included a fiber-based piezoelectric (piezo fiber) material consisting of PZT fibers of various diameters that were aligned, laminated, and molded in an epoxy [1]. These transducers are light and more and more cost-effective. However, their efficiency in the process of mechanical–electrical energy conversion remains a challenge [22]. Smart composite piezo fibers are commercially available in the 1–3 composites of the Smart Materials Corp. Active fiber composites (AFCs) (Figure 2a) are constituted of uniaxially oriented piezoceramic fibers embedded in a polymer matrix and sandwiched between two interdigitated electrodes (see Figure 2a), and were initially developed in the Active Materials and Structure laboratory (AMSL) at the Massachusetts Institute of Technology. AFCs are manufactured using a patented soft-mold technology that was invented at the Fraunhofer Research Facility in Germany. This process simply involves creating a soft mold from a positive form of the final structure, filling the mold with the piezoceramic material, and then firing the element [62]. Macro fiber composites (MFCs) (Figure 2b), often termed self-sensing actuators due to their electromechanical coupling characteristics, have been recently developed by the NASA Langley Research Center. They are being explored as alternative sensors for structural dynamics and control applications [59,63,64]. An AFC is an anisotropic actuator which employs round cross-section piezoelectric (PZT) fibers in the epoxy matrix. The combination of PZT fibers and a soft matrix provides a load transfer mechanism which increases robustness in relation to damage and offers conformability and flexibility. The MFC is like the AFC because both consist of the same three primary components; active piezoceramic fibers aligned in a unidirectional manner, interdigitated electrodes, and an adhesive polymer matrix. However, the MFC has one difference that greatly affects the manufacturing process and the performance of the actuator; it has rectangular fibers [1,52,53,64,65].

Table 2. General summary of piezoelectric materials.

Materials	Example	Advantages	Disadvantages	Application
Ceramics	PZT	Good piezoelectric, mechanical, and thermal properties; easy fabrication shaping, good stability, low cost	Toxic	Diverse applications

Table 2. *Cont.*

Materials	Example	Advantages	Disadvantages	Application
Polymers	PVDF	Good mechanical flexibility; higher chemical resistance	One order lower piezoelectric coefficient than PZT; narrow working temperature range.	Wearable, biocompatible
Lead-free	BT, BNT, KNN	Comparable piezoelectric property with PZT in the same composition.	Overall lower piezoelectric property than PZT; lower thermal stability, more difficulties in processing	Environmentally compatible; diverse application
Nanomaterials	ZnO	Easy to form nano structure; no poling is required; chemically stable, biological safe; low cost	Lower piezoelectric properties	Nano generator compatible
Single crystals	PMT-PT PZN-PT	Very good piezoelectric performance	Toxic lead; lower mechanical properties, higher cost; difficult to fabricate and process	General application
Composites	PTZ+PVDF	Possibility to have advantages of both phases in the compounds	Complicated processing required	Special scenario like both flexible and thermal properties are required
Macro fiber composite	MFC	It is extremely flexible, enabling bonding to structures with curved surfaces without concerns of accidental breakage or requiring additional surface treatment, unlike monolithic piezoceramic materials. Both d_{33} and d_{31} mode possible, low strain high frequency application, large area coverage, can be used as a bimorph element coverage	Very effective at attenuating the vibration of the first mode but ineffective at higher modes.	Heath monitoring device Shape Morphing of airfoils, spoiler, rudders. Vibration Control (Aerospace, Automotive, Buildings, and Consumer Products)

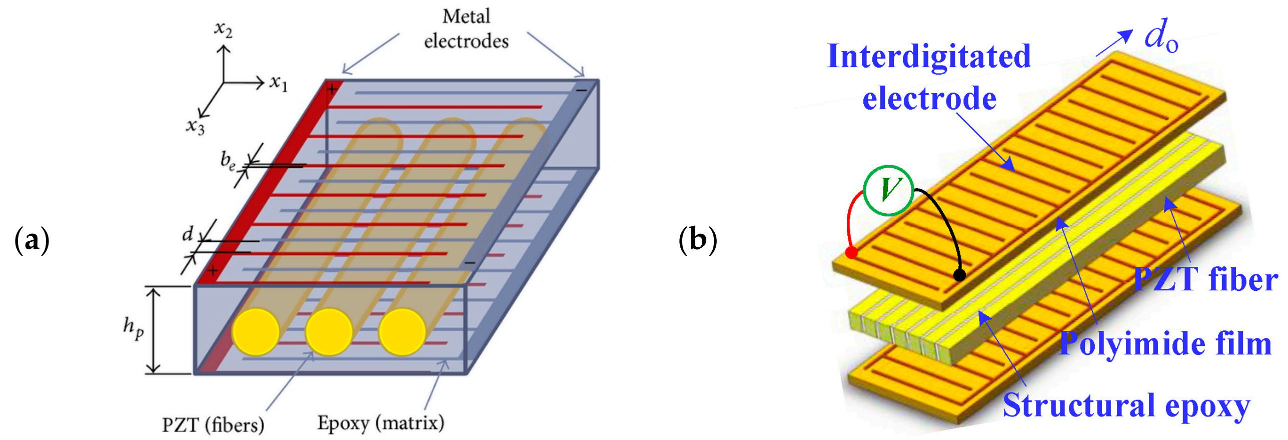
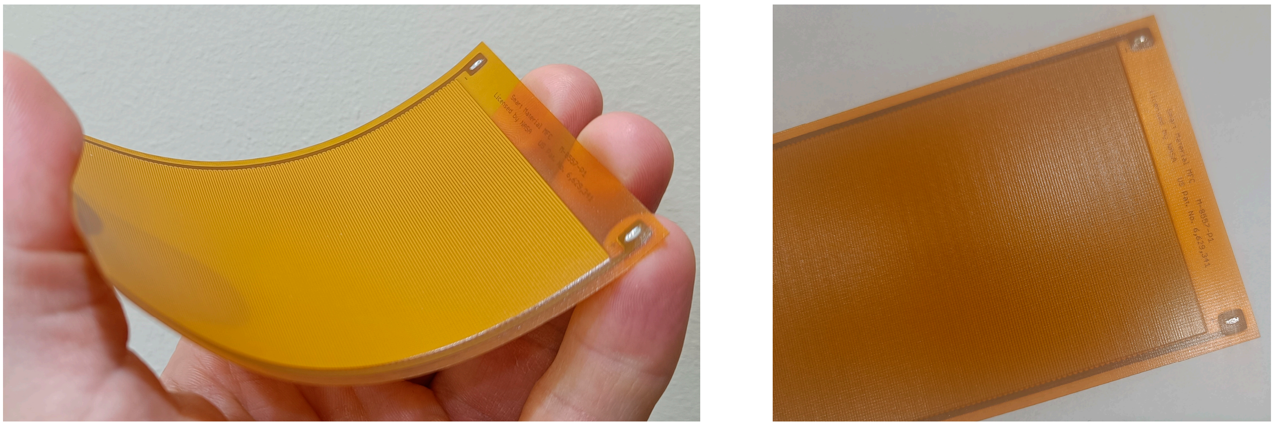


Figure 2. Active (**a**) and macro (**b**) fiber composite piezoelectric materials [64,65].

Piezoelectric transducers based on macro fiber composites (MFCs) are widely used for energy harvesting, actuation, and sensing because of the high conformability, reliability, and strong piezoelectric effect of MFCs (Figure 3). The analytical or numerical modelling of the heterogeneous MFC as a homogenous material with equivalent properties is usually required to predict the performance of the transducers. While piezoelectric ceramics, especially PZT, exhibit excellent piezoelectric properties and high energy transduction efficiency, their extreme brittleness restricts their ability to conform to curved surfaces and endure stress/strain without sustaining damage. A macro fiber composite transducer comprises rectangular PZT fibers embedded in an epoxy matrix, sandwiched between two electrode/epoxy layers. It possesses high strength, flexibility, and reliability, while retaining a strong piezoelectric effect. Consequently, it has garnered significant interest in both industrial applications and the academic community. At present, there is an ever-increasing array of research-grade and commercially available composites containing piezoelectric fibers [56,62]. In active fiber composites, the three main constituents are piezoceramic fibers, interdigitated electrodes, and a polymer matrix material. In contrast, macro fiber composites utilize piezoceramic fibers machined from low-cost piezoceramic wafers through computer-controlled dicing [51,66]. It is applicable in both d_{33} and d_{31} modes, suitable for low strain, high frequency applications, offers large area coverage, and can be used as a bimorph element. Mode d_{33} has a higher energy conversion rate but lower electrical current when compared with the d_{31}-mode. Layers of MFC are stacked after it is machined from a low-cost piezoceramic wafer using a computer-controlled cutting saw fabrication process [52,55,67]. Commercially available copper-clad polyimide film piezoceramic wafer, which is used to hold the fibers in place during handling and machining, is placed on top of a blue surface to create the interdigitated electrodes through the use of a photoresist-and-etch process. After being cut, the piezoceramic wafer is moved and adhered to the bottom electrode film using a thermosetting epoxy adhesive, which serves as the polymer matrix material [51,52,62,67,68].



(**a**) (**b**)

Figure 3. Macro fiber composite being bent to show its flexibility (**a**) and ready-to-use MFC transducer with visible structure of PZT fibers, electrodes, and connectors (**b**).

3. Piezoelectric Constitutive Equations

The IEEE standard assumes that piezoelectric materials are linear. When a poled piezoelectric material (P) is mechanically strained, it becomes electrically polarized, producing a fixed electric charge on the surface of the material (direct piezoelectric transducer). The mathematical relation can be expressed as follows [16,21,69]:

$$P_{pe} = d \times T, \quad (1)$$

where P_{pe} is the piezoelectric polarization vector; d is the piezoelectric strain coefficient; and T is the stress to which piezoelectric material is subjected.

For an indirect/reverse/piezoelectric effect, the strain produced by reverse effect is given by:

$$S_{pe} = d \times E, \quad (2)$$

where S_{pe} is the mechanical strain produced by reverse piezoelectric effect and E is the magnitude of the applied electric field.

The direct and reverse piezoelectric effects can alternatively be formulated as:

$$P_{pe} = d \times T = d \times c \times S = e \times S, \quad (3)$$

$$T_{pe} = c \times S_{pe} = c \times d \times E = e \times E, \quad (4)$$

where e is the piezoelectric stress constant.

When piezoelectric materials are subjected to strain, it will have two effects. First, it will generate elastic stress ($T_e = c \times S$) and second, it will generate piezoelectric polarization ($P_e = e \times S$). Polarization creates an internal electric field in the material E_{pe}.

The stress ($T_{pe} = e \times E_{pe}$), produced by the electric field E_{pe}:

$$E_{pe} = \frac{P_e}{\varepsilon} = \frac{e \times S}{\varepsilon}, \quad (5)$$

where ε is the dielectric constant of the material.

The total stress generated by strain, S:

$$T = T_e + T_{pe} = c \times S + e \times E_{pe} = c \times S + e\left(\frac{e \times S}{\varepsilon}\right) = \left(c + \frac{e^2}{\varepsilon}\right) \times S = \bar{c} \times S. \quad (6)$$

According to the constitutive equations of the piezoelectric property, the mechanical strain induced by the mechanical stress and the controllable actuation strain brought on by the applied electric voltage add up to the total strain in the transducer.

According to Hooke's law, stress causes strain:

$$S = \frac{T}{E} = C \times T. \quad (7)$$

In special materials, such as piezoelectric materials (reverse piezoelectric effect), the electrical field (E) causes strain as well:

$$S = d \times E. \quad (8)$$

From the linear electrical behavior of the material:

$$D = \varepsilon \times E. \quad (9)$$

The fundamental constitutive equation of any piezoelectric materials for the energy harvesting is governed by the stress and strain within the electric field and charge density effects:

$$D = \varepsilon^T E + d_{33} T, \quad (10)$$

$$S = d_{33} E + S^E T. \quad (11)$$

Equations (10) and (11) can be written in matrix form which gives Equation (3):

$$\begin{bmatrix} \text{direct effect} \\ \text{converse effect} \end{bmatrix} = \begin{bmatrix} D \\ S \end{bmatrix} = \begin{bmatrix} d & \varepsilon^T \\ S^E & d^t \end{bmatrix} \begin{bmatrix} E \\ T \end{bmatrix}. \quad (12)$$

A simplified method to describe both the direct and converse piezoelectric effects is represented by Equation (13):

$$\begin{cases} D = dT + \varepsilon E \\ S = sT + dE' \end{cases} \quad (13)$$

where T is stress; E electric field S^E is elastic compliance constant under a constant electrical field; ε^T is the permittivity of the material under a constant stress; and d and d^t are the piezoelectric strain constant for direct and converse piezoelectric effect, where the superscript t stands for the transpose.

Piezoelectric Constant Property

Piezoelectric has a physical property of anisotropic (physical property which has a different value when measured in different directions). The constants depend on both the direction of applied mechanical or electrical force and the direction perpendicular to the applied force. Each constant has two subscripts to indicate the direction of the two related quantities, such as stress $\left(\frac{F}{A}\right)$ and strain elasticity $\left(\frac{\Delta L}{L}\right)$. The direction X, Y, and Z are represented by 1, 2, and 3, respectively.

A Piezoelectric charge Constant (d):

The polarization obtained per unit of mechanical stress (T) applied to a piezoelectric material or, alternatively, is the mechanical strain (S) experienced by a piezoelectric material per unit of electric field applied [14].

The magnitude of the induced strain T by an external electric field E is represented by:

$$T = d \times E. \tag{14}$$

The piezoelectric voltage constant (g):

The mechanical strain experienced by piezoelectric materials per unit of electrical displacement applied or the electric field generated by piezoelectric materials per unit mechanical stress applied. The induced electric field E is related to an external stress T through the piezoelectric voltage constant g (an important figure of merit for sensor applications):

$$E = g \times T. \tag{15}$$

Considering the relation, D (or P) = dT, important relation between g and d:

$$g = \frac{d}{\varepsilon_0 \varepsilon^T}, \tag{16}$$

where ε^T represents relative permittivity.

Permittivity or dielectric constant (ε)

The piezoelectric property of dielectric displacement per unit electric field. ε^T permittivity at constant stress and ε^S permittivity and constant strain.

Elastic and Compliance:

Elastic compliance, s is the strain produced in a piezoelectric material per unit of stress applied and, for the 11 and 33 directions, is the reciprocal of the modulus of elasticity (Young's modulus, Y). S^D is the compliance under a constant electrical displacement; S^E is the compliance under a constant electric field. The first subscript indicates the direction of strain, the second is the direction of stress.

Electromechanical Coupling Factor K:

Electromechanical coupling is the indicator of which piezoelectric materials effectively undergo the conversion of mechanical energy to electrical or the conversion of electrical to mechanical energy by piezoelectric materials.

When an electric field E is applied to a piezoelectric material, K^2 can be calculated as:

$$K^2 = \frac{d^2}{\varepsilon {\varepsilon_0}^s}. \tag{17}$$

Mechanical Quality Factor Q_M:

A parameter that characterizes the sharpness of electromechanical resonance spectrum (ω_0):

$$Q_M = \frac{\omega_0}{2\Delta\omega}. \tag{18}$$

Four basic piezoelectric coefficients, d_{ij}, e_{ij}, g_{ij}, and h_{ij}, are defined in Equation (19):

$$\begin{cases} d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)^E = \left(\frac{\partial S_j}{\partial E_i}\right)^T \\ e_{ij} = \left(\frac{\partial D_i}{\partial S_j}\right)^E = \left(\frac{\partial T_j}{\partial E_i}\right)^S \\ g_{ij} = \left(\frac{\partial E_i}{\partial T_j}\right)^D = \left(\frac{\partial S_j}{\partial D_i}\right)^T \\ h_{ij} = \left(\frac{\partial E_i}{\partial S_j}\right)^D = \left(\frac{\partial T_j}{\partial D_i}\right)^S \end{cases} \quad (19)$$

4. Method of Modeling and Performance Improvement of Piezoelectric Energy Harvester

4.1. Mechanical Energy Harvesting

Mechanical energy, in general, serves as an alternative source for energy harvesting, ranging from low to high output power. Based on a vibration energy harvester (energy transduction) method, there are three primary methods for converting mechanical vibrational energy into electrical energy. These are electrostatic, electromagnetic, and piezoelectric [12,70].

The electrostatic method, which employs electric fields or electrostatic harvesting, harnesses the relative movement between charged capacitor plates that are electrically isolated to produce energy. It offers great device flexibility, a high conversion rate, and high-power density. However, it also has problems with durability and reliability, and its exact working mechanism is still unknown.

Electromagnetic (involving magnetic fields) systems typically involve coils and magnets; this is why they are best suited for high mechanical-to-electrical energy transfer efficiency. However, this comes with a bulky and complicated mechanism.

Piezoelectric energy harvesting is the solution for high voltage, high energy density, high capacitance, and minimal mechanical damping; however, it should be noted that piezoelectric materials can be toxic and brittle [2,16]. More than 500 research studies have been completed in the field of vibration-based energy harvesters in the last decade, especially based in piezoelectric because of its higher energy density for practical applications [70]. The process of electromagnetic harvesting utilizes electromagnetic induction that results from the relative motion of a conductor and a magnetic flux gradient. Electromagnetic and piezoelectric are used for vibration harvesting. From three energy harvesting modes, piezoelectric energy harvesting is preferred to the others because of the ability to harvest energy over a large frequency, its large energy conversion efficiency, high storage energy density, and simplicity for construction and design [71]. Table 3 presents a comparative analysis of each method [17,23].

Table 3. Comparison of energy harvesting vibration techniques [72,73].

	Piezoelectric	**Electromagnetic**	**Electrostatic**
Energy density	35.4 $\frac{\text{mJ}}{\text{cm}^3}$	24.8 $\frac{\text{mJ}}{\text{cm}^3}$	4 $\frac{\text{mJ}}{\text{cm}^3}$
Importance (advantages)	Maximum output power No need to control gap Small size	High output current Long life Rugged and durable	Easy to reduce size. High output voltage. Adjustable coupling coefficient.
Challenge (Draw back)	More expensive than electrostatic or electromagnetic options, and high-quality coupling materials are required to ensure sustained results	Electromagnetic devices have low-output voltages, higher material costs, and larger physical footprints, making them less than ideal for precision applications such as MEMS devices	Improper configuration of these devices can lead to potentially harmful and uncontrolled static energy discharges.

Energy harvesting from mechanical vibration involves the conversion of vibration, kinetic movement, or deformation power into electrical energy. Energy harvesters have wide-angle energy sources ranging from the movement of humans and animals, industrial machinery, vehicles, large-scale infrastructure such as buildings and bridges, as well as natural elements such as water flow and wind. PE harvesters are recognized as promising autonomous energy sources for low-power electronic devices, including wireless sensors, portable gadgets, and medical implants [13,74]. The physical power (energy) derived from motion can be categorized into two forms: dynamic energy resulting from rigid body motion and spring energy stemming from elastic deformation [75]. Consequently, there has been a significant surge in proposed mechanical energy harvesting (MEH) systems over recent decades [38]. Mechanical energy sources for harvesting include vibrations, body movements, acoustic fluctuations, and airflow [61]. The electromechanical device's reception component needs to be precisely built to match the vibration source's mechanical and/or acoustic impedance to be used effectively [13].

4.2. Mothed of Piezoelectric Energy Harvesting and Optimization

There are various strategies to improve the performance of the energy harvesting systems, such as the selection of piezoelectric materials, their structural modifications, hybridization, the selection of proper substrates, and the selection of preparation methods for piezoelectric materials [6,9,51,70].

The selection of materials presents very good prospects for mechanical energy conversion because the materials have a good electromechanical coupling effect. The selection of piezoelectric materials used in piezoelectric energy harvesters is not only based on the piezoelectric property, but also based on the application and design of the host device or harvesting system. The input frequency, occupiable volume, and type of mechanical input are some of the factors in the application system that need to be considered in the piezoelectric material selection. Appropriate material selection ensures not only economic feasibility but also reliability, enhanced product life, as well as better quality. In recent years, industrial and academic research units have focused their attention on harvesting energy from vibrations using piezoelectric transducers. PEH has been also much simpler than, for example, electromagnetic or electrostatic devices [76].

The mechanism of PEH is based on the direct piezoelectric effect, i.e., if the harvester is subjected to stresses, charges will be generated on the materials' surface proportionally. In contemporary times, energy harvesting and storage represent critical technologies within the power domain, offering the potential to replace batteries or significantly prolong their lifespan. Around the early 2000s, the optimal design significantly impacted power output, hinging on factors such as the shape, type, and positioning of piezoelectric materials when affixed to beam structures. The most straightforward approach to enhance power output from any piezoelectric material involves devising a flexible mechanism for the piezoelectric harvester and strategically arranging the harvester elements [61].

The frequency of mechanical vibrations plays a major role in the selection and development of structural elements used in energy harvester models. They can be divided into two primary groups based on the operating frequency: non-resonant systems, which are frequency-independent, and resonance-type devices, which function at or close to their resonance frequency. To construct piezoelectric energy harvesters, the formation of the piezoelectric layer structure is essential. Various structural geometries have been employed for power harvesting, including cantilever beams, stacks, cymbals, and diaphragms, designed to capture energy from stress and frequency vibrations (see Figure 4 and Table 4). The advancement and selection of structural elements and modelling energy harvester depends on the frequency of mechanical vibrations. The most common structure with a high strain capacity is a cantilever beam loaded with piezoelectric materials, which, when deflected, produces electrical energy from mechanical vibration and can cause significant deformation. Its construction is also easy to understand. The geometry of a cantilever beam is a critical factor influencing its oscillation displacement, which plays a significant role in generating both piezoelectric and thermoelectric voltages, wherein the bending force experienced by piezoelectric components varies linearly with length. At the fixed end, the bending stress is maximum, and it tends to be zero at the free tip [5,74]. To harvest maximum power from the beam with low frequency environmental vibrations, the effect of proof mass, beam shape, and damping are important during the model for the performance optimization. The beam structure of this harvester is known by the unimorph or bimorph structural geometry. Unimorph structural geometry is a cantilever structure which is a combination of one active and one passive layer, whereas bimorph structural geometry is a cantilever structure which combines two active layers or two active layers with a passive layer in between them. The active layer can be made up of any piezoelectric material like zinc oxide (ZnO) or lead zirconate titanate (PZT), etc. Table 4 presents PEH with different cantilever beam shapes and output power. For example, the cymbal shape harvester applicable for high impact excitation with environmental dynamic loading can generate output power of 1.2 μW and the electrical energy of 97.33 V from the excitation frequency of 20 Hz [58,60,63]. Researchers have altered the typical rectangular shape to consider various geometries to achieve a uniform and large strain distribution on the used piezoelectric materials in cantilevered PEHs. The average output power for circular diaphragm geometry is about 6.06 mW/cm^3 [59]. Large numbers of thin piezoelectric materials can be placed together in the direction of the electric field to generate a stack structure in addition to the cantilever and cymbal structures [2]. As voltages are applied to multi-layer piezoelectric transducer, it can be used as an actuator. When external force is applied, it can be used as a sensor or energy harvester. The stack configuration allows large deformation output with low voltage input within a compact size [77–79].

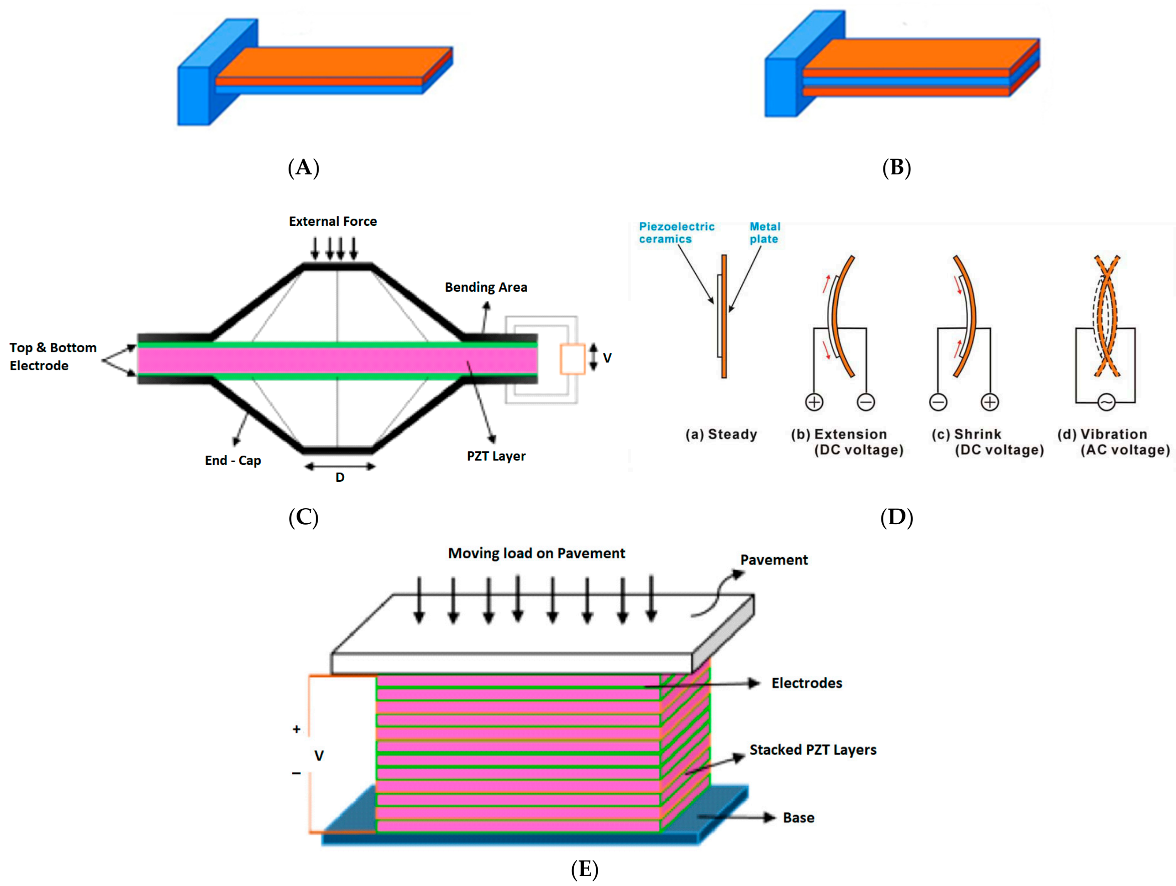


Figure 4. Structural configuration harvester (**A**) beam with unimorph geometry (**B**) beam with bimorph geometry (piezoelectric transducers are marked with orange), (**C**) cymbal geometry, (**D**) circular diaphragm geometry, and (**E**) stack geometry (the electrodes are marked by grey) [58–60].

Table 4. Piezoelectric energy harvester with different cantilever beam shapes and output power.

Cantilever Beam Shape	Power Output	Explanation and Reference
Triangle	0.64 W	Piezoelectric-based cantilever energy harvester with non-uniform width and height [80].
Rectangle Triangular Segment smooth Rectangle	6.549 W 10.7 W 13.8 W 13.9 W	Triangular cantilevers are ideal for low frequency applications because they produce the maximum vibration when deflected [81].
Triangular beam into some V-shaped beams	133.24 W	Bimorph V-shaped cantilevers and in comparison, with rectangular one, the simplest tapered cantilever beam can lead to maximum resonant frequency and highest sensitivity [82].

These diverse structural designs cater to different vibration scenarios, each exhibiting distinct capabilities and efficiencies in energy harvesting.

The fundamental challenge is to design a piezoelectric energy harvester that satisfies mechanical strength and reliability constraints and generates the maximum energy possible over a broad range of stress frequencies. Since the piezoelectric material can bend or deform in reaction to vibrational or mechanical stress, the support structure or mounting mechanism must be built with this in mind. Table 5 summarizes the four basic types of configurations for piezoelectric structures.

Table 5. The basic differences in piezoelectric structures with their advantages and disadvantages [16,83].

Structural Configuration	Advantage	Disadvantage
Stacked structure	Higher output from d33 mode Suitable for pressure mode operation Withstands high mechanical load	High stiffness.
Cymbal structure	Higher piezoelectric coefficient Higher charge generation Higher impact forces Easiness of fabrication and low cost	Limited resonant applications of cymbals, too low driving voltages. Manufacturing problems.
Rounded (circular) structure	Great potential for a wide range of actuation and sensors applications	Stiffer than a cantilever of the same size. Bulky and costly power amplification system.
Rectangular Beam structure	Compact and lightweight Efficient in converting mechanical energy to electrical or vice versa.	Inability to resist a high impact force.

In general, enhancing the performance and efficiency of piezoelectric harvesters involves exploring different design parameters such as shape, size, material properties, damping factors, and electromechanical parameters [84,85]. The structure of vibration absorbers is usually designed to have high damping factor capabilities while efficient energy harvesters need low damping factors; therefore, they are not effective for reductions in vibration. The design of an integrated device needs to consider the two conflicting requirements of the damping process [86]. Electromechanical coupling is an important parameter for piezoelectric materials as the energy harvester depends on the efficiency of the energy converters. The electromechanical coupling factor is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy or converts mechanical energy into electrical energy. It is the ratio of a stored mechanical energy to the input electrical energy, or the ratio of a stored electrical energy to the input mechanical energy. It depends on the direction of the applied electric field and on the mechanical strain (or stress) direction (from Equation (18)). The efficiency of piezoelectric transducers for energy harvesting is influenced by factors like resistance, frequency, and the electromechanical coupling coefficient in relation to the mechanical damping ratio. Optimizing the electrical load is essential for maximizing conversion performance, where electrical damping differs significantly from maximizing harvested power in strongly coupled electromechanical systems [87]. While mechanical vibration energy is abundant and easily accessible in the natural environment, the frequency of vibration sources is predominantly random, resulting in an unstable energy harvester output. When the natural frequency of the piezoelectric energy harvesting device matches the input frequency, the frequency response of the device operates at its best [16]. Therefore, frequency compensation techniques are applied to improve the overall output of the device [88]. Various modeling approaches are employed to simulate piezoelectric energy harvesters. The lumped parameter model, focusing on the dynamic behavior of energy harvesters, provides a single degree of freedom and is limited to the modal analysis. Another model, the Rayleigh–Ritz model, based on Bernoulli beam theory, offers a more accurate representation as a discretized model of the distributed parameter system. However, it tends to slightly overestimate natural frequencies and may not adequately describe the behavior of shorter beams due to its limitation in accounting for shear deformation across the beam's cross-section. To address this limitation, the Timoshenko beam theory considers shear deformation in the cross-section, providing a more reasonable approximation. Finally, the finite element model stands as one of the most precise approaches for energy harvesting. It discretizes equations and analyzes the structure in a highly accurate manner. In order to determine the highest-power-output form for cantilever beams subject to tip impact excitations, a finite element model was constructed using ANSYS.

Table 6 presents the juxtaposition of different energy harvesters based on piezoelectric materials presented in various research papers. The table includes the output power of the considered system, its operating frequency, generated electrical current voltage, the displacement the system was subjected to, and the volume of piezoelectric material (in cases where these data were available), as well as details and any comments regarding the studied system.

Table 6. Analysis of different piezoelectric harvesting materials [63].

Piezo Materials and Reference	Power Output	Frequency	Voltages	Displacement	Volume	Details
Lead based PZT [58]	52 mW	100 Hz	-	-	1.5 cm^3	The output of piezoelectric depends not only on their properties but also on parameters such as the amount of material used, design flexibility, and functionality of the application.
Lead-free $BaTiO_3$ [59]	7 mW/cm^3	100 Hz	-	-		
Piezoelectric cantilever beam with copper as substrate and PZT-5H [16]	14.85 µw	345.75 Hz	595.5 mV	70.9 µm	-	In terms of length, width, and thickness in millimeters, the piezoelectric cantilever beam for energy harvesting was 12 × 2.5 × 0.03 for piezoelectric layers.
Multi degree of micro energy harvester [71]	136 nW	97 Hz	1 V			The power output could be improved by increasing the size of the harvesting region, using different piezoelectric configurations or materials, and using more efficient electrical circuits.
Piezoelectric energy harvesters with aluminum nitride [89]	60 µW	572 Hz				Measurements of the output power obtained from mechanical vibrations have been made on micromachined harvesters with various geometries.
Piezoelectric material used is PZT-PZNM [90]	0.8 mW	20 Hz				Modeling and parametric analysis for performance improvement in piezoelectric energy harvesting tile.

Table 6. *Cont.*

Piezo Materials and Reference	Power Output	Frequency	Voltages	Displacement	Volume	Details
Transverse mode type piezoelectric generator model based on Euler–Bernoulli beam theory [84,91]	2.6 mW	13.4 Hz		0.5 m		Piezoelectric material location is important to the output power. Power generated from a cantilever steel beam with harmonic oscillations using PZT-PIC.
A thin-film PZT based MEMS power-generating device [92]	1.01 μW	150 Hz	2.4 V	-		To offer design guidelines for maximum power harvesting from environmentally available low frequency vibrations, the effects of proof mass, beam shape, and damping on the harvesting performance are studied.
Rotational piezoelectric energy harvester with storage system [85]	83.5–825 μW	7–13.5 Hz		-		Based on the experiment: the power output of 83.5–825 μW can be achieved at the rotating frequencies of 7–13.5 Hz. Provides enhanced configuration versatility in geometric parameters to frequencies and higher power. The harvester can extract enough energy from rotational motion.

In fact, the use of nonuniform structures could increase the coupling performance, and energy harvesters with alternative geometries have been shown to be of interest. For example, variations in the width (trapezoidal shape) of a beam can increase the efficiency, as was mentioned previously in this paper [17,70].

Energy harvesting technology is based on mechanical vibration, mechanical stress and strain, thermal energy from furnaces, heaters and friction sources, sun light or room light, the human body, chemical or biological sources, which can generate between μW and mW level power. To achieve the desired piezoelectric effect, the materials are usually attached to mechanical structures (such as flexible beams) that have the capacity to undergo deformation because of mechanical vibration, hence creating strain in the material [17,20].

The total power generated and the frequency at which vibration-based energy harvesters can successfully gather ambient vibrations for power generation are currently the limits of these devices. To enhance the performance of this technology, an effective technique to improve the output of ambient vibration-based energy harvesters, such as the amplification method, techniques for tuning harmonics, and introducing nonlinear oscillations, is important. The relationship between the harvested output power and the differential constant is simple. Electromechanical coupling depends on the electrical capacitance, which in turn depends on both the area and the shape of the piezoelectric device. To further enhance collection efficiency, methods combining multiple conversion mechanisms are being gradually adopted. One such method involves designing a flexible piezoelectric–thermoelectric hybrid energy harvester capable of harvesting more electrical energy from a single vibration [1,2,68].

Another method for enhancing performance involves utilizing modes 33 and 31 in PEH, which correspond to the direction of mechanical force and electrical charge collection. Figure 5 presents the coupling mode operation of 31 and 33 [7,80]. These modes have played a key role in performance enhancement. The d_{31} mode, the polarization direction "3", i.e., the electrical field, is perpendicular to the direction of the applied stress "1". This is the most used operation mode, and widely exists in bending-beam structures. Polarization and the applied stress are in the same direction in the d_{33} mode. The d_{33} mode appears in direct compressive/tensile harvesters or harvesters with the interdigitated electrode. In both the d_{31} and d_{33} modes, electrodes are made perpendicular to the poling direction, i.e., the electric field is aligned with the polarization [2,74]. The overall output of scavenged ambient energy depends on both the design of the device and the amplitude and frequency of the source vibrations.

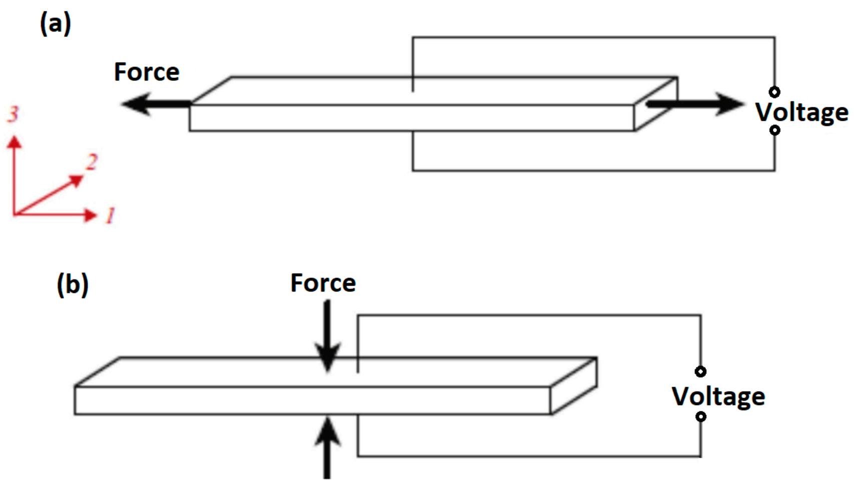


Figure 5. The 31 (**a**) and 33 (**b**) coupling modes of operation [2].

The energy extracted from low environmental excitations by piezoelectric materials can drastically lower the device's performance. The process of frequency up conversion involves raising the source frequency to efficiently extract energy from low frequency vibrations. The harvested energy reaches maximum value when the base excitation matches the natural frequency of the harvester. Another method for performance enhancement is optimize electrode to improve output power. The interdigitated electrodes (IDEs) in cantilever energy harvesters were theoretically examined and optimized. The harvester's performance is greatly impacted by the electrode size, IDE finger count, and piezoelectric thickness. It was determined that although the IDEs cannot produce more power than standard parallel plate electrodes, they can exhibit higher voltage responses [93].

5. Conclusions and Future Perspectives

This research involved the modeling of vibration-based piezoelectric energy, energy harvesting methodologies, and performance optimization, with a specific focus on composite smart materials. In this paper, the fundamental principles underlying energy modeling, performance optimization, and the characteristics of piezoelectric materials were investigated. Notably, advancements in piezoelectric composite materials, such as macro fiber composites (MFCs), have addressed challenges observed in monolithic piezoceramic counterparts, particularly brittleness, unreliability, and lack of conformability. This review emphasized the significance of factors such as resistance, frequency, electromechanical coupling coefficients, and mechanical damping ratios in determining the energy harvesting efficiency of piezoelectric transducers. In particular, macro fiber composites exhibit a remarkable ability to directly harvest energy from ambient vibrations, presenting substantial potential for various commercial and industrial applications. Energy harvesting remains pivotal for self-powered systems, especially within the rapidly growing market of portable and wireless electronics. Therefore, comprehensive modeling and performance analysis encompassing both mechanical and electrical energy parameters stand as critical factors in the development and application of PEH materials.

The proposed work outlined in this review emphasizes the optimization of piezoelectric energy harvesting as an alternative energy source. The primary goal is to establish a pollution-free energy resource by efficiently harnessing and utilizing wasted energy. In addition, it provides insights into the operational principles of piezoelectric energy harvesters and explores various geometric structures tailored for different energy sources.

This pursuit to obtain the best efficiency of energy harvester necessitates meticulous attention to detail and precision in design. To optimize energy harvesting, it is crucial to consider converting the piezoelectric substance's construction or employing advanced power harvesting material. Moreover, achieving enhanced efficiency in energy harvesting involves addressing the power output and voltage requirements, ensuring compatibility with the targeted applications. Implementing adaptive control mechanisms can further improve the energy conversion process, enabling better performance across varying conditions. Ultimately, the continuous advancement and innovation in piezoelectric materials and their integration into energy harvesting systems hold the promise of creating sustainable and efficient power sources, particularly in resource-constrained environments and for powering remote small-scale wearable devices.

This work underscores the pivotal role of optimizing piezoelectric energy utilization as an alternative energy source. To maximize the utilization of energy currently going to waste, aiming to establish an environmentally friendly energy resource. Analyzing the mechanism of piezoelectric energy harvesters and exploring diverse geometric structures enables the application of this technology across various energy sources, crucial for effective energy extraction from the surroundings.

To conclude the work, it can be pointed out that piezoelectric energy stands as a potential significant energy source, particularly in harnessing energy that is currently lost or unused. Selecting appropriate materials, optimizing their alignment, and understanding key parameters (such as resistance, frequency, and electromechanical coupling coefficients) are critical for effective and efficient piezoelectric energy harvesting.

This review lays the foundation for future investigations and development in optimizing piezoelectric energy utilization, suggesting the need for continued experimentation and numerical modelling using appropriate software to select optimal materials and structures for various energy applications.

Author Contributions: All authors have contributed substantially to the review presented. Conceptualization and methodology, D.G.W. and M.Ł.P.; writing original draft preparation, D.G.W. and writing review and editing, D.G.W. and M.Ł.P. All authors have read and agreed to the published version of the manuscript.

Funding: This review article has not received external funding.

Data Availability Statement: In the manuscript, pertinent information for the reviews has been incorporated.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Anton, S.R.; Sodano, H.A. A review of power harvesting using piezoelectric materials (2003–2006). *Smart Mater. Struct.* **2007**, *16*, R1. [CrossRef]
2. Sezer, N.; Koç, M. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. *Nano Energy* **2021**, *80*, 105567. [CrossRef]
3. Design, Modeling, and Analysis of Piezoelectric Energy Harvesters. Ph.D. Thesis, Aalborg University, Aalborg, Denmark, 2021. Available online: https://vbn.aau.dk/en/publications/design-modeling-and-analysis-of-piezoelectric-energy-harvesters (accessed on 15 November 2023).
4. Wang, Y.; Zhang, L.; Song, Y.; Han, K.; Zhang, Y.; Zhu, Y.; Kang, L. State-of-the-art review on evaluation indicators of integrated intelligent energy from different perspectives. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113835. [CrossRef]
5. Kim, S.B.; Shin, J.; Kim, H.S.; Lee, D.G.; Park, J.C.; Baik, J.M.; Kim, S.Y.; Kang, C.-Y.; Choi, W.; Song, H.-C.; et al. A synergetic effect of piezoelectric energy harvester to enhance thermoelectric Power: An effective hybrid energy harvesting method. *Energy Convers. Manag.* **2023**, *298*, 1174. [CrossRef]
6. Cao, Y.; Huang, H. Performance optimization and broadband design of piezoelectric energy harvesters based on isogeometric topology optimization framework. *Eur. J. Mech. A/Solids* **2023**, *97*, 104800. [CrossRef]
7. Yildirim, T.; Ghayesh, M.H.; Li, W.; Alici, G. A Review on Performance Enhancement Techniques for Ambient Vibration Energy Harvesters. Available online: https://ro.uow.edu.au/eispapers1 (accessed on 15 November 2023).
8. Clementi, G.; Ouhabaz, M.; Margueron, S.; Suarez, M.A.; Bassignot, F.; Gauthier-Manuel, L.; Belharet, D.; Dulmet, B.; Bartasyte, A. Highly coupled and low frequency vibrational energy harvester using lithium niobate on silicon. *Appl. Phys. Lett.* **2021**, *119*, 013904. [CrossRef]
9. Bairagi, S.; Shahid-ul-Islam Shahadat, M.; Mulvihill, D.M.; Ali, W. Mechanical energy harvesting and self-powered electronic applications of textile-based piezoelectric nanogenerators: A systematic review. *Nano Energy* **2023**, *111*, 108414. [CrossRef]

10. Chen, N.; Jung, H.J.; Jabbar, H.; Sung, T.H.; Wei, T. A piezoelectric impact-induced vibration cantilever energy harvester from speed bump with a low-power power management circuit. *Sens. Actuators A Phys.* **2017**, *254*, 134–144. [CrossRef]
11. Sarker, M.R.; Julai, S.; Sabri, M.F.M.; Said, S.M.; Islam, M.M.; Tahir, M. Review of piezoelectric energy harvesting system and application of optimization techniques to enhance the performance of the harvesting system. *Sens. Actuators A Phys.* **2019**, *300*, 111634. [CrossRef]
12. Ortiz, J.; Zabala, N.; Monje, P.M.; Cokonaj, V.; Aranguren, G. Energy generation based on piezoelectric transducers. *Renew. Energy Power Qual. J.* **2013**, *1*, 245–250. [CrossRef]
13. Uchino, K.; Ishii, T. Energy flow analysis in piezoelectric energy harvesting systems. *Ferroelectrics* **2010**, *400*, 305–320. [CrossRef]
14. Uchino, K. Piezoelectric Energy Harvesting Systems—Essentials to Successful Developments. *Energy Technol.* **2018**, *6*, 829–848. [CrossRef]
15. Todaro, M.T.; Guido, F.; Algieri, L.; Mastronardi, V.M.; Desmaele, D.; Epifani, G.; De Vittorio, M. Biocompatible, Flexible, and Compliant Energy Harvesters Based on Piezoelectric Thin Films. *IEEE Trans. Nanotechnol.* **2018**, *17*, 220–230. [CrossRef]
16. Covaci, C.; Gontean, A. Piezoelectric Energy Harvesting Solutions: A Review. *Sensors* **2020**, *20*, 3512. [CrossRef] [PubMed]
17. Liang, H.; Hao, G.; Olszewski, O.Z. A review on vibration-based piezoelectric energy harvesting from the aspect of compliant mechanisms. *Sens. Actuators A Phys.* **2021**, *331*, 112743. [CrossRef]
18. Ahmed, R.; Mir, F.; Banerjee, S. A review on energy harvesting approaches for renewable energies from ambient vibrations and acoustic waves using piezoelectricity. *Smart Mater. Struct.* **2017**, *26*, 085031. [CrossRef]
19. Zhao, X.; Zhou, Y.; Xu, J.; Chen, G.; Fang, Y.; Tat, T.; Xiao, X.; Song, Y.; Li, S.; Chen, J. Soft fibers with magnetoelasticity for wearable electronics. *Nat. Commun.* **2021**, *12*, 6755. [CrossRef]
20. Kim, H.S.; Kim, J.H.; Kim, J. A review of piezoelectric energy harvesting based on vibration. *Int. J. Precis. Eng. Manuf.* **2011**, *12*, 1129–1141. [CrossRef]
21. Płaczek, M.; Kokot, G. Modelling, and laboratory tests of the temperature influence on the efficiency of the energy harvesting system based on MFC piezoelectric transducers. *Sensors* **2019**, *19*, 1558. [CrossRef] [PubMed]
22. Yan, L.; Rodriguez, J.; Billon, K.; Lallart, M.N.; Collet, M.; Jean-Mistral, C.; Chesné, S. Energy Harvesting using Integrated Piezoelectric Transducer in a Composite Smart Structure for Self-powered Sensor Applications. *J. Intell. Mater. Syst. Struct.* **2023**, *34*, 825–835. [CrossRef]
23. Li, T.; Lee, P.S. Piezoelectric Energy Harvesting Technology: From Materials, Structures, to Applications. *Small Struct.* **2022**, *3*, 2100128. [CrossRef]
24. Jaiswal, K.K.; Chowdhury, C.R.; Yadav, D.; Verma, R.; Dutta, S.; Jaiswal, K.S.; B, S.; Karuppasamy, K.S.K. Renewable and sustainable clean energy development and impact on social, economic, and environmental health. *Energy Nexus* **2022**, *7*, 100118. [CrossRef]
25. Muñoz, C.Q.G.; Alcalde, G.Z.; Márquez, F.P.G. Analysis and Comparison of Macro Fiber Composites and Lead Zirconate Titanate (PZT) Discs for an Energy Harvesting Floor. *Appl. Sci.* **2020**, *10*, 5951. [CrossRef]
26. Pang, S.; Li, W.; Kan, J. Optimization Analysis of Interface Circuits in Piezoelectric Energy Harvesting Systems. *J. Power Technol.* **2016**, *96*, 1–7.
27. Shu, Y.C.; Lien, I.C. Efficiency of energy conversion for a piezoelectric power harvesting system. *J. Micromech. Microeng.* **2006**, *16*, 2429–2438. [CrossRef]
28. Stamatellou, A.-M.; Kalfas, A.I. On the Efficiency of a Piezoelectric Energy Harvester under Combined Aeroelastic and Base Excitation. *Micromachines* **2021**, *12*, 962. [CrossRef] [PubMed]
29. Gamboa, B.M.; Guo, R.; Bhalla, A. Piezoelectric stacked transducer evaluation and comparison for optimized energy harvesting. *Ferroelectrics* **2018**, *535*, 8–17. [CrossRef]
30. Atif, R.; Khaliq, J.; Combrinck, M.; Hassanin, A.H.; Shehata, N.; Elnabawy, E.; Shyha, I. Solution Blow Spinning of Polyvinylidene Fluoride Based Fibers for Energy Harvesting Applications: A Review. *Polymers* **2020**, *12*, 1304. [CrossRef] [PubMed]
31. Beeby, S.P.; Tudor, M.J.; White, N.M. Energy harvesting vibration sources for microsystems applications. *Meas. Sci. Technol.* **2006**, *17*, R175–R195. [CrossRef]
32. Maghsoudi Nia, E.; Wan Abdullah Zawawi, N.A.; Mahinder Singh, B.S. Design of a pavement using piezoelectric materials. *Mater. Werkst.* **2019**, *50*, 320–328. [CrossRef]
33. Mahapatra, S.D.; Mohapatra, P.C.; Aria, A.I.; Christie, G.; Mishra, Y.K.; Hofmann, S.; Thakur, V.K. Piezoelectric Materials for Energy Harvesting and Sensing Applications: Roadmap for Future Smart Materials. *Adv. Sci.* **2021**, *8*, 2100864. [CrossRef]
34. Jia, Y.; Wei, X.; Xu, L.; Wang, C.; Lian, P.; Xue, S.; Al-Saadi, A.; Shi, Y. Multiphysics vibration FE model of piezoelectric macro fibre composite on carbon fibre composite structures. *Compos. Part B Eng.* **2019**, *161*, 376–385. [CrossRef]
35. Morimoto, K.; Kanno, I.; Wasa, K.; Kotera, H. High-efficiency piezoelectric energy harvesters of c-axis-oriented epitaxial PZT films transferred onto stainless steel cantilevers. *Sens. Actuators A Phys.* **2010**, *163*, 428–432. [CrossRef]
36. Mishra, S.; Unnikrishnan, L.; Nayak, S.K.; Mohanty, S. Advances in Piezoelectric Polymer Composites for Energy Harvesting Applications: A Systematic Review. *Macromol. Mater. Eng.* **2019**, *304*, 1800463. [CrossRef]
37. Priya, S.; Song, H.C.; Zhou, Y.; Varghese, R.; Chopra, A.; Kim, S.G.; Kanno, I.; Wu, L.; Ha, D.S.; Ryu, J.; et al. A Review of Piezoelectric Energy Harvesting: Materials, Methods, and Circuits. *Energy Harvest. Syst.* **2019**, *4*, 3–39. [CrossRef]

38. Maamer, B.; Boughamoura, A.; Fath El-Bab, A.M.; Francis, L.A.; Tounsi, F. A review on design improvements and techniques for mechanical energy harvesting using piezoelectric and electromagnetic schemes. *Energy Convers. Manag.* **2019**, *199*, 111973. [CrossRef]
39. Wang, Z.L.; Song, J. Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays. Available online: https://www.science.org (accessed on 15 November 2023).
40. Karami, M.A.; Bilgen, O.; Inman, D.J.; Friswell, M.I. Experimental and analytical parametric study of single-crystal unimorph beams for vibration energy harvesting. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2011**, *58*, 1508–1520. [CrossRef] [PubMed]
41. Jaita, P.; Jarupoom, P.; Sweatman, D.R.; Rujijanagul, G. Energy harvesting, electrical, and magnetic properties of potassium bismuth titanate-based lead-free ceramics. *J. Asian Ceram. Soc.* **2021**, *9*, 947–963. [CrossRef]
42. Baek, C.; Park, H.; Hyuk Yun, J.; Kyung Kim, D.; Park, K.-I. Lead-free $BaTiO_3$ Nanowire Arrays-based Piezoelectric Energy Harvester. *MRS Adv.* **2017**, *2*, 3415–3420. [CrossRef]
43. Panda, P.K. Review: Environmentally friendly lead-free piezoelectric materials. *J. Mater. Sci.* **2009**, *44*, 5049–5062. [CrossRef]
44. Zheng, M.; Hou, Y.; Chao, L.; Zhu, M. Piezoelectric KNN ceramic for energy harvesting from mechanochemically activated precursors. *J. Mater. Sci. Mater. Electron.* **2018**, *29*, 9582–9587. [CrossRef]
45. Vatansever, D.; Hadimani, R.L.; Shah, T.; Siores, E. An investigation of energy harvesting from renewable sources with PVDF and PZT. *Smart Mater. Struct.* **2011**, *20*, 055019. [CrossRef]
46. Granstrom, J.; Feenstra, J.; Sodano, H.A.; Farinholt, K. Energy harvesting from a backpack instrumented with piezoelectric shoulder straps. *Smart Mater. Struct.* **2007**, *16*, 1810–1820. [CrossRef]
47. Keat, C.K.; Leong, K.S.; Tee, L.K. An experimental investigation of piezoelectric P(VDF-TrFE) thick film on flexible substrate as energy harvester. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *210*, 012078. [CrossRef]
48. Hamlehdar, M.; Kasaeian, A.; Safaei, M.R. Energy harvesting from fluid flow using piezoelectrics: A critical review. *Renew. Energy* **2019**, *143*, 1826–1838. [CrossRef]
49. Zhao, L.; Yang, Y. An impact-based broadband aeroelastic energy harvester for concurrent wind and base vibration energy harvesting. *Appl. Energy* **2018**, *212*, 233–243. [CrossRef]
50. Izadgoshasb, I.; Lim, Y.Y.; Lake, N.; Tang, L.; Padilla, R.V.; Kashiwao, T. Optimizing orientation of piezoelectric cantilever beam for harvesting energy from human walking. *Energy Convers. Manag.* **2018**, *161*, 66–73. [CrossRef]
51. Pandey, A.; Arockiarajan, A. Performance studies on Macro fiber composite (MFC) under thermal condition using Kirchhoff and Mindlin plate theories. *Int. J. Mech. Sci.* **2017**, *130*, 416–425. [CrossRef]
52. Sodano, H.A. Macro-Fiber Composites for Sensing, Actuation and Power Generation. Ph.D. Thesis, Virginia Tech, Blacksburg, VA, USA, 2003. Available online: https://vtechworks.lib.vt.edu/handle/10919/34289 (accessed on 15 November 2023).
53. Enab, T.A.; Enab, T.A.A. Prediction of Effective Electromechanical Coupling Coefficient for Segmented Piezoelectric Fiber Composites. 2006. Available online: https://www.researchgate.net/publication/236340581/ (accessed on 31 January 2024).
54. Khaligh, A.; Zeng, P.; Zheng, C. Kinetic Energy Harvesting Using Piezoelectric and Electromagnetic Technologies—State of the Art. *IEEE Trans. Ind. Electron.* **2010**, *57*, 850–860. [CrossRef]
55. Płaczek, M. Modelling and production process of the energy harvesting system based on MFC piezoelectric transducers. *Int. J. Mod. Manuf. Technol.* **2020**, *XII*, 106–114.
56. Kuang, Y.; Zhu, M. Evaluation and validation of equivalent properties of macro fibre composites for piezoelectric transducer modelling. *Compos. Part B Eng.* **2019**, *158*, 189–197. [CrossRef]
57. Sodano, H.A.; Park, G.; Inman, D.J. An investigation into the performance of macro-fiber composites for sensing and structural vibration applications. *Mech. Syst. Signal Process.* **2004**, *18*, 683–697. [CrossRef]
58. Aldahiry, D.A.; Bajaba, D.A.; Basalamah, N.M.; Ahmed, M.M. Piezoelectric Transducer as an Energy Harvester: A Review. *Yanbu J. Eng. Sci.* **2022**, *19*, 30–35. [CrossRef]
59. Kumari, N.; Trivedi, A. A review on modelling and techniques used for piezoelectric power generation from vibration of geo-structures. *e-Prime-Adv. Electr. Eng. Electron. Energy* **2022**, *2*, 100076.
60. Li, H.; Tian, C.; Deng, Z.D. Energy harvesting from low frequency applications using piezoelectric materials. *Appl. Phys. Rev.* **2014**, *1*, 041301. [CrossRef]
61. Lee, J.H.; Kim, J.; Kim, T.Y.; Al Hossain, M.S.; Kim, S.W.; Kim, J.H. All-in-one energy harvesting and storage devices. *J. Mater. Chem. A Mater.* **2016**, *4*, 7983–7999. [CrossRef]
62. Williams, R.B.; Park, G.; Inman, D.J.; Keats Wilkie, W. An overview of composite actuators with piezoceramic fibers. *Proc. IMAC XX* **2002**, *47*, 130.
63. Hajheidari, P. Performance Enhancement of Cantilever Beam Piezoelectric Energy Harvesters. Ph.D. Thesis, Concordia University, Montreal, QC, Canada, 2020.
64. Jemai, A.; Najar, F.; Chafra, M.; Ounaies, Z. Mathematical modeling of an active-fiber composite energy harvester with interdigitated electrodes. *Shock. Vib.* **2014**, *2014*, 971597. [CrossRef]
65. Zhang, J.; Yang, Y.; Lou, J.; Wei, Y.; Fu, L. Development, and hybrid position/force control of a dual-drive macro-fiber-composite microgripper. *Sensors* **2018**, *18*, 1301. [CrossRef] [PubMed]
66. Saravanan, M.P.; Marimuthu, K.; Jayabal, K. Characteristic investigation of macro fiber composite structure using FE model. *Arch. Met. Mater.* **2021**, *66*, 1059–1066. [CrossRef]
67. Priya, S.; Inman, D.J. *Energy Harvesting Technologies*; Springer: New York, NY, USA, 2009.

68. Song, H.C.; Kim, S.W.; Kim, H.S.; Lee, D.G.; Kang, C.Y.; Nahm, S. Piezoelectric Energy Harvesting Design Principles for Materials and Structures: Material Figure-of-Merit and Self-Resonance Tuning. *Adv. Mater.* **2020**, *32*, e2002208. [CrossRef] [PubMed]
69. Sharma, S.; Kiran, R.; Azad, P.; Vaish, R. A review of piezoelectric energy harvesting tiles: Available designs and future perspective. *Energy Convers. Manag.* **2022**, *254*, 115272. [CrossRef]
70. Viswanath Allamraju, K.; Srikanth, K. State of art: Piezoelectric Vibration Energy Harvesters. *Mater. Today Proc.* **2017**, *4*, 1091–1098. [CrossRef]
71. Rezaeisaray, M.; El Gowini, M.; Sameoto, D.; Raboud, D.; Moussa, W. Low frequency piezoelectric energy harvesting at multi vibration mode shapes. *Sens. Actuators A Phys.* **2015**, *228*, 104–111. [CrossRef]
72. Sojan, S.; Kulkarni, R.K. A Comprehensive Review of Energy Harvesting Techniques and their Potential Applications. *Int. J. Comput. Appl.* **2016**, *139*, 14–19. [CrossRef]
73. Poulin, G.; Sarraute, E.; Costa, F. Generation of electrical energy for portable devices: Comparative study of an electromagnetic and a piezoelectric system. *Sens. Actuators A Phys.* **2004**, *116*, 461–471. [CrossRef]
74. Yang, Z.; Zhou, S.; Zu, J.; Inman, D. High-Performance Piezoelectric Energy Harvesters and Their Applications. *Joule* **2018**, *2*, 642–697. [CrossRef]
75. Zhou, M.; Al-Furjan, M.S.H.; Zou, J.; Liu, W. A review on heat and mechanical energy harvesting from humans—Principles, prototypes, and perspectives. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3582–3609. [CrossRef]
76. Li, X.; Guo, M.; Dong, S. A flex-compressive-mode piezoelectric transducer for mechanical vibration/strain energy harvesting. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2011**, *58*, 698–703. [CrossRef]
77. Zhang, Y.; Lu, T.-F.; Peng, Y. Three-port equivalent circuit of multi-layer piezoelectric stack. *Sens. Actuators A Phys.* **2015**, *236*, 92–97. [CrossRef]
78. Degefa, T.G.; Wróbel, A.; Płaczek, M. Modelling, and study of the effect of geometrical parameters of piezoelectric plate and stack. *Appl. Sci.* **2021**, *11*, 11872. [CrossRef]
79. Kim, Y.-H. The effect of rectangular synthetic jet to the flat plate boundary layer in low Reynolds number. *EPJ Web Conf.* **2012**, *25*, 01101. [CrossRef]
80. Varadha, E.; Rajakumar, S. Performance improvement of piezoelectric materials in energy harvesting in recent days—A review. *J. Vibroeng.* **2018**, *20*, 2632–2650. [CrossRef]
81. Goldschmidtboeing, F.; Woias, P. Characterization of different beam shapes for piezoelectric energy harvesting. *J. Micromech. Microeng.* **2008**, *18*, 104013. [CrossRef]
82. Hosseini, R.; Hamedi, M. Resonant frequency of bimorph triangular V-shaped piezoelectric cantilever energy harvester. *J. Comput. Appl. Res. Mech. Eng. (JCARME)* **2016**, *16*, 65–73.
83. Qi, L.; Pan, H.; Pan, Y.; Luo, D.; Yan, J.; Zhang, Z. A review of vibration energy harvesting in rail transportation field. *iScience* **2022**, *25*, 103849. [CrossRef] [PubMed]
84. Ket Thein, C.; Lee Ooi, B.; Liu, J.; Gilbert, J.M. Modelling and optimization of a bimorph piezoelectric cantilever beam in an energy harvesting application. *J. Eng. Sci. Technol.* **2016**, *11*, 212–227.
85. Guan, M.; Liao, W.-H. Design and analysis of a piezoelectric energy harvester for rotational motion system. *Energy Convers. Manag.* **2016**, *111*, 239–244. [CrossRef]
86. Perfetto, S.; Infante, F.; Mayer, D.; Herold, S. Impact of Damping Factor on the Effectiveness of an Energy Harvesting Vibration Absorber. Available online: https://www.researchgate.net/publication/329238533/ (accessed on 31 January 2024).
87. Chang, S.H.; Rogacheva, N.N.; Chou, C.C. Analysis of methods for determining electromechanical coupling coefficients of piezoelectric elements. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **1995**, *42*, 630–640. [CrossRef]
88. Gu, S.; Xu, W.; Xi, K.; Luo, A.; Fan, K.; Wang, F. High-performance piezoelectric energy harvesting system with anti-interference capability for smart grid monitoring. *Renew. Energy* **2024**, *221*, 119742. [CrossRef]
89. Elfrink, R.; Kamel, T.M.; Goedbloed, M.; Matova, S.; Hohlfeld, D.; Van Andel, Y.; Van Schaijk, R. Vibration energy harvesting with aluminum nitride-based piezoelectric devices. *J. Micromech. Microeng.* **2009**, *19*, 094005. [CrossRef]
90. Adhikari, J.; Kumar, R.; Jain, S.C. Modeling and parametric analysis for performance improvement in piezoelectric energy harvesting tile. *Ferroelectrics* **2021**, *573*, 201–213. [CrossRef]
91. Lesieutre, G.A.; Ottman, G.K.; Hofmann, H.F. Damping because of piezoelectric energy harvesting. *J. Sound Vib.* **2004**, *269*, 991–1001. [CrossRef]
92. Nabavi, S.; John's, S.; Newfoundland, C. *Design and Optimization of Piezoelectric MEMS Vibration Energy Harvesters*; Memorial University of Newfoundland: St. John's, NL, Canada, 2019.
93. Kim, M.; Dugundji, J.; Wardle, B.L. Effect of electrode configurations on piezoelectric vibration energy harvesting performance. *Smart Mater. Struct.* **2015**, *24*, 045026. [CrossRef]