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Design Configurations, Application and Fatigue Reliability of Piezoelectric Vibration Energy Harvesters: A Comprehensive Review

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Abstract

Piezoelectric vibration energy harvesting (PVEH) has attracted sustained interest due to its potential to power low-consumption electronics by converting ambient mechanical energy into electricity. Despite the proliferation of research, existing reviews often treat structural design, application scenarios, and long-term reliability as separate topics, leaving a gap in integrating this understanding. This paper presents a critical review that systematically synthesizes these three interconnected dimensions. Firstly, the PVEH configurations, namely cantilever, cymbal, stacked, and flexible structure, were discussed, with an emphasis on output characteristics, operational bandwidth, and application suitability. Then, the practical deployments across various sectors were examined, including wearable electronics, structural health monitoring, and industrial wireless sensors, which highlighted the gap between laboratory performance and actual requirements. A distinctive focus is placed on fatigue life, an often overlooked yet critical factor that limits long-term reliability, by analyzing common failure modes, material degradation mechanisms, experimental protocols, and existing modeling approaches. By comparing findings across studies and identifying methodological inconsistencies, this review clarifies current research bottlenecks and outlines a coherent direction for future work, particularly the need for standardized testing protocols and integrated design frameworks that balance power output with durability. Hence, this review distinguishes itself from prior works by offering a cross-cutting synthesis of design, application, and reliability, rather than treating them in isolation.

Keywords: Piezoelectric; Vibration energy harvester; Geometric optimization; Fatigue life; Design and application.

1. Introduction

The research on vibration energy harvesting has made significant progress in recent decades. The benefits of vibration energy include resistance to electrical disturbance, a wide range of sources, high electromechanical coupling efficiency, and high energy density. In order to charge or provide electricity for self-powered wireless sensors and support for network configuration or intelligent systems, the vibrations produced by structures such as buildings, oceans, bridges, and vehicles can be gathered. Exploring vibration energy harvesting technology to power wireless sensors and mobile electronic devices autonomously is a promising endeavor.

Typically, electromagnetic, electrostatic, and piezoelectric technologies capture vibrational energy. Due to their small size, immunity to electromagnetic interference, and simplicity of downsizing, most researchers are interested in piezoelectric technologies. Numerous applications involving noise reduction, environmental monitoring, and energy harvesting from vibration devices can benefit significantly from the piezoelectric effect [1]. In the context of green and renewable energy sources, it is essential for the operation of low-power electronic equipment. Piezoelectric vibration energy harvesters (PVEH) have been the subject of extensive material and mechanical application research, which isan intelligent system designed to transform mechanical vibrations from the environment into usable electrical power.

Considerable efforts have been devoted to optimizing the structural configurations and output performance of PVEH [1]. Yet technology remains far from widespread adoption due to persistent obstacles: (1) Insufficient experimental validation under realistic conditions; (2) the need for miniaturization and system integration; and (3) Premature performance degradation caused by fatigue damage under repeated loading. Existing reviews have largely treated these challenges in isolation, some focusing on structural innovations, others on materials or fabrication,

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with reliability addressed only fragmentarily. A comprehensive synthesis connecting design strategies to application demands while critically assessing fatigue-related limitations is still lacking. This gap matters because design choices that maximize power output often exacerbate fatigue susceptibility, a trade-off that must be addressed for practical devices.

This review aims to fill this gap by offering an integrated examination across three interconnected dimensions. The objectives are threefold. First, to critically compare structural configurations, including cantilevers, cymbal-type, stacked multilayers, and flexible designs, in terms of their operational characteristics, power output, and suitability for different applications. Second, to evaluate the state of practical applications, identify the gap between controlled laboratory conditions and real-world deployment requirements. Third, to systematically analyze fatigue life issues, covering failure modes, degradation mechanisms, modeling approaches, and experimental protocols. By bridging these often-separated discussions, this review seeks to provide a coherent framework that clarifies current research bottlenecks and outlines directions for future work.

The remainder of this paper is structured accordingly. Section 2 reviews the fundamental principles of piezoelectric energy harvesting. Section 3 examines various design configurations, comparing their structural characteristics, advantages, and limitations. Section 4 surveys practical applications across domains such as wearable electronics, structural health monitoring, and industrial sensing. Section 5 provides an in-depth analysis of fatigue life, including failure mechanisms, experimental protocols, and modeling approaches. Section 6 concludes the review by summarizing key findings and identifying priority directions for future research aimed at realizing durable, practically deployable PVEH systems.

2. Piezoelectric Vibration Modes

A piezoelectric oscillator or vibrator is the core component of PVEH. According to the three independent piezoelectric strain constants of piezoelectric materials, they can be divided into three modes: d_{31}, d_{33}, and d_{15}. Theoretically, piezoelectric ceramics have the highest power conversion efficiency in d_{15}-mode, but d_{15}-mode is based on torsional deformation produced by piezoelectric ceramics, which is difficult to obtain in a real environment, so there are not much research and application. For d_{31}-mode, the polarization direction of piezoelectric materials and the stress direction causing strain are perpendicular to each other, which is often used in cantilever beam structures, while for d_{33}-mode, the polarization direction of piezoelectric materials is the same as the stress direction that causes strain, and it is often used in situations where piezoelectric elements are squeezed, such as stacked structures. The majority of frequently employed PVEH are almost in cantilever beams (d_{31}-mode), while d_{33}-mode PVEH is mostly used in piezoelectric stacks.

As illustrated in Fig. 1, the polarization directions of piezoelectric materials are all in ‘3’ directions. When force *F* acts in the ‘3’ direction, a potential difference is formed on its upper and lower surfaces, and the piezoelectric material is called the d_{33}-mode. If the piezoelectric material bears a load in the ‘1’ direction, the potential difference is generated on its upper and lower surfaces, and the piezoelectric material is called the d_{31}-mode.

Each mode comes with its own performance characteristics and practical limitations. The d_{31}-mode, typically implemented in cantilever beams, offers high compliance and low cost, making it a common choice for low-frequency applications such as human motion or ambient vibrations. Yet its electromechanical coupling is relatively modest, and strain distribution along the beam is uneven, leaving much of the piezoelectric material near the clamped end underutilized. To address this, researchers have proposed modifications like tapered beams or optimized electrode patterns.

The d_{33}-mode, often realized in stacked or multilayer configurations, provides higher coupling efficiency and greater mechanical strength, suited for heavy-load environments like industrial machinery. But its high stiffness and limited displacement make it less adaptable to low-frequency, large-amplitude excitations. Fabrication complexity and cost also hinder broader adoption.

The d_{15}-mode, despite theoretically offering the highest conversion efficiency, relies on shear deformation that is difficult to excite under typical ambient vibrations. Research in this area remains limited, and practical applications are scarce.

As shown in Table 1, compared to other piezoelectric working modes, the d_{31} mode offers easier fabrication, excellent mechanical-electrical conversion efficiency, and good suitability for low-frequency environments. Given that most ambient vibration sources are characterized by low-frequency excitation with a degree of randomness, the d_{31} mode has become the most widely adopted operating mode in piezoelectric energy harvesting applications. This choice of vibration mode directly shapes the subsequent structural design: the d_{31} mode naturally aligns with cantilever-type harvesters, while the d_{33} mode favors stacked or multi-layer architectures. This intrinsic connection between mode and structure lays the groundwork for comparing design configurations and their suitable application scenarios [2].

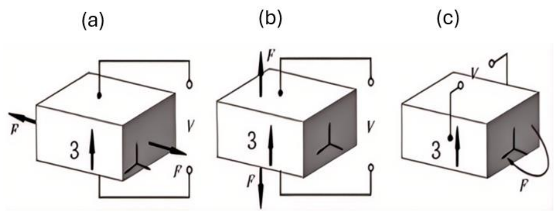

Figure 1. Diagram of the piezoelectric vibration modes reproduced with permission from Ref. [2]:
(a) d_{31}-mode; (b) d_{33}-mode; (c) d_{15}-mode

Table 1. Operating modes and characteristics of piezoelectric transducers

Piezoelectric modes	Vibration mode	Characteristics	Applicable range
d_{31}	Flexural vibration	Soft, easy to manufacture, large vibration amplitude, and high energy conversion efficiency	PVEH structure for flexural vibration in low to medium-frequency vibration environments
d_{33}	Flexural vibration	Easy to manufacture and process, suitable for applications where piezoelectricity is subjected to compression, not easily deformed, with a high piezoelectric coupling coefficient.	PVEH structure for flexural vibration in high-frequency vibration environments
d_{15}	Torsional vibration	Relatively difficult to obtain, uniform strain distribution, and small displacement space requirements	Structure utilizing eccentric mass for torsional vibration (Relevant research is limited)

3. Design Configuration and Technical Advances

On the basis of the mechanical-to-electrical positive piezoelectric effect (i.e., sensing ability), PVEHs of varying materials and structures have been designed for technical usage. Various energy collection systems and their respective benefits are discussed in the following section. Electrical energy capture efficiency and service life of piezoelectric ceramic are subjected to different mechanical structures. At present, the structures of PVEH are mainly designed as cantilever beam structures, cymbal structures, and simply supported beam structures.

3.1. Cantilever Beam Structure

3.1.1. Simple Cantilever Beam Structure

In a standard cantilever-type PVEH (Fig. 2(a)), one end of the beam is anchored, and the opposite end is fitted with a tip mass. The cantilever structure excels at generating vibrations with low frequency and modest amplitude. The mass block serves to increase vibration amplitude, resulting in significant deformation of the piezoelectric element. This is currently the most popular method due to its simplicity, reliable performance, and mature fabrication technology. Kardarakos et al. constructed a PVEH from prestressed beams (Fig. 2(b)) based on simulation and experimental testing, demonstrating that adding prestress increases energy harvesting efficiency [3].

Early parametric studies established fundamental relationships between beam geometry and dynamic behavior. Using ANSYS software, researchers in [4] determined that resonance frequency decreases as beam length increases. Although both width and thickness positively influence the resonance frequency, the effect of thickness is significantly greater than that of width. These findings were experimentally confirmed in [5] through a cross-shaped energy harvesting device. Uddin et al. showed that increasing end mass lowers resonance frequency but raises output voltage [6]. Further ANSYS analysis [7] confirmed the inverse relationship between length and resonance frequency. Additionally, output voltage increases linearly with aspect ratio due to increased strain concentration at the cantilever root [8].

A fundamental limitation of the rectangular cantilever, despite its widespread use due to manufacturing simplicity, is non-uniform stress distribution along the beam length [9]. Stress concentrates at the clamped end while much of the piezoelectric material remains underutilized, leading to suboptimal conversion efficiency. This limitation has driven extensive research into alternative geometries aimed at achieving a more uniform strain distribution.

To address this, Chen et al. [10] designed a trapezoidal cantilever beam. Subsequently, Hui and Tang proposed an inverted trapezoidal structure (Fig. 3(a)), showing improved low-frequency energy capture over rectangular designs [11]. Tianbing introduced a triangular beam with variable cross-section (Fig. 3(b)), concluding through modeling, simulation, and experimentation that triangular designs outperform both rectangular and trapezoidal configurations [12]. Lee et al. analyzed uniformly wide beams with different geometries, with length-strain curves shown in Fig. 3(c), finding that triangular beams distribute strain more uniformly [13].

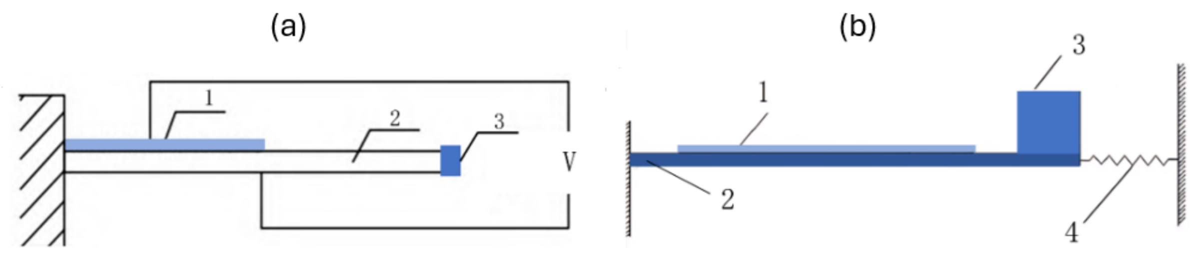

Figure 2. Structure of cantilever PVEH: (a) Conventional rectangular cantilever beam; (b) PVEH based on prestressed beam (1. PZT, 2. Substructure beam, 3. Tip mass, 4. Spring)

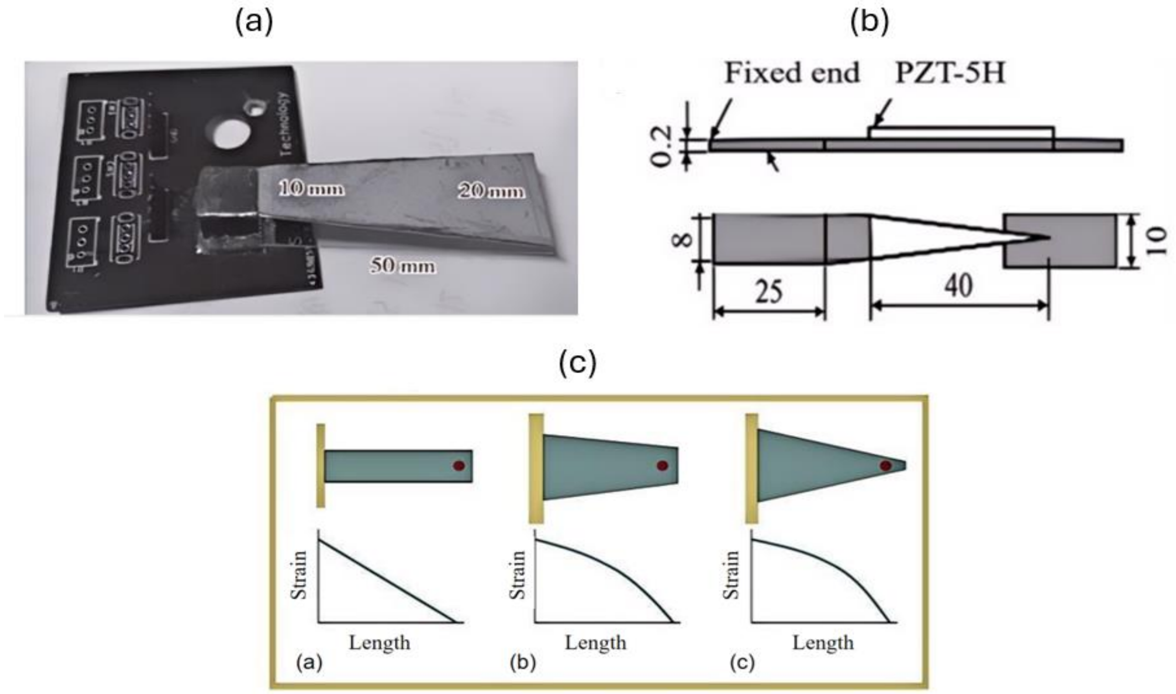

Figure 3. Tapering configuration of rectangular beam: (a) Trapezoidal cantilever PVEH reproduced with permission from Ref. [11]; (b) Triangular cantilever PVEH reproduced with permission from Ref. [12]; (c) Length-Strain curves of piezoelectric oscillators with different shapes reproduced with permission from Ref. [13]

A comparative experimental study [14] found that while triangular beams offer better strain uniformity, rectangular beams achieved the lowest resonant frequency and highest output voltage under low-frequency excitation, yielding greater overall energy yield. This reveals a fundamental trade-off: geometries that improve strain uniformity, which potentially benefit fatigued life, and do not necessarily maximize the power output. Conversely, designs that maximize output concentrate stress at the root, accelerating fatigue damage. Yet, remarkably, this trade-off remains largely unquantified in literature.

Further analytical work by Hosseini R derived a formula for trapezoidal V-shaped cantilevers using the Rayleigh-Ritz method, revealing that simple triangular tapers achieve the highest sensitivity and resonant frequency among thick designs, while increasing the trapezoidal base ratio reduces sensitivity [15]. Ceponis et al. [16] demonstrated that varying the cross-section along the beam length can produce more than triple the power output. Shindo and Narita [17] study showed that S-shaped beams reduce normal tension near the clamping end compared to rectangular beams under the same output voltage, suggesting potential fatigue benefits.

Synthesizing the evidence reveals several observations. First, while extensive research has established how geometric parameters affect output, most studies evaluate performance solely in terms of power generation, with little attention to fatigue life, robustness, or long-term reliability. Second, systematic cross-comparisons under consistent conditions are rare, making it difficult to draw definitive conclusions about design superiority. Third, the literature presents a fragmented picture: rectangular beams excel in low-frequency, high-output scenarios but suffer from stress concentration; triangular and trapezoidal designs improve strain uniformity at the cost of reduced output under certain conditions; S-shaped and variable-cross-section designs offer additional flexibility but introduce fabrication complexity.

Rather than identifying a single best design, the evidence suggests that geometry selection should be guided by application priorities. When peak power output is the primary concern, particularly in low-frequency and short-duration applications, rectangular beams remain a practical choice. When long-term durability and strain uniformity are prioritized, triangular or trapezoidal designs may be more suitable. Future research should move beyond single-metric optimization and adopt multi-objective frameworks that balance power output, operational bandwidth, and fatigue life, thereby better aligning laboratory findings with real-world deployment demands.

3.1.2. PVEH Innovative Design and Performance

Beyond the standard cantilever geometry, researchers have explored structural modifications to address two key limitations: narrow operational bandwidth and sensitivity to vibration direction.

One approach to broadening bandwidth involves introducing nonlinear stiffness through auxiliary spring structures. An analogous auxiliary spring construction examined in [8] was shown to provide nonlinear stiffness for improved cantilever beam performance. As illustrated in Fig. 4(a), Rezaei et al. [18] attached a spring to the free end, finding that the nonlinear spring can increase the frequency range. Fig. 4(b) illustrates the spring-mass construction used by Aladwani et al. [19] in place of the fixed end's base, achieving two-degree-of-freedom output characteristics. While these designs effectively broaden bandwidth, they introduce mechanical complexity and potential wear at spring connections, where reliability concerns are rarely addressed.

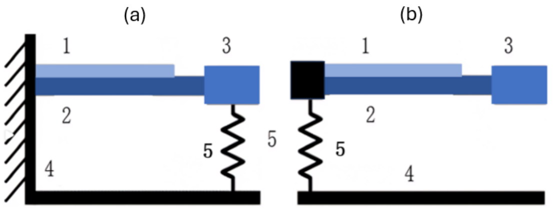

Figure 4. Auxiliary spring type PEH: (a) Free end spring; (b) Fixed end spring (1. PZT 2. Substructure beam 3. Tip mass 4. Base 5. Spring)

Multi-beam and segmented configurations have also been explored to enhance energy output. Park et al. [20] introduced a novel excitation piezoelectric collector configuration, achieving significant power increases. As shown in Fig. 5(a), Hu et al. [21] proposed a segment-type PVEH with rectangular, trapezoidal, and triangular shapes, demonstrating sufficient power to light 21 LEDs. Rafique and Bonello [22] designed a double cantilever arrangement. Zhang et al. [23] designed a circular PVEH (Fig. 5(b)) employing eight cantilever beams for automotive seat applications. These designs offer higher power output but increase form factors, fabrication complexity, and potential mechanical interference.

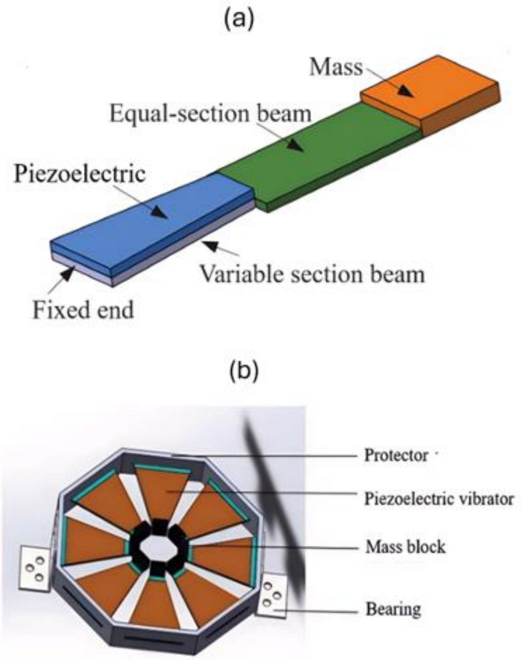

Figure 5. Structural variants and combinations: (a) Variable-section triangular structure reproduced with permission from Ref. [21];(b) Circular PVEH reproduced with permission from Ref. [23]

For multi-directional vibration sources, researchers have developed devices tailored to multi-dimensional and random excitations. As shown in Fig. 6(a), Ben Ayed et al. designed an M-shaped three-way PVEH [24] capable of harvesting energy in three directions simultaneously. Other studies further developed a dandelion-like cantilever array, achieving 0.28 mW output [25]. Fig. 6(b) depicts a multidirectional collector proposed by Priya [26], featuring windmill-like blades that rotate to excite piezoelectric sheets across a 360° plane. These innovations reveal inherent trade-offs. Bandwidth-broadening designs improve frequency range but add mechanical complexity and potential reliability issues. Multi-beam configurations boost total output but increase device footprint and fabrication difficulty. Multidirectional designs address orientation challenges but often sacrifice power density compared to directionally optimized counterparts.

A notable gap across these studies is the limited attention to long-term reliability. Designs with moving parts or complex assemblies may be more susceptible to wear and fatigue, yet these considerations are rarely evaluated. Systematic comparisons under identical conditions are also lacking. Collectively, the evidence suggests that design selection should be guided by application priorities: bandwidth broadening for variable-frequency environments, multi-beam configurations for high-power needs, and multidirectional designs for complex vibration sources. Future research would benefit from standardized metrics that include not only power output but also robustness and fatigue life.

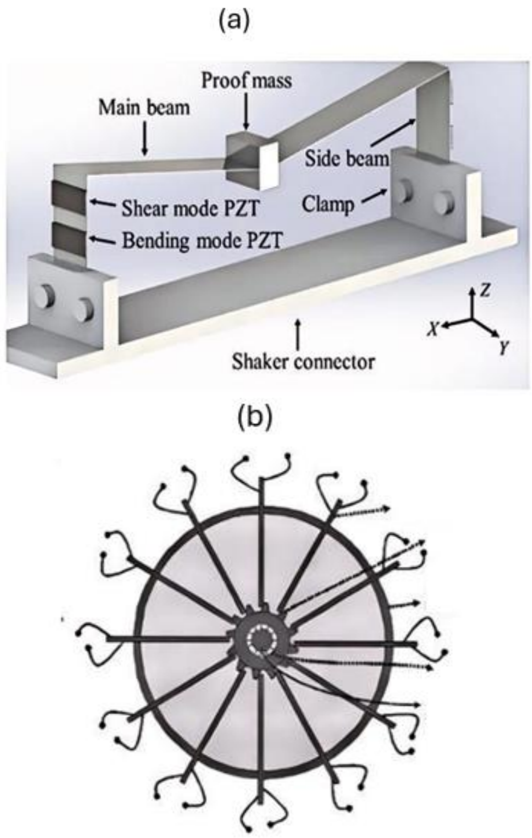

Figure. 6. Multi-directional PVEH: (a) M-shaped PVEH reproduced with permission from Ref. [24]; (b) 3-axial frequency-tunable PVEH reproduced with permission from Ref. [26]

3.1.3. Resonant Frequency-matched Piezoelectric Oscillator

There are different vibration sources from the environment, such as fixed-frequency vibration, variable frequency oscillation, and broadband oscillation, which result in different vibration characteristics. For these different vibration sources, the main requirement to match the excitation frequency with the structural resonance frequency needs to be investigated to have good energy harvesting efficiency. Therefore, in addition to studying the impact of pertinent factors on the maximum output, a good match between sources and harvesters in terms of mechanical resonance is needed.

3.1.3.1. Fixed Frequency Vibration Energy Harvesting

In order to reduce the operating frequency below 50 Hz, Fig. 7 depicts a novel microelectromechanical system (MEMS)-based PVEH design. It is made up of two Meandering-Trapezoidal springs and one seismic mass. Rapid resonance frequencies and the need for rapid acceleration are two challenges that conventional MEMS can surmount with this method [27]. Ben Ayed et al. [24] take the linear and secondary shape variations of the cantilever beam into account when designing a PVEH for efficient electrical energy generation in a low-frequency vibration environment. Cahill fabricated six PVEHs with different shapes and sizes, each tuned to a distinct frequency [28] in order to increase the low-frequency bandwidth of the host bridge.

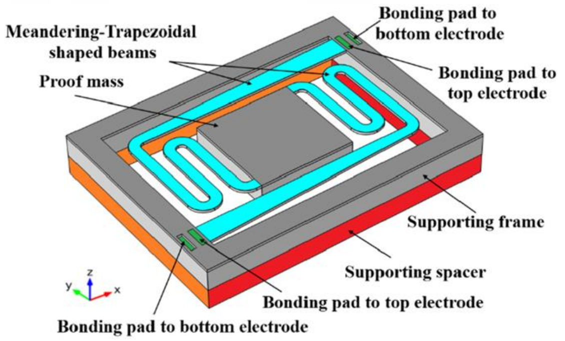

Figure 7. Two Meandering-Trapezoidal springs for energy collection reproduced with permission from Ref. [27]

Prior to this study, the efficacy of PVEHs was only analyzed in detail where the external excitation frequency was near the system's native frequency. A significant reduction in harvested power occurs when the excitation frequency diverges from the natural frequency of the system. If high amplitude is pursued with structural damping reduced, the system's operational frequency band will get too narrow. Thus, the system response at its first-order natural frequency is determined by the structure amplitude and bandwidth. If the damping coefficient is elevated beyond a certain point, the system output amplitude will decrease. In addition to the more conventional simple cantilever beam, researchers have turned to spatial arrangement, combination arrangement, and special-shaped design to extract more energy from ambient mechanical vibration. Three distinct approaches to this field of study are broadband, frequency modulation, and upscaling.

3.1.3.2. Broadband Vibration Energy Harvesting

The term "broadband vibration energy harvesting" is used to characterize the creation of a device that can collect vibration energy over a broad frequency band efficiently, including all peak frequencies in the ambient source power spectrum. As shown in Fig. 8(a), Chen and Li [29] invented a wideband energy absorption harvester that can absorb external vibration energy by utilizing a hybrid compliance mechanism harvesting based on a force amplifier and piezoelectric stack. Li et al. [30] investigated the peak frequencies and accelerations of low-level vibrations to determine their potential use as a power source for energy harvesters in microelectromechanical systems. This structure was devised for low-frequency vibration because it is conducive to the operation of low-resonance-frequency and low acceleration vibration energy harvesters. In an L-shaped beam configuration shown in Fig. 8(b), Zheng et al. [31] employ broadband and highly efficient energy harvesting by utilizing 1:2 internal resonances. In comparison to a linear energy harvesting device, the L-shaped harvester with 1:2 internal resonance is more effective across a broader spectrum of excitation frequencies. Energy harvesting can increase efficacy by up to 215 % and bandwidth by up to 405 %.

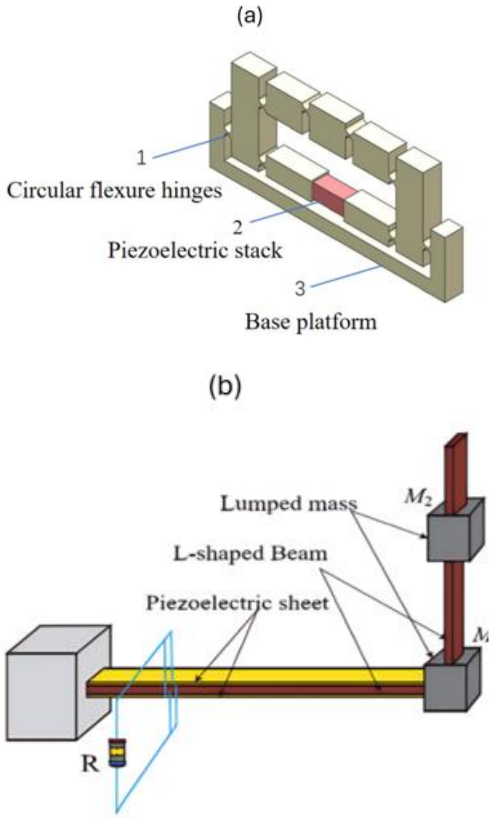

Figure 8. Innovative design of broadband PVEH: (a) Vibration absorber reproduced with permission from Ref. [29]; (b) L-shaped PVEH reproduced with permission from Ref. [31]

Wang et al. [32] developed the folding beam vibration energy harvester to expand the effective frequency range. Under conditions of frequency between 0 and 100 Hz and acceleration of 0.3 g, the efficacy of Z-type energy harvesters is 3 times that of L-type harvesters. Lowering the resonant frequency and increasing the resonance order of the low-frequency region can increase the energy harvesting efficacy of the folding beam. As depicted in Figure 9(a), Cahill et al. [28] employs a system with wideband energy harvesting that consists of 6 sets of PEH beams composed of aluminum plates and PVDF, which are arranged beneath a full-scale bridge. Six piezoelectric cantilever beams, with natural frequencies covering 6.2 Hz to 20.6 Hz, are applicable for monitoring bridge vibration frequencies. Fig. 9(b) depicts a multi-layer butterfly cantilever power generation device designed by Ruan et al. [33]. In this design, each layer of the piezoelectric cantilever beam is capable of producing the same quantity in electrical energy in response to the same external load. By modifying the size or weight of the mass block, the entire cantilever beam can be made to resonate under a controlled vibration environment to generate power over a broad frequency range. Xue et al. [34] were able to increase the working bandwidth of piezoelectric cantilever beams by installing piezoelectric cantilever beams with varying structural parameters (length, width, and thickness) on the same excitation basis and adjusting the structural parameters of each piezoelectric cantilever beam to obtain varying but close first-order natural frequencies. Qi et al. [35] proposed and investigated the dynamic performance of wideband vibration energy harvesters. The apparatus is composed of a principal beam with fixed ends and numerous smaller cantilever beams on both sides. These side-mounted cantilever beams adjust their natural frequencies by adding mass to achieve resonance at different frequencies. The vibration response of the device was predicted using the Rayleigh-Ritz model, and the experimental comparison showed that the output characteristics of the system could produce effective energy output over a wider operating frequency band compared to a single-cantilever piezoelectric energy harvester. Toyabur et al. [36] arranged different cantilever beams into "H" shaped structures and used the first four modes of the system to capture vibration energy in the range of 8 Hz ~ 22 Hz frequency band.

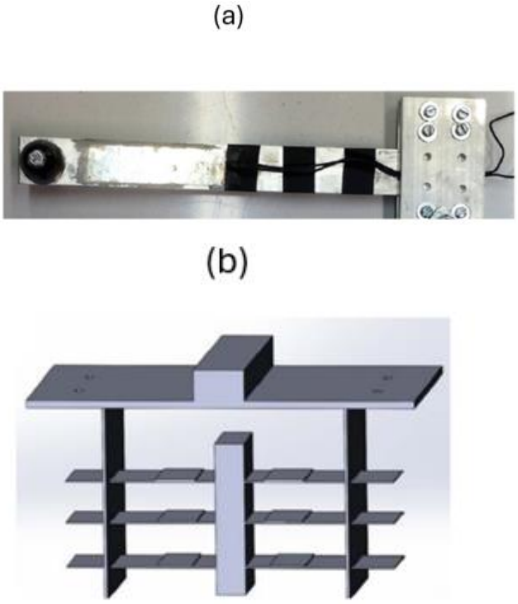

Figure 9. Different combinations of beams: (a) Folding PVEH reproduced with permission from Ref. [28]; (b) Multi-layer PVEH reproduced with permission from Ref. [33].

3.1.3.3. Active Frequency-modulation Vibration Energy Harvesting

Active frequency-modulated piezoelectric vibrators operate on the principle of tuning the system's resonance frequency by varying the equivalent rigidity or mass of the structure. For example, Karadag and Topaloglu [37] designed a new intelligent PVEH that can automatically adjust its resonant frequency, with experiments confirming that its tuning algorithm broadened the fractional bandwidth from 4 % to 10 %. Hou et al. [38] introduced a non-contact magnetism-toggled rotary energy harvester (MTREH), whose magnetic frequency modulation mechanism is illustrated in Fig. 10. Both innovations effectively widen the operational frequency range and sustain system resonance.

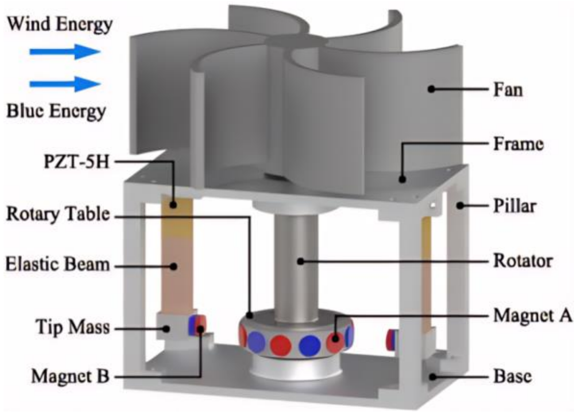

Figure 10. Three-dimensional schematic diagram of the non-contact MTREH reproduced with permission from Ref. [38].

3.1.3.4. Upscaling Piezoelectric Resonator

The core of the piezoelectric oscillator described previously is focused on frequency matching. However, in ultra-low frequency vibration energy harvesting, such as wave motion, wind-induced structural vibration, or biological movement, this principle poses additional challenges. Designing an oscillator to resonate at low frequencies typically requires either a large proof mass or very low stiffness. Large mass conflicts with miniaturization, while low stiffness compromise's structural reliability. Moreover, piezoelectric elements have inherent power density limitations under such conditions. A common strategy is to convert low-frequency excitation into higher-frequency oscillation through frequency up-conversion mechanisms.

Several researchers have developed frequency up-conversion designs for low-frequency environments. Fig. 11(a) depicts a rack-and-pinion-based upscaling PVEH [39]. External excitation drives a rack, which rotates a paddle shaft through gear meshing, repeatedly contacting piezoelectric beams to induce high-frequency vibration. Fig. 11(b) presents an impact-based design [40], where a low-frequency flexible driving beam actuates two high-frequency rigid piezoelectric elements through intermittent contact, achieving approximately 180 % bandwidth increase while maintaining over 62 % of peak power.

While these strategies effectively address low-frequency excitation, they introduce inherent trade-offs. The rack-and-pinion design [39] offers mechanical robustness but adds complexity through multiple moving parts, increasing fabrication cost, wear, and device footprint. The impact-based design [40] simplifies the mechanical architecture but introduces challenges related to impact dynamics and potential fatigue at contact points. Notably, neither study systematically evaluates long-term durability, leaving questions about wear and performance degradation unanswered.

A broader observation is that frequency up-conversion shifts the reliability bottleneck from the piezoelectric material to mechanical interfaces and moving components. The piezoelectric element may experience reduced fatigue due to intermittent operation, but mechanical transmission components become new failure points, a trade-off that rarely quantified in the literature. Frequency up conversion provides a pragmatic solution for low-frequency harvesting by decoupling excitation frequency from piezoelectric resonance. However, these designs must be evaluated not only by power output and bandwidth but also by mechanical complexity, reliability, and application suitability. Future work should include long-term durability testing alongside traditional performance metrics.

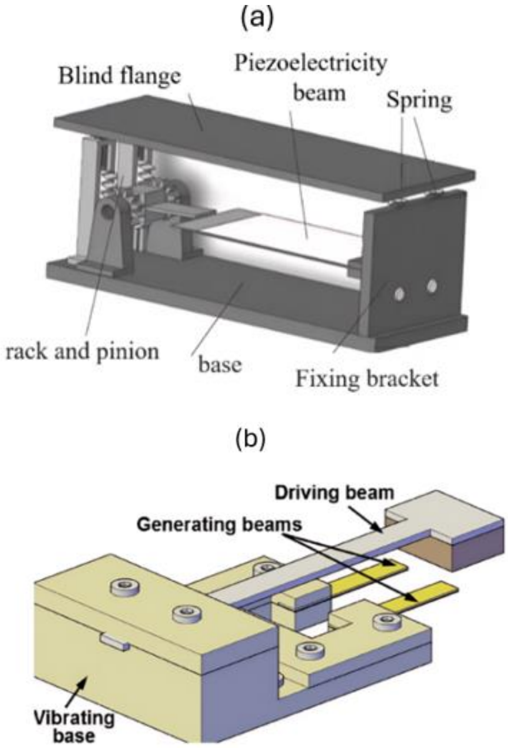

Figure 11. Frequency up-converted PVEH: (a) Harvester 3D structure reproduced with permission from Ref. [39]; (b) Schematic drawing of the PVEH reproduced with permission from Ref. [40]

3.2. Cymbal Structure

Since piezoelectric materials are brittle, they can be formed as cymbal-shaped structures by combining metal materials with piezoelectric materials for better elasticity. The cymbal piezoelectric support structure is composed of two arched metal caps that bond piezoelectric ceramic plates in the middle, so that the pressure acts uniformly on the piezoelectric ceramics. Due to its low impedance, high bending deformation, and high bearing capacity, this configuration is popular in situations with significant levels of vibration. The experimental findings presented in [41] indicate that, when the transducer is subjected to a force, the cymbal-shaped piezoelectric support structure converts a portion of the vertical force into lateral force. In addition, the cymbal-type transducer can increase the effective piezoelectric constant by a factor of 40, which has a high resistance to vibration stress [42]. A more uniform stress distribution to the conventional stacking device, a larger effective area of the piezoelectric effect, and higher energy harvesting efficiency of the acquisition device can be achieved. Modeling with finite elements of the structure of a cymbal-shaped piezoelectric transducer reveals that increasing the bottom diameter of the inner cavity and the thickness of the piezoelectric ceramic metal cover increases the output voltage of the transducer. The output voltage also decreases as the thickness and upper diameter of the inner cavity increase. All these variables can also be used to adjust the frequency of the oscillator. Sheng et al. [43], for example, proposed a d_{33}-mode dynamically amplified PVEH to capture vehicle-induced vibration energy from railway spans by combining the benefits of a cymbal-structure with a dynamic amplifier (Fig. 12(a)). This was intended to provide a practical solution to the problem of supplying electricity to railway bridges with condition monitoring devices. Li et al. [44] devised a system of piezoelectric generators to harvest energy from the suspension systems of maritime vehicles, as shown in Fig. 12(b). This configuration made excellent use of the advantages of simply supported beams and the distinctive structural characteristics of cymbals. The generators demonstrate that they can entirely charge millifarads or farads-sized capacitors in less than ten seconds.

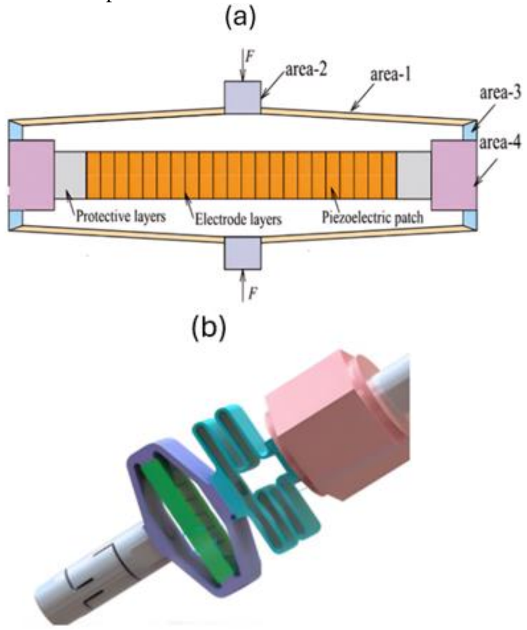

Figure 12. Cymbal Structure PVEH: (a) Cymbal structure reproduced with permission from Ref.[43]; (b) Single vibration suppression with cymbal structure reproduced with permission from Ref. [44]

3.3. Simply Supported Beam Structure

A simple support beam is a structure supported at both ends and suspended in the middle, as shown in Fig. 13. Typically fixed by gaskets, this configuration offers good fatigue resistance. Compared with cantilever beams under the same applied pressure, it exhibits smaller deformation, longer service life, and better stability, but produces lower electrical output. Experiments on simple support beams with varying span lengths [45] show that energy output is governed by the product of deformed piezoelectric volume and maximum deformation. While decreasing the span increases local stress and deformation, it reduces the volume of deformed material, resulting in a negligible net change in electrical output. This structure has been applied in specific contexts. A PVEH designed for rolling tires [46] uses a simple support beam with floating support at both ends and a fixed excitation mass in the middle to improve strength and power output. Li et al. [47] reduced resonance frequency and increased output voltage by modeling a double-ended PVEH using electromechanical coupling with a trapezoidal beam configuration.

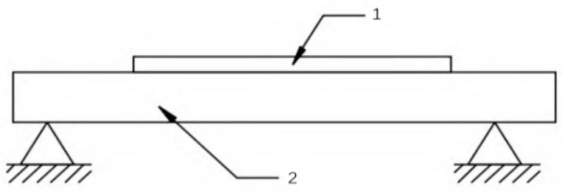

Figure 13. Piezoelectric device of simply supported beam structure (1. Piezoelectric element 2. Simple beam)

It can be seen from pertinent studies that PVEH has achieved good results in structural optimization and performance, particularly in the application of roads, bridges, and bioengineering, which propels PVEH a big step toward practical implementation. Numerous devices for mechanical-to-electrical energy conversion have been engineered, yet their real-world deployment is often constrained by stringent demands for high efficiency and reliability. A key limitation lies in the frequent mismatch between a PVEH's resonant frequency and ambient vibration spectra, coupled with its typically narrow operational bandwidth. These factors collectively hinder the device's ability to harness randomly varying vibration frequencies. Consequently, enhancing the performance of piezoelectric energy harvesters necessitates a dual approach, boosting the power output of PVEHs and expanding the operational bandwidth of PVEHs.

Table 2 shows the summary of classification, types, merits, demerits, and application of different piezoelectric harvester structures.

Table 2. Summary of classification, types, merits, demerits, and application of different piezoelectric harvester structures.

<table>
<tr><th>Classification</th><th>Types</th><th colspan="3">Demerits</th><th>Merits</th><th>Application</th></tr>
<tr><td rowspan="7">Cantilever Beam</td><td>Rectangular shape</td><td>Inflexibility to external excitation</td><td rowspan="4">It is difficult to obtain a lower first-order natural frequency</td><td rowspan="5">Trapping energy frequency range is only at the first-order resonance frequency; Narrow energy captures bandwidth and low efficiency</td><td>Simple structure and easy to manufacture</td><td rowspan="7">Mainly used with d_{31} mode piezoelectric ceramics,widely used in machinery, automobiles, wind energy, ocean, and other vibration fields.</td></tr>
<tr><td>Triangular shape</td><td rowspan="2">The piezoelectric film needs to be customized.</td><td>High energy density</td></tr>
<tr><td>Trapezoidal shape</td><td>Higher energy density</td></tr>
<tr><td>Special shaped: L-shape M-shape</td><td>Low space utilization</td><td>Broadens bandwidth and high collection efficiency to a certain extent; Structure can be derived and expanded; Lower resonant frequencies can be obtained</td></tr>
<tr><td>Segmented-type</td><td colspan="2">Costly in design and production</td><td>High utilization rate of piezoelectric material, low natural frequency, and high output voltage</td></tr>
<tr><td>Arrangement-type</td><td colspan="3">The whole structure is large, and the usable space is limited; the production process is complicated.</td><td>Enable broadband energy harvesting;High energy collection efficiency.</td></tr>
<tr><td>Collision-type</td><td colspan="3">Work reliability and practicality need to be verified</td><td>Used in a lower-frequency vibration environment with a simple structure</td></tr>
<tr><td>Cymbal Structure</td><td>Cymbal-shaped</td><td colspan="3">Application scope is limited to a high-vibration environment</td><td>High bearing capacity: The effective area of the piezoelectric effect is larger; The energy capture efficiency is higher.</td><td>Mainly used with d_{33} mode, it is widely used in roads, bridges, tracks, and other structures.</td></tr>
<tr><td>Supported Beam Structure</td><td>Fixed at both ends</td><td colspan="3">Small power output</td><td>High bearing capacity;
Durability and stability are better</td><td>Used with the d_{33} mode for higher pressure locations, such as rolling tires of a vehicle</td></tr>
</table>

4. Practical Application

4.1. Application in Vehicle Systems

4.1.1. Vehicle Suspension Energy Harvesting

Recent studies have examined the viability of piezoelectric harvesting for energy recovery from mechanical vibrations induced in vehicle suspension components. In modern automobiles, embedded electronic devices for passenger comfort and safety have become increasingly prevalent, and battery limitations have motivated research into vehicle vibration energy harvesting. In suspension systems, piezoelectric materials serve dual functions: shock absorption and mechanical-to-electrical energy conversion.

The energy-recovering chassis of Audi AG exemplifies this development. As shown in Fig. 14, the company developed an electromechanical rotary damper (eROT) that replaces conventional hydraulic shock absorbers. Each contraction generates electricity by pressing a micro-generator, charging the battery [48]. Morangueira et al. [49] proposed a device using original springs to deform cantilevered piezoelectric sheets. Liu [50] conducted simulation studies on piezoelectric crystals in suspension systems to assess power capture potential, and a Bond Graph model was developed to predict energy harvesting performance [51].

4.1.2. Vibration and Noise Reduction:

Vehicles experience vibrations and noise from road irregularities, braking systems, engine vibrations, and aerodynamic forces. PVEH can convert this mechanical energy into electrical energy, potentially reducing vibrations while powering other systems.

The tuned mass damper (TMD) has proven effective for integrated vibration control and energy harvesting, as validated by Rezaei's analytical and experimental study using an electrodynamic agitator (Fig. 15(a)) [51]. Near the brake interface, China's State Key Laboratory of Traction Power implemented a piezoelectric cantilever beam (PZT-beam) to dampen vibration and capture energy, using a braking dynamometer that simulates high-speed train braking (Fig. 15(b)). Results show that deforming the PZT beam reduces unstable vibrations and converts high-frequency vibration energy to electricity [52]

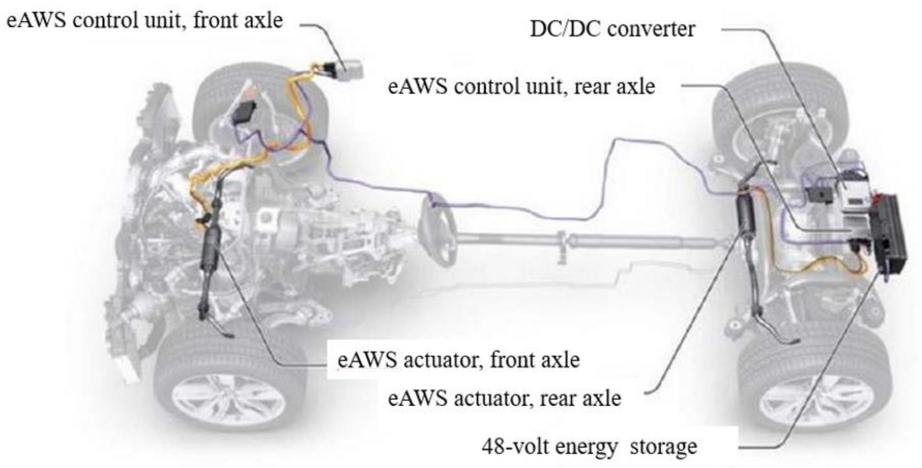

Figure 14. Audi energy recovery chassis reproduced with permission from Ref.[48].

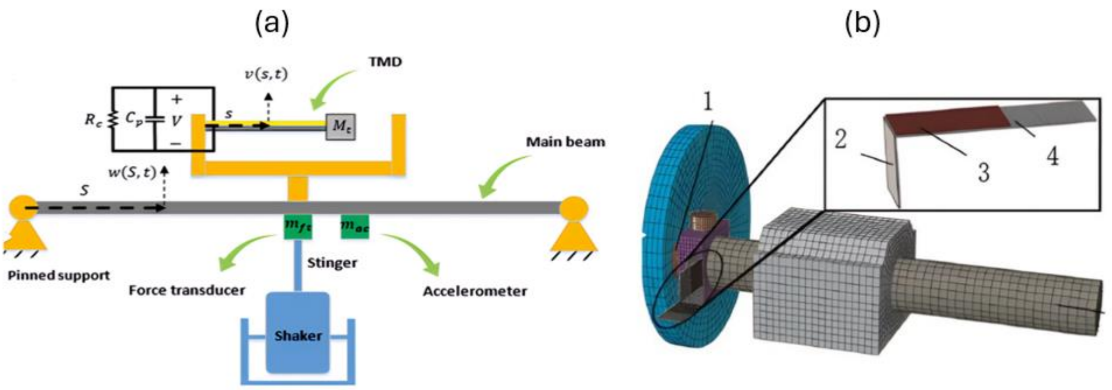

Figure 15. PVEH for vibration and noise reduction: (a) A piezoelectric TMD reproduced with permission from Ref. [51]; (b) Finite element model of the test device reproduced with permission from Ref.[52] (1. Friction block 2. Fixed end 3. Piezoelectric ceramics 4. Cantilever beam)

4.1.3. Tire Pressure Monitoring System (TPMS):

TPMS is a standard safety feature that alerts drivers to low tire pressure. To eliminate batteries and extend sensor longevity, piezoelectric harvesters can be integrated into valve stems or tire sidewalls to harvest energy from tire motion.

As shown in Fig. 16(a), Maurya et al. [53] designed a PVEH that extracts power from tire vibrations and deformations to power a pressure sensor. Delebarre et al. [54] presented a magnetic triboelectric nanogenerator (V-TENG) affixed to a vehicle (Fig. 16(b)) that harvests kinetic energy from tires and can directly power a TPMS sensor, with demonstrated capability to power a commercial wireless sensor for real-time data transmission.

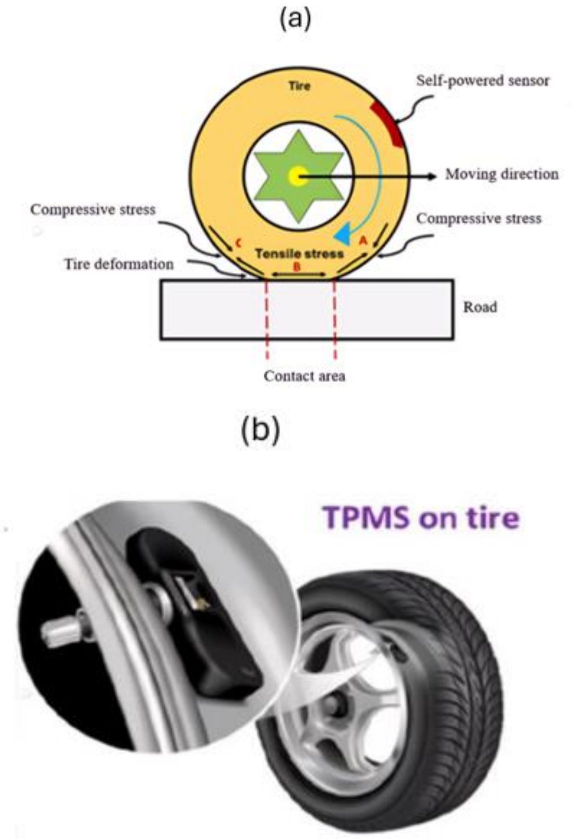

Figure 16. PVEH for monitoring system: (a) The load conditions of wheel rotating are reproduced with permission from Ref.[53]; (b) TPMS transmitter is located on a vehicle tire, reproduced with permission from Ref.[54].

4.1.4. Exhaust Gas Energy Harvesting

Approximately two-thirds of chemical fuel energy is lost as waste heat to exhaust, coolant, and lubricating fluids [55]. The thermal and pressure energy in vehicle emissions can be harnessed, leading to widespread research into waste heat conversion and secondary energy reuse technologies [56-59]. Yue et al. [60] proposed a device using shape memory alloy and piezoelectric material that produced 11.6 V when heated by 100°C hot air, charging a 1000 F/6.3 V capacitor to approximately 6 V.

4.1.5. Body Panel Energy Harvesting

Vehicle body panels experience vibrations and deformations from aerodynamic forces and road irregularities. Piezoelectric harvesters embedded in body panels can convert this mechanical energy into electrical power. Chan [61] placed a PVEH on the top deck near the front window of franchised buses in Hong Kong, reporting that 90 W of viable energy could be harvested across ten bus routes.

Across these vehicle applications, several common themes emerge. First, while PVEH technologies demonstrate technical feasibility in laboratory settings, long-term durability under real-world conditions, such as cyclic loading, extreme temperatures, and mechanical stress, remains largely unvalidated. Second, the economic case is unproven: added mechanical complexity and manufacturing cost must be weighed against modest power outputs (milliwatts to tens of watts) better suited for low-consumption sensors than vehicle propulsion. Third, while eliminating batteries offers clear green benefits, total lifecycle cost, including power management electronics and maintenance has not been systematically compared against conventional battery-powered solutions. Finally, the literature lacks systematic cost-benefit analyses, field testing under actual driving conditions, and multi-objective evaluations that balance energy harvesting against primary functional requirements. Addressing these gaps through standardized durability testing and lifecycle assessment is essential to determine investment readiness.

4.2. Application in Civil Engineering

4.2.1. Smart Infrastructure

PVEH can be embedded in roads or sidewalks to convert vehicle and pedestrian mechanical energy into electricity for smart infrastructure, including road lighting and traffic management systems [62]. Najoua et al. [63] proposed an optimized pavement structure using PZT ceramics for energy recovery [63]. The Haifa Institute of Technology developed a PVEH system claiming that a two-lane road with 700 vehicles could power over 700 households [64]. Wang et al. [65] used under-road PVEH to power road lamps, while Yang et al. [66] developed a stacked array with protection devices capable of powering LED signs even under fully loaded vehicles. Another study (Fig. 17) demonstrated that generator placement depth affects output, achieving 1.1 W per module, sufficient to illuminate four delineators under minimal traffic [67].

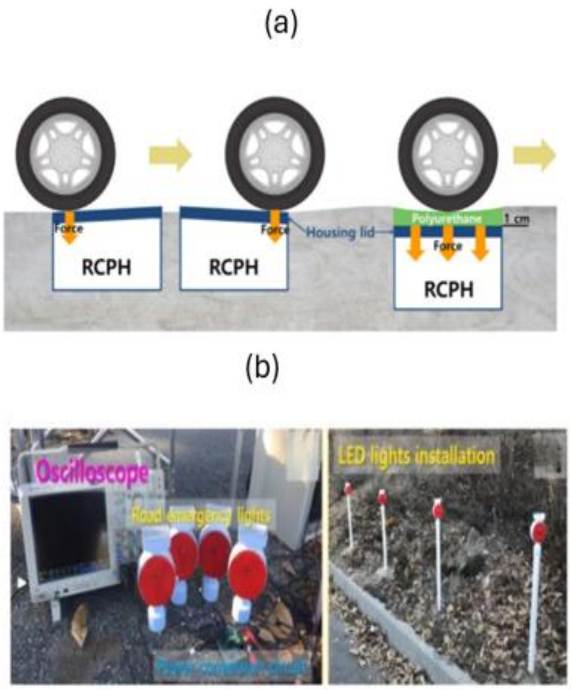

Figure 17. PVEH for civil engineering: (a) The visible and buried RCPH modules exhibit distinctly different patterns of movement in response to passing vehicles, reproduced with permission from Ref. [67]; (b) Roadway emergency lights that run on the RCPH electricity provided by the energy-harvesting pavement, reproduced with permission from Ref. [67].

4.2.2. Structural Health Monitoring (SHM):

Wireless sensors for bridge monitoring require strain, displacement, and frequency data. Attaching piezoelectric patches to bridge surfaces offers a simple method to harvest energy from traffic-induced vibrations. Cahill et al. [28] demonstrated that PEH can capture mechanical energy from passing vehicles for SHM applications, as shown in Figs. 18(a) and (b).

4.2.3. Human-Powered Energy Generation

PVEH integrated into walkways, stairs, or fitness equipment can power lighting and sensors. Pavegen installed piezoelectric flooring at Heathrow Terminal 3, generating 7 W per step to power wall lighting and enable wireless traffic monitoring [68]. A 100-meter shopping center path was estimated to produce 2,000 watts per hour based on average stride length [69]. As shown in Fig. 19, Takefuji [70] developed a 90 m² piezoelectric carpet that reportedly generated 500 kW per day in high-foot-traffic areas. Installed at Tokyo Station, the carpet-powered automatic ticket gates generated over 500 kW daily (766 kW peak) during a two-month trial.

From the above discussion, it can be seen that device-level power claims often overlook the scalability: extrapolations to household supply [64] or hundreds of kilowatts from flooring [70] rely on unverified assumptions about traffic density and coverage. Durability under real-world conditions, decades of heavy loading, thermal cycling, moisture, and mechanical wear, remains largely unvalidated, with long-term field studies scarce. Economic analysis is also lacking; installation costs, integration complexity, and maintenance are rarely weighed against modest energy returns, and comparisons with conventional solutions are absent. Finally, standardized reporting metrics such as installation density, lifespan, and cost per watt are still missing. Closing these gaps through long-term trials and consistent economic assessment is essential to determine genuine viability.

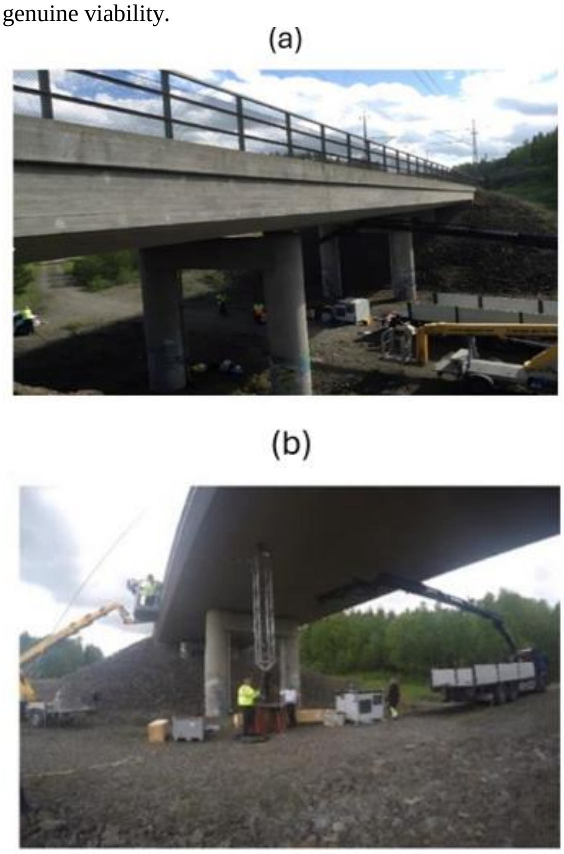

Figure 18. The layout and test progress of PVEH: (a) Testing deployment of energyharvesters reproduced with permission from Ref. [28]; (b) Photograph of shaker for providing excitation reproduced with permission from Ref. [28].

Figure 19. Piezoelectric carpets application and display reproduced with permission from Ref. [70].

4.3. Application in Fluid-flow Environment

Piezoelectric energy harvesters can also be used in fluid-flow environments, where they can harness energy from the flow of liquids or gases. Here are some potential applications of piezoelectric energy harvesters in fluid-flow environments:

4.3.1. Hydroelectric Power Generation

Global wave energy potential is estimated to be between 8,000 and 80,000 TWh/y, attracting significant research interest [71]. The UK has identified wave energy as key to achieving zero net carbon emissions by 2050 [72]. Researchers have integrated PVEH into buoys, pontoons, and riverbed installations to harness fluid-flow vibrations. Chen et al. [73] described a hybrid wave-current energy converter with three one-way clutches. Despite the vast resource potential, practical deployment faces formidable challenges: saltwater corrosion, biofouling, extreme wave forces, and storm survivability, the factors rarely accounted for in laboratory studies. Moving parts in hybrid designs introduce reliability concerns. Most reported outputs are milliwatts to watts, far below conventional wave energy converter scales. Without long-term field validation and realistic cost analysis, investment readiness remains speculative.

4.3.2. Water Distribution Networks

PVEH installed in pipelines, valves, or pumps can power remote monitoring systems, leak detection, or water quality sensors. Zhang et al. [74] used a T-shaped cantilever to harvest energy from vortex-induced vibration, achieving 1.0 µW at 0.33 m/s flow speed. Water distribution networks offer a plausible near-term application, but the reported 1.0 µW output is orders of magnitude below typical wireless sensor requirements (milliwatts). Installation requires pipe penetration, raising concerns about leakage and maintenance. Achieving milliwatt-level output reliably across varying flow conditions remains an unresolved challenge.

4.3.3. Environmental Monitoring Systems

Wind-induced vibration is a promising energy source for weather stations, buoys, and river monitors. Fig. 20(a) shows a circular cylinder on a cantilever beam [75]. Kan et al. [76] introduced a Downwind-Vibrating PVEH (DVPEH) (Fig. 20(b)) to address reliability under high wind speeds. Tao et al. [77] reported a wind turbine with a 1 m blade radius generating 150 W at 7.2 m/s. Sirohi and Mahadik [78] designed a miniature harvester using galloping vibrations, achieving 53 mW at 11.6 mph. Wang et al. [79] produced approximately 270 mW at 7 m/s using an isosceles triangular cross-section. Additional wind energy research includes Orregi et al. [80], Liu et al. [81], and Tan et al. [82]. Wind harvesting spans from milliwatt sensors to the 150 W turbine claim [77]. For small-scale applications, technology shows promise, though durability at low wind speeds and over-speed protection needs validation. The 150 W claim requires scrutiny: at this scale, cost competitiveness against mature rotary wind turbines is questionable. Across designs and standardized reporting, cut-in speed, rated power, durability, and lifecycle cost are absent, hindering cross-study comparison.

A diverse spectrum of ambient energy sources exists for power generation, encompassing natural flows like wind and water, as well as mechanical excitations from machinery. The resulting mechanical stresses and strains represent a specific category of such harvestable energy. Figure 21 depicts a comprehensive scenario illustrating the deployment of a vibration energy harvester to support networking and intelligent control systems for low-energy wireless sensor devices [83].

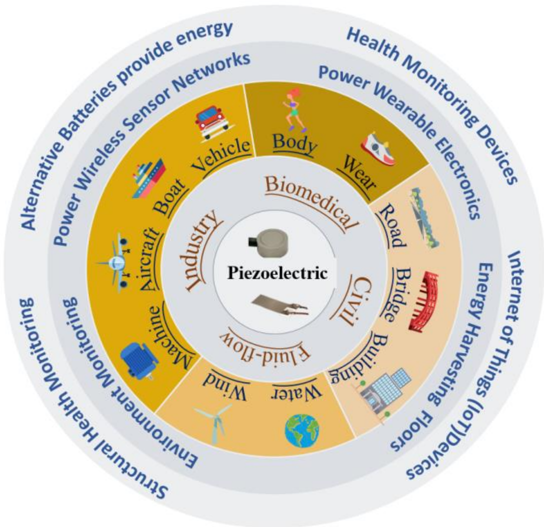

Figure 21. Applications for energy harvesting

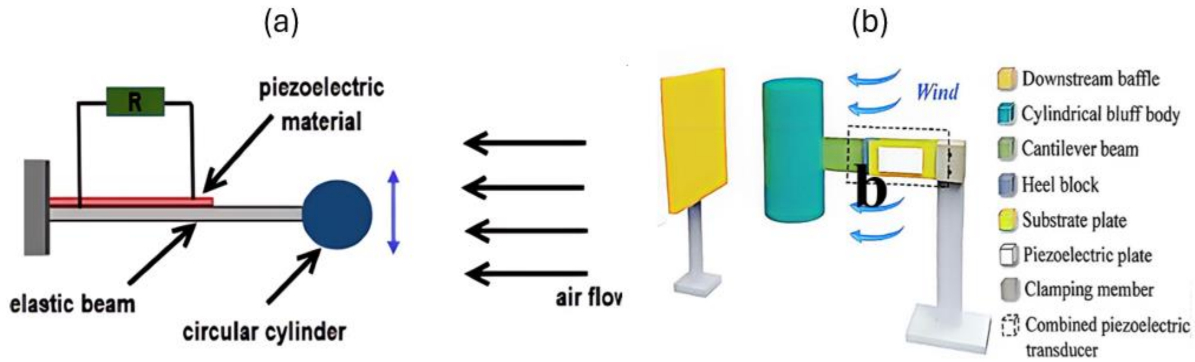

Figure 20. PVEH with wind energy: (a) Schematic of a fluid-flow-based piezoelectric energy harvester reproduced with permission from Ref. [75]; (b) DVPEH's schematic diagram reproduced with permission from Ref. [76]

5. Fatigue Life of PVEH

Fatigue life, defined as the number of cyclic mechanical loads a PVEH can sustain before its electrical output degrades or structural integrity fails, is often the bottleneck that limits the transition from laboratory prototypes to practical applications [84]. Ironically, many of the design strategies adopted to enhance power output, such as increasing excitation amplitude, turning to resonance, or adopting flexible substrates, tend to elevate internal strain levels, thereby accelerating fatigue damage. This section reviews existing fatigue-related studies not as isolated findings, but as interconnected pieces that reveal both the current understanding and the persistent gaps in predicting and mitigating fatigue failure in PVEHs.

5.1. Failure Modes

Reported failure behaviors fall into two categories: physical and functional. Physical failure includes crack initiation at the clamped end, delamination between the piezoelectric layer and the substrate, and complete cantilever fracture. Functional failure involves a gradual decline in output voltage, depolarization, and reduced electromechanical coupling, often occurring well before visible cracks appear.

A counterintuitive finding from Wu et al. [85] illustrates the complexity: after fatigue damage, output voltage initially increased alongside strain, attributed to altered stiffness or residual stress states. This temporary rise ultimately led to faster fatigue and shorter service life, suggesting that relying solely on voltage monitoring may underestimate early-stage damage, a point that is rarely considered in conventional assessments.

5.2. Material Degradation Mechanisms

At the material level, fatigue involves intertwined mechanical and electrical degradation. In soft piezoelectric like PZT-5H, cyclic loading promotes microcrack propagation and progressive depolarization. Wang et al. [86] showed that higher excitation loads and frequencies accelerate depolarization, indicating that electrical output loss stems not only from cracking but also from gradual polarization decay under cyclic electromechanical loading. This coupling distinguishes piezoelectric fatigue from conventional structural fatigue, yet most current models treat these effects separately.

Interface reliability adds another layer. Peddigari et al. [87] found that in soft matrix cantilevers, fatigue damage degrades both output voltage and vibration amplitude, with interface delamination as a key precursor. Pole et al. [88] similarly noted that in parallel-configured harvesters, repeated stress at bonding interfaces drives long-term instability. Across these studies, the interface between the piezoelectric material and structural layer emerges as the weakest link, yet it remains under-characterized in most reports.

5.3. Modelling Approaches

Modelling efforts have largely followed two directions. The first is empirical, establishing direct relationships between operating parameters and fatigue life. Zhang et al. [84, 89] found that strain in piezoelectric ceramics scales with excitation displacement amplitude, and fatigue life drops sharply as displacement increases. They also identified aspect ratio as a critical geometric factor affecting stress distribution, a finding that connects directly back to design choices discussed in Section 3.

The second direction aims to define safe operating boundaries. Upadrashta and Yang [90] proposed a safe strain threshold derived from reliability testing, offering a practical design constraint. Avvari et al. [91] linked increased loading to reduced stiffness and natural frequency under high-cycle fatigue, suggesting that resonant frequency shifts could serve as an indirect health indicator.

What remains missing is a unified model coupling mechanical fatigue evolution with electrical performance decay. Most existing models treat fatigue as either a mechanical fracture problem or an electrical degradation problem, but rarely both limit their predictive power for real-world applications where the two co-evolve.

5.4. Experimental Procedure

Experimental characterization relies heavily on accelerated life testing. Peddigari et al. [92] applied such methods to estimate the lifetime of hard-type macro-fiber composite harvesters. Pole et al. [88] conducted force-controlled cyclic tests at 10 Hz with loads from 50 N to 600 N over millions of cycles on parallel-configured devices. While these provide valuable comparative data, test conditions rarely reflect the variable, non-stationary excitations encountered in actual applications.

A deeper issue is the lack of standardized protocols. Studies use different excitation modes (displacement-controlled vs. force-controlled), failure criteria (50 % voltage drop vs. visible cracking), and environmental conditions, making cross-study comparison difficult. Moreover, as Wu et al. [85] noted, monitoring only output voltage may mask early-stage functional degradation, suggesting that more sensitive indicators like impedance changes or electromechanical coupling coefficient evolution are needed but seldom adopted.

5.5. Design Considerations

Geometric optimization offers a relatively low-cost route. Adjusting aspect ratio and layer thicknesses directly influences peak strain levels [84, 89]. However, geometry changes that reduce strain may also lower power output, a trade-off that is rarely quantified in optimization studies. Safe strain thresholds, as proposed by Upadrashta and Yang [90], provide straightforward design rules. Yet the threshold itself likely varies with material type, operating conditions, and desired lifespan, and no consensus exists on standard values.Material selection matters: hard-type piezoceramics [92] generally exhibit superior fatigue resistance compared to soft-type materials like PZT-5H [86], but at the expense of lower electromechanical coupling. The choice thus depends on whether the priority is raw output or long-term stability. Structural configurations that distribute stress more evenly, such as parallel designs [88, 93], can reduce localized stress concentrations. However, they may introduce new failure modes at bonding interfaces, a reminder that mitigating one risk often creates another.

An observation across these strategies is that literature rarely quantifies the trade-off between fatigue life and power output. Designs that boost power by increasing strain or operating near resonance typically shorten fatigue life, yet few studies have attempted to optimize both objectives concurrently. This gap points to a broader issue: fatigue is often treated as an afterthought in structural design, rather than being integrated from the outset.

5.6. Research Gaps

Based on previous studies, several persistent gaps stand out. First, most fatigue studies are conducted under idealized laboratory conditions, steady sinusoidal excitation, controlled temperature, and short durations. Long-term behavior under real-world, variable excitations remains largely unexplored, due to time and resource constraints. Second, no established standard for fatigue testing of PVEHs exists, making results across studies difficult to compare. Third, the coupling between mechanical fatigue and electrical degradation is conceptually acknowledged but rarely modeled or experimentally quantified in an integrated way. Fourth, most fatigued life predictions are empirical fits rather than physics-based models that could be extrapolated beyond tested conditions.

In short, the literature provides a solid diagnosis of the fatigue problem but falls short on prescribing practical solutions. Future efforts need to move beyond listing influencing parameters toward developing integrated frameworks that combine accelerated testing, physics-based modeling, and application-relevant validation. Equally important, fatigue considerations should be embedded into the structural design process from the beginning, treating durability not as a separate topic but as a core constraint alongside power output and bandwidth. Until that happens, PVEH technology will remain impressive in the lab but uncertain in the field [84–93].

6. Conclusion, Challenge, and Future Work

This review sets out to examine piezoelectric vibration energy harvesting from three interconnected perspectives: design configuration, practical application, and fatigue life. When these dimensions are considered together, a central theme emerges that runs through every stage of PVEH development: the inherent tension between efficiency and robustness.

Structural innovations, whether geometric optimization of cantilever beams, frequency up-conversion mechanisms, or multi-directional designs, consistently pursue higher power output and broader bandwidth. Yet almost without exception, these improvements come at the cost of increased internal strain, greater mechanical complexity, or new failure modes. The very strategies that make PVEH more effective in the laboratory are operating at resonance, maximizing strain, and adding moving parts, making it more vulnerable in the field. This trade-off is not incidental; it is fundamental to technology. Applications across vehicle systems, civil infrastructure, and fluid-flow environments illustrate the same pattern. While numerous field trials and laboratory demonstrations confirm technical feasibility. They also reveal a persistent gap between reported performance and deployment-ready reliability. Power outputs that appear impressive on a test bench often prove difficult to sustain under real-world conditions characterized by variable excitations, temperature swings, moisture, and mechanical wear. The green technology promise of PVEH by eliminating batteries and enabling self-powered sensors remains compelling, but the economic case hinges on durability that has yet to be systematically validated.

The fatigue life analysis further reinforces this central theme. Studies consistently show that higher power output correlates with shorter fatigue life, yet literature rarely quantifies this trade-off or proposes frameworks that balance both objectives. Existing research offers a thorough diagnosis of failure modes and degradation mechanisms but provides a weak prescription for mitigation. Design guidelines remain fragmented, experimental protocols lack standardization, and long-term field validation is conspicuously absent.

The next generation of progress must center on durability as a design constraint, not an afterthought. To move in this direction, future work should prioritize the following:

1. Embed fatigue considerations into structural design from the outset. Rather than optimizing geometry or configurations solely for power output, researchers should adopt multi-objective frameworks that treat fatigue life as a core performance metric alongside power and bandwidth. The trade-off between efficiency and robustness should be quantified, not merely acknowledged.
2. Develop standardized testing protocols. The field currently lacks consensus on failure criteria, excitation methods, and reporting metrics. Establishing standards that cover cut-in thresholds, power curves, operational lifespan, and cost per watt would enable meaningful cross-study comparison and accelerate technology maturation.
3. Prioritize long-term field validation. Laboratory testing under idealized conditions is insufficient. Future studies should deploy PVEH devices in real-world environments such as on vehicles, bridges, roads, and in water distribution networks, for extended periods to generate durability data that reflects actual operating conditions.
4. Investigate hybrid mitigation strategies. Given that mechanical complexity often introduces new failure modes, research should explore approaches that balance simplicity with reliability. This includes interface engineering to prevent delamination, protective packaging for harsh environments, and self-sensing capabilities that enable predictive maintenance.
5. Integrate economic analysis with technical development. Investment readiness depends not only on power output but also on lifecycle cost, installation complexity, and maintenance requirements. Future work should include cost-benefit analyses that compare PVEH solutions against conventional alternatives such as battery-powered sensors, grid extension, or small wind turbines.

In summary, the field of piezoelectric vibration energy harvesting has produced an impressive body of knowledge on how to generate power from ambient vibrations. The challenge ahead is no longer about how to maximize output, but how to make that output reliable, durable, and economically viable over the long term. Addressing this challenge will require a shift in mindset, from treating fatigue as a separate reliability topic to embedding robustness as a foundational design principle. Only then will PVEH fulfill its promise of powering the next generation of self-powered wireless sensors and intelligent infrastructure

CRediT authorship contribution statement

Ping Yang: Methodology and writing. **Nabil Mohamad Usamah:** Methodology. **Abdullah Aziz Saad:** Resources. **Ahmad Zhafran Ahmad Mazlan:** Review, supervision, and resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare that they used AI-assisted tools to check and improve the grammar, sentence structure, and overall clarity of the manuscript, to ensure it meets the journal's standards.

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