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Review

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Revolutionizing wind energy: exploring triboelectric and piezoelectric nanogenerators for sustainable power generation

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Abstract: Nanogenerator technologies have gained significant attention as sustainable methods for harvesting energy and powering various applications. We review the research progress and obstacles related to triboelectric and piezoelectric nanogenerators utilized for wind energy extraction. This is crucial given the increasing demand for clean energy sources and the importance of technologies that can efficiently harvest such energy. We highlight the role of triboelectric and piezoelectric nanogenerators as promising solutions for capturing mechanical energy from wind sources. First, the fundamental physics modes of triboelectric and piezoelectric nanogenerators are discussed. The mechanisms underlying the triboelectric effect and the piezoelectric effect are explained, emphasizing their relevance to energy harvesting applications. An overview of energy harvesting using triboelectric and piezoelectric nanogenerators is then provided, encompassing the latest developments in the field. This review encompasses the design principles, materials, and fabrication techniques employed in the construction of triboelectric and piezoelectric nanogenerators. Specifically, we delve into how nanogenerators are utilized for wind energy harvesting. Various approaches for optimizing the performance of these devices are examined, along with methods of integration into wind energy harvesting systems. The potential applications of these devices are highlighted, along with the challenges that may come with their implementation. We conclude by discussing the current state of research, future perspectives, and insights into wind energy harvesting using triboelectric and piezoelectric nanogenerators. Accordingly, we recommend that future research addresses issues such as scalability, durability, and system integration. This review provides a comprehensive analysis of the use of triboelectric and piezoelectric nanogenerators for wind energy harvesting. It serves as a reference for researchers and engineers working in wind engineering, offering insights and directions for future advancements.

Key words: Energy harvesting; Triboelectric nanogenerator (TENG); Piezoelectric nanogenerator (PENG); Wind engineering

1 Introduction

The growing need for environmentally friendly and renewable energy sources has spurred substantial research into energy harvesting technologies. Among these technologies, triboelectric and piezoelectric nanogenerators have emerged as promising solutions for converting mechanical energy into electrical energy (Alavi et al., 2016; Liu HQ et al., 2021; Nazar et al., 2021a, 2021c, 2022a; Varmaghani et al., 2021; Ayegba et al., 2022; Rayegani and Nouri, 2022; Wang et al., 2022). In the field of wind engineering, where wind resources are renewable and abundant, the utilization of these nanogenerators for energy harvesting holds great potential (Egbe et al., 2022). Accordingly, we thoroughly evaluate the current progress, obstacles, and outlook for utilizing triboelectric and piezoelectric nanogenerators for wind energy harvesting and engineering (Papadimitratos et al., 2009; Gandomi et al., 2014; Li and Li, 2020; Egbe et al., 2021; Sadeghi et al., 2021; Nazar et al., 2023; Rayegani et al., 2023a, 2023b). Triboelectric nanogenerators (TENGs) use the triboelectric effect for energy conversion, while piezoelectric nanogenerators (PENGs) utilize the piezoelectric effect to generate electricity from mechanical actions (Jiao et al., 2022b). By harnessing the piezoelectric effect, wind-induced vibrations and movements can be transformed into usable electrical power (Fabish and Duke, 1977; Wang and Song, 2006; Chen and Wang, 2017; Wang ZL et al., 2017; Jiao et al., 2020, 2022a;

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Wang, 2020; Nazar et al., 2021b, 2022b; Sardo et al., 2022; Rayegani et al., 2023b).

We provide a review of energy harvesting methods based on triboelectric and piezoelectric nanogenerators, showcasing the significant progress made in this field. Researchers have explored various design strategies, materials, and fabrication techniques to enhance the performance and efficiency of these nanogenerators (Liu D et al., 2021). Our review encompasses a wide range of studies, which discuss advancements in device architecture, electrode materials, and interface engineering, among other aspects. Moreover, we explore the integration of these nanogenerators into energy harvesting systems, such as wind turbines or wearable devices, highlighting the potential for practical applications (Wang CF et al., 2017; Li et al., 2019a; Ke and Chung, 2020; Wang, 2021).

Harnessing wind-powered TENGs represents a promising approach for capturing energy from wind sources (Choi et al., 2023). By exploiting the airflow-induced motion or vibration of structures, TENGs can efficiently convert wind energy into electrical energy. Various design considerations, such as the selection of suitable materials, electrode configurations, and optimization of structural parameters, play a crucial role in achieving high-performance energy harvesting systems (Zhu et al., 2012, 2015; Wang, 2014; Wu CS et al., 2019). Therefore, this review examines different development strategies for wind-driven TENGs and discusses their potential applications in wind engineering, such as structural health monitoring, environmental sensing, and self-powered wireless sensor networks.

Wind-powered PENGs have also gained considerable attention for energy harvesting applications (Bensaid et al., 2012; Hirose and Matsuo, 2012; Singh, 2013; Kim et al., 2014; Tayebi et al., 2014; Jung et al., 2017; Siddique et al., 2017; Yu et al., 2019). These nanogenerators utilize the piezoelectric effect to convert wind-induced mechanical vibrations and deformations into electrical energy. Our review accordingly explores advancements in piezoelectric nanomaterials, device designs, and fabrication techniques for efficient wind energy harvesting (Gandomi et al., 2014). The potential applications of wind-powered PENGs are discussed, including wireless sensor networks, devices for internet of things (IoT), and environmental monitoring systems (Na et al., 2020; Zhao et al., 2022).

Despite the progress made, certain challenges must be addressed for the effective implementation of wind energy harvesting using triboelectric and piezoelectric nanogenerators (Papadimitratos et al., 2009; Li and Li, 2020; Egbe et al., 2021; Jiao et al., 2022b; Sardo et al., 2022). These challenges include scalability, durability, power management, and system integration. Addressing these issues is crucial for realizing the full potential of these nanogenerators in practical wind energy harvesting systems (Fan et al., 2012; Yang et al., 2013b; Guldentops et al., 2016; Seung et al., 2020; Zhu et al., 2020). As a result, in this review, we provide insights and recommendations to overcome these challenges, and offer perspectives on future research directions.

This review emphasizes several unique aspects compared to previous review papers on piezoelectric and TENGs. First, we focus specifically on the application of such nanogenerators for wind energy extraction, addressing challenges and opportunities that are unique to this domain. This is because existing reviews have instead concentrated on general energy harvesting or specific energy sources other than wind. Second, we provide a comprehensive analysis of the progress, obstacles, design principles, materials, fabrication techniques, optimization strategies, potential applications, challenges, and future perspectives for both types of nanogenerators in the context of wind engineering, offering a broad yet deep investigation. Lastly, by analyzing both triboelectric and piezoelectric nanogenerators, we offer multiple perspectives and approaches within a single holistic framework, facilitating insights into potential synergies between the nanogenerators in wind energy applications.

Wind energy harvesting based on triboelectric and piezoelectric nanogenerators is of vital importance, given the increasing demand for clean and sustainable energy sources that can help mitigate climate change. These nanogenerators offer promising solutions for capturing mechanical energy from wind sources, thus advancing renewable energy technologies. It is also crucial to address challenges such as scalability, durability, and system integration to make further advancements in wind energy harvesting, such as leaps in efficiency, reliability, and accessibility. Therefore, our comprehensive analysis serves as a valuable resource for researchers and engineers, which can guide future research directions and contribute to the realization of a future with sustainable energy.

2 Fundamental physics modes of triboelectric and piezoelectric nanogenerators

Triboelectric and piezoelectric nanogenerators are innovative technologies that employ various principles to transform mechanical energy into electrical power (Chen L et al., 2018). Nanogenerators, including TENGs, have garnered interest for their efficiency and versatility in energy harvesting. TENGs generate electric charges via the triboelectric effect, wherein contact between dissimilar materials transfers electrons and creates charge imbalances on their surfaces (Niu et al., 2013, 2014; Yang et al., 2013a; Niu and Wang, 2015; Roshani et al., 2016; Wang, 2017; Shi and Lee, 2019; Zhang ZL et al., 2019). The separation of these materials then creates a potential difference, and when an external load is connected, electrons flow from the higher potential to the lower potential, resulting in the generation of electrical current. The fundamental advantages of TENGs are effective charge transfer and their ability to operate in series to maximize power output (Hu et al., 2020). By carefully selecting materials with different electronegativities and optimizing the surface morphology, TENGs can efficiently convert various mechanical inputs into electrical energy, such as tapping, rubbing, or even airflow (Chen B et al., 2018).

The piezoelectric effect refers to the generation of electric charges when mechanical strain or pressure is applied to certain materials (called piezoelectric materials). When mechanical energy is exerted on a piezoelectric material, it undergoes deformation, leading to the separation of charges and the generation of an electric field (Xie et al., 2014; Niu et al., 2015; Guo et al., 2018; Qian et al., 2018; Kang et al., 2019; Lai et al., 2019; Li et al., 2019b; Jiang et al., 2021). This electric field creates a potential difference, and when an external load is connected, the flow of electrons produces an electrical current. PENGs utilize piezoelectric materials with high piezoelectric coefficients and favorable mechanical properties to effectively generate current (Mao et al., 2015; Heo et al., 2018; Kim et al., 2019; Wu WJ et al., 2019; Jin et al., 2021; Lee et al., 2021; Nazar et al., 2021b; Yang et al., 2021). By optimizing the geometry and structure of a PENG, such as its thickness, shape, and piezoelectric material layout, the mechanical deformation and strain can be enhanced, resulting in increased power output. PENGs can efficiently harvest energy from various mechanical sources, including vibrations, bending, or compression.

The distinct modes of triboelectric and piezoelectric nanogenerators offer unique advantages and make them suitable for various energy harvesting applications. For instance, TENGs are particularly effective in capturing energy from external mechanical sources such as human motion, wind, or water flow (Zhang CG et al., 2021b). They have proved useful in a wide range of applications, including wearable devices, self-powered sensors, and even smart textiles. TENGs offer a practical avenue for energy harvesting, as they can harness mechanical energy present in our daily lives. On the other hand, PENGs excel in converting ambient mechanical vibrations and motions into electrical energy (Zhang H et al., 2021). They find applications in fields such as structural health monitoring, wireless sensor networks, and implantable devices. PENGs can power low-energy electronic devices and enable self-sustaining systems by utilizing mechanical energy that exists in the environment.

The concepts of triboelectric and piezoelectric nanogenerators are illustrated in Fig. 1. The figure is divided into two parts, with Fig. 1a showcasing the fundamental modes of TENGs, and Fig. 1b depicting the application of the piezoelectric effect for sensing and harvesting. In Fig. 1a, four fundamental modes are depicted, highlighting the various ways in which mechanical energy can be converted into electrical energy through the triboelectric effect. On the other hand, Fig. 1b demonstrates the piezoelectric effect's dual functionality for sensing and energy harvesting. In Fig. 1b(I), we showcase a piezoelectric material in a state devoid of stress, maintaining a state of equilibrium. As the material undergoes polarization to a designated level, P_s, an accumulation of charge at the material's surface ensues to preserve the charge balance, resembling the behavior of poled ferroelectric materials. However, when a compressive stress is applied to the material, as illustrated in Fig. 1b(II), the polarization level decreases. This reduction facilitates the movement of surface charge, and generates an electric current to run through an external circuit. Following the cessation of stress or the imposition of a tensile stress, the material's polarization level changes to provide a flow of current in the opposing direction, thus upholding the charge equilibrium and showcasing

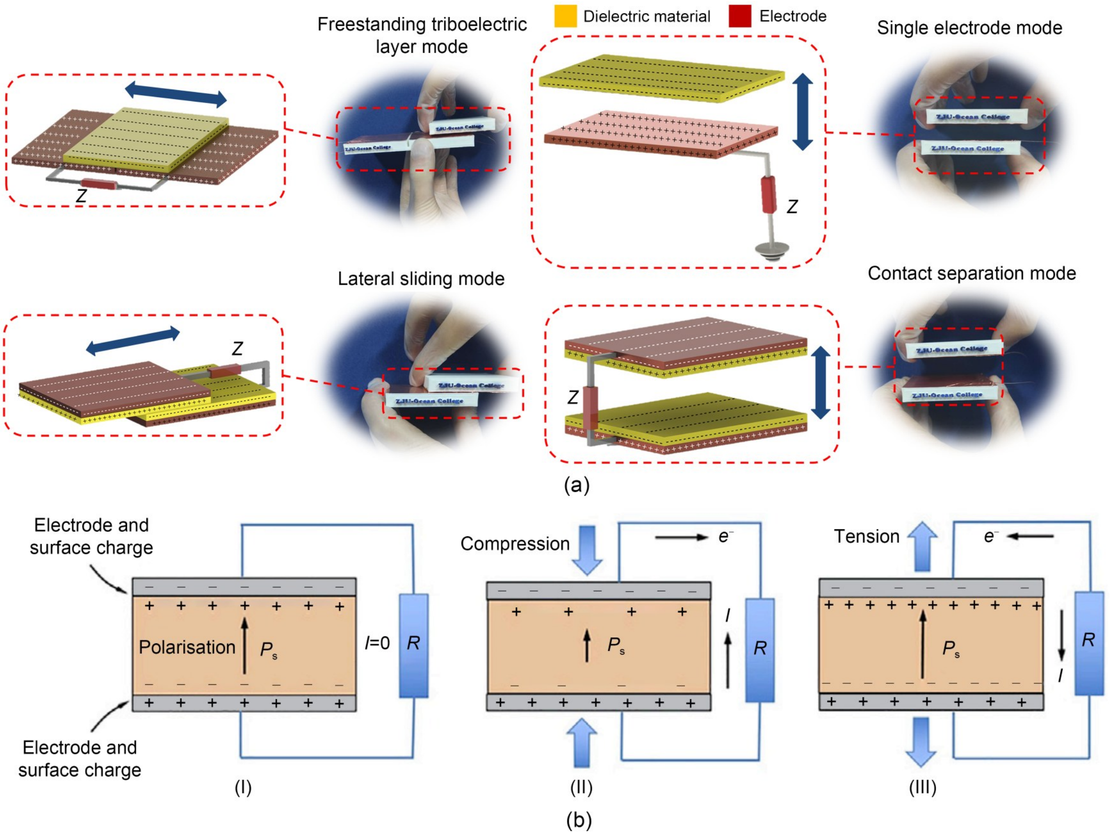


Fig. 1 Concepts of triboelectric and piezoelectric nanogenerators: (a) four core modes of TENGs (Rayegani et al., 2023b); (b) utilization of the piezoelectric effect for sensing and energy harvesting (Pan et al., 2020). *Z* represents the impedance of the system, *I* represents the current, and *R* represents the resistance

the cyclic behavior of piezoelectric materials under varying stress conditions (Fig. 1b(III)).

3 Overview of energy harvesting based on triboelectric and piezoelectric nanogenerators

Triboelectric and piezoelectric nanogenerators have emerged as promising technologies for converting wind energy into usable electrical power (Yang et al., 2014; Chen et al., 2015; Zhang XQ et al., 2019; Du TL et al., 2021; Du Y et al., 2021; Zhang CG et al., 2021a, 2022; Zhou et al., 2021; Son et al., 2022; Zhang C et al., 2022). When wind interacts with TENGs, it induces relative motion between the contacting surfaces, leading to the generation of electrical charges. The wind-induced motion causes materials with different triboelectric properties to rub against each other, resulting in the transfer of electrons and the accumulation of charges. This charge accumulation can be utilized to generate electrical power (Zhang QY et al., 2021). The key to efficient energy conversion in TENGs lies in the selection of appropriate materials with ideal surface properties. Materials with distinct triboelectric properties are thus carefully chosen to facilitate efficient charge generation (Wang SH et al., 2014; Wang X et al., 2016; Shi et al., 2017, 2019; Li et al., 2019c; Qin et al., 2019; Tao et al., 2021). After selecting materials with contrasting electronegativities and optimizing the surface morphologies, TENGs can achieve enhanced charge transfer and higher power output. Furthermore, the design of TENGs is crucial for effective wind energy capture. Utilizing flexible and lightweight materials, incorporating structures that promote wind flow, and optimizing the dimensions of the device can significantly improve the energy harvesting efficiency (Jiao et al., 2022a).

Meanwhile, when wind interacts with PENGs, it induces mechanical deformation in the piezoelectric materials, resulting in the separation of charges and the generation of electrical power (Jiao et al., 2020). The wind-induced vibrations, bending, or compression are efficiently converted into electrical energy by the PENG (Shu and Lien, 2006). In wind energy harvesting, the selection of appropriate piezoelectric materials is crucial for maximizing power generation. Materials with high piezoelectric coefficients and desirable mechanical properties enable efficient energy conversion. Additionally, optimizing the design and geometry of PENGs is essential for enhancing their performance (Wang XF et al., 2017). Factors such as the thickness, shape, and piezoelectric material layout can influence the mechanical deformation and distribution of strain, ultimately impacting the power output of the device.

Both TENGs and PENGs offer numerous advantages in wind energy harvesting. They are lightweight, scalable, and can be integrated into various applications. TENGs are particularly suitable for capturing wind energy from external sources, such as wind turbines, windmills, or even natural wind flows (Gonzalez et al., 2011; Datta et al., 2017; Shen et al., 2018; Yang et al., 2018; Zhang et al., 2020; Lu et al., 2021). They can be employed in applications such as self-powered sensors, wearable devices, and environmental monitoring systems. On the other hand, PENGs are highly efficient in harvesting wind energy from vibrations and mechanical motions. They find applications in areas such as structural health monitoring, wireless sensor networks, and energy harvesting from infrastructure vibrations (Yuan et al., 2021). The integration of triboelectric and piezoelectric nanogenerators into wind energy harvesting systems holds tremendous potential for sustainability and self-powered efficiency. By harnessing abundant wind energy resources, these nanogenerators could help reduce our reliance on traditional energy and promote environmentally friendly practices. Moreover, the integration of TENGs and PENGs into other energy harvesting technologies, such as solar panels or thermoelectric generators, could help develop hybrid systems that enhance the overall efficiency and reliability of energy harvesting.

4 Harnessing wind-powered TENGs for energy harvesting

TENGs can utilize airflow-induced motion or vibrations of structures to convert mechanical energy into electrical energy. Through careful selection of materials, electrode configurations, and optimization of structural parameters, energy harvesting systems can be made more efficient. TENGs demonstrate significant potential in various wind engineering applications, including structural health monitoring, environmental sensing, and self-powered wireless sensor networks. By capturing mechanical energy from wind and converting it into usable electricity, these systems offer a sustainable approach to powering remote or off-grid devices, helping advance clean energy technologies.

The TENG in Fig. 2a exhibits a unique design wherein the dielectric films are bent in four directions, thereby enabling the collection of wind energy from all directions. This is different from conventional wind-driven TENGs, which can only harvest wind energy from a single direction. The addition of an aluminum (Al) layer within the dielectric film, as mentioned in reference (Shin et al., 2021), improved electrostatic induction and triboelectric performance. The continuously rotating triboelectric nanogenerator (CR-TENG) in Fig. 2b was designed to lower rotor resistance at low wind speeds (about 3.5 m/s) and boost sliding contact efficiency, by using a one-dimensional fiber instead of two-dimensional contact surfaces. According to a recent study, a compact CR-TENG device measuring 2 cm in diameter was able to generate electrical energy (measuring 5.1, 8.5, and 23.8 V) when exposed to artificial wind conditions (at 10, 20, and 30 m/s) within a mobile carrier. This suggests that developing a small, highly-integrated CR-TENG device with improved mobility is a promising avenue for future research (Rayegani et al., 2023b). Fig. 2c illustrates a TENG that operates under breeze-induced motion. The breeze-driven triboelectric nanogenerator (BD-TENG) exhibits a low start-up wind speed of 3.3 m/s, achieved with lightweight rotor materials and appropriately designed wind scoop structures. At a wind speed of 4 m/s, the BD-TENG achieves a 12.06% energy conversion efficiency, enabling it to power a soil thermometer using only natural wind energy. Consequently, the BD-TENG has potential for agricultural applications, such as networks of smaller sensors utilized in farming. According to a previous study (Li et al., 2022), the BD-TENG exhibits promise in the field of smart agriculture, and could facilitate its sustainable advancement.

Fig. 3a depicts a TENG that can collect energy from omnidirectional wind across a broad spectrum of velocities. The harvester is comprised of a pliable cylindrical casing and a vertical support. Both components

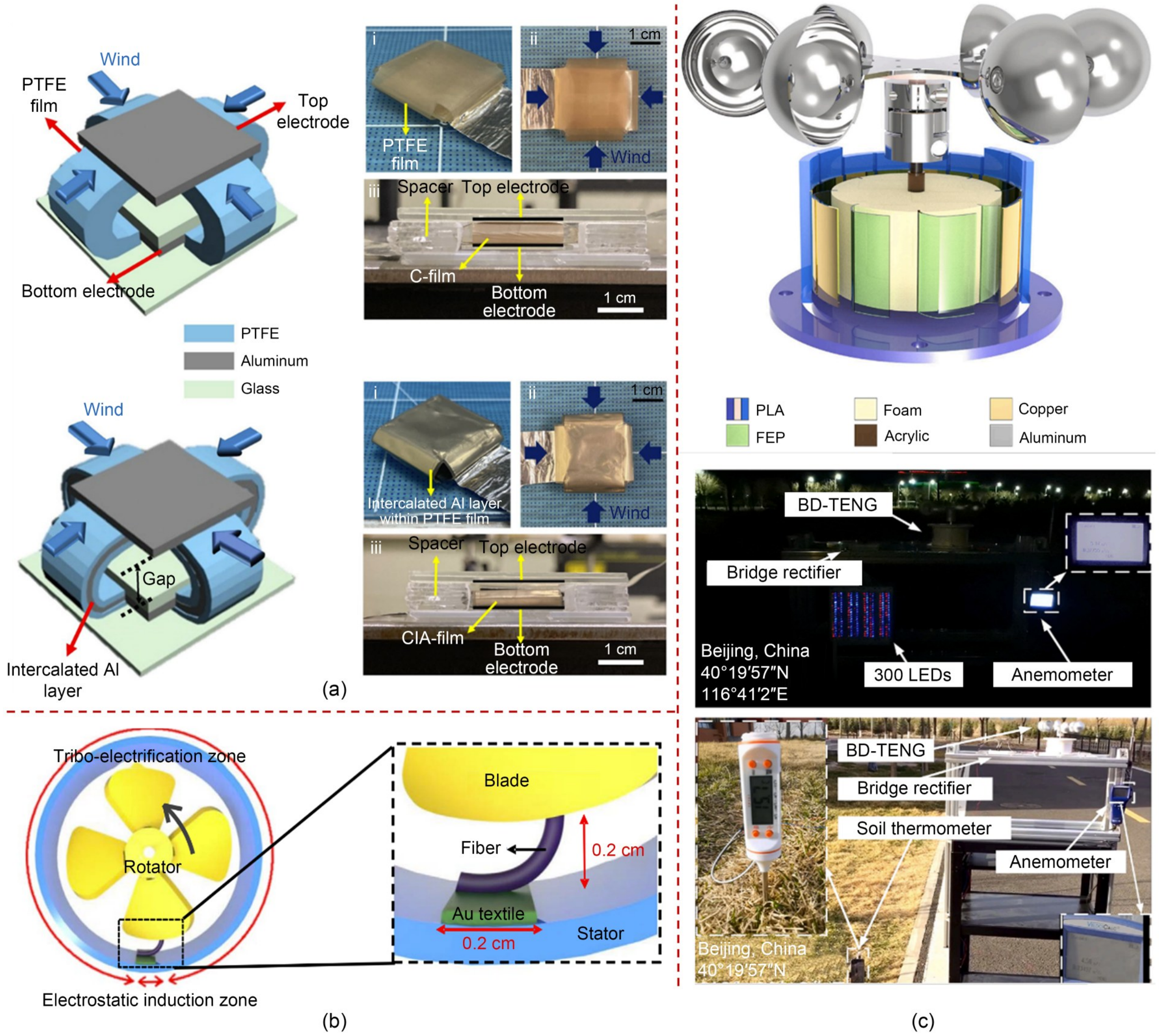


Fig. 2 Harnessing wind-powered TENGs for energy harvesting: (a) design principal of cross-shaped triboelectric nanogenerator (C-TENG) (Shin et al., 2021); (b) basic CR-TENG design and various CR-TENG structures with different tribo-materials on the stator (reprinted from (Park et al., 2017), Copyright 2017, with permission from Elsevier); (c) BD-TENG structure (reprinted from (Li et al., 2022), Copyright 2022, with permission from Elsevier). PLA: polylactic acid; FEP: fluorinated ethylene propylene; LED: light-emitting diode. References to color refer to the online version of this figure

are made of aluminum and polytetrafluoroethylene (PTFE), which act as triboelectric materials. The Coulombic attraction between two triboelectric materials forms a self-suspended structure comprised of a thin shell. Consequently, the continuity of the electrical connection between the aluminum and electrodes is preserved, making the system deformable even under low-velocity winds. Altering the separation of the two charged layers facilitates energy acquisition through the triboelectric energy conversion mechanism.

Because of its cylindrical configuration, the harvester can efficiently generate energy across all wind orientations. Experimental results have confirmed a direct relationship between the wind speed and the generated voltage and current. Specifically, an increase from 0.3 to 10.0 m/s in wind speed resulted in a corresponding increase in voltage and current. The root mean square (RMS) power density resulting from a wind velocity of 10 m/s was 8.43 mW/m^2. The voltages measured at the electrodes on the PTFE layer, which was divided into eight sections, exhibited asymmetry along any given direction. The study showcased that the harvester could function as a wind-monitoring sensor that is self-powered and durable, due to the strong

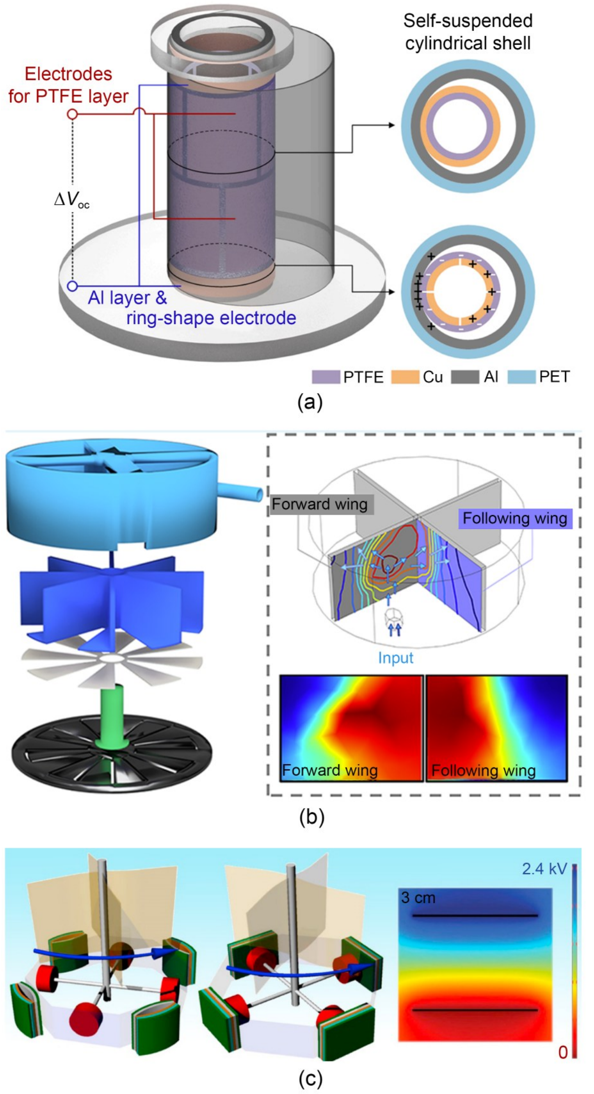


Fig. 3 Using wind-driven TENGs for energy harvesting: (a) diagram of the self-suspended shell-based TENG (reprinted from (Ko et al., 2022), Copyright 2022, with permission from Elsevier); (b) schematics of the P-TENG (reprinted from (Roh et al., 2019), Copyright 2019, with permission from American Chemical Society); (c) magnetic-assisted noncontact TENG design concept (reprinted from (Huang et al., 2016), Copyright 2016, with permission from Elsevier). PET: polyethylene terephthalate. References to color refer to the online version of this figure

relationship between generated voltage and wind speed and direction (Ko et al., 2022). Fig. 3b illustrates a TENG which utilizes a rotating disk to generate electrical energy from wind, also incorporating a propeller. TENGs are commonly used because of their ability to produce a relatively high output current, which is attributed to their high frequency of rotation. A comprehensive examination of the gas flow within a TENG is imperative for enhancing its energy conversion efficiency. Prior research has treated the propeller and TENG as distinct components that individually capture wind energy and produce electrical energy. The electrical outputs are calculated using the inlet's height and angle, as well as the number of wings on the propeller. Following optimization, the propeller triboelectric nanogenerator (P-TENG) exhibited an impressive output power density of 283.95 mW/m^2, which enabled the illumination of 205 light-emitting diodes and the operation of a small commercial electronic device. Furthermore, the optimization of the P-TENG enabled it to provide enduring power to a self-sufficient wireless sensor system (Roh et al., 2019). Therefore, the described study presented a novel approach for wind and blue energy harvesting, utilizing a magnetic-assisted noncontact TENG, as depicted in Fig. 3c (Huang et al., 2016).

The diagram in Fig. 4a illustrates a possible configuration of TENGs on a farm, harnessing wind energy at scale. The TENG system, which operates in a freestanding mode via contact electrification between two disks featuring micro-sized circular sectors, has the capability to convert both weak and strong wind energies into electrical power. In one study, a performance comparison was made between TENG and Darrieus turbines through both experimental and theoretical analyses. The findings suggested that TENGs have a distinct advantage at low rotation speeds. A TENG farm has thus been identified as a promising approach for large-scale wind energy harvesting, due to its lightweight nature, cost-effectiveness, eco-friendliness, and ease of connectivity (Ahmed et al., 2017). The utilization of wind energy through a wind-rolling triboelectric nanogenerator (WR-TENG) is illustrated in Fig. 4b. The WR-TENG generates electricity by spinning a lightweight dielectric sphere on a substrate with a vortex whistle. Boosting the dielectric's wind-converted kinetic energy is crucial for making an efficient WR-TENG.

The results indicated that the electrical power can be augmented by utilizing various electrode configurations within a singular apparatus, and by increasing the number of dielectric spheres in the WR-TENG. The wind-rolling TENG is therefore an innovative method for achieving sustainable wind-driven energy harvesting. Its design is responsive and dependable in the presence of varying wind flows, and it could accordingly utilize untapped wind energy in the future (Yong et al., 2016).

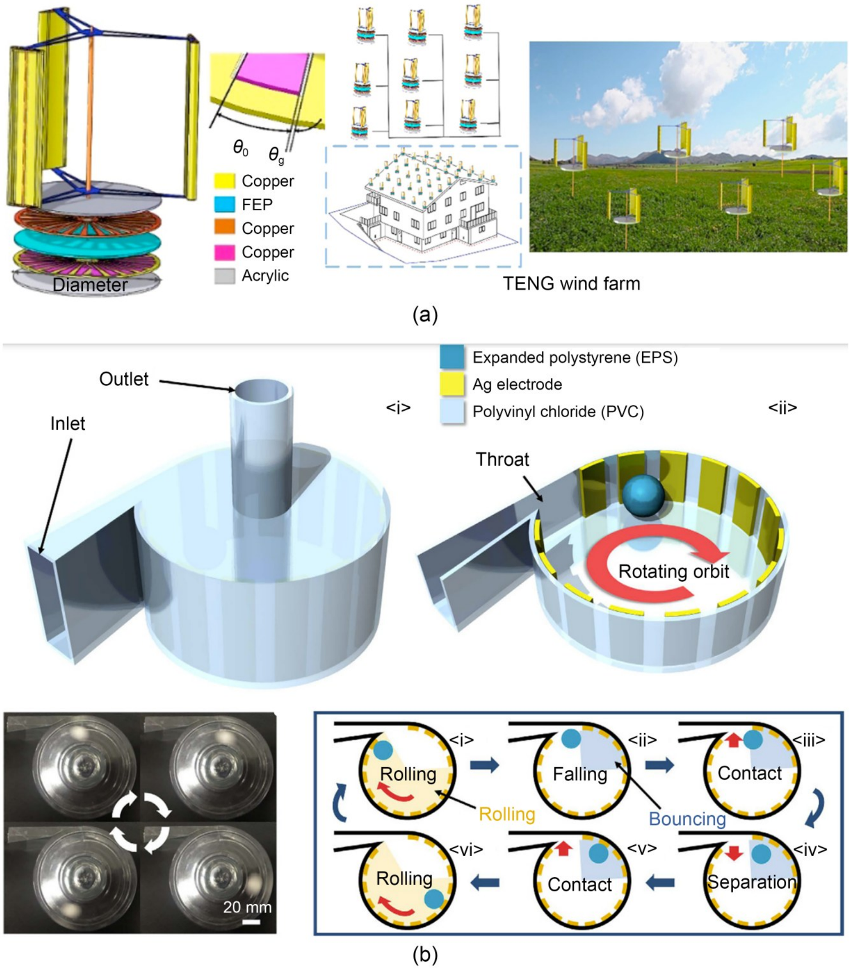
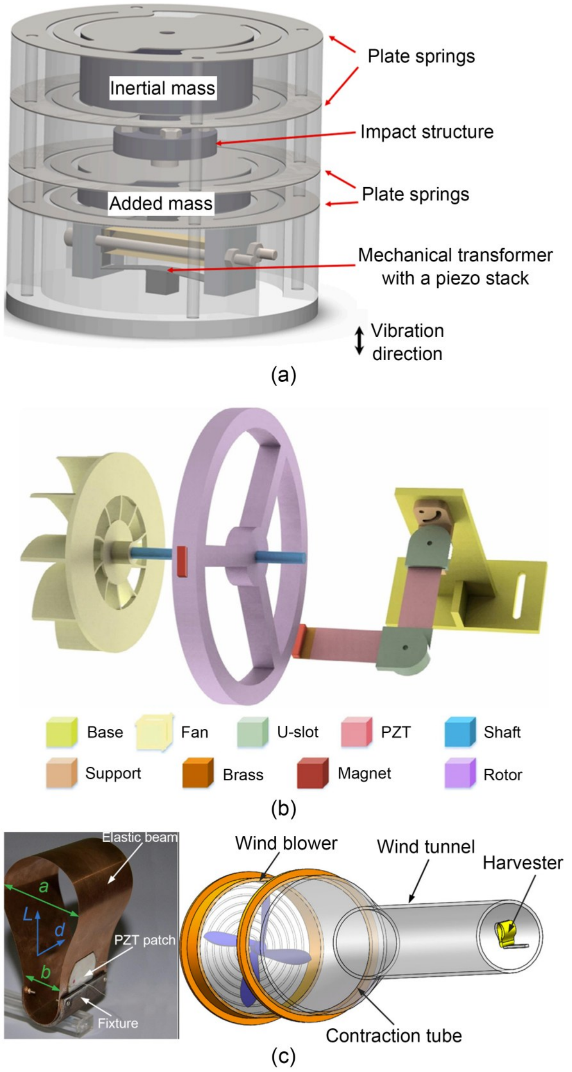


Fig. 4 Wind-powered TENGs for energy harvesting: (a) schematic of a two-part triboelectric generator (rotator and stator) and its operating principle (reprinted from (Ahmed et al., 2017), Copyright 2017, with permission from Elsevier); (b) inner structure schematic of the WR-TENG (Yong et al., 2016). θ_0: static contact angle of the material; θ_g: dynamic contact angle during the triboelectric effect. References to color refer to the online version of this figure

5 Wind-powered PENGs for energy harvesting

Wind-driven PENGs use the piezoelectric effect to transform vibrations and deformations into electricity. These nanogenerators employ materials with piezoelectric properties to create electric charge from wind-induced mechanical stress or strain. Such technologies offer a promising avenue for energy harvesting in wind engineering applications. They can be integrated into various systems such as wireless sensor networks, IoT devices, and environmental monitoring systems, providing a sustainable and self-sufficient power source. The development of advanced piezoelectric nanomaterials, device designs, and fabrication techniques has led to enhanced performance in wind energy harvesting, making wind-powered PENGs a promising avenue for achieving clean and renewable energy.

We depict the design, modeling, and experimentation of a piezo stack energy harvester in Fig. 5a. The proposed mechanism is equipped with a frequency up-conversion feature, which enables the collection of energy from railway track vibrations. The proposed harvester is engineered to satisfy the size, frequency, and stress prerequisites of railway track applications. A condensed configuration that merges the inertial mass and piezo stack transducer systems is used to meet the physical requirements of the frequency up-conversion mechanism. As illustrated in Fig. 5b, the harvester employs plate springs to fit the railroad track and resultingly increase the frequency bandwidth. Experiments



(a)

(b)

(c)

Fig. 5 Wind-powered PENGs for energy harvesting: (a) Schematic of the energy harvester using frequency up-conversion (Shan et al., 2022); (b) S-PEH design concept (reprinted from (Yu et al., 2022), Copyright 2022, with permission from John Wiley and Sons); (c) Arc-shaped piezoelectric generator for multi-directional wind energy capture (reprinted from (Zhao et al., 2015), Copyright 2015, with permission from Elsevier). PZT: piezoelectric lead zirconate titanate; *a*: length of the elastic beam; *b*: width of the elastic beam; *d*: distance between the PZT patch and the fixture; *L*: distance between points on the elastic beam. References to color refer to the online version of this figure

show that the piezo stack transducer's mechanical transformer can handle stress and has two resonant frequencies: 17 and 20 Hz. Low-frequency vibrations are shifted to a 94 Hz resonance through an up-conversion process (Yu et al., 2022).

This results in the conversion of mechanical energy into electrical energy. The unique configuration of the transducer's cantilever beam, which is sickle-shaped, is highly efficient at capturing wind energy in low-frequency settings, thus expanding the scope of wind speed harvesting in high-voltage applications. This theoretical analysis of the structure and principles of sickle-shaped cantilever beam piezoelectric energy harvester (S-PEH) has also been experimentally verified (Yu et al., 2022). The authors of the study presented a piezoelectric wind energy harvester, as shown in Fig. 5c, to overcome the constraints associated with current methodologies, such as unidirectional functionality and a limited range of operational wind speeds. This harvester utilizes an arc-shaped elastic beam, as opposed to traditional thin cantilever beams, for the purpose of wind energy extraction. The harvester can harness wind energy from various directions due to the arc-shaped structure and elasticity of the beam, without requiring any additional accessories. A model was constructed to examine the impact of wind direction and structural parameters on the electrical output. During experimentation, this harvester model demonstrated optimal performance across various wind directions and speeds ranging from 2–17 m/s, resulting in a maximum open-circuit voltage output of 34 V. Furthermore, the usefulness of the harvester was confirmed when it simultaneously illuminated 18 LEDs that were connected in series, harnessing the wind with a speed of 10.5 m/s (Zhao et al., 2015).

The potential use of rotational energy harvesters is explored in Fig. 6a. The rotor disk, which is comprised of six permanent magnets (PMs), magnetically interacts via rotation with the PMs of the tip-mass of the stator's counterpart cantilever. The trapezoidal shape of the cantilever beams was chosen to allow transverse mode operation, which utilizes a planar electrode made of Ag/Pd that is printed onto a thick film of piezoelectric lead zirconate titanate (PZT). The optimized distance between the PMs on the rotor and the stator was determined to be roughly 10 mm vertically. This distance was chosen to maximize the deflection of the piezoelectric cantilever beam while avoiding the formation of cracks. The optimized trapezoidal piezoelectric cantilever had a theoretical maximum resistance torque of 46 mN·m.

The proposed energy harvester was also utilized to harness wind energy. The maximum harvested output power was approximately 22 mW, when the wind speed was 10 m/s and a resistive load of 30 kΩ was applied.

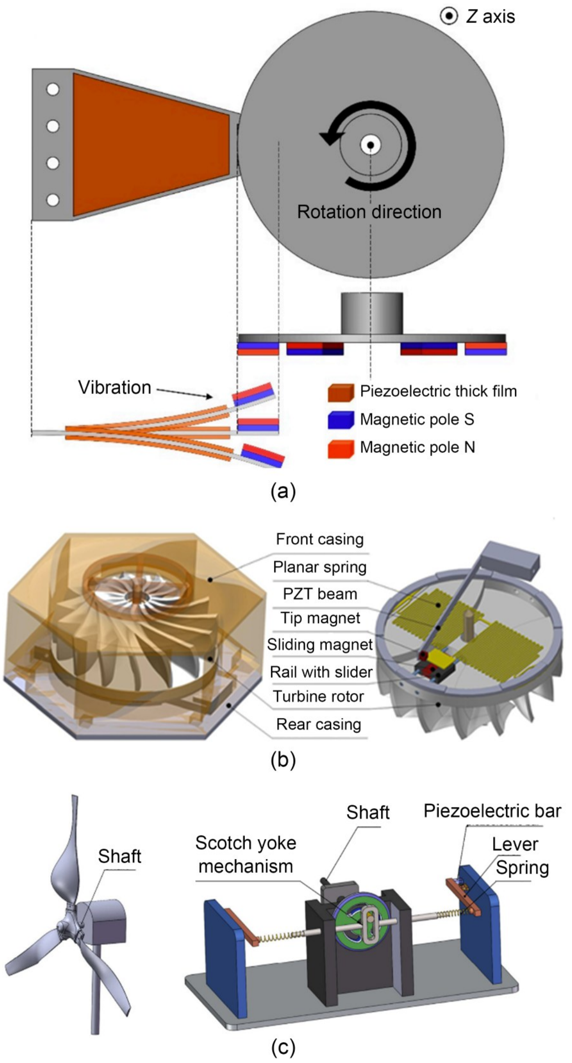


Fig. 6 Wind-powered PENGs for energy harvesting: (a) trapezoidal piezoelectric cantilevers with magnetic coupling for rotational energy harvesting (Na et al., 2021); (b) schematic of a small piezoelectric wind turbine with a dynamic regulator (reprinted from (Fu and Yeatman, 2015), Copyright 2015, with permission from AIP Publishing); (c) diagram of a horizontal piezoelectric wind turbine (reprinted from (Tao et al., 2017), Copyright 2017, with permission from Elsevier). References to color refer to the online version of this figure

The energy harvester demonstrates an impressive output, thereby enabling the provision of power to many low-power applications, such as smart sensor systems (Na et al., 2021). The micro-planar spring in Fig. 6b serves as a dynamic regulator, lowering the startup airflow speed of the piezoelectric turbine. It achieves this by adjusting the magnetic interaction between the turbine rotor and a piezoelectric cantilever using a spring. The finite element method (FEM) was used to design optimal springs with various shapes and sizes. A micro spring was produced through laser machining of titanium foil, exhibiting an ultra-low spring constant of 0.78 N/m. This spring was installed within the miniaturized air turbine in order to attain self-regulation. According to Fu et al. (2016), the turbine's cut-in speed increased by 30%, reaching 2.34 m/s higher than an unregulated turbine.

A wind power harvester utilizing the piezoelectric effect is depicted in Fig. 6c. This apparatus uses a wind turbine to harness the kinetic energy of the wind and transform it into the rotational motion of a shaft. The rotational shaft is linked to a Scotch yoke mechanism, which transforms rotational motion into the linear vibrations of two piezoelectric levers through springs. A mathematical model was formulated to compute the RMS magnitude of the electric power produced. The authors examined the impact of various factors, like the rotational velocity of the wind turbine and the rigidity of the springs, on the RMS of the produced power. According to their findings, a piezoelectric wind turbine with a blade radius of 1 m can generate a power output of up to 150 W when exposed to a wind speed of 7.2 m/s, and designed to rotate at an angular velocity of 50 rad/s (Tao et al., 2017).

Fig. 7a showcases the utilization of magnetic coupling in vibrational turbine piezoelectric nanogenerators (VT-PENGs), for energy harvesting in amphibious settings. The VT-PENG employs silicon rubber strips that are integrated with piezoelectric films. The deflection of piezo-rubber strips by tip-driven magnets in strip-anchored systems results in the efficient triggering of the VT-PENG, accordingly generating electrical energy from mechanical vibration. VT-PENG prototypes have been manufactured and their energy harvesting efficacy has been tested, specifically with regards to voltage and electrical power. This has included both individual and multiple strip forms of the VT-PENG. The experimental results were also validated through numerical simulations, showing a satisfactory level of agreement.

Ultimately, the efficacy of energy harvesting was tested in a real lake. According to Egbe et al. (2021), the VT-PENG has great potential for applications with low-to-medium energy harvesting requirements, using energy from diverse flow fields. The findings depicted in Fig. 7b demonstrate that the device is effective not only as an energy generator, but also as a sensor for wind velocity and direction. Employing an otherwise

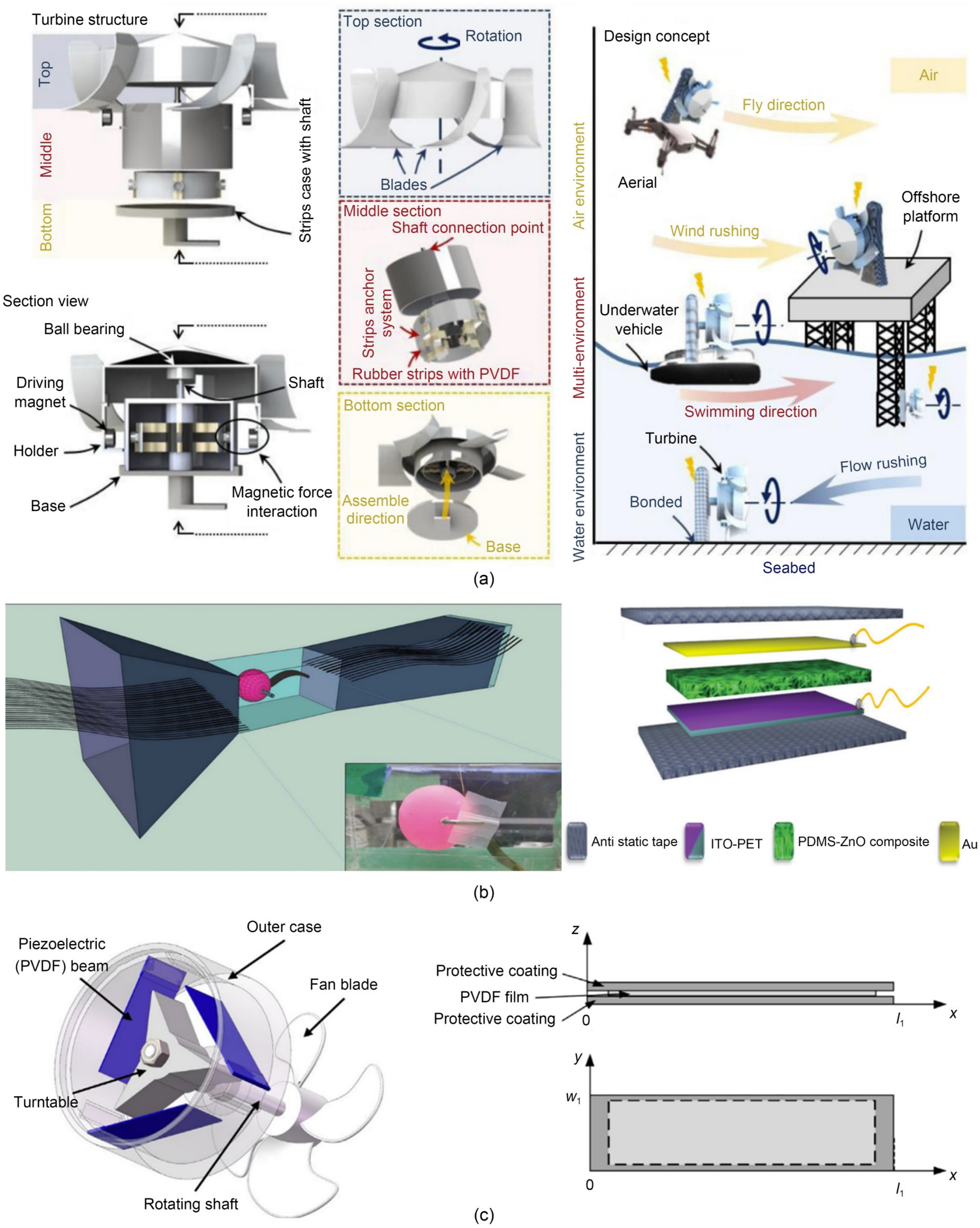


Fig. 7 Wind-powered PENGs for energy harvesting: (a) VT-PENG comprised of top, middle, and bottom segments (reprinted from (Egbe et al., 2021), Copyright 2021, with permission from Elsevier); (b) La-doped ZnO ultra-flexible flutter-PENG for energy harvesting and sensing—an innovative renewable energy source (reprinted from (Pandey et al., 2019), Copyright 2019, with permission from Royal Society of Chemistry); (c) schematic of the rotational piezoelectric energy harvester and the piezoelectric beam (reprinted from (Zhang et al., 2017), Copyright 2017, with permission from Elsevier). ITO: indium tin oxide; PDMS: polydimethylsiloxane; w_1: width of the PVDF beam; l_1: length of the PVDF beam. References to color refer to the online version of this figure

identical methodology, lanthanum was introduced as a dopant into ZnO nanorods, resulting in an apparatus with a threefold increase in output compared to the regular PENG. Moreover, the ultimate output of the PENG was improved through an annealing process. This methodology was used to create a device that is lightweight yet sensitive, functioning even under a light breeze (2.8–3.8 m/s).

At a wind velocity of 3.8 m/s, the device generated a voltage exceeding 1.6 V. These results suggest that the device has the potential to function as a self-powered wind velocity sensor. Additionally, it can serve as a sensor for wind direction within the range of 0° to 90°. A finite element simulation was conducted in order to examine the fundamental mechanisms of the device's operation. Furthermore, a stability test was performed on the sensor for over 4500 cycles, revealing that the device exhibits a high level of stability. Fig. 7c illustrates how a piezoelectric energy harvester with rotational capabilities can effectively harness wind energy. The polyvinylidene fluoride (PVDF) beam operates on the principle of piezoelectricity, whereby mechanical stress or impact-induced vibrations are converted into electrical energy. An analytical model is also introduced and subjected to simulations via the FEM.

Another study obtained the transient responses of a piezoelectric beam when it was subjected to an impulse pressure. A correlation analysis between the RMS output voltage and the frequency of excitation was performed. The frequency of impact was identified as a crucial factor influencing the harvester's performance. When the frequency of impact surpasses a critical threshold, the power output of the harvester will diminish as the wind speed increases. Certain methods aim to enhance the performance of the harvester by adjusting the vibration frequency of the PVDF beam. The wind energy can then be efficiently transformed by the harvester, as reported in reference (Zhang et al., 2017).

6 Challenges, perspectives, and insights into wind energy harvesting utilizing triboelectric and piezoelectric nanogenerators

Wind energy harvesting using triboelectric and piezoelectric nanogenerators offers promising opportunities for sustainable and renewable energy generation. However, there are several challenges that need to be addressed to realize the full potential of these technologies. We accordingly discuss the key challenges, provide perspectives, and offer insights into the future development of triboelectric and piezoelectric nanogenerators for wind energy harvesting.

One of the primary challenges in wind energy harvesting is scalability. While laboratory-scale development of triboelectric and piezoelectric nanogenerators has been impressive, scaling up these technologies for practical applications remains a daunting task. Achieving high power output and efficiency at large scales with low cost is crucial for widespread adoption. Researchers therefore need to explore scalable manufacturing techniques, optimize device architectures, and develop novel materials that can withstand the harsh environmental conditions associated with wind energy harvesting.

Durability is another critical challenge. Wind energy harvesting systems are exposed to various environmental pressures, such as high wind speeds, temperature fluctuations, high moisture, and mechanical stress. These factors can negatively impact the performance and lifespan of triboelectric and piezoelectric nanogenerators. Ensuring the long-term reliability of these devices is essential for their successful deployment in real-world scenarios. As a result, strategies such as protective coatings, encapsulation methods, and packaging designs need to be developed to enhance the durability of these energy harvesting systems.

Power management is a significant concern in wind-driven energy harvesting. The electrical energy generated by triboelectric and piezoelectric nanogenerators is typically intermittent, and varies with the wind conditions. Efficient power management strategies, such as utilizing energy storage systems and power conditioning circuits, are required to regulate and store harvested energy for reliable and continuous use. Developing power management approaches that can adapt to varying wind conditions and optimize energy utilization will be essential for maximizing efficiency.

Integration and system compatibility are key challenges for practical implementation. Triboelectric and piezoelectric nanogenerators need to be seamlessly integrated into existing infrastructure in order to be effective. This requires compatibility with different devices, systems, and networks, ensuring efficient power transfer and synchronization. Collaborative standardization efforts between researchers, engineers, and industry stakeholders are crucial for establishing common protocols and interfaces, enabling these energy harvesting technologies to be integrated into various wind engineering applications.

Triboelectric and piezoelectric nanogenerators also hold great promise for autonomous or self-powered wind energy systems. These technologies offer the potential to power remote sensors, wireless communication devices, and environmental monitoring systems, enabling real-time data collection and analysis without the need for external power sources. In wind farms, such systems can improve the monitoring and maintenance of the machinery, contributing to improved efficiency and reliability. Moreover, nanogenerators can contribute to the development of energy-independent and sustainable communities. In remote areas where access to conventional power sources is limited, these energy harvesting systems can provide a reliable and renewable source of electricity. This can lead to increased socioeconomic development, improved quality of life, and reduced reliance on non-renewable energy resources.

To address these challenges and unlock the full potential of triboelectric and piezoelectric nanogenerators for wind energy, several research directions should be considered. First, it is crucial to develop novel materials with enhanced performance and durability, such as flexible and stretchable piezoelectric polymers or advanced triboelectric materials. Exploring new device designs that optimize power generation and collection efficiency will also be beneficial. Additionally, increasing understanding of wind patterns and their impact on energy harvesting could help optimize systems and strategies.

The efficiency and functionality of TENGs and PENGs, particularly for harnessing wind energy, are dependent on factors such as design, materials, and operational mechanisms. Examining existing devices reveals significant disparities across key areas. Notably, some devices are tailored for portable energy harvesting while others are integrated into large-scale renewable energy systems. Moreover, the choice of materials, ranging from polymers to metals, profoundly impacts performance and durability. Furthermore, operational nuances, such as electrode arrangements and mechanical structures, influence energy conversion efficiency and responsiveness to varying wind conditions.

Efficiency values for TENGs and PENGs fluctuate widely in the literature, due to factors such as contact area, material properties, and device design. While reported efficiencies range from a few percent to over 50% for TENGs, and up to around 20% for PENGs, achieving consistently high efficiencies remains a challenge, especially for large-scale applications. Thus, there are ongoing efforts to optimize nanogenerator designs for wind energy harvesting, for which there are detailed experimental results (Choi et al., 2023). Table 1 compares the performances of various TENG and PENG devices for wind energy harvesting. These devices were evaluated using parameters such as power generation efficiency, output voltage, and output current under varying wind conditions. The data highlights the diverse capabilities and potential applications of TENGs and PENGs in harnessing sustainable wind energy.

7 Conclusions

This review has highlighted the advancements and challenges associated with triboelectric and piezoelectric nanogenerators used for wind energy harvesting. The triboelectric and piezoelectric effects which underly these devices' functions were discussed, emphasizing how they enable the conversion of mechanical energy into electrical energy. We provided an overview of the latest research and developments into energy harvesting based on triboelectric and piezoelectric nanogenerators. For both nanogenerator technologies, various optimization techniques and integration strategies were discussed, along with potential applications and associated challenges.

We also identified several challenges that need to be addressed for the successful implementation of wind-driven triboelectric and piezoelectric nanogenerators. These include scalability, durability, power management, and system integration. Future research efforts should focus on developing scalable manufacturing techniques, enhancing the durability of nanogenerators, and implementing efficient power management systems. Despite these challenges, we underscore the great potential of wind energy harvesting based on triboelectric and piezoelectric nanogenerators. These technologies offer sustainable methods for powering autonomous systems, monitoring wind turbines, and providing electricity in remote areas. This review contributes to

Table 1 Summary of various TENG and PENG techniques for energy harvesting

Structure	Reference	Max-open circuit voltage	Max-short circuit current	Surface power density	Power	Average power or voltage
TENG	Shin et al. (2021)	233 V	348 μA	46.1 W/m^2	–	~150 V
TENG	Park et al. (2017)	21.6 V	0.6 μA	–	–	~12 V
TENG	Li et al. (2022)	330 V	7 μA	–	2.81 mW	~300–330 V
TENG	Ko et al. (2022)	47.68 V	–	8.43 mW/m^2	–	~30–35 V
TENG	Roh et al. (2019)	62.4 V	8.3 μA	283.95 W/m^2	–	~60–62 V
TENG	Huang et al. (2016)	206 V	30 μA	–	3 mW	~120–160 V
TENG	Ahmed et al. (2017)	600 V	0.38 μA	–	0.6 W	~300 V
TENG	Yong et al. (2016)	11.2 V	1.86 μA	–	–	~9 V
PENG	Shan et al. (2022)	4.01 V	–	–	6.72 mW	~1.16 V
PENG	Yu et al. (2022)	120 V	–	–	563 μW	–
PENG	Zhao et al. (2015)	34 V	–	–	1.73 mW	~20 V
PENG	Na et al. (2021)	60 V	2 mA	–	22 mW	~35–45 V
PENG	Fu et al. (2016)	2.64 V	–	–	742 μW	~1.4 V
PENG	Tao et al. (2017)	–	–	–	553 W	~150 W
PENG	Egbe et al. (2021)	15 V	–	–	9 μW	~10–12 V
PENG	Pandey et al. (2019)	1.6 V	–	–	–	~1.0–1.2 V
PENG	Zhang et al. (2017)	160.2 V	–	–	2566.4 μW	~100–140 V

existing knowledge by providing insights, perspectives, and future directions for the advancement of wind engineering using nanogenerators. By addressing the associated challenges and leveraging the unique capabilities of these technologies, researchers and engineers can unlock the full potential of wind energy harvesting and contribute to a greener and more sustainable future.

Author contributions

Ali MATIN NAZAR crafted the methodology, visualized the data, and penned the original draft. Mingfeng HUANG handled the data curation and contributed to the reviewing and editing process. Haiwei XU spearheaded the conceptualization, allocated resources, supervised the project, and participated in reviewing and editing the manuscript.

Conflict of interest

Ali MATIN NAZAR, Haiwei XU, and Mingfeng HUANG declare that they have no conflict of interest.

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