
Review

Wind-driven triboelectric nanogenerators: Fundamental mechanisms, device architectures, and emerging applications

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Abstract: Wind energy is an abundant and sustainable renewable resource, yet its stochastic and low-frequency characteristics pose significant challenges for efficient utilization. Triboelectric nanogenerators (TENGs) have emerged as a promising technology for harvesting ambient wind energy, owing to their lightweight structures, low startup wind speeds, and excellent adaptability to irregular airflow conditions. Over the past decade, wind-driven TENGs have undergone rapid development, evolving from simple energy harvesters into multifunctional platforms capable of efficient energy conversion and self-powered sensing. Consequently, a timely review of this rapidly advancing field is highly desirable. This review provides a systematic overview of recent advances in wind-driven TENGs, covering their fundamental mechanisms, structural evolution, and emerging applications. The development of wind-driven TENGs from fluttering and rotary architectures to advanced direct-current systems is summarized, with key strategies for improving energy harvesting and output performance. Emerging applications in sustainable energy harvesting and self-powered sensing are highlighted, demonstrating the growing potential of wind-driven TENGs for energy utilization and environmental perception. Finally, future opportunities and challenges are discussed, including higher-efficiency energy harvesting, intelligent self-powered sensing, and integrated autonomous systems. This review aims to provide insights into future developments of wind-driven TENGs toward sustainable energy technologies and intelligent self-powered infrastructures.

Keywords: triboelectric nanogenerator; wind energy harvesting; self-powered sensing; emerging applications

1. Introduction

The increasing global demand for sustainable energy and the urgent need to mitigate environmental challenges associated with fossil fuel consumption have accelerated the development of renewable energy technologies [1–3]. Among various renewable energy resources, wind energy has attracted extensive attention owing to its abundance, widespread distribution, environmental friendliness, and enormous energy potential [4–7]. To date, large-scale wind turbines have been successfully commercialized for grid-level electricity generation and have become one of the fastest-growing renewable energy technologies worldwide [8–10]. However, a substantial amount of low-speed, intermittent, and distributed wind energy remains largely underutilized in natural and urban environments [11–14]. Meanwhile, the rapid emergence of the Internet of Things (IoT) has promoted the large-scale deployment of distributed wireless sensor networks, which have been systematically summarized in previous review works [15–17]. To fulfill the demands of real-time environmental monitoring, such distributed systems require flexible sensing units for pressure and physical signal perception, where iontronic devices provide feasible technical solutions toward adaptive sensing applications [18–20]. The widespread proliferation of distributed electronics puts forward high requirements for sustainable, maintenance-free power supplies. Systematic reviews have summarized various energy-harvesting strategies developed for wireless sensor network nodes [21]. A series of studies have demonstrated ambient-wind-driven approaches to construct self-powered sensing nodes for flow-rate measurement and meteorological monitoring scenarios [22–27]. Beyond physical signal sensing and energy harvesting, iontronic platforms can also implement logic-control functions for distributed systems through the regulation of dynamic electrical double layers [28]. Conventional batteries generally suffer from limited lifetimes and require periodic replacement, which increases the operating cost and maintenance burden of distributed devices [29–31]. In addition, the disposal and recycling of batteries raise notable environmental concerns, making them less suitable for sustainable distributed systems [32–34]. Therefore, there is a strong demand for alternative powering strategies that can support long-term operation without frequent human intervention [27,35,36]. Consequently, developing efficient technologies capable of harvesting ambient wind energy and directly powering distributed electronics has become an important research direction toward sustainable and self-powered systems. Multiple technical routes have been explored to capture ambient wind energy for distributed electronic applications [37,38]. Various optimized structural designs have been proposed to boost energy-harvesting output and operational stability under practical wind conditions [39,40]. Magnet-assisted configurations have further been investigated to realize steady and continuous energy output for real-world deployment [41]. Besides, bio-inspired vibration principles and hybrid energy-harvesting architectures are also adopted to improve environmental adaptability for variable-speed wind scenarios [42–44].

Since the invention of triboelectric nanogenerators (TENGs) in 2012, they have emerged as a transformative technology for converting ambient mechanical energy into electricity through the coupling of contact electrification and electrostatic induction [24,38,45–47]. Compared with conventional electromagnetic generators, TENGs possess several unique advantages, including lightweight structures, low fabrication cost, high voltage output, broad material selection, and excellent adaptability to low-frequency mechanical excitations [24,37,47–50]. These characteristics make TENGs particularly suitable for harvesting distributed and irregular mechanical energy that is difficult to efficiently utilize using traditional energy conversion technologies [45,48,51–53]. Electromagnetic generators (EMGs) offer high current output, but their relatively large size, heavy structures, and poor performance at low frequencies limit their suitability for small-scale wind-energy harvesting;

piezoelectric generators (PEGs) provide compact form factors, but their performance is constrained by limited material selection, relatively high fabrication cost, and modest output under irregular excitation; and dielectric elastomer generators (DEGs) can achieve high energy density, but they typically require pre-straining and large operating voltages, which complicate practical deployment. This comparison clearly contextualizes why wind-driven TENGs are uniquely suited for distributed micro-energy harvesting at low wind speeds and why hybrid systems such as TENG-EMG and TENG-PEG are increasingly pursued to overcome the limitations of individual energy-conversion mechanisms. Among various ambient mechanical energy sources, wind energy is especially attractive because it is naturally ubiquitous, continuously renewable, and capable of providing relatively high energy density over large spatial scales [4,40,41,54]. Consequently, extensive efforts have been devoted to the development of wind-driven TENGs for efficient wind energy harvesting [4,44,46,55,56]. Over the past decade, significant progress has been achieved in device design, output performance, and practical applications. A series of studies have advanced the structural design and wind-energy harvesting performance of wind-driven TENGs [37,49], while other works further explored their multifunctional applications and optimized device configurations [57–65]. Diverse wind-driven TENG architectures have been developed to accommodate different airflow conditions and energy harvesting requirements, leading to continuous improvements in energy conversion efficiency, environmental adaptability, and practical functionality [57–61]. Recently, the development of rotary direct-current (DC) TENGs has further improved charging efficiency and facilitated direct integration with energy storage systems [62–66]. It is worth noting that the liquid-solid triboelectric interaction exploits charge accumulation at the liquid-dielectric interface, offering unique advantages such as self-cleaning capability, reduced mechanical wear, and excellent conformability to irregular surfaces [67,68]. As a result, wind-driven TENGs have evolved from simple energy harvesters into multifunctional platforms capable of self-powered sensing and intelligent system integration [57,65, 69–76].

Despite these rapid advances, current studies remain scattered across different operating mechanisms, device architectures, and application scenarios [73,77–82]. Existing reviews mainly focus on general triboelectric nanogenerator technologies, specific wind energy harvesting systems, or individual device configurations, whereas a comprehensive understanding that links fundamental mechanisms, representative architectures, and emerging applications of wind-driven TENGs remains lacking [83–88]. In particular, the evolutionary development from fluttering structures to advanced rotary and rotary DC systems has yet to be systematically summarized. Given the rapid expansion of this field and the increasing demand for efficient and intelligent wind energy utilization technologies, a unified perspective is highly desirable for understanding the relationships among operating mechanisms, device architectures, and application functionalities.

To address this gap, we provided a systematic overview of recent advances in wind-driven TENGs from the perspectives of fundamental mechanisms, device architectures, and emerging applications. The fundamental operating principles governing triboelectric wind-energy conversion are first introduced, establishing the basis for understanding energy generation and output regulation in wind-driven TENGs. Subsequently, the structural evolution of wind-driven TENGs is comprehensively discussed, covering the development from fluttering architectures to rotary systems and emerging direct-current TENGs (DC-TENGs), with particular emphasis on strategies for enhancing energy-harvesting efficiency, broadband wind adaptability, output stability, and DC generation (Figure 1). For each representative category, the underlying physical mechanisms for performance enhancement, structural design advantages, and inherent limitations (such as wind fluctuation, material fatigue, aerodynamic instability, or output irregularity) are explicitly elucidated to evaluate their practical potential. Furthermore, representative applications in sustainable energy

harvesting and self-powered sensing are summarized, highlighting the expanding role of wind-driven TENGs in smart agriculture, intelligent transportation, marine monitoring, and autonomous sensing systems. Finally, current challenges and future opportunities are discussed to provide perspectives for the development of next-generation wind-driven TENGs. By establishing clear relationships among fundamental mechanisms, device architectures, and application functionalities, this review aims to provide guidance for the rational design and practical deployment of efficient wind-driven triboelectric energy-harvesting and self-powered sensing systems.

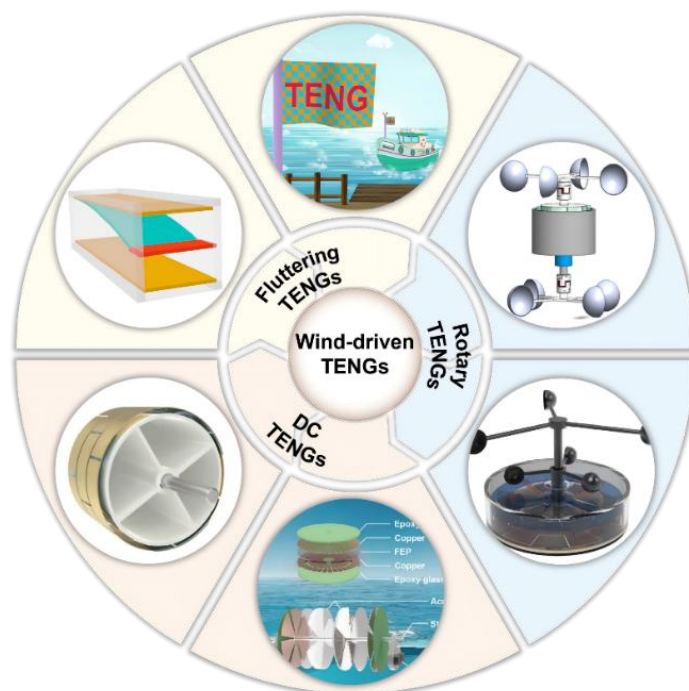


Figure 1. The structural evolution of wind-driven TENGs is comprehensively discussed, covering the development from fluttering TENGs [43,89] to rotary TENGs [90,91] and emerging DC-TENGs [92,93].

2. Fundamental mechanisms of wind-driven TENGs

TENGs convert mechanical energy into electricity through the coupling of contact electrification and electrostatic induction. When two materials with different triboelectric polarities come into physical contact, opposite triboelectric charges are generated on the corresponding surfaces. Subsequent relative motion between the charged surfaces breaks the electrostatic equilibrium and creates a potential difference between the electrodes, driving electrons to flow through an external circuit. Through repeated mechanical excitation, continuous charge transfer and electrical output can be achieved (Figure 2). In wind-driven TENGs, airflow-induced mechanical motions, including fluttering, flapping, swinging, sliding, and rotational movements, serve as the driving force for periodic triboelectric interactions. Depending on how the relative motion between triboelectric surfaces occurs, TENGs can generally operate in four fundamental modes [92]: contact-separation mode [94,95], lateral sliding mode [52], single-electrode mode [87], and freestanding triboelectric-layer mode [88] (Figure 3). These four modes constitute the theoretical foundation of virtually all reported wind-driven TENG architectures.

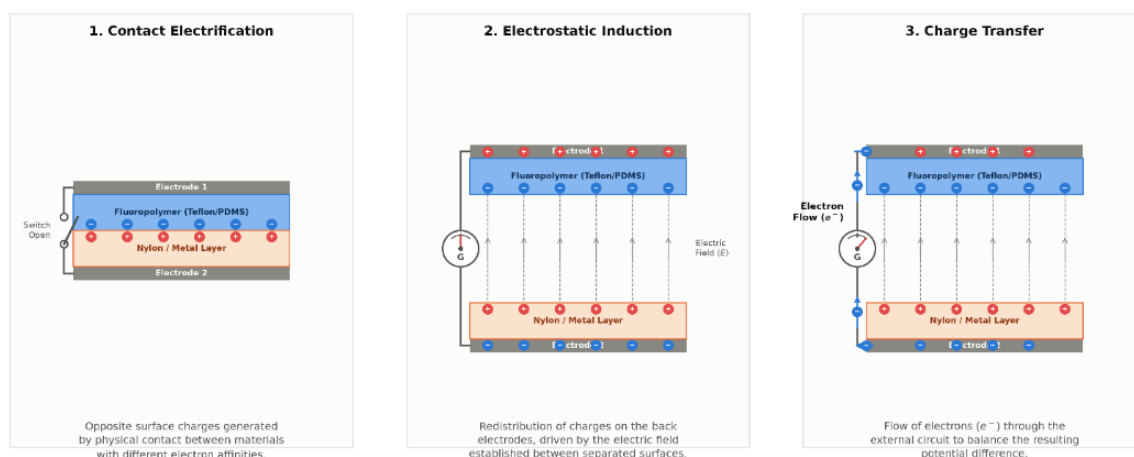


Figure 2. The three fundamental processes governing TENG operation.

In the contact-separation mode (Figure 3a), two triboelectric layers periodically contact and separate under external mechanical excitation. During contact, opposite triboelectric charges are generated on the two surfaces. As the layers separate, an electric field is established between the electrodes, inducing electron transfer through the external circuit. When the layers return to the original contact state, the potential difference vanishes, and the electrons flow back, resulting in alternating-current output. Owing to its simple structure and high charge generation capability, this mode is widely employed in fluttering wind-driven TENGs, where airflow-induced vibrations periodically drive contact and separation between flexible dielectric films. In the lateral sliding mode (Figure 3b), electricity is generated through the relative in-plane displacement of two triboelectric surfaces. After triboelectrification occurs, lateral movement continuously changes the charge distribution and induces a varying electric potential difference between the electrodes. Compared with the contact-separation mode, the lateral sliding mode generally exhibits higher charge utilization efficiency because a larger proportion of triboelectric charges participates in the induction process. Consequently, this mode is frequently adopted in rotary wind-driven TENGs, where turbine-induced rotational motion drives continuous sliding between rotor and stator components.

To simplify structural design and accommodate freely moving objects, the single-electrode mode was developed (Figure 3c). In this configuration, only one electrode is connected to the TENG, while the ground or surrounding environment serves as the reference electrode. When a charged object periodically approaches or departs from the triboelectric surface, the resulting change in electric field distribution induces electron transfer between the electrode and ground. The absence of direct electrical connections to moving components significantly improves device flexibility and adaptability, making this mode particularly suitable for flag-type TENGs and self-powered wind sensing systems. The freestanding triboelectric-layer mode is regarded as one of the most efficient triboelectric energy conversion mechanisms (Figure 3d). In this mode, a charged triboelectric layer moves freely between two stationary electrodes without directly contacting them. The movement of the freestanding layer periodically modulates the electric field distribution, thereby inducing electron transfer between the electrodes. Because electrostatic screening effects are largely minimized, higher charge transfer efficiency and enhanced electrical output can be achieved. Furthermore, the reduced mechanical friction contributes to improved durability and long-term operational stability. Therefore, the freestanding mode has become a dominant mechanism in many advanced rotary wind-driven TENGs.

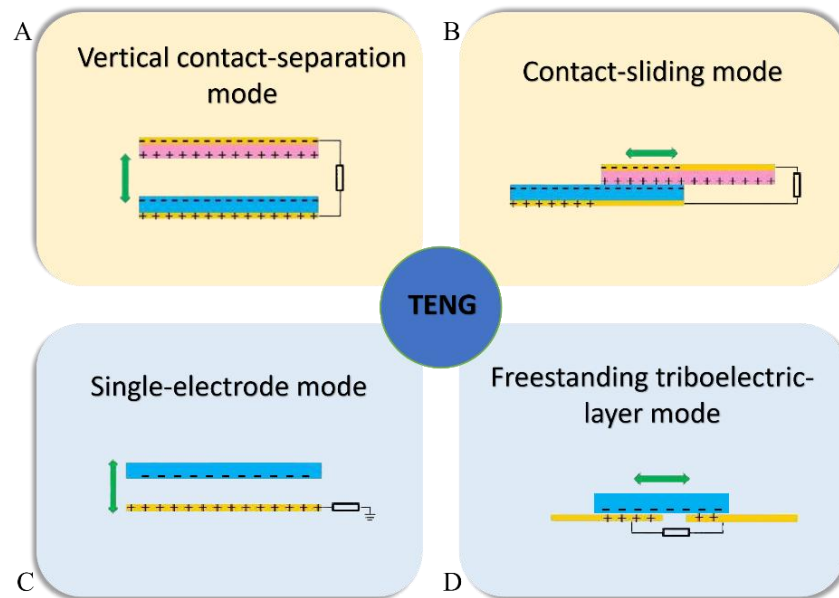


Figure 3. Depending on how the relative motion between triboelectric surfaces occurs, TENGs can generally operate in four fundamental modes: (a) contact-separation mode [102], (b) lateral sliding mode [51], (c) single-electrode mode [95], and (d) freestanding triboelectric-layer mode [86,88].

Although these four operating modes differ in structural configuration and charge transfer behavior, they share the same fundamental energy conversion mechanism based on contact electrification and electrostatic induction. More importantly, they provide the theoretical basis for the diverse device architectures developed for wind energy harvesting. Generally, contact-separation and single-electrode modes are predominantly employed in fluttering and flag-type wind-driven TENGs, whereas lateral sliding and freestanding triboelectric-layer modes are widely adopted in rotary architectures. Understanding the characteristics of these fundamental operating mechanisms is essential for the rational design and performance optimization of wind-driven TENGs, which will be discussed in the following sections.

The four operating modes described above provide a qualitative framework for wind-driven TENGs. However, a quantitative link between the fluid-dynamic parameters (wind speed, vortex-shedding frequency, and membrane stiffness) and triboelectric charge generation is essential for rational device design.

For fluttering TENGs, the flutter onset of a flexible film with length L , natural frequency f_n , and wind speed U is governed by the reduced velocity $U^* = U/(f_n L)$. Self-sustained oscillation occurs above a critical U^* , and the resulting contact frequency f_c is typically close to the film's structural natural frequency:

$$f_n = \left(\frac{1}{2\pi}\right) \sqrt{\left(\frac{k}{m_{\text{eff}}}\right)} \quad (1)$$

k and m_{eff} are the effective stiffness and mass. The triboelectric charge generated per cycle is

$$Q = \sigma A_{\text{eff}} \quad (2)$$

σ is the surface charge density, and A_{eff} is the effective contact area, which scales with the vibration amplitude and mode shape. Therefore, the short-circuit current $I_{\text{SC}} \propto \sigma A_{\text{eff}} f_c$ directly couples the air flow, membrane stiffness (through f_n), and charge output. Bae et al. (2014) [37] identified three distinct flutter regimes (single-contact, double-contact, and chaotic-contact) and correlated them with the output voltage and current waveforms, providing early experimental evidence of this coupling.

For rotary TENGs, the aerodynamic driving torque is

$$T_{\text{wind}} = \frac{1}{2} \rho A_{\text{rot}} C_T U^2 R \quad (3)$$

ρ is the air density, A_{rot} the rotor swept area, C_T the torque coefficient, and R the rotor radius. The angular speed ω is determined by

$$J d\omega/dt = T_{\text{wind}} - T_{\text{load}} \quad (4)$$

The output power is

$$P = \sigma A_{\text{eff}} N \omega \quad (5)$$

with N being the number of electrode segments. Thus, both A_{eff} and ω are the main levers for output improvement. Adaptive structures, such as the driving-torque self-adjusted TENG by Wang et al. (2022), exploit centrifugal force to increase both A_{eff} and input torque as wind speed rises, leading to a 4.3-fold improvement in power growth rate over conventional rotary TENGs [96,97]. This illustrates the quantitative benefit of adaptive parameter matching in fluid-electromechanical coupling.

Numerical simulations have become indispensable for capturing these multiphysics interactions. Bae et al. (2014) [37] performed fluid-structure interaction (FSI) analysis to predict the dynamic response of a flutter-driven TENG and identify the contact regimes. Shen et al. (2025) [98] used computational fluid dynamics (CFD) to simulate vortex shedding behind cylinders and coupled the unsteady pressure field to flag deformation, successfully reproducing the enhanced flutter amplitude and output. For rotary systems, multiphysics simulations combining turbulent flow models with equivalent-circuit models of TENGs have been employed to optimize blade shapes and electrode configurations. These simulation studies provide predictive design tools and reduce reliance on trial-and-error experiments. Future work should aim at fully coupled fluid-structure-electrical models that incorporate complex geometries, multi-phase flows, and long-term material degradation, thereby accelerating the transition from empirical development to model-driven engineering of wind-driven TENGs.

3. Fluttering wind-driven TENGs

3.1. Conventional fluttering TENGs

Fluttering wind-driven TENGs are among the earliest and most widely studied approaches for harvesting ambient wind energy. By directly utilizing airflow-induced vibrations, oscillations, or flapping motions of flexible triboelectric structures, these devices convert wind energy into electricity through triboelectrification and electrostatic induction. Compared with turbine-based systems, fluttering TENGs feature simple structures, lightweight configurations, low startup wind speeds, and excellent adaptability to irregular airflow environments, making them particularly suitable for distributed and low-speed wind energy harvesting. Over the past decade, extensive efforts have been

devoted to improving the output performance, structural stability, and environmental adaptability of fluttering TENGs. According to the mobility of the electrode system, these devices can generally be classified into two categories: conventional fluttering TENGs with fixed electrodes and flag-type fluttering TENGs with movable electrodes. The evolution from fixed-electrode configurations to highly flexible flag-type architectures has significantly expanded the application potential of fluttering TENGs in both wind energy harvesting and self-powered sensing.

Conventional fluttering TENGs represent the earliest and most widely investigated class of wind-driven triboelectric nanogenerators. In these devices, the electrodes are fixed on stationary substrates, while flexible triboelectric films undergo periodic fluttering under airflow excitation. The resulting contact-separation process generates alternating electrical outputs through triboelectrification and electrostatic induction. Owing to their simple configuration, ease of fabrication, and effective utilization of low-speed airflow, conventional fluttering TENGs established the foundation for wind-driven triboelectric energy harvesting. Early designs typically employed a flexible dielectric membrane oscillating between two stationary electrodes, demonstrating the feasibility of directly converting wind-induced fluttering motions into electricity and paving the way for subsequent developments in wind-driven TENG technologies.

The earliest development of conventional fluttering wind-driven TENGs focused on demonstrating the feasibility of directly converting wind-induced vibrations into electrical energy. A pioneering breakthrough was reported by Yang et al. [43] in 2013, who developed the first wind-driven TENG based on a free-standing fluorinated ethylene propylene (FEP) film oscillating between two aluminum electrodes under airflow excitation (Figure 4(i)). Benefiting from periodic contact-separation interactions between the fluttering FEP membrane and the stationary electrodes, the device generated stable electrical outputs with an open-circuit voltage (V_{OC}) of approximately 100 V, a short-circuit current (I_{SC}) of 1.6 μA (Figure 4(ii)), and a maximum output power (P_R) of about 0.16 mW. The harvested energy was sufficient to directly illuminate multiple commercial light-emitting diodes, demonstrating for the first time the feasibility of harvesting ambient wind energy through triboelectrification. More importantly, by integrating multiple TENG units, the authors further developed a self-powered wind vector sensor capable of simultaneously detecting wind speed and wind direction (Figure 4(iii)). This pioneering work not only marked the birth of wind-driven triboelectric nanogenerators but also established the fundamental structural framework of conventional fluttering wind-driven TENGs. Following the initial demonstration of wind-driven triboelectric energy harvesting, considerable efforts were devoted to understanding the underlying flutter dynamics and improving energy conversion performance. In 2014, Bae et al. [37] developed a flutter-driven TENG employing a flexible conductive textile flag and a PTFE-covered rigid plate. Unlike the previously reported membrane-based configuration, the fluttering flag exhibited a unique contact-propagation-separation process during wind-induced oscillation, resulting in more efficient triboelectric interactions. Through systematic fluid-structure interaction analysis, the authors identified three distinct flutter regimes, namely single-contact, double-contact, and chaotic-contact modes, thereby establishing the intrinsic relationship between flutter behavior and electrical output characteristics. Owing to the enhanced charge generation associated with the propagating contact area and high-frequency self-sustained fluttering, the device achieved an output V_{OC} of up to 250 V and an I_{SC} of approximately 70 μA , representing a substantial improvement over the first-generation fluttering TENG. More importantly, this work provided the first comprehensive understanding of the fluid-structure-electrical coupling mechanism governing flutter-based triboelectric energy harvesting and established the theoretical foundation for subsequent structural optimization of fluttering wind-driven TENGs.

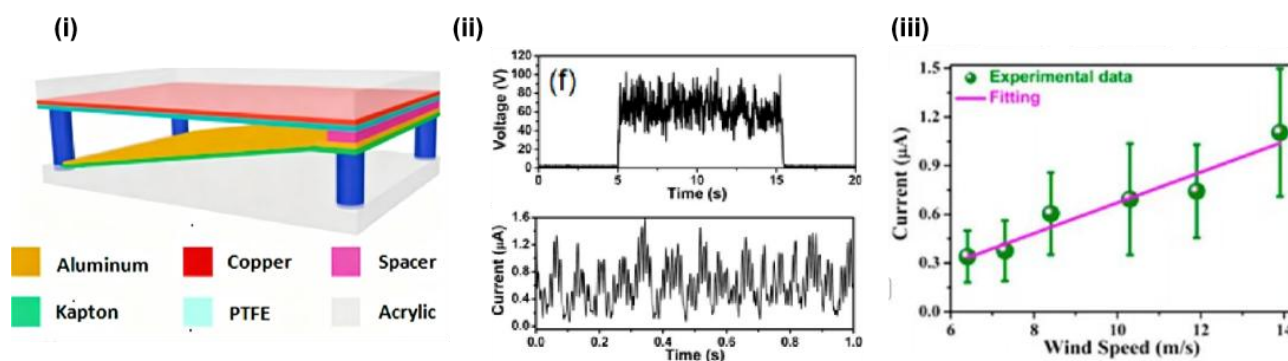


Figure 4. Early development of conventional fluttering wind-driven TENGs. The first wind-driven TENG for ambient wind energy harvesting and self-powered wind sensing was developed by Yang et al. in 2013 [43].

As the output performance of fluttering TENGs continued to improve, research attention gradually shifted from energy generation toward efficient energy utilization and practical power supply. To address the intrinsic high-impedance characteristics of TENGs, Wang and Yang [99] developed a hybridized electromagnetic-triboelectric nanogenerator that integrated a flutter-driven TENG with an electromagnetic generator (EMG) in 2017. In this design, a double-end-fixed Kapton vibration film simultaneously drives triboelectric and electromagnetic energy conversion processes under wind excitation, enabling the complementary utilization of the high-voltage characteristics of TENGs and the high-current capability of EMGs. The triboelectric component generates an output V_{OC} of approximately 51 V and an I_{SC} of 40 μA , corresponding to a P_R output of 1.7 mW, while the electromagnetic component delivers an I_{SC} output of 3.7 mA with a P_R of 2.5 mW. Furthermore, a dedicated power management circuit incorporating coupled inductors and switching control was introduced to optimize energy storage efficiency, resulting in a 112% enhancement compared with conventional rectification approaches. The harvested energy was successfully utilized to continuously power a commercial temperature sensor, representing an important transition from proof-of-concept energy harvesting toward practical self-powered electronic systems.

Collectively, these pioneering studies established the fundamental framework of conventional fluttering wind-driven TENGs and demonstrated the feasibility of harvesting ambient wind energy through triboelectrification. Through continuous improvements in flutter dynamics, energy conversion efficiency, and energy management strategies, the output performance of fluttering TENGs was significantly enhanced, paving the way for their practical applications. Building upon these early achievements, subsequent research has focused on further improving flutter stability, charge generation efficiency, and environmental adaptability through advanced structural and material engineering, leading to the development of a new generation of high-performance conventional fluttering TENGs. Following the establishment of the fundamental operating principles of conventional fluttering wind-driven TENGs, recent research efforts have increasingly focused on overcoming the performance limitations of early fluttering architectures. In particular, enhancing energy conversion efficiency under low wind speeds, extending the operational range toward extreme wind environments, and improving effective output power have become major research objectives. To address these challenges, a variety of advanced structural designs and aerodynamic optimization strategies have been developed, leading to substantial improvements in output performance and practical applicability.

A representative example was reported by Ren et al. [100], who developed a gentle-wind TENG for harvesting low-speed breeze energy in 2020 (Figure 5a(i)). The device employed an ultra-stretchable AgNW-modified nanofiber electrode integrated with a perforated elastic structure, enabling rubber-band-like fluttering behavior under weak airflow conditions. Benefiting from the synergistic optimization of electrode elasticity and aerodynamic coupling, this TENG effectively operated over a wind-speed range of $0.7\text{--}6\text{ m}\cdot\text{s}^{-1}$ (Figure 5a(ii)) and achieved a volumetric P_R density of $20\text{ mW}\cdot\text{m}^{-3}$ with a maximum energy conversion efficiency of 7.8% (Figure 5a(iii)). Furthermore, the harvested energy was successfully utilized for capacitor charging and wireless signal transmission, demonstrating the feasibility of harvesting ubiquitous low-speed wind energy for self-powered microsystems. While low-speed wind harvesting represents one important research direction, extending the operational capability of fluttering TENGs toward extreme wind environments has also attracted considerable attention. Bai et al. [101] developed a double-ended fixed fluttering TENG capable of stable operation under ultrahigh wind speeds up to $81\text{ m}\cdot\text{s}^{-1}$ in 2025 (Figure 5b(i)). Through optimization of the fluttering layer dimensions and aerodynamic configuration, the device maintained stable flutter behavior over an exceptionally broad wind-speed range while generating ultra-high-frequency electrical outputs. Remarkably, a signal frequency of $12,260\text{ Hz}$ was achieved at $81\text{ m}\cdot\text{s}^{-1}$ (Figure 5b(ii)), accompanied by an output V_{OC} exceeding 3000 V and a maximum P_R output of 132 mW (Figure 5b(iii)). These results significantly expanded the application boundary of conventional fluttering TENGs from ambient breeze harvesting toward extreme-wind energy utilization scenarios such as subway tunnels and high-speed railway systems.

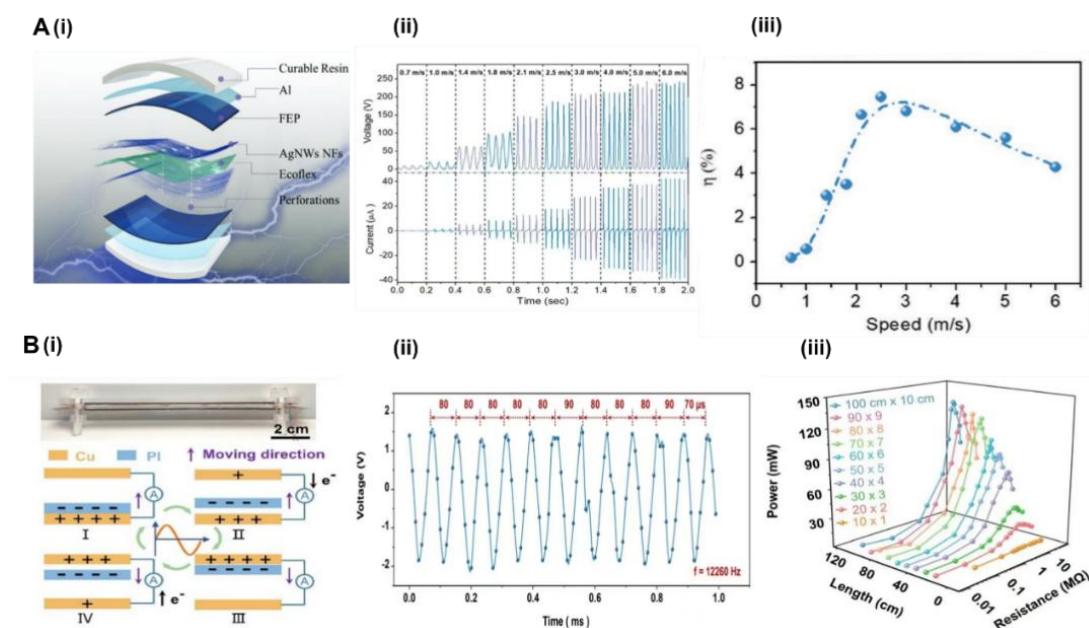


Figure 5. Recent advances in conventional fluttering wind-driven TENGs. (a) Efficient low-speed wind energy harvesting was achieved using a gentle-wind TENG with an ultra-stretchable perforated electrode developed by Ren et al. in 2020 [100]. (b) Wind energy harvesting under extreme wind conditions and ultrahigh-frequency electrical generation were achieved using a double-ended fluttering TENG developed by Bai et al. in 2025 [110].

More recently, efforts have shifted toward improving the effective output current and practical power delivery capability of fluttering TENGs. To address the intrinsic limitation of low current output in conventional electrostatic-induction-based devices, Jeon et al. [102] proposed an end-linked multistrip flutter TENG in 2026. By dividing a single conductive flutter sheet into multiple electrically connected but mechanically independent strips, the device simultaneously enhanced electrostatic discharge generation and discharge frequency. The multistrip architecture increased the probability of discharge initiation at locations with maximum electric-field concentration while enabling charge redistribution among neighboring strips, thereby significantly amplifying current output. Compared with a conventional single-strip design, the optimized MSF-TENG exhibited a 90% increase in discharge current, a 21.9% increase in discharge frequency, and a 422% increase in RMS current output. The optimized device generated an open-circuit voltage of 412.4 V, a closed-circuit current of 1.09 A, and an RMS power output of 2.83 mW at a wind speed of 4 ms⁻¹. Moreover, practical demonstrations, including powering a commercial thermo-hygrometer and illuminating 3000 LEDs, further highlighted the potential of advanced fluttering TENGs for real-world energy harvesting applications. Collectively, these recent advances demonstrate that the performance of conventional fluttering wind-driven TENGs can be substantially enhanced through rational structural and aerodynamic engineering. From low-speed breeze harvesting and extreme-wind operation to high-current and high-power output optimization, conventional fluttering TENGs have evolved far beyond their original proof-of-concept stage. These developments not only broaden the operating wind-speed range and improve energy conversion performance but also significantly promote the practical deployment of fluttering TENGs in sustainable energy harvesting and self-powered electronic systems. Conventional fluttering TENGs provide an elegant and space-efficient solution for harvesting localized, low-speed wind energy in structured, predictable environments such as indoor ventilation systems. However, their reliance on a narrow wind-velocity lock-in range and their vulnerability to rapid fatigue-induced mechanical failure severely hinder their outdoor viability. Future development must focus on designing multi-stable structures to broaden the wind-velocity response bandwidth and implementing fatigue-resistant, self-healing elastomeric materials to guarantee long-term operational durability.

3.2. Flag-type fluttering TENGs

Compared with conventional fluttering TENGs, flag-type TENGs provide greater deformation freedom by allowing the entire triboelectric structure, including both the triboelectric layers and electrodes, to participate in wind-induced fluttering motions. Such a configuration enables more effective aerodynamic coupling with airflow and facilitates omnidirectional wind energy harvesting. Consequently, flag-type architectures have emerged as an important branch of wind-driven triboelectric nanogenerators, attracting extensive attention for their superior adaptability to complex outdoor environments.

The development of flag-type wind-driven TENGs can be traced back to the pioneering work reported by Zhao et al., who proposed a freestanding woven TENG flag for harvesting wind energy from arbitrary directions (Figure 6a(i)) [103]. Unlike conventional fluttering TENGs that generally require fixed supporting structures or specific airflow orientations, this TENG flag adopted a fully flexible woven architecture consisting of Ni-coated textile belts and Kapton-coated conductive belts. Under airflow excitation, the entire flag structure underwent continuous fluttering, generating periodic contact-separation interactions between adjacent woven units and converting wind energy into electricity through contact electrification and electrostatic induction. Benefiting from its freestanding design, the device automatically aligned with changing airflow directions and effectively harvested wind energy over

a full 360° range. The optimized TENG flag generated a V_{OC} of approximately 40 V (Figure 6a(ii)) and an I_{SC} of about 30 μA (Figure 6a(iii)), corresponding to a P_R density of 135 $\text{mW} \cdot \text{kg}^{-1}$ (Figure 6a(iv)). Furthermore, multiple TENG flags could be integrated to achieve enhanced electrical outputs and successfully power wireless environmental monitoring systems. This work established the fundamental architecture of flag-type TENGs and demonstrated their unique advantages for omnidirectional wind energy harvesting. Building upon the pioneering TENG flag concept, Wang et al. [104] developed a humidity-resistant and wind-direction-adaptive flag-type TENG to address one of the major limitations of outdoor triboelectric energy harvesters: environmental humidity. By encapsulating the triboelectric layers and conductive electrodes within sealed PET membranes, the device effectively isolated the active triboelectric surfaces from ambient moisture and maintained stable electrical outputs under humid conditions. Meanwhile, the freestanding flag architecture preserved omnidirectional wind-energy harvesting capability through automatic alignment with changing wind directions. More importantly, the authors introduced an aerodynamic coupling strategy by placing two flag-TENG units at an optimized separation distance, enabling periodic flag-flag contact induced by pressure fluctuations within the airflow. This design significantly enlarged the effective contact area and enhanced the electrical output, yielding a V_{OC} of 20.8 V and an I_{SC} of 6.8 μA , corresponding to an approximately 40-fold increase in output power compared with a single flag configuration. In addition to energy harvesting, the flutter frequency of the flag was directly correlated with wind speed, enabling simultaneous wind-speed and wind-direction sensing. These advances substantially improved the environmental robustness and practical applicability of flag-type TENGs for long-term outdoor deployment.

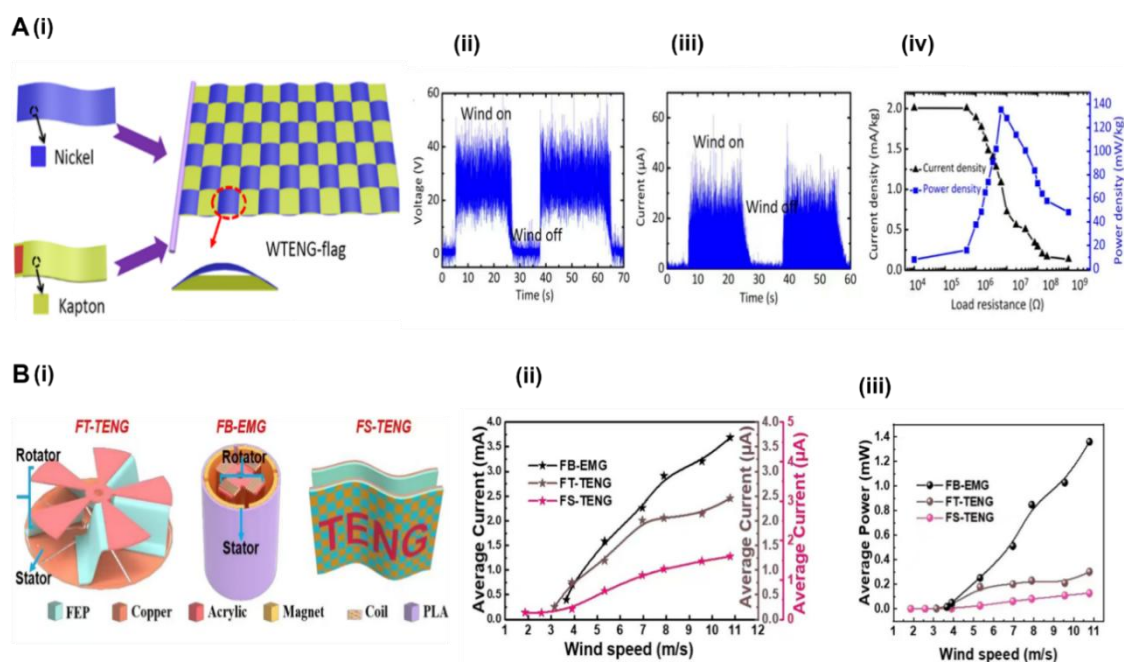


Figure 6. Representative developments of flag-type wind-driven TENGs. (a) Omnidirectional wind energy harvesting was achieved using a freestanding woven flag-type TENG developed by Zhao et al. in 2016 [103]. (b) Broadband wind energy harvesting was achieved using a triboelectric-electromagnetic hybrid nanogenerator (FTEHG) developed by Ye et al. in 2021 [89].

To further broaden the operating wind-speed range of flag-type wind energy harvesters, Ye et al. [89] proposed a broadband triboelectric-electromagnetic hybrid generator by integrating a rotary TENG, an EMG, and a flutter-driven TENG into a single flagpole architecture (Figure 6b(i)). By exploiting the complementary advantages of TENGs under lower-frequency excitation and electromagnetic generators under higher-speed rotational conditions, the hybrid system effectively harvested wind energy over a broad wind-speed range of $1.55\text{--}15\text{ m}\cdot\text{s}^{-1}$. In particular, the flutter-driven TENG enabled ultralow-speed wind energy harvesting with a startup wind speed of only $1.55\text{ m}\cdot\text{s}^{-1}$, while the electromagnetic module provided significantly enhanced current outputs under stronger airflow conditions (Figure 6b(ii)). The flutter-driven TENG generated open-circuit voltages up to 331 V, short-circuit currents of $18\text{ }\mu\text{A}$, and a maximum output power of 2.7 mW (Figure 6b(iii)). Through this multistage energy-harvesting strategy, the authors introduced the concept of broadband wind-energy harvesting, substantially improving overall wind-energy utilization efficiency. Furthermore, the harvested energy was successfully used to power electronic devices and simultaneously perform self-powered wind-speed sensing. More recently, research on flag-type TENGs has gradually evolved from empirical structural optimization toward fluid-dynamics-guided design. A representative example was reported by Shen et al. [107], who developed a vortex-shedding-enhanced flag TENG based on flow-induced vibration theory. Unlike previous studies that primarily focused on structural modifications, this work systematically investigated the relationship between vortex shedding, airflow instability, flag fluttering behavior, and electrical output performance. By introducing optimized side-by-side dual cylindrical bluff bodies upstream of the flag structure, stable Kármán vortex streets were generated to periodically excite the downstream flag. Computational fluid dynamics simulations and experimental investigations revealed that the vortex shedding effect substantially enhanced flutter amplitude and energy conversion efficiency. The optimized TENG achieved a reduced startup wind speed of only $2.9\text{ m}\cdot\text{s}^{-1}$ and generated a V_{OC} of 180V, an I_{SC} of $5.7\text{ }\mu\text{A}$, and a P_R density of $\sim 47\text{ mW}\cdot\text{m}^{-2}$ at a wind speed of $7.8\text{ m}\cdot\text{s}^{-1}$, representing a 220% improvement compared with conventional flag TENGs. More importantly, this work established a fluid-structure-electricity coupling framework for wind-driven triboelectric energy harvesting, providing a new design strategy for next-generation, higher-performance flag-type TENGs through fundamental fluid dynamics optimization.

Collectively, these representative studies illustrate the continuous evolution of flag-type wind-driven triboelectric nanogenerators from omnidirectional wind-energy harvesting and environmental adaptability to broadband energy utilization and fluid dynamics-guided performance optimization. Compared with conventional fluttering architectures, flag-type TENGs exhibit superior flexibility, environmental adaptability, and wind-energy utilization efficiency, making them particularly promising for sustainable energy harvesting and self-powered sensing applications in complex outdoor environments. Nonetheless, their low conversion efficiency and susceptibility to material failure at the anchoring points and trailing edges remain significant bottlenecks. Bridging the gap to practical application requires reinforcing stress-concentration zones with gradient-stiffness composites, optimizing flag shapes to stabilize wave dynamics, and designing specialized power management circuits to capture chaotic, low-frequency electrical inputs.

Overall, fluttering wind-driven TENGs have undergone remarkable development over the past decade, evolving from simple proof-of-concept energy harvesters into increasingly efficient and multifunctional platforms for sustainable wind energy utilization. Conventional fluttering TENGs established the fundamental framework of wind-driven triboelectric energy harvesting and achieved continuous improvements in output performance through structural optimization, aerodynamic engineering, and material innovation. More recently, flag-type architectures have further expanded the capability of fluttering TENGs by enabling omnidirectional wind energy harvesting, enhanced

environmental adaptability, broadband wind-speed utilization, and advanced fluid dynamics-guided performance optimization. Despite these significant advances, fluttering TENGs still face several inherent challenges. Their electrical outputs strongly depend on airflow-induced vibration characteristics, making performance susceptible to wind-speed fluctuations and structural instability under extreme operating conditions. In addition, the relatively random nature of fluttering motions often limits energy conversion efficiency and output consistency. Nevertheless, owing to their simple structures, lightweight designs, low startup wind speeds, and excellent adaptability to distributed airflow environments, fluttering TENGs remain highly attractive for harvesting low-speed and irregular wind energy. These unique advantages make them particularly suitable for self-powered sensing, environmental monitoring, and distributed energy harvesting applications, while also providing an important foundation for the development of more controllable and efficient rotary wind-driven TENG systems.

Table 1. Key data comparison of flutter-type wind-driven TENGs.

Subtype	Test wind speed (m/s)	Peak output power	Power density	Application scenarios
Two-sided fixed single-film TENG	10	0.16 mW	—	Self-powered wind speed and direction sensor
Flag textile flutter TENG	7.5–22	17.5 mW	—	Weather vane, outdoor ambient wind harvesting
Fixed-electrode hybrid tribo-electromagnetic TENG	18	EMG: 2.5 mW	—	Distributed field temperature and humidity monitoring
Ultra-stretchable breeze TENG	0.7–6	—	20 mW·m ⁻³	Airflow from laptop cooling fans, roadside vehicle-induced breeze
Dual-fixed ultra-high-speed flutter TENG	Max 81	132 mW (18 m/s)	—	Energy collection in subway tunnels
Multi-strip electrostatic enhanced MSF-TENG	4	RMS 2.83 mW	—	Urban low-speed breeze, commercial hygrometer-thermometer
Omni-directional woven flag WTENG-flag	3–32	—	135 mW·kg ⁻¹	High-altitude floating platforms
Moisture-resistant single flag TENG	3.2–7.5	36.72 μW	0.0408 mW·cm ⁻³	Self-powered wind sensor, miniature IoT equipment
Flag hybrid tribo-electromagnetic FTEHG	1.55–15	FT-TENG peak: 0.88 mW	—	Full-range meteorological monitoring, continuous power supply
Vortex-induced vibration enhanced VEF-TENG	2.9–7.8	356 μW (7.8 m/s)	47.47 mW·m ⁻²	Urban breeze IoT sensors, low-power LED illumination

4. Rotary wind-driven TENGs

Compared with fluttering architectures, rotary wind-driven triboelectric nanogenerators utilize turbine-based structures to convert wind energy into continuous rotational motion, enabling more

stable mechanical excitation and improved energy conversion efficiency. Benefiting from controllable rotational dynamics, rotary TENGs generally exhibit higher output performance, enhanced operational stability, and greater adaptability to a wide range of wind conditions. Over the past decade, extensive efforts have been devoted to optimizing rotor configurations, reducing startup wind speeds, improving energy conversion efficiency, and integrating complementary energy harvesting mechanisms. As a result, rotary wind-driven TENGs have evolved from simple triboelectric generators into highly efficient and multifunctional energy harvesting systems.

The development of rotary wind-driven triboelectric nanogenerators can be traced back to the pioneering work reported by Xie et al. in 2013, who demonstrated the first rotary TENG for wind energy harvesting (Figure 7a(i)) [105]. Inspired by conventional wind-cup structures, the device converted wind energy into continuous rotational motion and subsequently generated electricity through triboelectric interactions between a flexible PTFE rotor and stationary aluminum stators. More importantly, a hybridized contact-sliding-separation mechanism was introduced, combining the advantages of both contact-separation and sliding modes to enhance charge generation and transfer efficiency. Benefiting from nanowire-structured PTFE surfaces and optimized rotor-stator interactions, the device achieved a V_{OC} of 250 V (Figure 7a(ii)), an I_{SC} of 250 μA (Figure 7a(iii)), and a maximum output P_R of 62.5 mW, corresponding to a P_R density of approximately $39 \text{ W}\cdot\text{m}^{-2}$. Furthermore, the harvested energy was successfully utilized to charge capacitors, illuminate 164 LEDs, and perform self-powered wind-speed sensing. This pioneering work represented the first successful integration of triboelectric nanogenerators with conventional wind-harvesting technologies and established the fundamental framework for subsequent rotary wind-driven TENGs.

Although the pioneering rotary TENG demonstrated the feasibility of rotary triboelectric wind energy harvesting, the relatively large frictional resistance and high startup wind speed limited its applicability under weak airflow conditions. To address this challenge, Park et al. [106] developed a continuously rotating TENG based on one-dimensional fiber friction and hybrid sliding contact/noncontact mechanisms. By replacing conventional two-dimensional sliding interfaces with microstructured fibers, such as rabbit fur, the frictional resistance was substantially reduced while maintaining effective charge generation. In addition, the triboelectrification zone and electrostatic induction zone were spatially separated, enabling more efficient energy conversion during continuous rotation. As a result, stable electrical outputs were achieved at wind speeds as low as $3.5 \text{ m}\cdot\text{s}^{-1}$, producing a V_{OC} of 21.6 V and an I_{SC} of 0.6 μA . This work highlighted the importance of minimizing rotational resistance and represented a significant step toward harvesting naturally distributed low-speed wind energy.

Building upon these advances, rotary wind-driven TENGs gradually evolved toward high-efficiency hybrid energy harvesting systems. A representative example was recently reported by Liu et al. [90] in 2026 (Figure 7b(i)), through the development of a differential wind-driven triboelectric-electromagnetic hybrid generator. Unlike conventional single-rotor architectures, this system incorporated upper and lower wind scoops coupled through a differential transmission mechanism, enabling simultaneous utilization of wind energy from different spatial regions while significantly increasing the relative rotational velocity between triboelectric interfaces. More importantly, the device integrated triboelectric and electromagnetic generation units within a single platform, thereby combining the high-voltage characteristics of TENGs with the high-current output capability of electromagnetic generators. Benefiting from the differential speed-increasing mechanism and hybridized energy conversion strategy, the triboelectric unit generated a V_{OC} of 257 V and an output P_R of 4 mW (Figure 7b(ii)), while

the electromagnetic unit delivered an output P_R of 6.17 mW (Figure 7b(iii)). Compared with conventional single-wind-scoop systems, the differential configuration increased the overall output power by approximately 37% while maintaining a low startup wind speed of $3.6 \text{ m}\cdot\text{s}^{-1}$. Furthermore, the harvested energy was successfully utilized to illuminate hundreds of LEDs and power wireless sensing systems, demonstrating the practical potential of hybrid rotary wind energy harvesters.

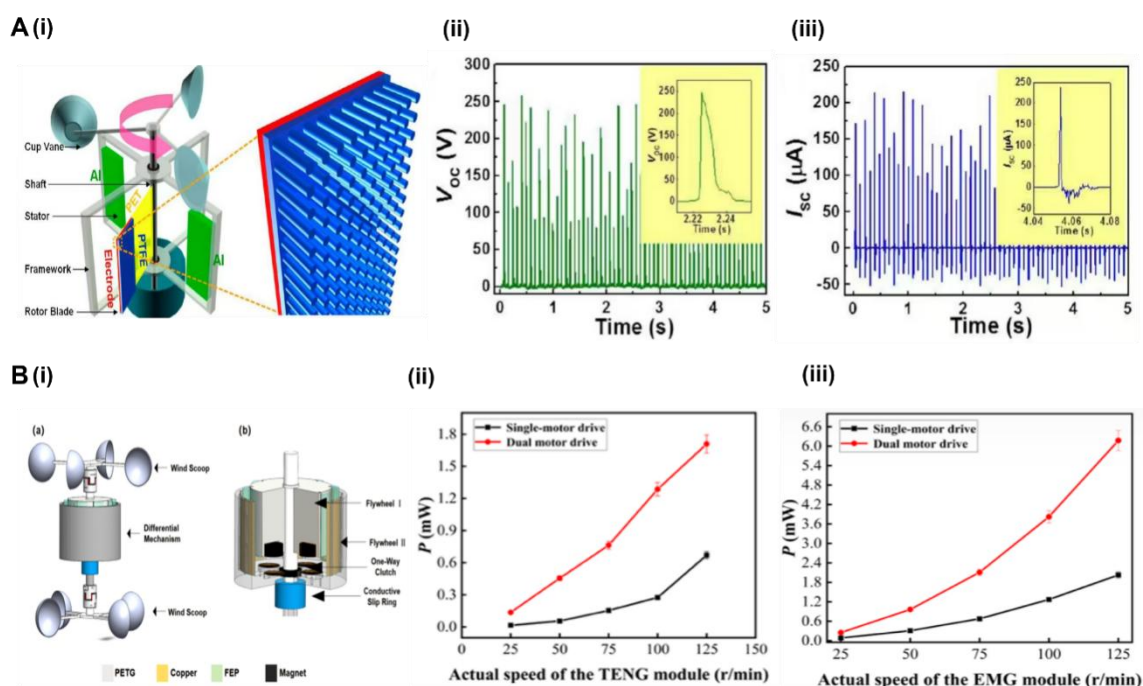


Figure 7. Development of conventional rotary wind-driven TENGs. (a) The first rotary wind-driven TENG was developed by Xie et al. in 2013 through the integration of a wind-cup turbine and a hybridized contact-sliding-separation triboelectric mechanism [105]. (b) A differential triboelectric-electromagnetic hybrid wind energy harvester was developed by Liu et al. in 2026 to enhance wind energy utilization through dual-wind-scoop energy collection and speed-amplification mechanisms [99].

Collectively, these pioneering studies established the fundamental development pathway of conventional rotary wind-driven TENGs. Beginning with the first demonstration of turbine-assisted triboelectric wind energy harvesting, followed by low-startup-speed optimization through friction reduction and structural innovation, and ultimately advancing toward differential-driven triboelectric-electromagnetic hybrid systems, rotary wind-driven TENGs have evolved significantly in terms of energy harvesting efficiency, environmental adaptability, and practical applicability.

While the pioneering developments established the fundamental framework of rotary wind-driven TENGs, further improvements in practical energy harvesting performance require addressing a critical challenge associated with the broadband and highly variable nature of wind resources. In real environments, wind speed continuously fluctuates over a wide range, resulting in significantly different energy-harvesting requirements under low- and high-wind-speed conditions. At low wind speeds, insufficient aerodynamic torque often limits rotor startup and energy conversion efficiency, whereas at high wind speeds, the available wind energy increases dramatically and requires enhanced harvesting capability for effective utilization. Consequently, recent research efforts have increasingly

focused on adaptive energy-harvesting strategies capable of dynamically matching device characteristics with changing wind conditions.

One effective strategy is the implementation of multistage aerodynamic energy harvesting through adaptive structural design. To address the limited operating range of conventional single-rotor systems, Yong et al. [91] developed an auto-switching dual-rotation-shaft TENG capable of harvesting wind energy efficiently over a broad range of wind speeds in 2021 (Figure 8a(i)). The device incorporated two concentric rotary TENG units with different aerodynamic characteristics and startup requirements. Specifically, the inner rotor was optimized for low-wind-speed operation, while the outer rotor became activated at higher wind speeds to enhance energy capture capability. Through automatic switching between different harvesting stages, efficient wind energy utilization was achieved without external control circuitry. Benefiting from this multistage harvesting strategy, this TENG exhibited an ultralow startup wind speed of $2.2 \text{ m}\cdot\text{s}^{-1}$ and operated efficiently over a broad wind-speed range of $2.2\text{--}16 \text{ m}\cdot\text{s}^{-1}$ (Figure 8a(ii)). The optimized device delivered a V_{OC} of 306 V, an I_{SC} of $32 \text{ }\mu\text{A}$, and a P_R output of 5.2 mW (Figure 8a(iii)). More importantly, this work introduced the concept of hierarchical wind-energy utilization into rotary TENG systems, providing a new route toward broadband wind energy harvesting.

Beyond aerodynamic adaptation, improving energy conversion efficiency across different wind-speed regimes has also become an important research direction. Because triboelectric nanogenerators generally exhibit superior performance under low-speed conditions, whereas electromagnetic generators perform more efficiently at higher rotational speeds, the integration of complementary energy-conversion mechanisms offers an attractive solution for broadband energy harvesting. Based on this concept, Li et al. [107] developed a flexible-cooperation triboelectric-electromagnetic hybrid energy harvester in 2022 (Figure 8b(i)), in which triboelectric and electromagnetic generation units were adaptively activated according to wind-speed conditions. Unlike conventional hybrid systems that operate both mechanisms simultaneously, the hybrid energy harvester employed a centrifugal-force-triggered activation strategy that enabled independent TENG operation under low wind speeds and cooperative TENG-EMG energy harvesting at higher wind speeds. Through this flexible energy-conversion mechanism, the device dynamically optimized its harvesting efficiency across a broad range of operating conditions. The optimized hybrid energy harvester exhibited a startup wind speed of $4 \text{ m}\cdot\text{s}^{-1}$ (Figure 8b(ii)) and achieved peak powers of 1.95 mW (Figure 8b(iii)) and 2.56 mW (Figure 8b(iv)) for the TENG and EMG units, respectively. Furthermore, the harvested energy was successfully utilized to power hundreds of LEDs and wireless sensing systems, demonstrating the effectiveness of adaptive hybrid energy conversion for broadband wind-energy utilization. More recently, adaptive parameter regulation has emerged as an effective strategy for maximizing energy harvesting under highly variable wind conditions. Instead of switching between different structures or generation mechanisms, in 2022, Wang et al. [97] developed a driving-torque self-adjusted TENG capable of dynamically matching its operating characteristics with changing wind speeds. The device incorporated a centrifugal force-driven self-adjusting unit that automatically regulated both the effective generation area and driving torque according to the external wind conditions. As wind speed increased, centrifugal force-induced structural deformation expanded the effective triboelectric contact area and simultaneously increased the driving torque, thereby maintaining efficient energy conversion over a broad operating range. The self-adjusted TENG demonstrated stable self-adjustment across wind speeds ranging from 5.0 to $13.2 \text{ m}\cdot\text{s}^{-1}$ and achieved a P_R output of 7.69 mW. Compared with conventional rotary TENGs and electromagnetic generators, the power growth rate was improved by more than 4.3 and 3.2 times, respectively, while the energy-conversion efficiency was enhanced by factors of 12.2 and 6.5. Furthermore, the harvested

energy successfully powered environmental monitoring sensors, demonstrating its practical applicability as a distributed energy source. This work highlighted the importance of dynamic parameter matching between energy harvesters and stochastic wind resources.

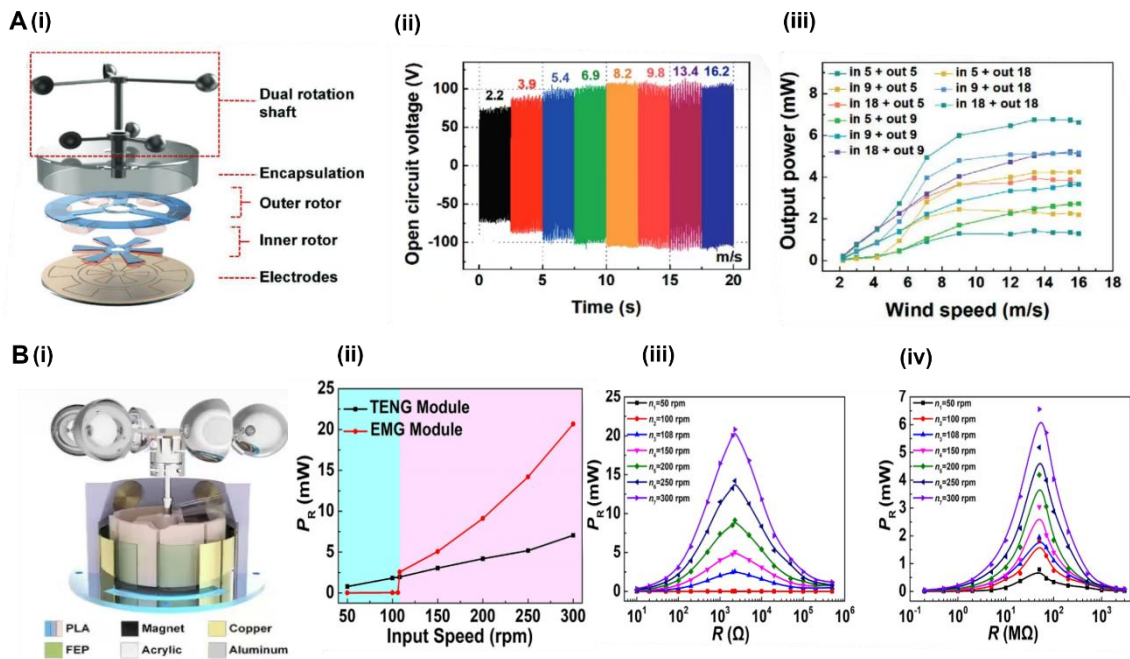


Figure 8. Adaptive energy-harvesting strategies for broadband wind energy utilization in conventional rotary wind-driven TENGs. (a) A multistage wind energy harvesting strategy based on an auto-switching dual-rotation-shaft triboelectric nanogenerator was developed by Yong et al. in 2021 to efficiently utilize wind resources over a broad operating range [100]. (b) A flexible triboelectric-electromagnetic cooperative energy-harvesting strategy was developed by Li et al. in 2022 to dynamically optimize energy conversion under different wind-speed conditions [116].

Collectively, these studies demonstrate the evolution of rotary wind-driven TENGs from passive energy harvesters toward adaptive broadband wind-energy harvesting systems. Through multistage aerodynamic design, flexible energy-conversion cooperation, and self-adjusted parameter regulation, increasingly efficient utilization of variable wind resources has been achieved. More importantly, these adaptive harvesting strategies reveal a common design philosophy: dynamically matching the energy-harvesting characteristics of the device with the stochastic nature of ambient wind energy. Such developments not only significantly improve output performance and energy-conversion efficiency but also provide important guidance for the future design of intelligent, self-adaptive, and high-performance wind-driven triboelectric energy harvesting systems.

Despite the significant advances in broadband wind-energy harvesting discussed above, the electrical outputs of most rotary wind-driven TENGs remain strongly affected by the stochastic and intermittent nature of ambient wind. Consequently, substantial fluctuations in rotational speed and electrical generation inevitably occur under real environmental conditions, resulting in unstable power outputs and reduced energy-utilization efficiency. Such output irregularity poses major challenges for practical applications, including energy storage, wireless sensing, and continuous operation of electronic systems. Therefore, recent research efforts have gradually shifted from maximizing

energy-harvesting performance toward achieving controllable and stable electrical generation through mechanical energy regulation strategies.

One effective approach is the introduction of intermediate energy-storage and controlled-release mechanisms to decouple environmental fluctuations from electrical generation. Based on this concept, in 2021, Liu et al. [40] developed a magnetic-switch-structured TENG capable of converting random wind energy into continuous and regular electrical output. Unlike conventional rotary TENGs, whose electrical outputs directly follow wind-speed variations, the magnetic-switch-structured TENG incorporated magnetic energy storage and triggering modules between the wind-capturing unit and the triboelectric generation unit. During operation, wind energy was first converted into rotational mechanical energy and subsequently stored as magnetic potential energy. Once the stored magnetic energy exceeded a predefined threshold, rapid magnetic triggering occurred, releasing the accumulated energy to drive the triboelectric generation unit. Through repeated cycles of energy storage and controlled release, random wind excitation was transformed into periodic and controllable mechanical motion, thereby generating stable electrical output. Benefiting from this magnetic energy modulation strategy, the critical rotational speed for continuous operation was significantly reduced from 560 to 230 rpm. The optimized device achieved a V_{OC} of 410 V, an I_{SC} of 18 μA , and a P_R output of 4.82 mW. Furthermore, the harvested energy successfully powered 500 LEDs and continuously operated electronic devices under fluctuating wind conditions, demonstrating the feasibility of magnetic-assisted output regulation for practical wind energy harvesting systems.

While magnetic switch-assisted energy regulation effectively regularized intermittent energy release, achieving truly steady electrical generation under highly variable wind conditions remained a significant challenge. To further improve output stability, in 2021, Wang et al. [108] developed a gravity TENG, which utilizes gravitational potential energy as an intermediate energy-storage medium to realize steady electrical generation from stochastic wind resources. The gravity TENG consists of an energy input module, an energy storage module, and an energy output module. Wind energy captured by the wind scoop is first converted into rotational mechanical energy and subsequently stored as gravitational potential energy by lifting a mass block. After sufficient energy accumulation, the stored gravitational energy is gradually released, driving the triboelectric generation unit at an approximately constant rotational speed independent of instantaneous wind fluctuations. Through this process, random wind energy is transformed into stable electrical output. More importantly, the separation of energy-harvesting and power-generation processes effectively decouples environmental disturbances from electrical generation, enabling highly stable operation even under randomly varying wind conditions. The optimized gravity TENG achieved a V_{OC} of 500 V and an I_{SC} of 15 μA . To quantitatively evaluate output stability, the authors further introduced the fluctuation degree parameter, which reached a minimum value of only 2.3%, while the standard deviation of current peaks was reduced below 0.31 μA , indicating excellent output stability. Moreover, the device successfully powered LED arrays with uniform brightness and continuously operated a commercial thermometer under natural outdoor wind environments, demonstrating its practical capability as a reliable self-powered energy source.

Collectively, these studies demonstrate an important transition in the development of rotary wind-driven TENGs, from maximizing wind-energy capture toward regulating electrical output quality. By introducing intermediate mechanical energy-storage mechanisms, including magnetic potential energy storage and gravitational potential energy buffering, random wind excitation can be effectively decoupled from electrical generation. As a result, intermittent and stochastic wind energy can be transformed into controllable, regular, and even quasi-steady electrical outputs. These advances represent a critical step toward the practical deployment of wind-driven triboelectric energy harvesting

systems and provide important design principles for future self-powered electronic and sensing platforms. Rotary TENGs represent the most technologically mature and high-performing configuration for wind energy harvesting, offering high output power and relatively stable electrical quality suitable for micro-grids. However, the fundamental trade-off between contact friction (for charge generation) and mechanical durability remains a critical barrier. To advance toward commercialization, future research must focus on lowering the cut-in wind speed and mitigating material wear. Promising pathways include transitioning to rolling-contact or noncontact electrostatic induction mechanisms, alongside the deployment of self-lubricating triboelectric composites or liquid lubricants.

Table 2. Key data of various rotary-type wind-driven triboelectric nanogenerators.

Subtype	Test wind speed (m/s)	Peak output power	Power density	Application scenarios
Cup-driven rotary R-TENG	15	62.5 mW	39 W/m ²	Self-powered wind speed sensor, driving hundreds of LEDs
1D-fiber friction CR-TENG	3.5	12.96 μ W	—	Low-speed breeze energy harvesting, compact
Differential-mechanism hybrid DW-TEHG	14.4	TENG:4 mW; EMG:6.17 mW	—	Urban variable-wind environment, driving 900 LEDs
Dual-rotation-shaft auto-switching D-TENG	2.2–16	5.2 mW	—	Broad-band breeze-to-moderate wind harvesting
Cup-driven flexible-cooperation hybrid FC-TEH	4–8	TENG:1.95 mW EMG:2.56 mW	—	Unstable natural wind harvesting, powering Bluetooth thermometer
Driving-torque self-adjusted SA-TENG	5.0–13.2	7.69 mW	—	Random fluctuating wind energy, power for distributed environmental monitoring sensors

5. Direct-current wind-driven TENGs

Although substantial progress has been achieved in improving wind-energy harvesting efficiency, broadband adaptability, and output stability, most rotary wind-driven triboelectric nanogenerators still generate alternating-current (AC) electrical outputs. Consequently, external rectification circuits and power-management modules are generally required before the harvested energy can be directly utilized, inevitably increasing system complexity and energy losses. To address this limitation, extensive efforts have recently been devoted to the development of rotary wind-driven DC-TENGs, which are capable of directly converting wind energy into usable DC electricity. DC-TENGs are distinguished primarily by their output characteristics and intrinsic charge-generation mechanisms rather than by structural configuration alone. According to their direct-current generation mechanisms, DC-TENGs can generally be classified into three categories: mechanical rectification, phase coupling, and dielectric breakdown. These strategies represent distinct approaches for achieving direct-current output, ranging from mechanical current commutation and multiphase waveform engineering to intrinsic direct-current generation through electrostatic breakdown. Collectively, they provide promising routes toward highly integrated and efficient wind-powered self-powered systems.

As one of the earlier strategies for realizing triboelectric direct-current generation, in 2021, Qiao et al. [41] developed a bidirectional DC-TENG based on a mechanical rectification mechanism. Unlike conventional TENGs that require external bridge rectifiers, the bidirectional DC-TENG

integrates a triboelectric generation unit and a mechanical commutation module into a unified architecture. By employing rolling electric brushes and a commutator, alternating triboelectric signals generated during rotor rotation are mechanically converted into unidirectional current outputs. Furthermore, a micro-arch-structured FEP triboelectric layer was introduced to reduce frictional wear and enable efficient energy harvesting under both forward and reverse rotational motions. As a result, the generated current maintained a constant direction regardless of rotation direction, realizing bidirectional direct-current generation. The optimized device achieved a V_{OC} of approximately 480 V, an I_{SC} of 12 μA , and a P_R density of $0.96 \text{ W}\cdot\text{m}^{-2}$. Moreover, the generated direct-current output successfully charged capacitors and powered commercial electronic devices without external rectification circuits, demonstrating the feasibility of mechanically integrated triboelectric DC generation.

Although mechanical rectification effectively eliminates external rectifiers, the output characteristics still depend on mechanical commutation processes. To further improve current continuity and output stability, in 2020, Wang et al. [93] proposed a cylindrical phase-coupled DC-TENG based on multiphase triboelectric synchronization (Figure 9a(i)). Instead of mechanically switching current direction, the device utilized multiple triboelectric generation units arranged with precisely controlled phase differences. During rotation, each unit generated alternating current pulses with identical amplitudes but sequential phase delays. After rectification and phase superposition, the temporal gaps between adjacent current peaks were effectively filled, producing a quasi-continuous DC output. By systematically optimizing the phase number and group number, the authors demonstrated substantial improvements in current smoothness and charging efficiency. The optimized three-phase five-group architecture achieved a V_{OC} of 149.5 V, an I_{SC} of 21.6 μA (Figure 9a(ii)), and an average output power of 2.04 mW. More importantly, the crest factor was reduced to 1.08 (Figure 9a(iii)), indicating that the output current approached an ideal constant-current signal. The device further demonstrated efficient capacitor charging and stable powering of electronic devices under wind-driven rotational conditions, establishing phase coupling as an effective strategy for generating high-quality direct-current outputs.

A fundamental breakthrough in DC-TENG technology was subsequently achieved through the introduction of dielectric-breakdown-based DC generation. Inspired by the natural coupling between triboelectrification and lightning discharge, in 2019, Liu et al. [109] developed a next-generation DC-TENG that directly harvests charges generated during controlled electrostatic breakdown (Figure 9b(i)). In this design, a charge-collecting electrode was strategically positioned near the triboelectric surface. As triboelectric charges accumulated during relative motion, an extremely strong local electric field was generated. Once the field exceeded the dielectric strength of air, controlled electrostatic breakdown occurred between the triboelectric surface and the charge-collecting electrode, resulting in unidirectional electron transport through the external circuit. Unlike mechanical rectification and phase coupling, which still rely on conventional triboelectric induction followed by output regulation, dielectric-breakdown DC-TENGs intrinsically generate direct-current electricity through a fundamentally different energy-conversion mechanism. Benefiting from this strategy, a triboelectric charge density of $430 \mu\text{C}\cdot\text{m}^{-2}$ was achieved, substantially exceeding the charge-density limit of conventional TENGs. The rotary DC-TENG further delivered nearly constant-current outputs with a crest factor approaching unity, producing an I_{SC} of up to 17 μA (Figure 9b(ii)) and an output V_{OC} as high as 750 V (Figure 9b(iii)). More importantly, electronic watches, scientific calculators, and LED arrays were directly powered without any rectification circuits, demonstrating the unique capability of intrinsic direct-current generation. Overall, these studies illustrate the evolutionary development of rotary wind-driven DC-TENGs from mechanical current commutation to multiphase waveform engineering, and ultimately to intrinsic direct-current generation through electrostatic breakdown. Among these

approaches, dielectric-breakdown-based DC-TENGs represent a paradigm shift in triboelectric energy conversion because DC electricity is generated intrinsically rather than obtained through post-processing of alternating outputs. These advances significantly improve charging efficiency, simplify system architectures, and establish an important technological foundation for next-generation wind-powered self-powered systems.

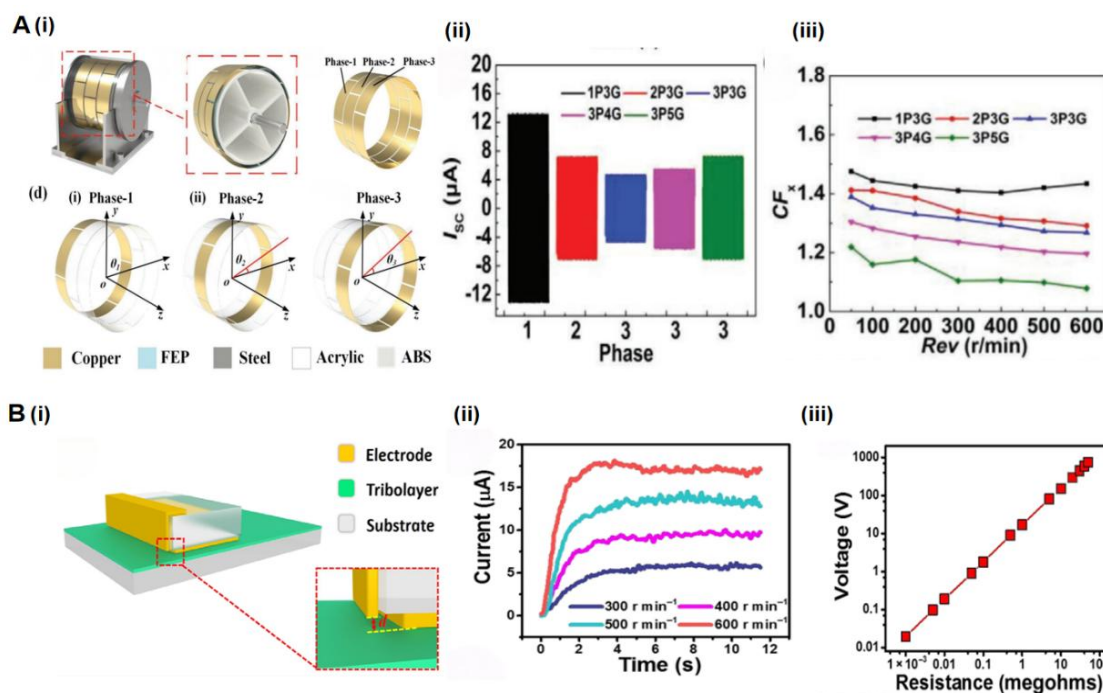


Figure 9. Evolution of rotary wind-driven DC-TENGs based on different direct-current generation mechanisms. (a) A phase-coupled cylindrical DC-TENG was developed by Wang et al. in 2020 to generate quasi-continuous direct-current output through multiphase triboelectric synchronization [102]. (b) An electrostatic-breakdown-based DC-TENG was developed by Liu et al. in 2019 to realize intrinsic DC generation through controlled charge collection during dielectric breakdown [109].

With the rapid development of DC-TENGs, several emerging strategies have recently been proposed, including mechanical rectification, phase control, and tribovoltaic effects. Tribovoltaic-effect-based DC generation [110] represents a fundamentally different physical pathway exploiting the coupling of triboelectrification and photovoltaic-like charge separation, self-charging, and self-discharging dynamics, enabling autonomous energy management without external circuits. Other emerging strategies include air-discharge mechanisms and ternary dielectric designs that extend charge density beyond conventional limits.

The DC output capability eliminates the need for external rectification circuits, thereby significantly simplifying system integration and improving energy utilization efficiency in practical wind-energy harvesting scenarios. More importantly, it enables more direct and efficient powering of distributed electronics, energy storage systems, and self-powered sensing nodes, thereby providing a strong rationale for the application examples presented in the subsequent section.

Despite the potential advantages of micro-spark-discharge-based DC-TENGs, their long-term reliability and system-level compatibility remain subject to several unresolved concerns. First,

repeated micro-spark discharge can progressively degrade polymer dielectric surfaces through localized carbonization and chemical damage, resulting in increased surface roughness, chain scission within fluoropolymer backbones such as PTFE and FEP, and a gradual decline in effective surface charge density. This degradation may compromise both output stability and operational lifetime. Second, the high-current discharge pulses can generate localized Joule heating at metal-electrode contact regions, inducing thermal fatigue and potentially causing electrode delamination during prolonged cycling. Third, air ionization during electrical breakdown may produce ozone (O_3), which raises environmental and occupational-safety concerns and may accelerate the oxidative aging of nearby polymeric dielectrics and electrode materials. Finally, the high-frequency electromagnetic interference (EMI) associated with discharge pulses can interfere with telemetry transmission and signal acquisition in co-located wireless sensors. These issues indicate that the practical advantages of DC output must be assessed alongside the associated degradation, environmental, and electromagnetic risks, particularly when DC-TENGs are integrated into long-term, densely packed self-powered sensing platforms.

Table 3. Key data of various direct-current-type wind-driven triboelectric nanogenerators.

Subtype	Test wind speed (m/s)	Peak output power	Power density	Application scenarios
Magnetic-switch energy-storage MS-TENG	—	4.82 mW	—	Regular output from intermittent random wind energy
Gravitational-potential-energy storage G-TENG	—	6.7 mW	—	Low-fluctuation steady output under variable natural wind
Mechanical-commutator bidirectional BD-TENG	≈ 7	—	$0.96 \text{ W} \cdot \text{m}^{-2}$	No rectifier bridge required, lighting 210 LEDs, powering a calculator
Multiphase phase-coupled cylindrical DC-TENG	≈ 13.9	2.04 mW	—	Low-ripple nearly constant DC output, powering LED arrays
Electrostatic-breakdown constant-current DC-TENG	—	10 mW	—	Rectifier-free, directly powering electronic watches, calculators

6. Emerging applications of wind-driven TENGs

Benefiting from their unique advantages, including lightweight structures, low startup wind speeds, excellent adaptability to irregular airflow conditions, and the capability of simultaneously harvesting energy and generating electrical signals, wind-driven TENGs have evolved far beyond simple energy-harvesting devices [51–53]. Over the past decade, extensive efforts have been devoted to exploring their practical applications in diverse scenarios. On one hand, wind-driven TENGs can effectively convert ambient airflow into usable electrical energy, providing sustainable power sources for distributed electronics in various environments [16,17,19,22,23,27]. On the other hand, the direct correlation between wind-induced mechanical stimuli and electrical outputs enables wind-driven TENGs to function as self-powered sensors without requiring external power supplies [20–22,24,25]. Consequently, wind-driven TENGs have demonstrated significant potential in both energy harvesting and self-powered sensing applications, establishing an important foundation for future sustainable and intelligent systems.

One of the most important applications of wind-driven TENGs is sustainable energy harvesting

in distributed and resource-constrained environments. Owing to their lightweight structures, low startup wind speeds, simple fabrication processes, and excellent adaptability to irregular airflow conditions, wind-driven TENGs provide a promising solution for powering decentralized electronic systems where conventional power infrastructures are inaccessible or economically impractical. Over the past decade, extensive efforts have been devoted to deploying wind-driven TENGs in diverse real-world scenarios, including smart agriculture [12], intelligent transportation systems [111,112], and marine environmental monitoring[92], demonstrating their significant potential for sustainable energy utilization.

Smart agriculture has emerged as an important application scenario for wind-driven TENGs because agricultural environments typically possess abundant distributed wind resources while lacking convenient access to stable electrical power. Meanwhile, the increasing deployment of wireless sensor networks for crop growth monitoring, environmental sensing, and intelligent irrigation systems has created growing demands for sustainable and maintenance-free power supplies. A representative example was reported by Li et al. [12] in 2022, who developed a breeze-driven TENG specifically designed for agricultural environments. By employing lightweight structural components and optimized aerodynamic designs, the device achieved an ultralow startup wind speed of only $3.3 \text{ m}\cdot\text{s}^{-1}$, matching the typical natural wind conditions encountered in farmland. The TENG delivered an output V_{OC} of approximately 330 V, an I_{SC} of $7 \text{ }\mu\text{A}$, and a P_R of 2.81 mW, while achieving an energy conversion efficiency of 12.06% under low-speed wind conditions. More importantly, the harvested wind energy was successfully utilized to power agricultural monitoring systems, including soil-temperature sensors and supplementary agricultural lighting. These demonstrations verified the feasibility of utilizing ambient breeze energy as a sustainable power source for distributed agricultural electronics and precision farming systems.

Beyond agricultural applications, wind-driven TENGs have also demonstrated considerable potential in intelligent transportation infrastructures. Modern transportation systems rely heavily on distributed electronic facilities, including traffic signals, road-condition monitoring units, environmental sensors, and communication nodes. Supplying power to these widely distributed devices remains a persistent challenge, particularly in remote or energy-constrained locations. To address this issue, in 2024, Jiang et al. [112] developed a fur-brush dish TENG for self-powered transportation systems (Figure 10a). Benefiting from an optimized freestanding triboelectric architecture and soft-contact friction interface, the device effectively harvested low-speed ambient wind energy and achieved a peak power density of $3.275 \text{ W}\cdot\text{m}^{-3}$. Through integration with energy-storage and power-management circuits, the harvested energy was continuously utilized to operate traffic-light systems without external power supplies. This work demonstrated the capability of wind-driven TENGs to serve as sustainable energy sources for distributed transportation infrastructures, providing a practical pathway toward self-powered traffic management systems and intelligent urban transportation networks.

Marine environments contain abundant wind and wave resources that can provide continuous renewable energy for long-term ocean observation systems. However, powering distributed marine monitoring nodes remains a major challenge because conventional batteries suffer from limited lifetimes, high maintenance costs, and difficult replacement procedures under harsh offshore conditions. In 2026, He et al. [92] reported a hybrid blue-energy harvesting system based on a constant-voltage TENG (Figure 10b), which simultaneously harvested wave energy and wind energy through the integration of soft-contact and noncontact triboelectric modules. Benefiting from phase-coupling and charge-excitation strategies, the system achieved an average power density of $7.9 \text{ W}\cdot\text{m}^{-3}$ under practical marine conditions while exhibiting exceptional durability, with only 0.68% performance degradation after

more than 2.3 million operation cycles. More importantly, the harvested blue energy successfully powered commercial temperature-humidity sensors and water-quality detectors while enabling wireless data transmission to mobile terminals. By integrating energy harvesting, environmental monitoring, and wireless communication into a unified platform, this work demonstrated the feasibility of self-powered marine environmental monitoring and highlighted the potential of wind-driven triboelectric systems for future ocean Internet-of-Things applications.

Collectively, these representative studies demonstrate the broad applicability of wind-driven triboelectric nanogenerators across diverse environments. From precision agriculture and intelligent transportation infrastructures to marine environmental monitoring systems, wind-driven TENGs have evolved from simple energy-harvesting devices into practical, sustainable power sources for distributed electronics. Their capability to efficiently utilize ambient wind resources while supporting long-term autonomous operation highlights their significant potential for future smart infrastructures and sustainable energy systems.

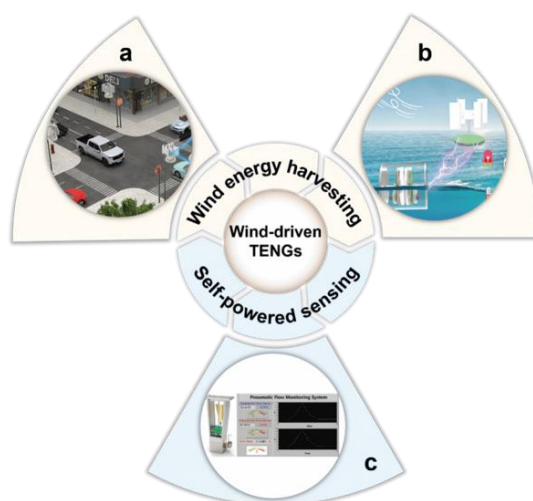


Figure 10. Representative application fields of wind-driven TENGs for sustainable energy harvesting and self-powered sensing. (a) Intelligent transportation systems [112]. (b) Marine environmental monitoring [101]. (c) Gas-flow monitoring [113].

In addition to sustainable energy harvesting, wind-driven TENGs have demonstrated remarkable potential as self-powered sensing platforms. Owing to the intrinsic coupling between airflow-induced mechanical stimuli and triboelectric electrical outputs, wind-driven TENGs can directly convert environmental, industrial, and physiological airflow information into measurable electrical signals without requiring external power supplies. Compared with conventional sensing technologies, triboelectric self-powered sensors offer several unique advantages, including simple device architectures, low power consumption, high sensitivity, excellent environmental adaptability, and long-term autonomous operation. Consequently, extensive efforts have been devoted to developing wind-driven TENG-based sensing systems for diverse applications ranging from environmental monitoring and industrial flow detection to human healthcare.

Wind speed and wind direction monitoring represent the most direct and widely investigated sensing applications of wind-driven TENGs. Accurate wind information is essential for meteorological forecasting, agricultural management, transportation safety, marine engineering, and renewable energy

utilization. However, conventional wind-monitoring systems generally require external power supplies and frequent maintenance, limiting their deployment in distributed and remote environments. A representative example was recently reported by Shen et al. [114] in 2025, who developed a self-powered noncontact triboelectric wind sensor capable of simultaneously monitoring wind speed and wind direction. By integrating a rotational wind-speed sensing unit with a multi-channel wind-direction sensing module, the device achieved comprehensive wind-environment perception within a single platform. Benefiting from the noncontact triboelectric architecture, the sensor exhibited an ultralow startup wind speed of only $0.2 \text{ m}\cdot\text{s}^{-1}$ and maintained excellent linearity over a wide wind-speed range of $0.2\text{--}29 \text{ m}\cdot\text{s}^{-1}$. In addition, the device demonstrated outstanding environmental robustness, exhibiting minimal signal degradation under high-temperature and high-humidity conditions. For wind-direction sensing, an optimized electrode configuration enabled accurate discrimination of eight different wind directions with high signal-to-noise ratios and rapid response characteristics. More importantly, the authors further integrated the triboelectric sensor with wireless communication modules, cloud servers, and mobile terminals to establish a self-powered remote monitoring system. Real-time wind information could be automatically transmitted to cloud platforms and visualized through smartphones and computers, demonstrating the feasibility of integrating triboelectric wind sensors into distributed meteorological monitoring networks and Internet-of-Things systems.

Beyond atmospheric wind sensing, TENGs have also been extensively explored for monitoring gas flow in industrial pneumatic systems. Accurate flow measurement is critically important for industrial automation, process control, pipeline management, and safety monitoring. Conventional flow meters generally rely on external power supplies and sophisticated electronic circuits, resulting in increased system complexity and energy consumption. To address these challenges, in 2019, Wang et al. [113] developed a self-powered triboelectric flow sensor based on a float-cone architecture for quantitative gas-flow monitoring (Figure 10c). The device consisted of a movable PTFE-coated float and a triangular electrode structure. Variations in gas-flow rate induced changes in the float position, thereby modulating the triboelectric output signals. Owing to this unique mechanical design, the output voltage exhibited a highly linear relationship with flow rate over a broad operating range of $30\text{--}300 \text{ L}\cdot\text{min}^{-1}$. The sensor achieved an excellent linear correlation coefficient of 0.997 and a flow resolution higher than $5 \text{ L}\cdot\text{min}^{-1}$. Furthermore, the triboelectric flow sensor demonstrated remarkable reliability under varying pressure conditions and showed negligible hysteresis during operation. Practical demonstrations further revealed its capability for real-time industrial flow monitoring, abnormal-flow detection, and automatic safety warning. These results highlight the considerable potential of triboelectric self-powered sensors for intelligent industrial monitoring and smart pneumatic systems.

Besides environmental and industrial applications, triboelectric airflow sensors have recently attracted significant attention for physiological monitoring. Respiration is one of the most important vital signs and provides valuable information regarding pulmonary function, physical condition, and overall health status. Conventional respiratory monitoring systems often require external power sources, bulky instrumentation, or direct skin-contact sensors, which may compromise portability and user comfort. A representative example was reported by He et al. [115] in 2021, who developed a respiration-monitoring TENG integrated into a nanofibrous mask filter. The device employed electrospun PAN and PVDF nanofiber membranes that simultaneously served as filtration materials and triboelectric layers. During inhalation and exhalation, airflow-induced deformation periodically brought the nanofibrous layers into contact and separation, generating electrical signals that directly reflected respiratory activity. Unlike most previously reported respiratory sensors that only monitored breathing frequency, the respiration-monitoring TENG was capable of simultaneously measuring multiple clinically relevant respiratory indices, including respiratory rate, inhalation time, exhalation

time, and inhalation/exhalation ratio. Validation experiments using a medical ventilator demonstrated excellent sensing accuracy. The monitored respiratory rate exhibited perfect agreement with preset values, while the measured inhalation/exhalation ratio achieved a correlation coefficient of 0.9963 and an agreement of 93.53%. Moreover, the device maintained stable sensing performance for more than 40 h of continuous operation. Beyond respiration monitoring, the nanofibrous mask simultaneously provided a filtration efficiency of approximately 99% for airborne particles, enabling the integration of respiratory protection and physiological monitoring within a single self-powered platform. Furthermore, on-body demonstrations confirmed that the respiration-monitoring TENG could continuously track respiratory variations under different exercise intensities, highlighting its potential for wearable healthcare monitoring, respiratory disease diagnosis, and intelligent protective equipment.

Collectively, these representative studies demonstrate the remarkable versatility of wind-driven TENGs as self-powered sensing platforms. From environmental wind monitoring and industrial flow measurement to physiological respiration sensing, triboelectric sensors have evolved far beyond simple airflow detectors and increasingly integrate wireless communication, cloud-based data management, and intelligent information processing. These advances establish a solid foundation for future self-powered environmental monitoring systems, smart industrial infrastructures, and wearable healthcare technologies.

7. Outlooks and challenges

Wind-driven TENGs have evolved from proof-of-concept energy harvesters into multifunctional platforms capable of energy harvesting, self-powered sensing, and intelligent system integration. Looking forward, several important research directions are expected to drive the next stage of development. First, achieving broadband and high-efficiency wind energy harvesting remains a central objective. Although significant progress has been achieved through aerodynamic optimization, adaptive structures, hybridized generators, and DC-TENG technologies, efficiently utilizing highly stochastic wind resources across a wide range of wind speeds remains challenging [12,69,90,107]. Future research should therefore place greater emphasis on advanced aerodynamic optimization strategies that improve flow capture and structural response under variable wind conditions, as well as on the development of emerging triboelectric materials with higher charge densities and improved charge-retention capabilities. In parallel, integrating multiple energy-conversion mechanisms within a single device framework may offer an effective route toward maximizing energy extraction efficiency under complex environmental conditions. Second, wind-driven TENGs are expected to evolve from single-parameter sensors toward intelligent self-powered sensing systems [18,19,53,55,73]. By integrating advanced signal-processing algorithms, wireless communication technologies, and artificial intelligence-assisted data analysis, future triboelectric sensors may simultaneously perceive multiple environmental and physiological parameters, enabling more accurate environmental monitoring, industrial diagnostics, and healthcare management. Third, the integration of energy harvesting, sensing, communication, and information processing within unified self-powered platforms represents an important future direction. Benefiting from their inherent capability to simultaneously harvest wind energy and generate sensing signals, wind-driven TENGs provide a promising foundation for autonomous systems capable of long-term operation in smart agriculture, intelligent transportation, marine monitoring, and distributed Internet-of-Things networks [15,16,74–76]. In this context, intelligent power management will play an increasingly critical role. Strategies such as impedance-matching circuits, energy-storage integration, and self-regulating power-conditioning

modules are expected to significantly improve energy utilization efficiency and provide more stable power output for downstream electronics and sensing units. In addition, hybrid energy harvesting systems that combine TENGs with electromagnetic, piezoelectric, and solar energy conversion technologies are likely to become an important avenue for future exploration. Such hybridized platforms can exploit the complementary advantages of different harvesting mechanisms, thereby improving overall output performance, broadening environmental adaptability, and enhancing the reliability of self-powered systems under fluctuating operating conditions.

Despite the significant advances in energy conversion efficiency, output quality, and application breadth discussed above, several critical challenges must be addressed before large-scale practical deployment can be achieved. First, the relatively low charge density and limited energy-conversion efficiency of triboelectric systems still restrict output performance. Charge generation, retention, and utilization processes are often accompanied by significant losses, while the stochastic nature of wind excitation further limits overall harvesting efficiency [90,117,118]. Second, long-term stability and environmental durability remain major concerns for outdoor applications. Continuous mechanical excitation, material wear, humidity, temperature fluctuations, ultraviolet exposure, and corrosive environments can gradually degrade device performance, particularly in marine and transportation infrastructures where maintenance is difficult [17,38,54,59,61]. Third, significant challenges remain in system-level integration and practical deployment. Most current studies focus on individual devices or laboratory demonstrations, whereas real-world applications require the seamless integration of energy harvesting, energy storage, sensing, communication, and data-processing modules [64,65]. Moreover, large-scale deployment will require further progress in standardized performance evaluation protocols, modular system integration strategies, and scalable fabrication approaches to facilitate comparison across studies and accelerate translation from laboratory research to practical implementation. With this in mind, noting that current TENG research suffers from non-standardized testing conditions (varying wind scoop dimensions, custom wind-tunnel configurations, and inconsistent humidity levels), we now propose key elements of a standardized protocol, including defined wind-tunnel inlet geometry, controlled temperature and humidity conditions, standardized electrode-contact configurations, and unified output measurement methodology (e.g., matched-load power measurement). This would enable meaningful cross-study performance comparisons and accelerate technology benchmarking.

Practical encapsulation strategies: We discuss how long-term stable outdoor performance can be achieved through hydrophobic and hermetic encapsulation for marine environments subject to salt spray corrosion and water immersion; dust-resistant and oil-repellent protective structures for transportation infrastructure deployments where particle contamination and lubricant exposure are common; and self-cleaning surface designs that leverage the triboelectric surfaces themselves as superhydrophobic interfaces. Addressing these challenges will require collaborative advances in materials science, device engineering, power management, and intelligent system design. Through continued interdisciplinary efforts, wind-driven TENGs are expected to evolve from standalone energy harvesters and sensors into practical self-powered platforms that support future sustainable energy systems and intelligent infrastructures.

In summary, wind-driven TENGs have emerged as a promising technology for sustainable energy harvesting and self-powered sensing. This review systematically summarizes the fundamental mechanisms, structural evolution, and emerging applications of wind-driven TENGs. Driven by continuous advances in triboelectric materials, aerodynamic designs, and device architectures, wind-driven TENGs have evolved from early fluttering generators to advanced rotary systems capable of broadband energy harvesting, controllable power generation, and direct-current output. Beyond

energy harvesting, wind-driven TENGs have demonstrated broad application potential in smart agriculture, intelligent transportation, and marine monitoring, while also enabling diverse self-powered sensing functions, including wind speed and direction detection, gas-flow monitoring, and respiration sensing. These developments highlight the unique capability of wind-driven TENGs to simultaneously support energy utilization and environmental perception. Although challenges related to output performance, long-term durability, and system integration remain, continued advances in materials engineering, structural optimization, and intelligent system design are expected to further accelerate the development of this field. With ongoing progress toward high-efficiency energy harvesting and multifunctional self-powered systems, wind-driven TENGs are poised to play an increasingly important role in future sustainable energy technologies and intelligent infrastructures.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

All authors declared that there are no conflicts of interest.

Author contributions

Supervision, Conceived the concept: Yuying Cao; Xiang Li. Investigation, Performed the research: Hang Yu; Yancheng Bao. Analyzed the results and wrote the paper: Zhiyu Su; Zhenyang Yan.

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