Wind Energy based on Triboelectric Nanogenerators

Subjects: Nanoscience & Nanotechnology
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The utilization of various distributed energy is becoming a prominent research topic due to the rapid development of the Internet of Things and wireless condition monitoring systems. Among the various distributed energy sources, wind energy has the advantages of being widely distributed, renewable and pollution-free, and is a very promising mechanical energy for power supply. Traditional wind energy harvesting methods based on electromagnetic and piezoelectric effects have issues with complex structure, large size, severe mechanical structures, and high installation costs. The low frequency and irregular nature of ambient mechanical energy makes these methods generally inefficient and inevitably hinders the further exploitation of wind energy. The triboelectric nanogenerators (TENGs) based on frictional charging and electrostatic effects can also be used for wind power generation and are increasingly favored by researchers as TENGs are easier to be miniaturized and assembled, and can realize large-scale manufacturing in comparison.

triboelectric nanogenerator | wind energy | energy harvesting

1. Introduction

With the worldwide commitment to promote carbon-free power generation, wind power is becoming an increasingly important part of human daily life and is of great importance for the sustainable development of human society [1][2][3]. In 2012, Dr. Zhong Lin Wang proposed a new energy collection method—triboelectric nanogenerator, which is particularly suitable for the harvesting of irregularly distributed low mechanical frequency vibrational energy such as wind energy [4][5][6]. The concept of a wind-driven triboelectric nanogenerator (WD-TENG) has been developed to take advantages of the characteristics of wind energy and the high conversion efficiency of TENG.

As shown in **Figure 1**, to summarize recent work in the TENG for wind energy harvesting and sensing and, most importantly, to explore possible new key areas to help guide the future direction of the TENG in fluid dynamics sensing by addressing key challenges.

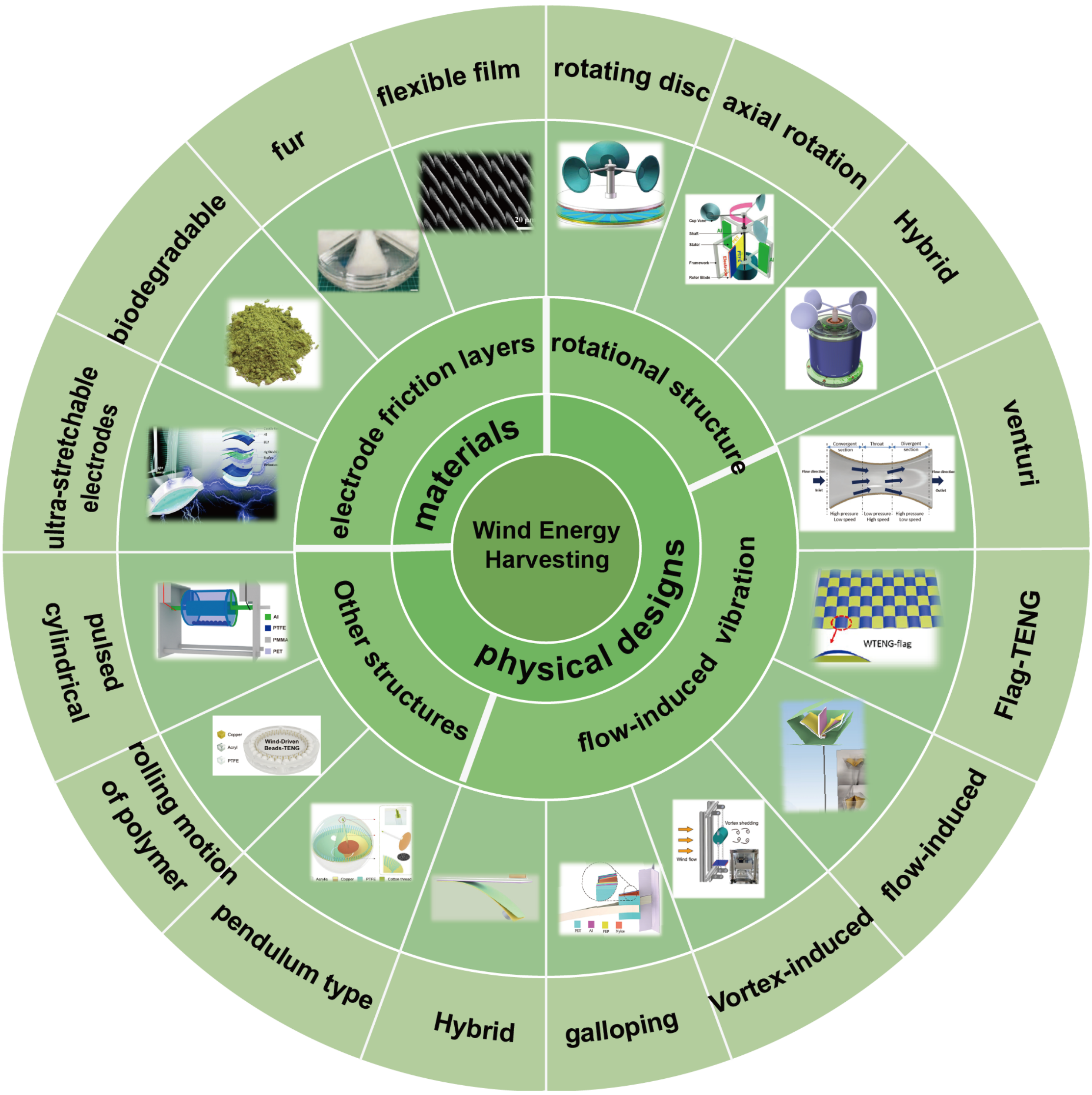

Figure 1. Overview of common materials and structures for WD-TENGs. Rotating disc. Reproduced with permission of [7], Copyright 2015, Nano Energy. Axial rotation. Reproduced with permission of [8], Copyright 2013, American Chemical Society. Hybrid rotation structure. Reproduced with permission of [9] , Copyright 2018, Elsevier. Venturi system. Reproduced with permission of [10], Copyright 2019, Elsevier. Flag-TENG. Reproduced with permission of [11] , Copyright 2016, American Chemical Society. Flow-induced WD-TENG. Reproduced with permission of [12], Copyright 2020, Elsevier. Vortex-induced WD-TENG. Reproduced with permission of [13], Copyright 2022, Elsevier. Galloping WD-TENG. Reproduced with permission of [14], Copyright 2020, Elsevier. Hybrid flow-induced WD-TENG. Reproduced with permission of [15], Copyright 2020, Springer. A pendulum type. Reproduced with permission of [16], Copyright 2019, Elsevier. WD-TENG based on rolling motion of beads. Reproduced with permission of [17], Copyright 2018, Elsevier. Pulsed WD-TENG. Reproduced with permission of [18], Copyright 2021, Elsevier. Ultra-stretchable electrodes. Reproduced with permission of [19], Copyright 2020, John Wiley and Sons. Biodegradable materials. Reproduced with permission of [20], Copyright 2019, Elsevier. Fur. Reproduced with permission of [21], Copyright 2021, John Wiley and Sons. Flexible film. Reproduced with permission of [22], Copyright 2021, Elsevier.

2.Historical Research and Progress of WD-TENG

2.1. Material Electrification Mechanism

The materials utilized to make WD-TENG must not only be widely apart in the triboelectric sequence, but they must also be resilient, durable, and cost-effective. **Table 1** lists the classification, advantages and disadvantages of the materials commonly used in the production of WD-TENG. And **Figure 2** illustrates the various types of materials mentioned in **Table 1**.

Table 1. Summary and comparison of frequently used tribo-active materials for WD-TENG.

Classification	Categories	Advantages	Disadvantages
Metals and its derivatives	Metal, alloy, semiconductor metallic nanoflakes/nanoparticles/nanowires	Excellent electrical conductivity,high stability,high mechanical robustness,simple process	Low flexibility
Conducting polymers	PTFE, PVDF, PDMS, PMMA	Easy structural control,heat resistance,corrosion resistance,light weight,good flexibility	Relatively high cost,poor conductivity,low stability,Non-biodegradable,Not-recyclable
Carbonaceous fillers	Graphite, CNT, Graphdiyne	High conductivity,high stability,good mechanical properties	Cumbersome processing technology
Natural materials	Rabbit Fur, leaves	Flexible,low cost,biodegradable and easy to process	Poor electrical conductivity,poor durability
Composite materials	Combination of different conductive materials(e.g., graphene-PDMS)	Synergistic effect	Increased preparation cost and workload

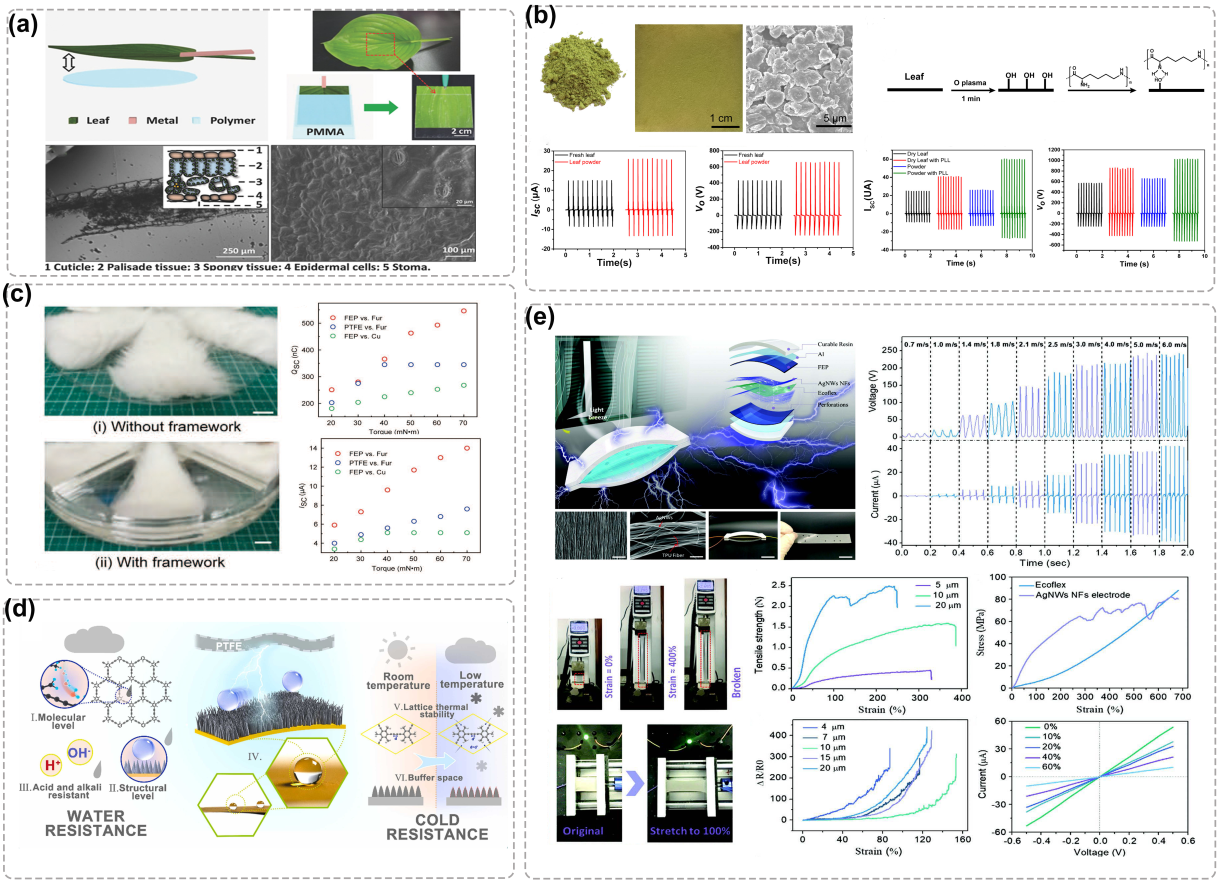

Figure 2. Typical materials of WD-TENG. (**a**) Natural plant leaves as friction layer. Reproduced with permission of [23], Copyright 2018, John Wiley and Sons. (**b**) The leaf powder-based TENG. Reproduced with permission of [20], Copyright 2019, Elsevier. (**c**) Rabbit fur as friction layer. Reproduced with permission of [21] Copyright 2021, John Wiley and Sons. (**d**) Schematic diagram of M-GDY resisting water interference during power generation. Reproduced with permission of [24], Copyright 2021, Elsevier. (**e**) The unidirectional TPU spinning NFs modified by ultra-long AgNWs. Reproduced with permission of [19], Copyright 2020, John Wiley and Sons.

2.2. Utilization Mechanism of Mechanical Energy

2.2.1. Infrastructure and principles

TENG used for wind energy collection can be divided into “rotary type” and “flow induced vibration type”[25][26][27] according to the way of energy collection. The structural design of rotating wind energy collection TENG is mainly inspired by the traditional electromagnetic wind turbine, with the help of wind cup or other structures to collect wind energy, and convert it into rotating mechanical energy to drive the contact separation of TENG friction layer, so as to produce electrical output. Wind energy collection devices based on rotating structure usually have dense peak output and high output power, mostly in the form of separate layers and rotating slides. **Figure 3**a-c shows a typical rotating slip structure. Although rotary wind energy collection can effectively realize wind power generation, such devices must first convert wind energy into rotary kinetic energy before driving TENG to work. There is a large energy loss in this process. As a result, scientists prefer to convert the flowing wind energy directly into the device’s vibration energy, which is why the flow-induced TENG was invented [28]. **Figure 3**d-f shows the basic structure and principle of the flow-induced TENG.

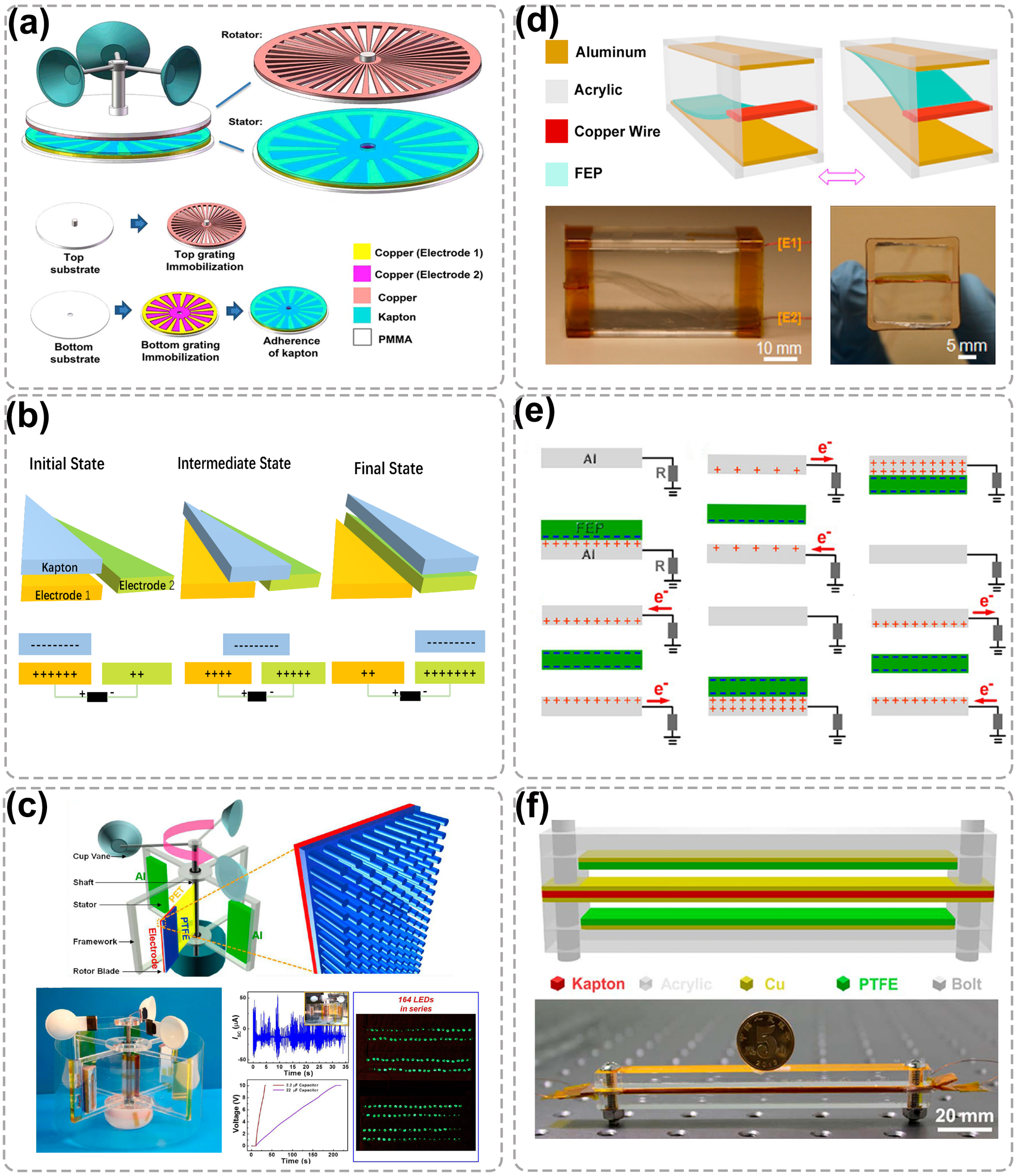

Figure 3. Typical structure and mechanism of WD-TENG. (**a**) In-plane cycled sliding mode of WD-TENG. Reproduced with permission of [7], Copyright 2015, Elsevier. (**b**) Working mechanism of rotary WD-TENG. (**c**) Rotational sweeping mode of WD-TENG. Reproduced with permission of [8], Copyright 2013, American Chemical Society. (**d**) Single-side-fixed mode of WD-TENG. (**e**) Working mechanism of flutter-driven WD-TENG. Reproduced with permission of [29], Copyright 2013, American Chemical Society. (**f**) Double-side-fixed mode of WD-TENG. Reproduced with permission of [30], Copyright 2015, American Chemical Society.

2.2.2. Structural display of WD-TENG

For the rotating disc type WD-TENG, researchers adopted methods such as transiting the operating mode from contact to non-contact and optimizing the rotation axis length to improve its performance. In addition, Flow-excited vibrations offer significant advantages in the field of miniaturization, integrated wind energy harvesting devices and the harvesting of breeze energy. Four flow-induced vibration phenomena are generally used to convert fluid energy into mechanical kinetic energy: vortex vibration, galloping, flutter and wake-galloping. Based on these theories, researchers have been constantly updating their structures to improve the efficient use of wind energy in recent years. **Figure 4** shows these structures. And **Figure 5** illustrates some of the special structures.

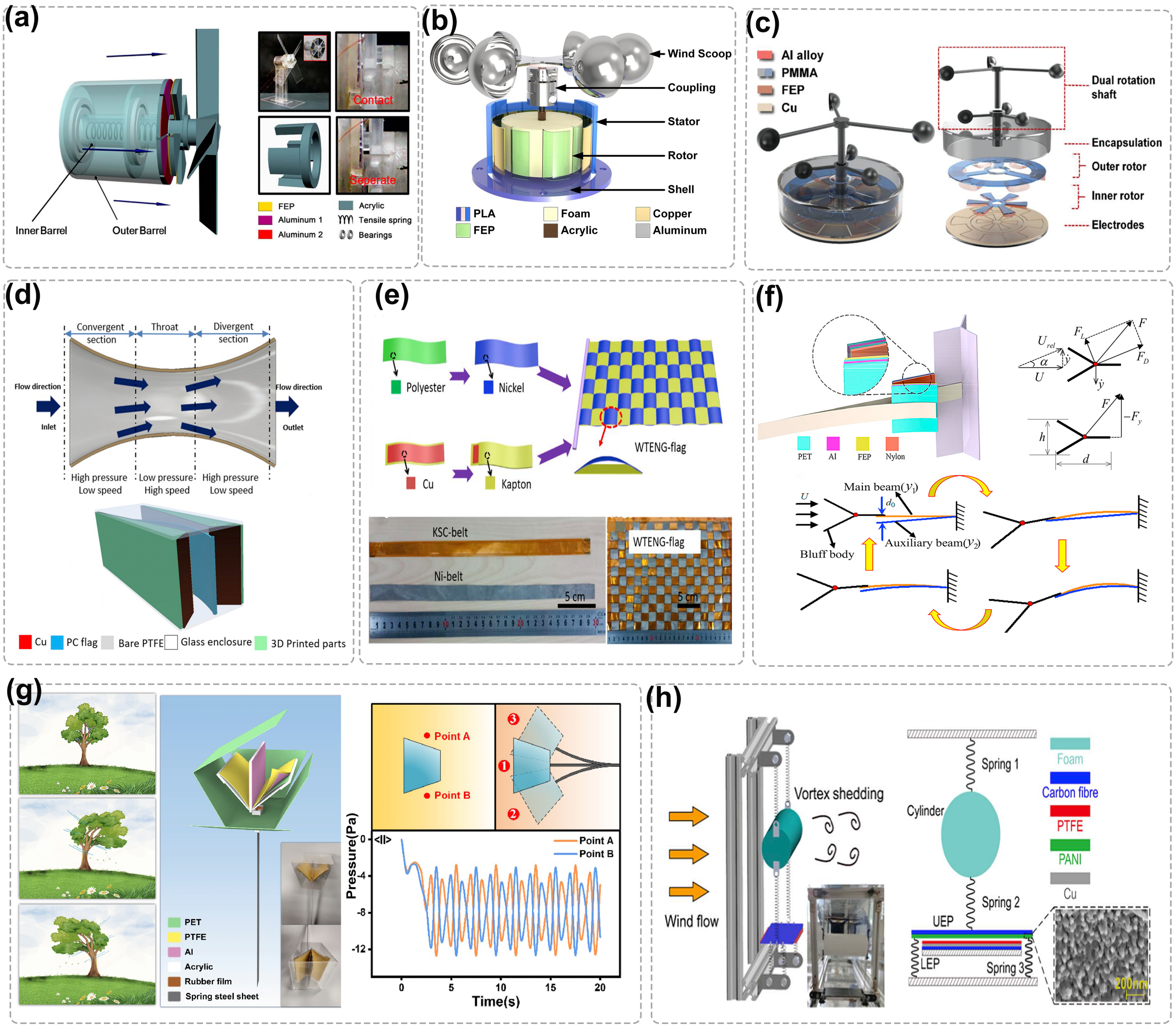

Figure 4. Various structures of WD-TENG: (**a**–**c**) Rotary structures. (**a**) WD-TENG switching between contact and non-contact modes. Reproduced with permission of [31], Copyright 2015, American Chemical Society. (**b**) Rotary WD-TENG with lightweight rotor. Reproduced with permission of [32], Copyright 2021, Elsevier. (**c**) A dual-rotation shaft WD-TENG. Reproduced with permission of [33], Copyright 2021, John Wiley and Sons. (**d**–**f**) Structures based on flow-induced vibration. (**d**) TENG based on wind actuated venturi design. Reproduced with permission of [10], Copyright 2019, Elsevier. (**e**) Woven WD-TENG flag. Reproduced with permission of [11], Copyright 2016, American

Chemical Society. (**f**) WD-TENG based on galloping response. Reproduced with permission of [14], Copyright 2020, Elsevier. (**g**) WD-TENG based on cantilever beam structure. Reproduced with permission of [12], Copyright 2020, Elsevier. (**h**) Vortex-induced vibration based WD-TENG. Reproduced with permission of [13], Copyright 2022, Elsevier.

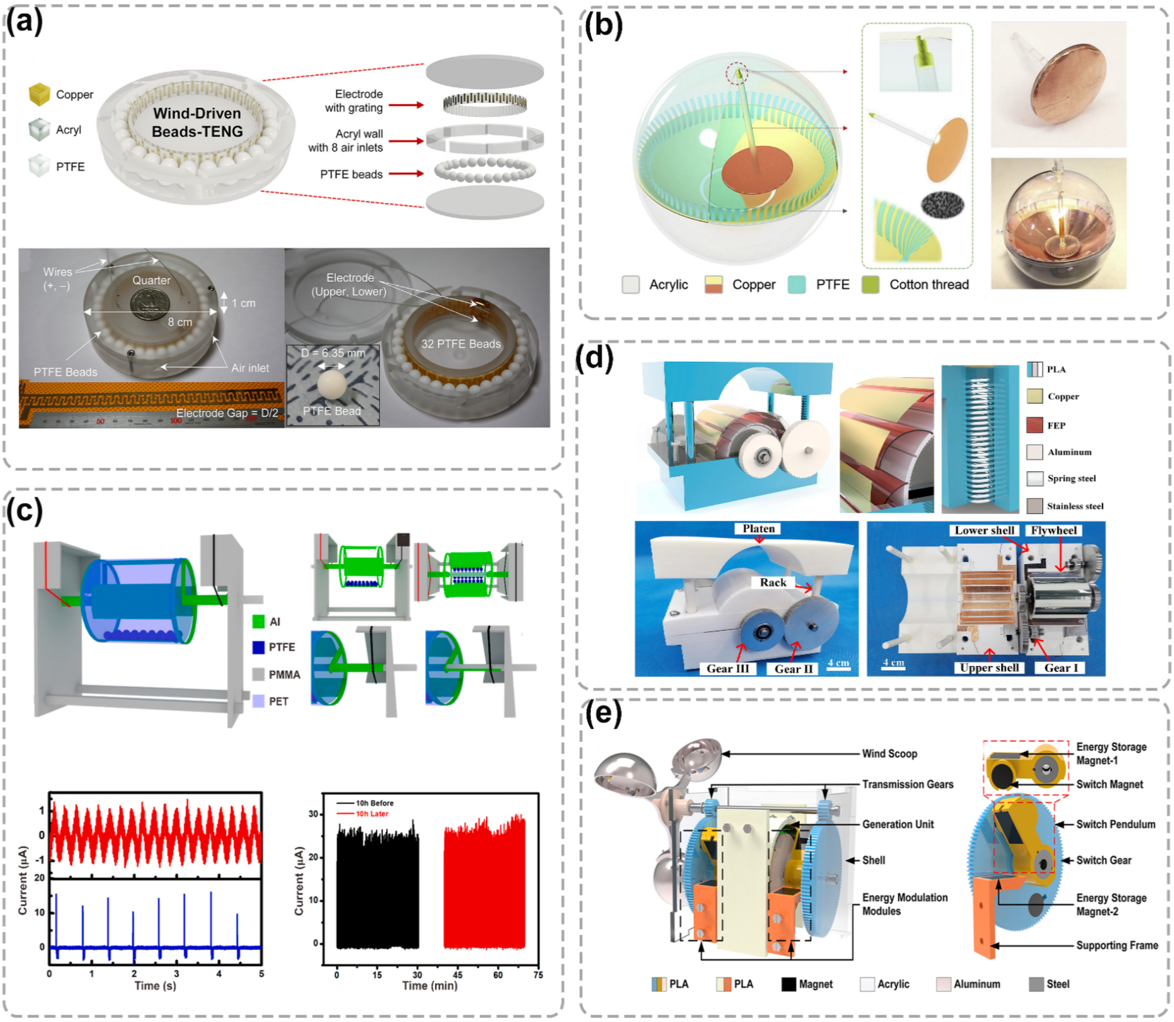

Figure 5. Other structures of WD-TENG. (**a**) WD-TENG based on rolling motion of beads. Reproduced with permission of [17], Copyright 2018, Elsevier. (**b**) A pendulum-spired WD-TENG. Reproduced with permission of [16], Copyright 2019, Elsevier. (**c**) A pulsed cylindrical WD-TENG. Reproduced with permission of [18], Copyright 2021, Elsevier. (**d**) A bidirectional gear transmission triboelectric nanogenerator (BGT-TENG). Reproduced with permission of [34], Copyright 2020, Elsevier. (**e**) WD-TENG controlled energy collection by magnetic switch. Reproduced with permission of [35], Copyright 2021, Elsevier.

4. Applications of WD-TENG

As the designs of WD-TENG become smaller, lighter, and more durable, they become more adaptable to varying wind speeds, humidity, and other external environmental conditions . WD-TENG shows great potential in various applications such as powering small electronic devices, as secondary energy stored in capacitors, as self-powered sensors for wind vectors or parameters such as humidity, and self-powered electrochemical systems, as depicted in **Figure 6**a–f.

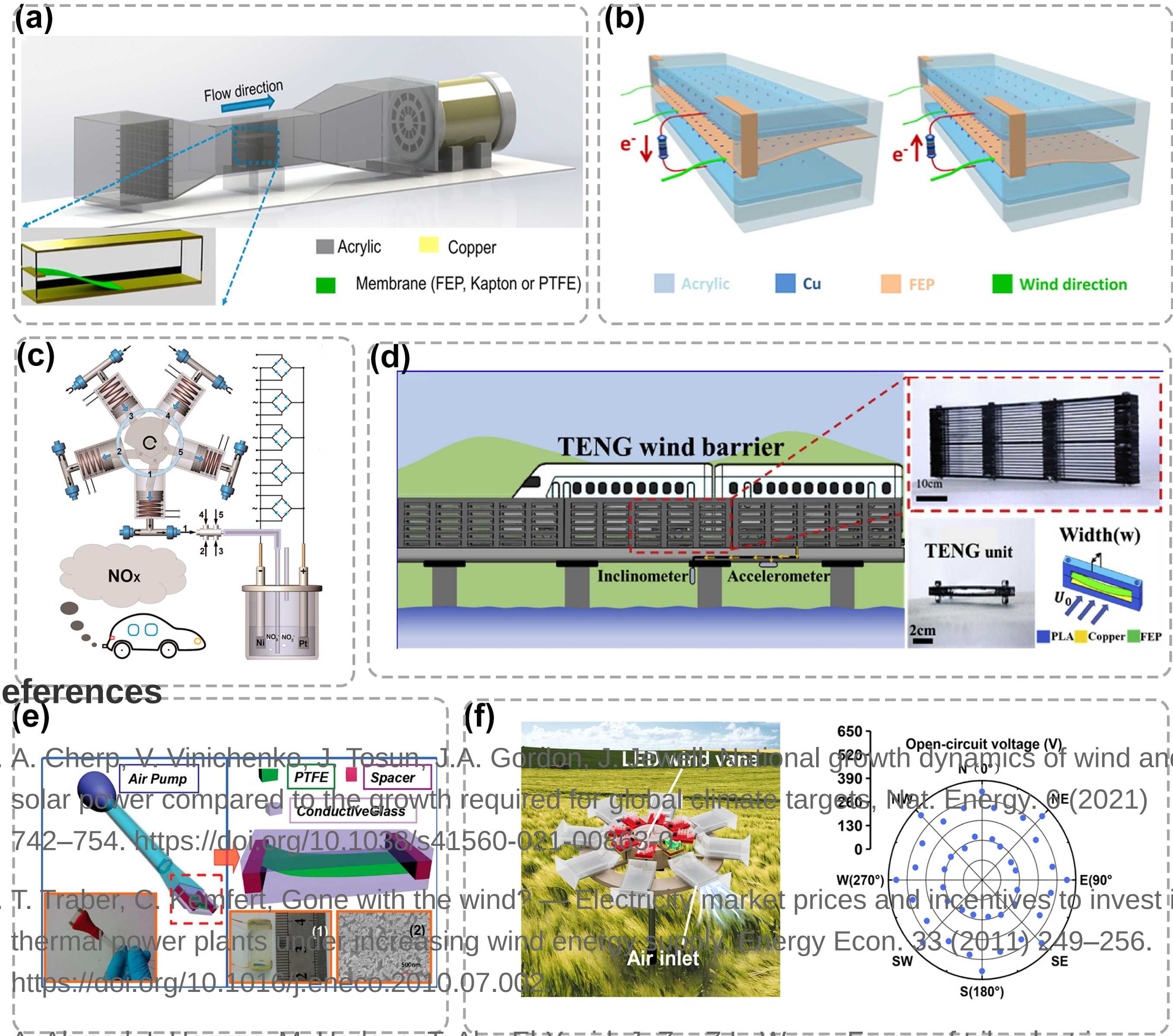

Figure 6. Applications of WD-TENG. (**a**) Experimental set-up and characterization of fluttering behavior of AF-TENG. Reproduced with permission of [36], Copyright 2017, Elsevier. (**b**) Schematic diagram and working mechanism of ferroelectric BTO disk polarized by WD-TENG. Reproduced with permission of [37], Copyright 2017, Elsevier. (**c**) Self-powered air purification system. Reproduced with permission of [38], Copyright 2020, ACS Nano. (**d**) Application scenario of the TENG-based wind barrier. Reproduced with permission of [39], Copyright 2020, Nano Energy. (**e**) Schematic diagram and digital photograph for the designed TENG sensor. Reproduced with permission of [40], Copyright 2021, American Chemical Society. (**f**) WD-TENG is used to realize self-powered wind vector monitoring. Reproduced with permission of [41], Copyright 2021, Elsevier.

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5. WD-TENG Hybridized with Other Types of Generators

In order to realize the complementary advantages of various energy conversion mechanisms in obtaining mechanical energy and self-powered sensing, the combination of TENGs with electromagnetic and piezoelectric energy collection mechanisms is con-sidered. **Figure 7**a-d shows its structure when combined with various energy conversion mechanisms in pyroelectric, piezoelectric and photoelectric. Among these mixing mechanisms, the most common is the mixing between TENG and EMG. **Figure 8** shows the comparison of output performance between TENG and EMG under rectification, which suggests that the TENG is better suited to derive energy from low frequency motion than the ENG. **Figure 9** shows several ways to optimize the combination of EMG and TENG.

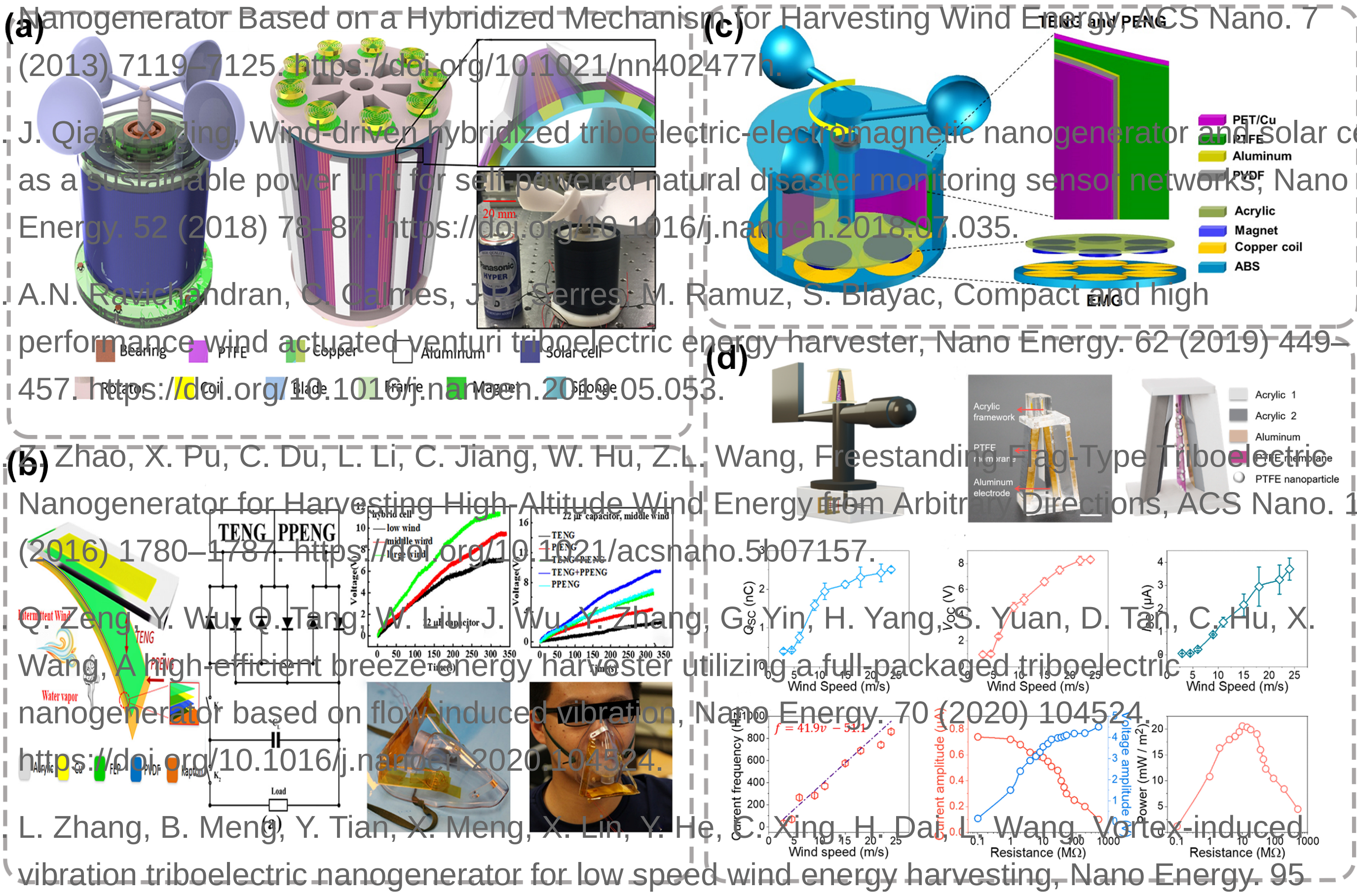

Figure 7. WD-TENG hybridized with other generators. (**a**) Hybrid TENGs combined with EMG and TENG. Reproduced with permission of [9], Copyright 2018, Elsevier. (**b**) Hybrid TENGs combined with PPENG and TENG. Reproduced with permission of [42], Copyright 2018, American Chemical Society. (**c**) Hybrid TENGs combined with PENG and TENG. Reproduced with permission of [43], Copyright 2018, Elsevier. (**d**) WD-TENG combined with photoelectric technology. Reproduced with permission of [44], Copyright 2021, Elsevier.

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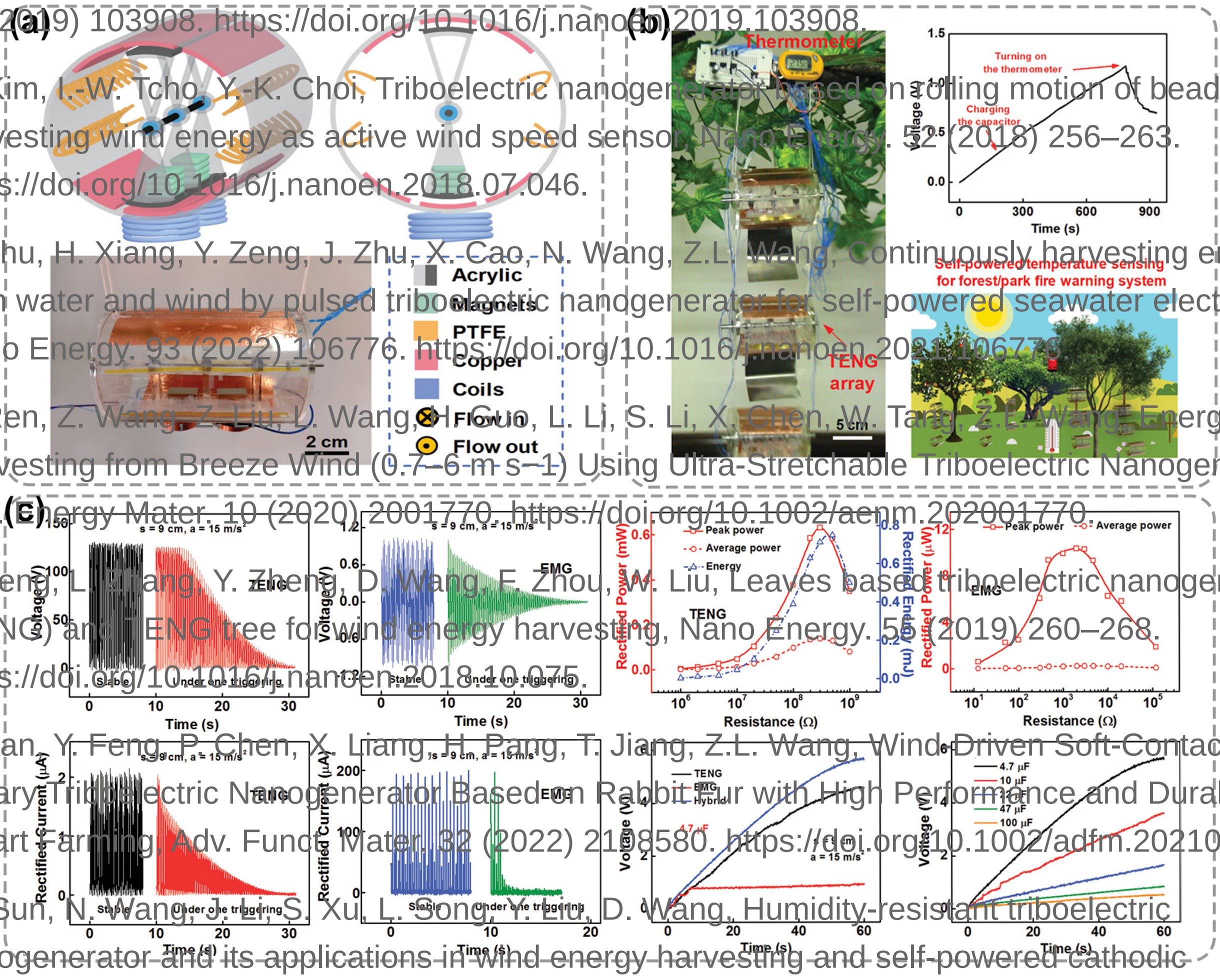

Figure 8. (**a**) A swinging breeze collection system consisting of EMG and TENG. (**b**) Photograph of a digital thermometer powered by a SS–TENG array under the wind triggering. (**c**) Output performance of the TENG part and EMG. Reproduced with permission of [48], Copyright 2021, John Wiley and Sons.

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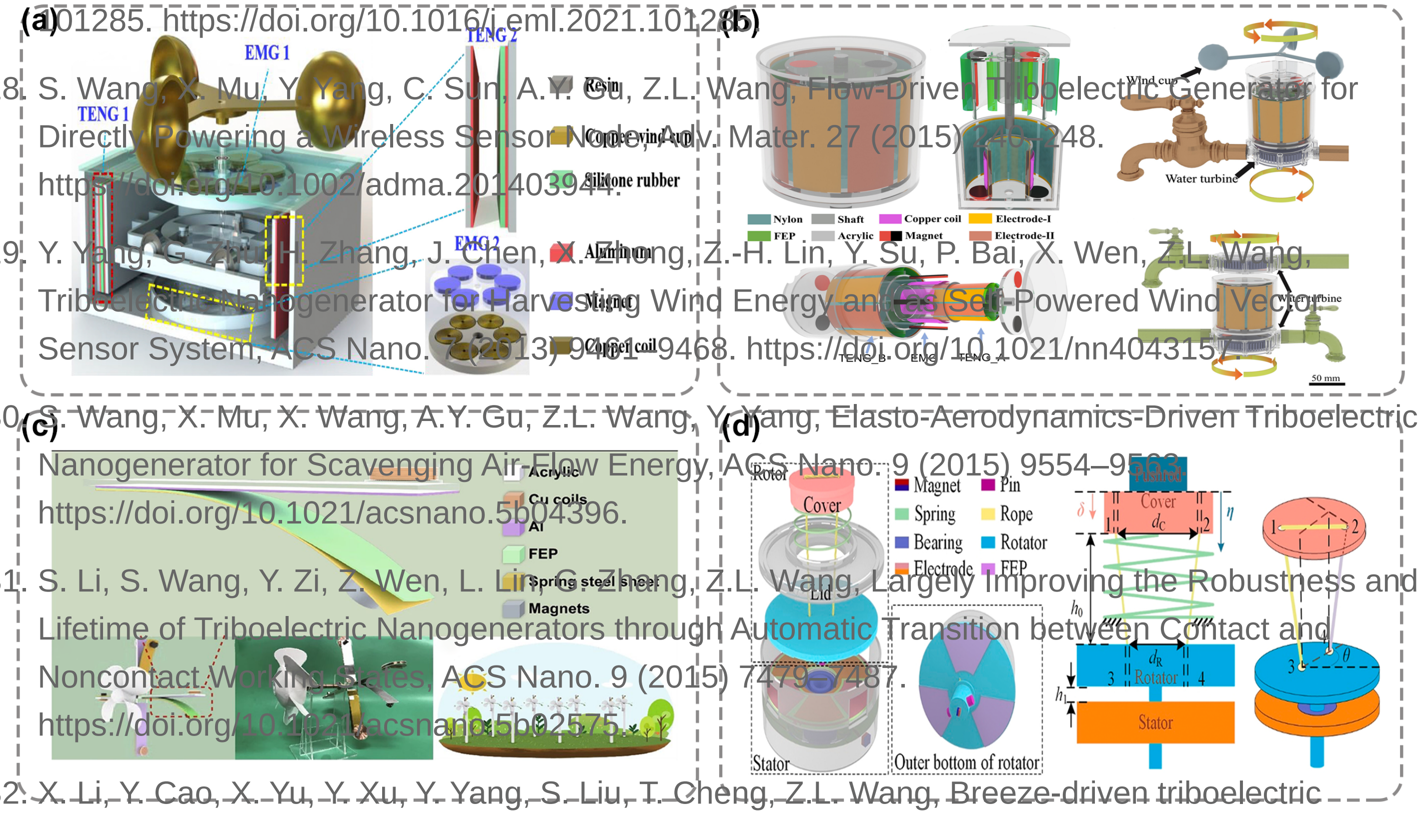

Figure 9. Hybrid TENGs combined with EMG and TENG. (a) The structure of the TEHG. Reproduced with permission of [46], Copyright 2019, Elsevier. (b) Structural design of the MCNG. Reproduced with permission of [47], Copyright 2021, Elsevier. (c) Schematic illustration of the W-HNG. Reproduced with permission of [15], Copyright 2020, Springer. (d) Structure and working principle of the IC-TENG. Reproduced with permission of [48], Copyright 2021, Elsevier.

The selection of WD-TENGs should be made in conjunction with the advantages and disadvantages of the WD-TENG classification and specific application scenarios. summarizes the reported WD-TENGs suitable for energy harvesting in breezy environments, and it is observed that wind power generation in low wind environments can be achieved by selecting flexible, low-density materials and optimizing the structure. It is expected that these more detailed presentations can provide methodological guidance and design inspiration for future research and applications of WD-TENGs in breezy environments.

Table 2. Summary and comparison of various WD-TENGs.

Structures	Triboelectric Materials	Modes	Voltage(v)	Current (uA)	Power	Ref
Rotational sweeping mode	Al & PTFE	CS&LS	250	250	62.5 mW (900 r/min)	[8]

Rotational sweeping mode	**Al & PTFE**	**SE**	**55**	**–**	**0.03 mW**	[49]
Rotational sweeping mode	**Al & PVDF**	**FT**	**650**	**50**	**10 mW** **(900 r/min)**	[50]
In-plane cycled sliding mode	**Cu & Kapton**	**FT**	**320**	**3400**	**–**	[7]
bidirectional gear transmission structure	**FEP & Cu**	**CS**	**-**	**-**	**4 mW** **(50 MΩ)**	[34]
Transform the rotating structure into a linear structure	**PTFE & Cu**	**CS**	**200**	**2.9**	**180 μw** **(1 subunit, 60 rpm)**	[51]
Transform the rotating structure into a linear structure	**PTFE & Cu**	**CS**	**320**	**20**	**0.37 mW** **(6 subunit,60 rpm)**	[52]
Single-side-fixed	**Al & FEP**	**CS**	**100**	**1.6**	**0.16 mW** **(100 MΩ)**	[29]
Single-side-fixed	**Au & PTFE**	**CS**	**200**	**60**	**0.86 mW** **(15 m/s)**	[53]

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Single-side-fixed	**FTO & PTFE**	**CS**	**36**	**4.1**	**–**	[40]
Single-side-fixed	**Al & PTFE**	**CS**	**400**	**60**	**3.7 mW**	[28]
Single-side-fixed	**FEP & Cu**	**CS**	**36**	**11.8**	**0.15 mW**	[54]
Single-side-fixed	**PTFE & Al**	**CS**	**297**	**-**	**0.46 Mw** (10 m/s)	[26]
Single-side-fixed	**Hosta Leaf & PMMA**	**SE**	**230**	**9.5**	**45 mW/m^2** (1×10^7 Ω)	[23]
Single-side-fixed	**wheat straw & FEP**	**SE**	**250**	**20**	**404 μW/m^2**	[55]
Single-side-fixed	**PTFE & MGDY**	**CS**	**100**	**3.5**	**-**	[24]
Single-side-fixed	**PLL modified leaf powder & PVDF**	**CS**	**1000**	**60**	**17.9 mW** (11 MΩ)	[20]
Double-side-fixed	**Al & PTFE**	**CS**	**334**	**67**	**5.5 mW**	[56]
Double-side-fixed	**Cu &PTFE**	**CS**	**342**	**140**	**-**	[30]
Lawn structure	**ITO & PET**	**CS**	**78**	**16.3**	**-**	[57]

Energy. 56 (2019) 269–276. https://doi.org/10.1016/j.nanoen.2018.11.037.

59. W. Sun, Z. Ding, Z. Qin, F. Chu, Q. Han, Wind energy harvesting based on fluttering double-flag type triboelectric nanogenerators, Nano Energy. 70 (2020) 104526.

Angle-shaped	**FEP& Al**	**CS**	**64**	**2.5 (10 m/s)**	**-**	[58]
Venturi tube	**PTFE& PC**	**CS**	**-**	**-**	**4.5 mW (5 m/s)**	[10]
Flag structure	**Ni & Kapton**	**CS**	**40**	**30**	**135 mW/kg (22 m/s)**	[11]
fluttering double-flag type	**FEP & Cu**	**CS**	**-**	**-**	**600 mW/m^2 (10 m/s)**	[59]
Vortex-induced	**PANI & PTFE**	**CS**	**-**	**-**	**96.79 mW/m^2 (2.78 m/s)**	[13]
galloping structure	**Nylon & FEP**	**CS**	**200V(1.4 m/s)**	**-**	**6 μW (1.4 m/s)**	[14]
Cantilevered structure	**PTFE & Al**	**CS**	**270**	**7.6**	**0.9 mW (2.9 m/s,44 MΩ)**	[12]
rolling motion of polymer beads	**PTFE & Cu**	**FT**	**17.8**	**5.3**	**1.36 mW/cm^2 (20 m/s)**	[60]
structure of the magnetic switch	**FEP & Cu**	**FT**	**410**	**18**	**4.82 mW**	[35]

Table 3. Summary and comparison of various WD-TENGs for harvest breeze wind.

Structures	Triboelectric Materials	Characteristic	Start-UpWindSpeed	Electric Output	Ref
Rotational sweeping mode	FEP &Cu	Low density rotor material, a suitable wind scoop structure	3.3 m/s	330 v, 7 μA; Pmax = 2.81 mW(4 m/s)	[32]
Rotational sweeping mode	FEP &Cu	Coupling of TENG with different structural parameters	2.2 m/s	5.2 mW	[33]
Rotational sweeping mode	FEP &Cu	Adopt the dielectric film with high flexibility	3.5 m/s	-	[61]
Vortex-induced vibration	PANI & PTFE	wind energy harvesting based on vortex-induced vibration	2.78 m/s	392.72 μW	[13]
Single-side-fixed	PTFE &Al	Controls the thickness and size of the film and the distance between the plates	3.4 m/s	297 v; 3.9 μA; P = 0.46 mW(10 m/s)	[26]
Single-side-fixed	PTFE &Al	By changing the material, size and aspect ratio of the film	2.9 m/s	2.06 μW (10 MΩ)	[44]
Single-side-fixed	PTFE & MGDY	Unique material, film geometry parameter control	1.6 m/s	-	[24]

Galloping structure	**Nylon & FEP**	**Through the design of two flexible beams to achieve galloping behavior**	**1 m/s**	**6 uW(1.4 m/s)**	[14]
Cantilevered structure	**Al& PTFE**	**Change electrode structure, electrode weight, rotating radius and cantilever length.**	**2.9 m/s**	**-**	[12]
Variable diameter channel	**Al & FEP**	**A square variable diameter channel combined with an ordinary double-ended fixed W-TENG**	**0.4m/s**	**2 V(2 m/s)**	[62]

6. Summary and Outlook

Wind energy is a widely distributed, clean, renewable and green energy source, and wind power is an important direction for future new energy development. Based on the advantages of TENG in collecting irregular low-frequency energy, WD-TENG, a new wind energy harvesting technology, is proposed to realize the effective conversion of wind energy in different applications. The existing single WD-TENG device can generate an output voltage up to 1000V. In addition, WD-TENG can be fabricated with environmentally friend materials and the existing WD-TENG can provide power supply for low-power systems such as LEDs, temperature and humidity sensors, environmental monitor and even air cleaning device. Researchers review the evolution of WD-TENG structure, the latest progress in material selection, and compiles the output performance, advantages and disadvantages of various designs. Then, researchers summarize the desirable methods for WD-TENG to work effectively at different wind speeds. In addition, WD-TENG can work in concert with other mechanisms to broaden its application areas.