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Recent Progress in Flow Energy Harvesting and Sensing Based on Triboelectric Nanogenerators

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Triboelectric nanogenerators (TENGs), as a novel energy harvesting technology, have attracted increasing attention. This review paper focuses on the application of TENGs in flow energy harvesting and self-powered flow sensing systems, as well as the latest research progress in this field. First, the working principle of TENG is introduced in detail, including the electrification mechanism and four basic working modes. Subsequently, the common applications of TENG-based flow energy harvesting are systematically classified and summarized. In addition, the designs and principles for harnessing wind energy, wave energy, water flow energy, and droplet energy are illustrated individually. Furthermore, the common applications of TENG in flow sensing are elucidated, involving flow velocity and direction, flow rate measurement, respiration monitoring, water level, and wave motion monitoring. Finally, the current challenges in this field, such as the stability of TENG performance, scalability and integration, environmental impact and durability, etc., are discussed and future research directions, such as developing new TENG materials and designing more high-efficiency TENG structure, are proposed. It is hoped that this review paper can actively promote the research and application of TENGs and contribute to the development of this field.

1. Introduction

In recent decades, the extensive adoption of microelectronic devices has profoundly transformed human life and work, providing unparalleled convenience and a myriad of new functionalities. This revolution has been further accelerated by the rapid advancement of the Internet of Things (IoT) technology, which has led to an ever-growing demand for energy-efficient solutions, sustainable energy sources, and advanced wireless communication technologies. As a result, research on pioneering energy harvesting techniques has gained paramount importance as a response to these emerging needs.[1] Triboelectric nanogenerators (TENGs) have risen to prominence as a state-of-the-art energy harvesting technology, attracting significant attention from researchers and industry professionals worldwide.[2–5] This interest arises from the exceptional energy density and self-powered capabilities of TENGs. In addition, their environmentally friendly characteristics align with the global push toward sustainability and green energy solutions.[6–10] The development of TENGs has been bolstered by several factors. These include the rising dependence on portable electronic devices and the expansion of IoT networks. Awareness of the environmental impact of traditional energy generation methods is also growing. As microelectronics continue to permeate various aspects of modern life, TENGs have the potential to become a vital component in meeting the energy demands of these devices, further fueling innovation and promoting sustainable development. Over recent years, TENGs have achieved substantial progress in a diverse range of applications,[11–25] including wearable devices,[11–15] self-powered sensor networks,[16–20] intelligent home systems,[21–25] and more. This progress highlights the versatility and potential of TENG technology in catering to the energy needs of various emerging technologies. However, the majority of existing TENG systems primarily focus on harvesting energy from simple or periodic mechanical motions, such as vibrations or human movements.[26–30] As a result, the potential of TENGs in capturing and sensing flow energy within fluid media remains largely untapped and presents a significant challenge for researchers and engineers.

Flow energy, which is generated by the movement of fluid media, represents a vast and underutilized energy source that can be found in numerous natural and industrial processes.[31–33] In an effort to harness this continuous flow of energy, various large-scale wind turbines and hydropower plants have been constructed worldwide, providing indispensable energy support for human productivity, daily life, and economic growth.[34–38] These renewable energy sources have contributed significantly to the global energy mix, helping reduce the dependence on fossil fuels and promoting sustainable development. However, such

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large-scale installations typically require higher flow field strength and stability, which often leads to a more centralized and location-dependent approach to energy generation.[39–41] This reliance on specific environmental conditions and infrastructure can result in relatively inefficient installations for remote regions or outdoor monitoring equipment. In such areas, the availability and accessibility of consistent flow field strength and stability may be limited. Moreover, the installation, maintenance, and operation costs associated with these large-scale systems can be prohibitive, particularly for smaller-scale applications or in areas with limited resources.[42–45] Therefore, there is a growing need for decentralized, flexible, and efficient energy harvesting technologies that can adapt to various flow conditions and environments. With the ability to capture energy from various mechanical motions, distributed and low-cost, TENGs can play a key role in addressing these challenges and harnessing the potential of flow energy for a more sustainable future. By tackling the challenges related to capturing flow energy from fluid media, researchers can enhance the efficiency, versatility, and potential of TENGs. This, in turn, contributes to the advancement of innovative and environmentally friendly energy harvesting technologies for diverse industries and applications. In the face of the limitations posed by current large-scale installations, these emerging energy harvesting technologies have the potential to significantly broaden the applications of streaming energy. They can enable more widespread and efficient utilization in remote areas, outdoor monitoring devices, and other emerging technologies.[46–55]

In the context of the IoT era, the development and proliferation of microdevices and IoT technology are faced with considerable challenges, particularly in terms of energy management and sustainability. With the exponential growth in the number of interconnected devices, there is a rising demand for energy solutions that are efficient, reliable, and environmentally friendly. These solutions need to power the devices and ensure their optimal performance. Integrating TENG technology to harvest the flow energy that is abundantly present in the environment presents a promising opportunity to address these challenges and create sustainable energy solutions for the ever-expanding IoT landscape.[56–58] By capturing and converting flow energy into usable electrical power, TENGs can enable distributed devices to operate autonomously and without reliance on traditional power sources, such as batteries or grid connections. This self-powered capability not only reduces the environmental impact and maintenance requirements associated with battery-powered devices but also enhances the flexibility and scalability of IoT systems, making them more adaptable to various applications and environments.[59–63] Moreover, by leveraging the unique properties of TENGs, researchers and engineers can develop innovative energy harvesting techniques that take advantage of the vast untapped potential of flow energy. These advances could lead to the creation of new, sustainable energy solutions that are better suited to meet the demands of the IoT era. Ultimately, this can promote greater energy efficiency, reducing greenhouse gas emissions and fostering a more sustainable future for all.

The air we breathe and the water we drink are both fluids, which play an exceedingly crucial role not only in sustaining our life but also in various production activities and daily routines. Fluid dynamics are integral to numerous natural phenomena and industrial processes, and understanding the characteristics of fluid flow is essential for optimizing efficiency, safety, and sustainability in many applications. Moreover, the fluid flow state often contains valuable information that, if captured and monitored in real time, could yield tremendous economic and safety benefits across various industries and sectors.[64–78] Real-time monitoring of fluid flow characteristics, such as flow velocity, flow rate, pressure, and turbulence, can enable informed decision-making, enhance process control, and facilitate predictive maintenance.[64–71] For instance, in hydropower, wind power, and oil extraction industries, real-time monitoring of flow velocity and flow rate is of paramount importance for maximizing energy efficiency and optimizing operational parameters.[72–78] Accurate and timely measurements of fluid flow can help identify bottlenecks, predict equipment failures, and improve overall system performance. These improvements result in cost savings, environmental sustainability, and enhanced safety.[79–81] By harnessing the power of data-driven insights and innovative technologies, such as TENGs and IoT devices, we can unlock the full potential of fluid flow information and create more sustainable, efficient, and resilient energy systems for the future. Despite the availability of numerous commercial sensors for various applications, they often come with drawbacks. These include high manufacturing costs and the need for external power sources to sustain their operation.[82,83] The reliance on external power supplies not only leads to periodic replacements and costly maintenance but also increases the environmental footprint. The disposal of large quantities of batteries presents significant risks to the environment due to their hazardous components and associated waste management challenges.

By leveraging the innovative TENG technology, self-powered sensing can be realized, consequently reducing operating expenses, minimizing maintenance requirements, and safeguarding the environment.[84–90] Implementing TENG-based sensors eliminates the need for traditional power sources, such as batteries or grid connections, and allows devices to operate autonomously by harvesting energy directly from their surroundings. This approach not only enhances the sustainability of sensor networks but also increases their adaptability and scalability, enabling their deployment in remote or hard-to-reach locations where conventional power sources are not feasible.[91–93] As TENG technology continues to advance and mature, its expanded implementation across various industries and applications could unlock a new era of sustainable, efficient, and eco-friendly energy solutions. By integrating TENGs into the next generation of sensing devices, researchers and engineers can unlock the untapped potential of environmental energy sources. This integration will pave the way for innovative self-powered systems that are well-equipped to meet the escalating demands of our interconnected and resource-conscious world.

In light of the aforementioned background, the primary objective of this review article is to provide an overview of the classifications and advancements of flow energy harvesting and sensing technologies based on TENGs, the main content is shown in **Figure 1**. We will discuss the principles and structural designs behind TENGs, as well as their various applications in flow energy harvesting and self-powered flow sensing. This review is structured into the following sections: Section 2 introduces the working principles of TENGs, including the triboelectric effect and electrostatic induction, along with the contact-separation and

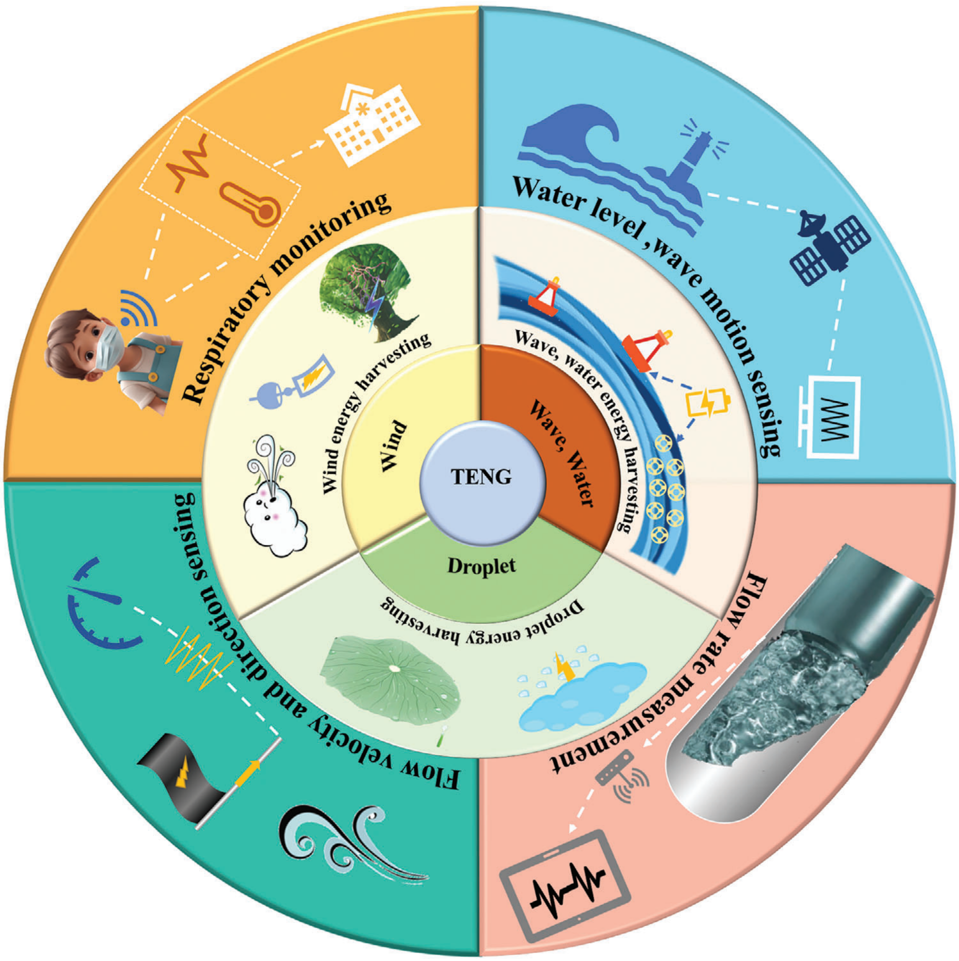

Figure 1. Overview diagram of TENG-based flow energy harvesting and sensing.

charge transfer mechanisms. Section 3 presents the applications of TENGs in flow energy harvesting, covering wind energy, wave and water flow energy, and droplet energy harvesting. Section 4 delves into self-powered flow sensing applications using TENGs, such as flow velocity sensors, flow rate sensor, water level and wave motion monitoring, and respiration monitoring. Finally, Section 5 provides a summary of the current challenges and future research directions for TENG-based flow energy harvesting and sensing technologies. These include enhancing output performance and conversion efficiency, improving material durability and device stability, miniaturization and system integration, as well as developing self-powered flow sensing networks based on TENGs.

2. Theoretical Background and Working Principles of TENGs

To better understand the potential of TENGs in flow energy harvesting and sensing applications, it is essential to have a clear understanding of their theoretical background and working principles. In this section, we will discuss the fundamental concepts, mechanisms, and basic modes of TENG.

2.1. Fundamental Concepts and Mechanisms

TENGs are a type of energy harvesting device that converts mechanical energy into electrical energy based on the coupling of triboelectric effect and electrostatic induction.[94–96] Triboelectrification or contact electrification is an ancient physical phenomenon that was discovered as early as 2600 years ago in ancient Greek civilization. Despite being discovered long ago, the exact mechanism behind triboelectrification is not completely clear.[97–99] Recently, the electron cloud/potential model proposed by Wang provides a comprehensive understanding of the triboelectrification effect.[100] As shown in **Figure 2**a, according to this model, before two materials come into contact, the electron clouds of the two materials remain separated without overlap, and the potential well binds the electrons to prevent them from escaping. When the two materials come into contact, the electron clouds overlap to form ionic or covalent bonds due to the physical contact, resulting in the initial single potential changing to an asymmetric double-well potential (Figure 2b). As the strong electron clouds overlap, the energy barrier between the two atoms is lowered, and electrons can be transferred from one to the other, leading to triboelectrification. Figure 2c shows a general representation of the interactions between atoms. For two atoms that form a chemical

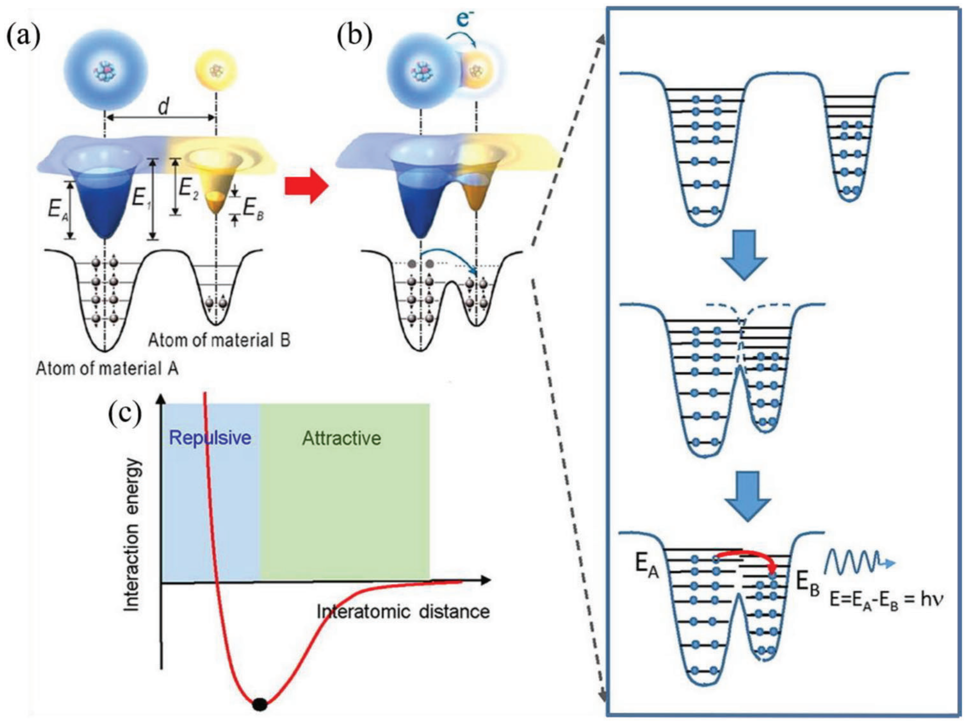

Figure 2. The electron cloud and potential energy distribution maps (3D and 2D) of two atoms, respectively belonging to materials A and B, are shown when they are: a) before contact and b) in contact, c) the interatomic potential between two atoms and the force acting between them when they are in an equilibrium position. b1–b3) The detailed description of (b) indicates that the increased electron cloud overlaps result in a lower potential barrier between the two atoms, leading to interatomic electron transitions and possible photon emission. Adapted with permission.[100] Copyright 2019, Elsevier.

bond, it means that there is some overlap of electron clouds or wave functions, establishing an equilibrium distance known as bond length or interatomic distance. When the two materials are separated, the transferred electrons will remain on the surface of the materials. The triboelectric charges produced by the contact and separation of two different dielectric materials create a potential difference due to their different electron affinity, resulting in the production of an alternating electrical current in the external circuit through the coupling of triboelectrification and electrostatic induction. This principle is the basis for the operation of TENGs, which can convert various mechanical energies, such as vibration, bending, and rotation, into electrical energy.

In summary, triboelectrification/contact electrification is a phenomenon that involves the transfer of electrons between two materials in contact and their separation. The electron cloud/potential model proposed by Wang provides a comprehensive understanding of the triboelectrification effect, which involves the overlap of electron clouds, the lowering of energy barriers, and the transfer of electrons. TENGs operate based on the coupling of triboelectrification and electrostatic induction, which can convert various mechanical energies into electrical energy.

2.2. Basic Modes of TENG

TENGs can be classified into four primary modes of operation based on the configuration and movement of the triboelectric materials and electrodes (as shown in **Figure 3**). Each mode offers specific advantages and can be tailored to suit various flow energy harvesting and sensing applications.[101–107]

Vertical contact-separation mode (Figure 3a): In this mode, the triboelectric materials are in direct contact, and their separation and subsequent re-contact generate the electric potential. The electrodes are placed on the back sides of the triboelectric materials, and the electric current flows between them during the contact-separation process. This mode is suitable for harvesting energy from linear motion or oscillatory motion, such as cylinder-based or flapping-based TENGs.[101,102]

Lateral sliding mode (Figure 3b): In the lateral sliding mode, the triboelectric materials slide against each other, creating a lateral displacement of the surface charges. The electrodes are placed on the back sides of the triboelectric materials, and the electric current flows between them during the sliding process. This mode can be utilized for harvesting energy from sliding or rotational motion.[103,104]

Freestanding triboelectric-layer mode (Figure 3c): In the freestanding triboelectric-layer mode, a single layer of triboelectric material is sandwiched between two electrodes. The electric potential is generated by the deformation of the triboelectric layer and the subsequent change in the capacitance between the electrodes. This mode can be applied for harvesting energy from various types of motion, such as linear, oscillatory, or rotational motion, as well as for sensing applications.[105,106]

Single-electrode mode (Figure 3d): In this mode, only one electrode is used, and it is placed on one of the triboelectric materials. The other material acts as the counter electrode. The electric potential is generated by the contact and separation between the triboelectric materials, and the electric current flows between the electrode and the ground (or a reference electrode) during

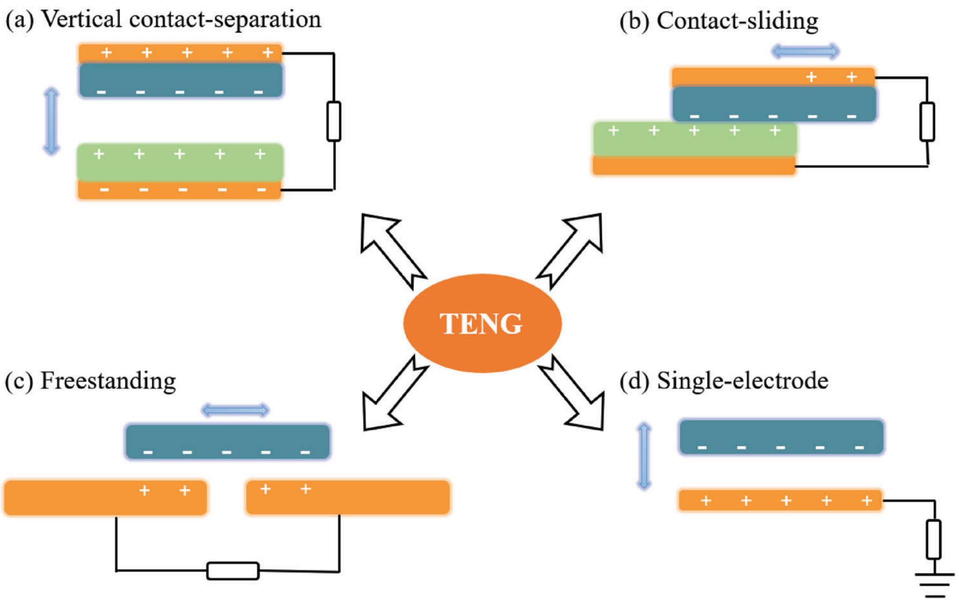

Figure 3. Basic modes of operation of triboelectric nanogenerators. a) The vertical contact-separation mode (V-CS). b) The contact-sliding mode (CS). c) The freestanding mode (FT). d) The single-electrode mode (SE).

the process. This mode can be employed for harvesting energy from various types of motion, such as linear, oscillatory, rotational motion, or droplet sliding.[107,108]

In conclusion, the underlying working principles and diverse modes of operation of TENGs offer a versatile platform for designing and customizing devices to suit a myriad of flow energy harvesting and sensing applications. By carefully selecting the most suitable mode and meticulously optimizing the arrangement of the triboelectric materials and electrodes, researchers and engineers can create TENG-based devices that boast high efficiency and sensitivity, catering to a broad spectrum of applications. This adaptability enables TENG technology to address pressing energy and sensing needs across various industries and environments, paving the way for a more sustainable and connected future. As research continues to advance in this field, we can anticipate further breakthroughs and innovations that will expand the potential of TENGs, contributing to the development of smarter, greener, and more efficient technologies.

3. Flow Energy Harvesting Applications

TENGs have exhibited exceptional potential in a diverse array of flow energy harvesting applications, harnessing renewable energy sources to power small electronic devices and sensors. In this section, we discuss some TENG-based flow energy harvesting and applications (**Figure 4**). Flow energy includes wind energy, wave and current energy, and droplet energy. The essence of these flowing energies is kinetic energy, which can be converted into electrical energy by using TENG, and finally distributed TENGs provide sustainable and environmentally friendly solutions for remote sensors, small electronic devices, and Internet of Things applications.

3.1. Wind Energy Harvesting

Wind energy is a form of renewable energy that harnesses the power of wind to generate electricity. It is a clean, sustainable,

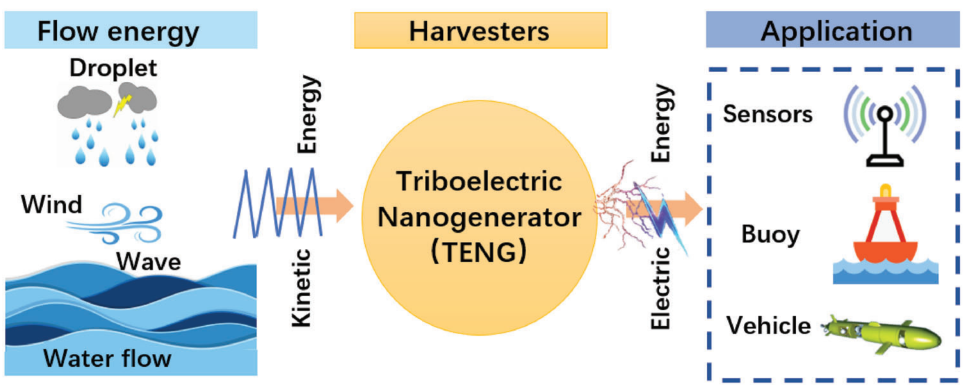

Figure 4. Schematic of flow energy harvesters and application.

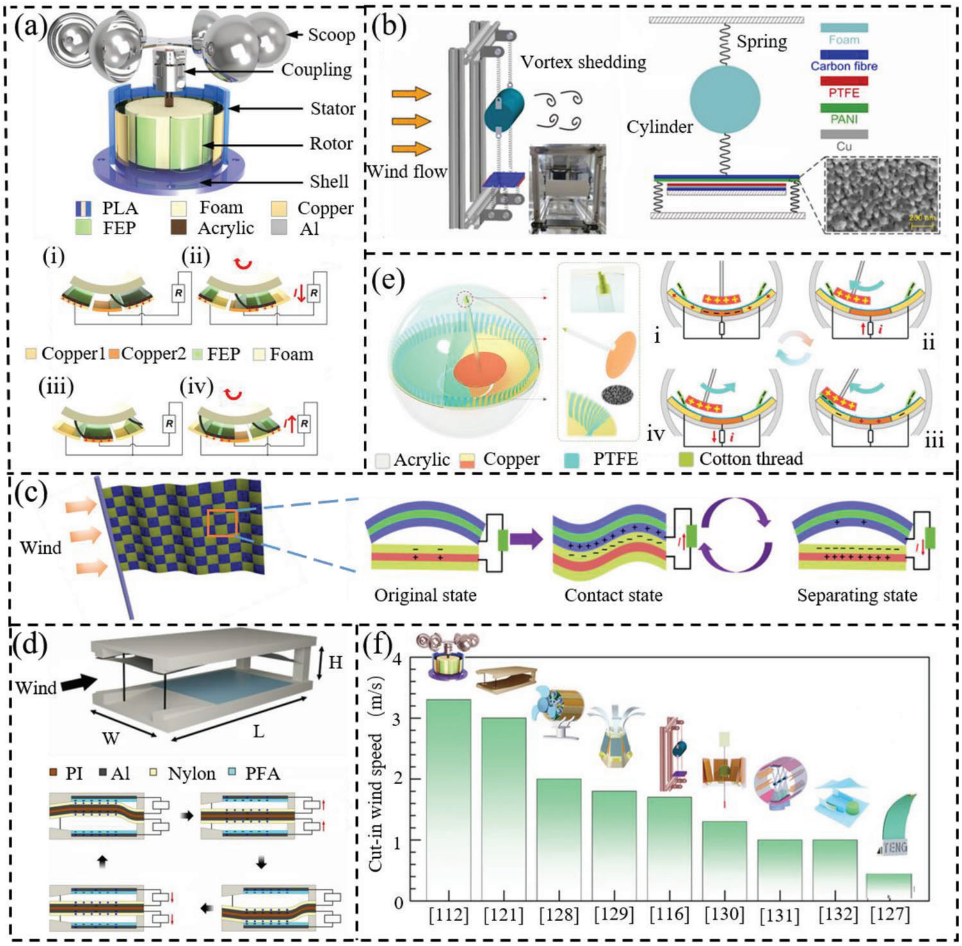

Figure 5. Triboelectric wind energy harvesting device. a) Rotating turbine structure energy harvester. Adapted with permission.[109] Copyright 2021, Elsevier. b) Vortex-induced vibration energy harvester. Adapted with permission.[113] Copyright 2022, Elsevier. Copyright 2016, American Chemical Society. d) Cavity type flexible flag type. Adapted with permission.[118] Copyright 2022, Elsevier. e) Swing-type energy harvester. Adapted with permission.[123] Copyright 2019, Elsevier. e) Flexible flag energy harvester. Adapted with permission.[117] Copyright 2016, American Chemical Society. f) Energy harvester cut-in wind speed comparison. Adapted with permission.[124] Copyright 2023, Wiley-VCH GmbH.

and abundant source of energy that has been utilized by humans for centuries, dating back to the use of windmills for grinding grains and pumping water. In modern times, wind energy is primarily harnessed using wind turbines, which are large structures consisting of a tower, rotor, and blades. As the wind blows, it causes the blades to rotate, which in turn spins the rotor. This mechanical motion is then converted into electrical energy through the use of a generator. Despite these advantages, wind energy also faces some challenges, such as intermittency (wind is not always blowing), visual and noise impacts, and potential harm to wildlife. TENGs with the characteristics of small size, distributed, and low noise have been extensively studied for wind energy harvesting due to their ability to convert the kinetic energy of wind into electrical energy. Various designs have been proposed to maximize the efficiency and output of TENG-based wind energy harvesting systems, including rotating wind turbines,[109–112] vortex-induced vibration (VIV),[113–116] and fluttering flags.[117–122] Each design has unique advantages and challenges, which are briefly described below.

3.1.1. Rotating Wind Turbines

A TENG-based rotating wind turbine utilize the principles of the triboelectric effect to generate electricity from the rotation of wind turbine blades.[109–112] In such a design, the blades would be coated with materials having different triboelectric properties. As the wind causes the blades to rotate, these materials come into contact and separate, creating a charge transfer between them. This continuous charging and discharging process generates an electric current that can be harvested and used for various applications. As shown in **Figure 5**a, a breeze-driven triboelectric nanogenerator (BD-TENG) that can provide energy for smart agricultural production systems is demonstrated.[109] It consists of a wind scoop, coupler, rotor, stator, and casing. The wind scoop collects natural wind, driving the FEP film to generate sliding friction with copper electrodes. Consequently, the BD-TENG achieves the conversion of natural wind energy into electrical energy. The four working states during the power generation process are also illustrated in the figure The FEP film is an electronegative material, and copper is an electropositive material. When they come into contact, electrons on the copper-1 surface transfer to the FEP film surface according to the triboelectric principle [as shown in Figure 5a(i)]. In Figure 5a(ii), the FEP film gradually slides toward copper-2. During this process, electrons transfer from the copper-2 surface to copper-1, generating a current in the opposite direction in the external circuit. As shown in Figure 5a(iii), the FEP film is entirely attached to copper-2, and the electrons on the copper-2 surface are completely transferred. As illustrated in Figure 5a(iv), when the FEP film gradually slides toward copper-1, electrons on the copper-1 surface transfer to the copper-2 surface, generating a current in the opposite direction in the external circuit. When the FEP film separates from copper-2 again, one electron transfer cycle is completed. The idea of incorporating TENGs into wind turbines is promising because it has the potential to improve energy harvesting efficiency and provide an alternative means of electricity generation. The integration of TENG technology with traditional wind turbines could also result in hybrid systems that make use of both electromagnetic generators and triboelectric nanogenerators to optimize energy production and reduce the impact of intermittency associated with wind energy. However, TENG-based wind turbines are still in the early stages of research and development. More studies and practical demonstrations are needed to assess their feasibility, efficiency, and long-term performance in real-world applications.

3.1.2. Vortex-Induced Vibration

Energy harvesting from cylindrical VIV using TENGs is an emerging approach that holds great promise for harnessing flow energy from fluid-induced vibrations.[113–116] As illustrated in Figure 5b, a cylinder is connected to the TENG using a stretched spring, and when the cylinder is subjected to lateral wind flow, it acts as an oscillator, converting wind energy into kinetic energy.[113] The TENG then takes responsibility for transforming the kinetic energy into electrical energy through the periodic contact and separation behavior between the two electrode plates. Based on this conceptual design, VIV-TENG can capture wind energy from the surrounding environment to power a wireless sensor network (WSN) deployed in remote areas. This method offers several advantages, including the ability to harvest energy from various types of fluids (air, water, etc.) and a wide range of flow velocities. Furthermore, the cylindrical VIV-based TENGs can be designed to be self-adaptive, as their output is naturally modulated by the flow conditions. However, challenges remain in terms of optimizing the TENG materials, design, and fabrication for improved efficiency, robustness, and durability under various environmental conditions. Future research efforts should focus on addressing these challenges to fully exploit the potential of cylindrical VIV-based TENGs for flow energy harvesting applications.

3.1.3. Fluttering Flags

In flag-based TENGs, two different friction materials are typically used to create a friction layer, which can be formed into a flag by weaving the two materials together (as shown in Figure 5c),[117] or by directly bonding the edges of the two materials to form a flag. Another form is the structure shown in Figure 5d, where a flexible flag is placed inside a cavity.[118] When the flag flutters in the wind, the two friction layers repeatedly come into contact and separate, resulting in charge transfer between the layers due to the triboelectric effect. The charges are then collected by electrodes to generate a current that can be collected and utilized.[117–122] Flag-based TENGs can be deployed in various environments, including urban areas, where space limitations and turbulent wind patterns may reduce the efficiency or impracticality of traditional wind turbines. In addition, compared to traditional wind turbines, flag-based TENGs have fewer moving parts, which may reduce maintenance requirements and costs. However, it should be noted that this technology is still in the early stages of development and its output performance is often influenced by wind speed and direction. Therefore, further research on materials, design optimization, and practical applications is necessary to improve the feasibility and efficiency of flag-based TENGs. If successful, this technology could provide an innovative and complementary approach to harvesting wind energy alongside traditional wind turbines.

3.1.4. Other Structures

In addition to the three mainstream methods for wind energy harvesting mentioned above, there are many other structures proposed.[123–128] Figure 5e shows a swing-type TENG, in which the oscillation of the ball under the action of wind drives the internal pendulum to contact and separate from the internal different electrodes.[123] In order to collect wind energy more efficiently, many studies have been conducted to enable energy collection even under light winds. Li et al.[124] proposed a leaf-like triboelectric nanogenerator (LL-TENG), which utilizes the contact electrification phenomenon caused by the damping forced vibration of the topology-optimized structure. The structure consists of a flexible blade, a vein-bearing plate, and a balance block (the last device in Figure 5f). It solves the problem of reduced output due to electrostatic adsorption between blade surfaces, and reduces the cut-in (0.2 m s^{-1}) and rated wind speed (2.5 m s^{-1}). The starting wind speeds for common methods are summarized in Figure 5f.[109,113,118,124–129]

These devices can be implemented in large-scale wind farms, urban environments, or even portable electronics for self-powering applications. TENG-based wind energy harvesting systems offer advantages such as low-cost fabrication, high efficiency, and the ability to work in low-wind-speed conditions, making them a promising alternative or supplement to traditional wind turbines. Moreover, TENGs can be integrated with other renewable energy technologies, such as solar panels, to create hybrid energy harvesting systems for more efficient and reliable power generation.

3.2. Wave and Water Flow Energy Harvesting

Wave and water flow energy are two types of renewable energy sources that harness the power of water to generate electricity. Both forms of energy make use of the kinetic and potential energy

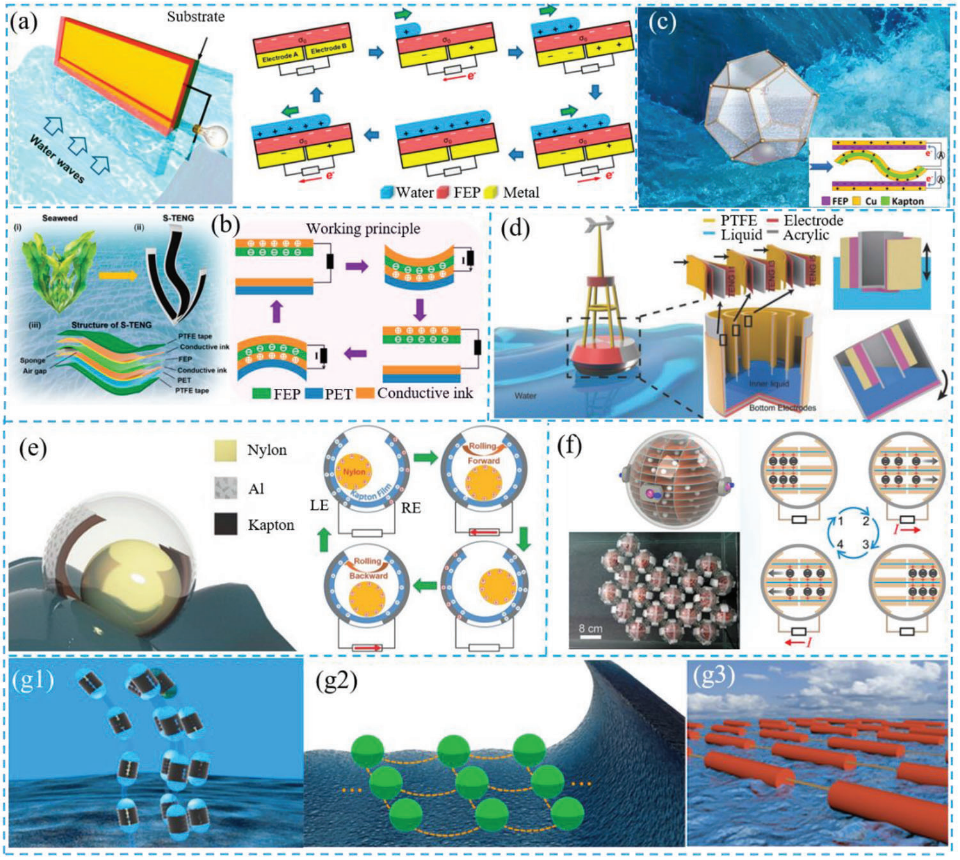

Figure 6. Triboelectric wind energy harvesting device. a) Integrated design, no moving parts device. Adapted with permission.[130] Copyright 2014, American Chemical Society. b) Water flow energy harvester imitating seaweed. Adapted with permission.[132] Copyright 2021, American Chemical Society. c) A wavy TENG integrated into a floating dodecahedron. Adapted with permission.[135] Copyright 2016, Elsevier. d) Buoy type wave energy harvester. Adapted with permission.[136] Copyright 2018, Wiley-VCH GmbH. e) Rolling Nylon ball type TENG. Adapted with permission.[137] Copyright 2015, Wiley-VCH GmbH. f) Small ball packaged wave energy harvester. Adapted with permission.[138] Copyright 2019, Elsevier. g) Parallel form of large-scale power generation. Adapted with permission.[139–141] Copyright 2019, American Chemical Society; Copyright 2017, Elsevier; Copyright 2018, Elsevier.

in water to produce clean, sustainable power. Waves are formed by the wind blowing over the surface of the ocean, transferring energy from the air to the water. Wave energy is the use of the energy of ocean waves to generate electricity. Water flow energy harnesses the kinetic energy present in the natural flow of rivers, streams, and ocean currents. Traditional uses include oscillating water column systems, point absorbers, floating attenuators, and hydrodynamic turbines to capture the energy of waves and currents. These devices convert the motion of the waves into mechanical energy, which is then converted into electrical energy using generators. However, the maintenance cost of these devices is huge, and the requirements for the strength and stability of the flow are relatively high. In this context, TENG-based current and wave energy harvesting systems with high efficiency, low maintenance cost, and the ability to work under various flow conditions have been rapidly developed. These systems typically use buoyant or flexible structures that respond to water flow or wave motion, generating an electric potential difference through the triboelectric effect. Ultimately, they could be utilized for large-scale power generation, powering underwater devices, or providing energy to remote coastal communities. As research and development continue, water flow and wave energy technologies hold great potential to contribute to the global transition toward clean, renewable energy sources. According to the attributes and characteristics of the device structure, it is mainly divided into three categories, namely Integrated design with no movable parts,[130,131] flexible structures,[132–134] and buoyant structures,[135–141] which will be introduced respectively below.

3.2.1. Integrated Design with No Movable Parts

First, there is a type of power generation device that does not have any moving parts. These devices typically utilize an integrated design that does not require any reciprocating separation.[130,131] The entire process of contact and separation is accomplished by water surface waves or droplets. This design can improve the longevity and stability of the equipment. **Figure 6**a shows a solid-liquid electrification generator based on a fluorinated ethylene propylene (FEP) film, with a series of electrodes manufactured underneath it.[130] As water contacts the electrified film, the surface of the film is charged. The nanowires created on the film make it hydrophobic and increase its surface area. Subsequently, the asymmetric screening of surface charges by water waves appearing and submerging on the surface allows free electrons on the electrodes to flow through external loads, thereby generating electricity. This generator produces sufficient output power to drive a small array of electronic devices by directly interacting with water bodies, including water surface waves and falling droplets. Surface modification of polymer nanowires increases the contact area of the liquid–solid interface, resulting in an increase in surface charge density, which achieves an energy output efficiency of 7.7%. The planar structure generator adopts a fully integrated design that does not require any separable or movable components to capture and transmit mechanical energy. It is very lightweight and compact, providing a portable, flexible, and convenient power solution that can be applied to ocean/river surfaces, coastal/offshore areas, and even rainy areas. Given the demonstrated scalability, if the layered planar sheets are connected into a network, it may also be used for large-scale energy generation.

3.2.2. Flexible Structures

The second type is TENG based on flexible structures, designed to bend and deform under the influence of water flow or waves.[132–134] The water-induced deformation causes the triboelectric layers to come into contact and separate, generating an electric potential difference. Figure 6b shows a flexible seaweed-shaped triboelectric nanogenerator (S-TENG), which is composed of a FEP film coated with conductive ink, a polyester (PET) film coated with conductive ink, and two layers of polytetrafluoroethylene (PTFE) film.[132] The friction layers of FEP and PET films sealed within the PTFE layers are protected and do not come into contact with water, which would cause the surface charge of the electrically active materials to dissipate. When the S-TENG undergoes periodic vibration induced by waves, as shown in Figure 6b, the FEP film periodically contacts and separates from the PET film. Upon contact with the conductive ink-coated PET film, the FEP film becomes negatively charged. Based on the nature of electrostatic induction, when the ink electrodes of PET and FEP films are in sufficient contact, a significant amount of positive charges will occupy the ink electrode on the PET film. When the S-TENG bends, electrons flow from the electrode connected to FEP to the electrode connected to PET (through an external circuit), generating a transient current. Subsequently, when the FEP and ink electrode separate, positive charges flow back to the upper electrode. This design offers the potential for high output performance and adaptability to various water flow conditions but can be sensitive to environmental factors such as flow speed, turbulence, and debris.

3.2.3. Buoyant Structures

Buoyant structure-based TENGs utilize floating devices that rise and fall with water waves, causing contact and separation between the triboelectric layers.[135–141] Due to the natural buoyancy of seawater and the pattern of surface undulation, buoyancy-based structures are still the most widely studied for harvesting wave energy. Buoyancy-based TENGs utilize a floating device that rises and falls with water waves, causing the contact and separation of friction layers, thereby converting wave energy into electrical energy. Figure 6c–f shows several common structural designs. In Figure 6c, the wave-shaped TENG is integrated into a dodecahedron that floats on the water surface, with a rigid ball weighing 200 g placed in the center.[135] When the dodecahedron moves up and down with the waves, the steel ball compresses the TENG to achieve contact and separation. Figure 6d is a buoy-shaped liquid–solid contact TENG that includes both internal and external TENGs, and contact and separation occur under both up-and-down and swaying states.[136] In Figure 6e, a nylon ball is encapsulated in a large ball with a Kapton film inside, and the small ball rolls inside the film to output an electrical signal as the waves move.[137] Figure 6f also uses a large-ball-over-small-ball structure, but energy density is increased through a multilayered structure.[138] Another advantage of using buoyancy-based structures is the ease of networking, as shown in the form of Figure 6g1–g3, where individual floating structures are connected in parallel to achieve large-scale power generation.[139–141] The strength of this design lies in its simplicity and ability to capture energy from a wide range of water wave amplitudes and frequencies, and with the abundant distribution of oceans on Earth, this form has enormous potential. However, its output performance may be affected by the wave speed and direction, which may be variable and unpredictable, so it also faces great challenges on the road of development.

3.3. Droplet Energy Harvesting

Droplet energy harvesting is an emerging field in energy research that focuses on capturing the energy generated from the motion or impact of liquid droplets, such as rain or condensation. The energy generated from droplets can be used for low-power applications, such as powering sensors, wearable devices, or small electronic devices. TENGs rely on the triboelectric effect, where a charge is generated due to the contact and separation of two different materials. In droplet-based TENGs, one of the materials is a liquid droplet, while the other is a solid/liquid surface. When droplets impact and separate from the solid/liquid surface, an electric charge is generated, which can be harvested as energy.[142–146]

As shown in **Figure 7**a, a single-electrode TENG with solid–liquid contact is composed of three layers: a PTFE film for contact electrification, a copper film for electrostatic induction, and a PMMA plate for support.[142] Due to its high-power generation capacity and stability, PTFE is chosen to contact with liquid droplets to generate charges. Its surface morphology (roughness of ≈20 nm) and water contact angle (115°) are favorable for the efficient contact electrification. Due to its surface chemical properties (rich in fluorine) and appropriate surface roughness, PTFE is a hydrophobic material. Therefore, the water droplet can easily slide off the tilted PTFE film. The figure also shows the morphological changes of the water droplet after impacting the polymer surface, which becomes conical at $t = 2$ ms, then becomes basin-shaped at 15 ms, rebounds at 34 ms, and starts to slide on the surface in a standing and sitting manner until it separates from its tip. As shown in Figure 7b, a liquid–liquid triboelectric nanogenerator structure is demonstrated, displaying the dynamic contact-separation process between a water droplet and

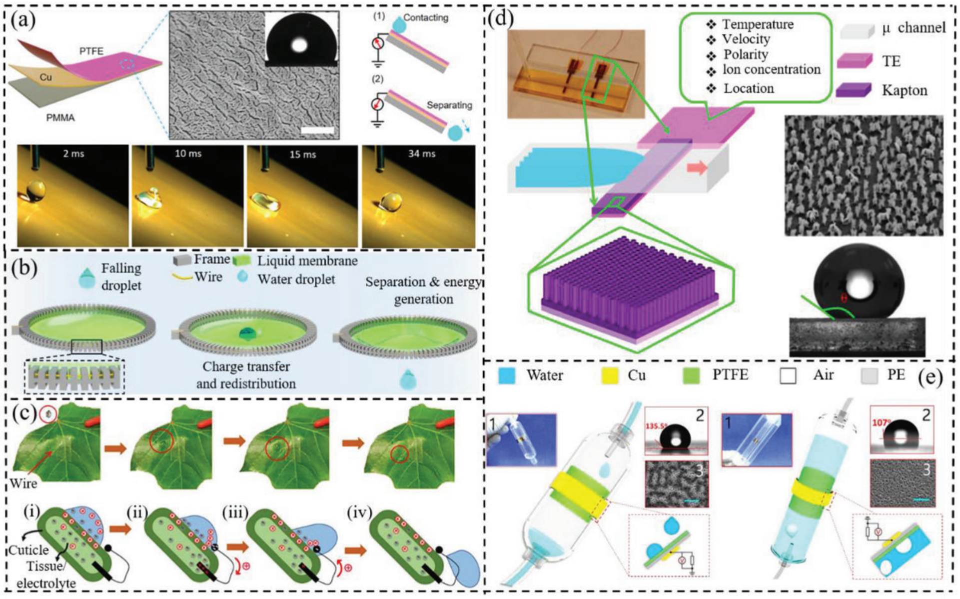

Figure 7. a) Droplet energy harvesting device: solid–liquid contact droplet energy harvesting. Adapted with permission.[142] Copyright 2020, American Chemical Society. b) Liquid-liquid contact. Reproduced under the term of CC-BY license.[144] Copyright 2019, The Authors, published by Springer Nature. c) Energy harvesting using leaves. Adapted with permission.[145] Copyright 2020, American Chemical Society. d) Droplet signal acquisition in microfluidic systems. Adapted with permission.[143] Copyright 2015, American Chemical Society. e) Droplet in medical treatment and bubble signal acquisition. Adapted with permission.[146] Copyright 2016, American Chemical Society.

a liquid film.[144] The surface tension of the liquid film is maintained by a circular frame, while the wire is integrated into the groove of the circular frame, allowing direct contact with the liquid film for charge extraction. The penetrability and self-healing ability of the liquid film enable repeatable contact-separation motion between the two liquid objects, and the conductive property of the liquid film enables direct connection to the external circuit. By relying on the permeability of the liquid film, mechanical energy can be harvested without blocking or capturing the moving droplets. Figure 7c shows the use of the cuticle layer of a leaf blade and internal conductive tissues as the frictional material and electrode, and the use of water droplets as the frictional material and electrode.[145] By using the water droplet to connect the originally disconnected components to a closed-loop electrical system, the energy from water droplet impact on plant leaves is successfully harvested. This research offers a strategy for utilizing the ubiquitous static charges in a nature-friendly way. In addition to harvesting energy from natural droplets, there are also microfluidic energy harvesting systems based on TENGs, as shown in Figure 7d, which use the contact electrification between droplets in microchannels or microdevices and the TENG surface.[143] In the medical field, for example during intravenous infusion, electrical signals can be generated when droplets or bubbles pass through TENG electrodes, as shown in Figure 7e.[146] These systems can be used for various applications, such as chip laboratory equipment, wearable electronic devices, and energy harvesting in enclosed spaces.

Droplet energy harvesting offers several advantages, including the ability to generate power from ambient sources, such as rain or condensation, and the potential for integration with other renewable energy systems, such as solar panels or wind turbines. However, the energy output of droplet-based systems is generally low, making them most suitable for low-power applications. Further research and development are needed to improve the efficiency and scalability of droplet energy harvesting technologies to enable more widespread adoption.

Through exploring TENG's applications in harvesting wind energy, water flow energy, wave energy, and droplet energy, **Table 1** additionally provides a summary of TENG's performance in collecting flow energy. TENG-based flow energy harvesting technology has the potential to play a significant role in energy harvesting and offer a sustainable and independent energy supply solution. However, additional research and development is still required to enhance efficiency, stability, and scalability, and to be applicable in a broader range of practical scenarios.

4. Flow Sensing Applications of TENG

TENGs can also be harnessed as self-powered flow sensors, effectively eliminating the reliance on external power sources or batteries. The distinct properties of TENGs, such as their capacity to produce electrical signals in response to mechanical stimuli, render them apt for an extensive range of flow sensing applications. In this section, we will explore some promising flow sensing applications, encompassing flow velocity and direction sensing, flow rate measurement, as well as water level and wave motion sensing. **Figure 8** shows the application concept diagram of the TENG-based sensing system. The buoy of the flag-shaped TENG can sense the wind speed and direction in real time, and provide accurate and timely marine meteorological signals. The seaweed-like TENG can sense changes in water currents, and synchronize information such as underwater ocean currents and fish migration to the information center. The offshore platform relies on TENG's perception of wave motion to compensate and

Table 1. Summary of achievements in fluid-based triboelectric energy harvesting.

Mode	Fluid	Materials	Structures	Output power	Start speed/Range	Reference
FT	Wind	Copper /FEP	Rotary	2.81 mW	3.3 m s^{-1}	[109]
FT	Wind	Copper /FEP	Rotary	0.47 mW	2.7 m s^{-1}	[111]
FT	Wind	Copper /Kapton	Rotary	438.9 mW kg^{-1}	3.5 m s^{-1}	[112]
V-CS	Wind	PANI /PTFE	VIV	96.79 mW m^{-2}	1.85 m s^{-1}	[113]
FT	Wind	Copper /PTFE	VIV	62.2 W m^{-2}	1.5 m s^{-1}	[115]
FT	Wind	Copper /PTFE	VIV	N/A	3.1 m s^{-1}	[116]
V-CS	Wind	Ni/Kapton	Flutter	135 mW kg^{-1}	3 m s^{-1}	[117]
FT	Wind	Resin /Nylon	Flutter	3.64 W m^{-3}	3 m s^{-1}	[118]
FT	Wind	Carbon /PTFE	Flutter	0.0408 mW cm^{-3}	3.6 m s^{-1}	[119]
FT	Wind	PVDF/Leaf	Others	N/A	2 m s^{-1}	[123]
V-CS	Wind	Al/PTFE	Others	4 mW	4.5 m s^{-1}	[127]
V-CS	Wind	Al/FEP	Others	1.6 W m^{-2}	25 m s^{-1}	[128]
FT	Water	Water/FEP	Integrated design	0.12 mW	0.5 m s^{-1}	[130]
FT	Wave	Conductive textile /Water	Integrated design	1.03 mW	12 cm (wave height)	[131]
V-CS	Water	Conductive ink/FEP	Flexible structures	10.56 µW	0.04–0.4 m s^{-1}	[132]
FT	Water	Conductive ink/PTFE	Flexible structures	52.3 µW (0.461 m s^{-1})	0.133 m s^{-1}	[133]
V-CS	Wave	Copper /FEP	Buoyant structures	0.425 J m^{-3}	1 m s^{-1}	[134]
V-CS	Wave	Water /PTFE	Buoyant structures	3.68 µJ m^{-2}	N/A	[135]
FT	Wave	Nylon /Kapton	Buoyant structures	10 mW	1.43 Hz	[136]
FT	Wave	Copper /FEP	Buoyant structures	8.69 W m^{-3}	1.5 Hz	[137]
SE	Droplet	Droplet /Kapton	Cavity-confined	0.25 nW	10 mL H^{-1}	[144]
SE	Droplet	Droplet /liquid membrane	Liquid membrane	137.4 nW	40 µL	[145]

control in real time to maintain stability. Real-time breathing signals of divers on the seabed are monitored to ensure their safety.

4.1. Flow Velocity and Direction Sensing

TENGs can be used to measure flow velocity and direction by capturing the mechanical energy from fluid flows and converting it into electrical signals, providing real-time measurements without the need for external power sources. Different TENG designs, such as flapping-based, cylinder-based, and turbine-based TENGs, can be employed for this purpose.[147–152]

Figure 9a1 demonstrates a multifunctional wind barrier integrated with multiple TENG units. Figure 9a2,a3 shows the composition of each unit, the TENG units consist of two copper electrodes and a FEP film, with both ends fixed on a 3D-printed channel.[147] Based on the optimized structure of each TENG unit, the wind barrier is composed of 66 TENG units connected in parallel. Each TENG unit of the wind barrier can serve as a self-powered anemometer to monitor the condition of the barrier. The study found that, at a wind speed of 10 m s^{-1}, the wind barrier can generate up to 440 µA and 26 mW of output current and power, respectively. Equally important, the TENG-based wind barrier can harvest slipstream energy caused by passing vehicles. More significantly, the wind-blocking efficiency of the TENG-based barrier is 35% higher than that of traditional porous barriers, substantially enhancing the safety of transportation.

Another approach to measure flow velocity involves the use of a rotating structure, as shown in Figure 9b1, which demonstrates a hybrid generator consisting of three TENG-EMG

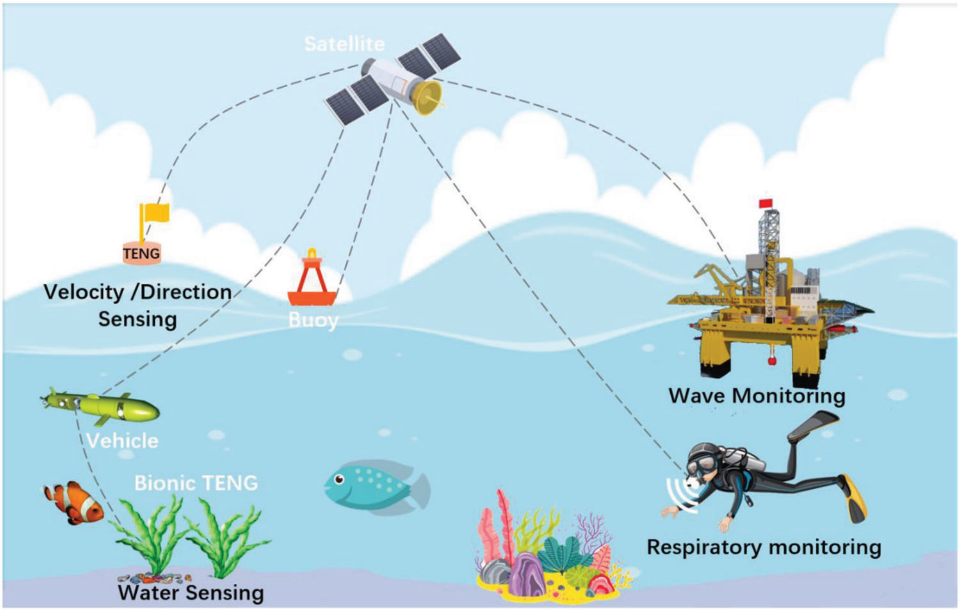

Figure 8. Application conception of TENG-based sensing system.

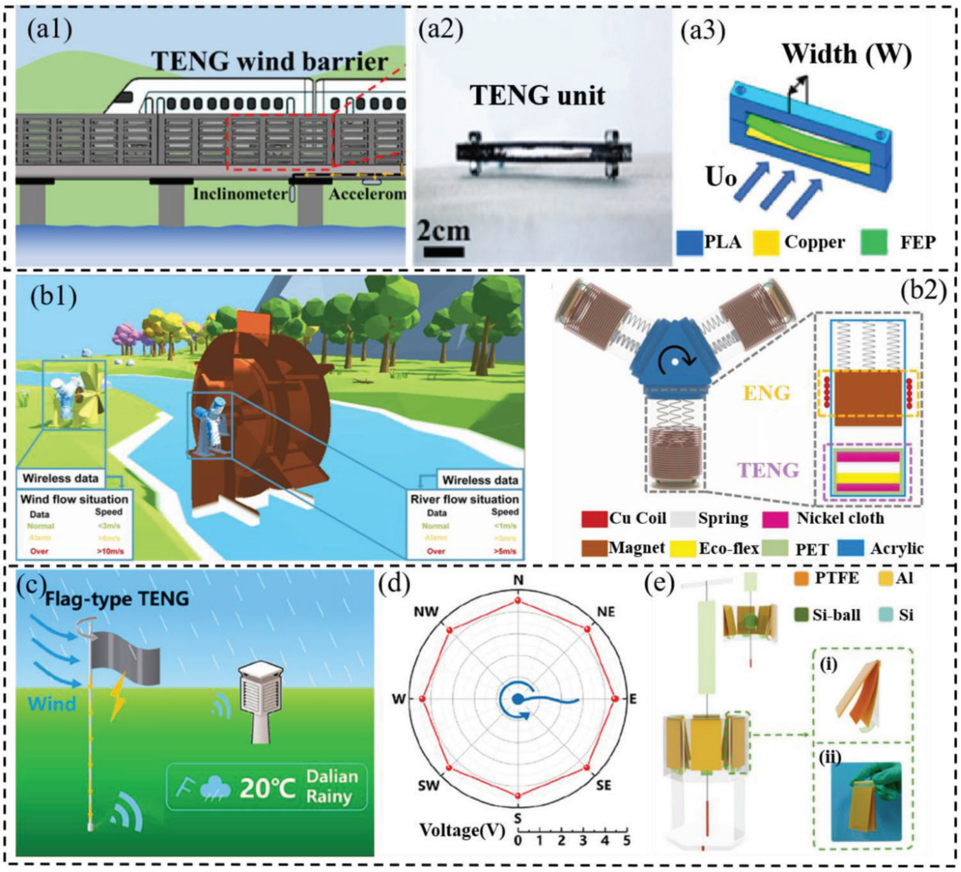

Figure 9. Flow rate and direction sensing device. a) Measurable wind speed multifunction windshield. Adapted with permission.[147] Copyright 2020, Elsevier. b) Piston-type rotary speed measuring device. Adapted with permission.[148] Copyright 2021, Elsevier. c) Banner-type wind speed and direction speed measuring device. Adapted with permission.[119] Copyright 2020, Elsevier. d) Schematic diagram of wind direction sensing. Adapted with permission.[119] Copyright 2020, Elsevier. e) Wind chime wind speed and wind direction sensing device. Adapted with permission.[127] Copyright 2019, Tsinghua University Press and Springer-Verlag GmbH Germany.

modules for rotation sensing. Due to the significant influence of environmental humidity on the output, the TENG requires an enclosed structure for packaging; thus, an acrylic tube is used to encase the spring and magnet slider (weight = 300 g) to create a single module. Virtual scenarios for water flow and wind monitoring are illustrated in Figure 9b2.[148] The gear-based structure can efficiently convert and collect the mechanical energy of water at low flow velocities while expanding the sensing range for wind velocity detection. The normal velocities of wind and water flow can satisfy the energy requirements for wireless transmission while monitoring real-time wind and water flow velocities. Therefore, the proposed TENG-EMG hybrid generator demonstrates enormous potential in environmental monitoring at unmanned weather stations, disaster early warning, and meteorological record-keeping.

As shown in Figure 9c, the flag-type TENG demonstrates constant output performance when the wind direction changes in any direction, indicating that wind energy can be efficiently harvested from any direction.[119] As the wind direction changes, the flag drives the flagpole to rotate, and through the design of the structure and circuit, wind direction sensing can be achieved. In Figure 9d, the flag-type TENG drives a switch connected to the base of the flagpole, and when the wind moves the flag to a certain direction, the corresponding LED can be illuminated.[119] Therefore, it can also be used to indicate real-time wind direction. As shown in Figure 9e, a fluttering effect-based triboelectric nanogenerator has been designed for harvesting low wind speed breeze energy from any direction.[127] The wind-driven part of the device is separated from the TENG unit. Due to the good linear relationship between wind speed and electric output signal, a high-sensitivity, fast-response real-time wind speed monitoring system based on LabVIEW software has been realized. At the same time, this structure can also achieve wind direction sensing like Figure 9d.

These self-powered flow sensors can be utilized in various applications, such as environmental monitoring, wind energy resource assessment, or fluid dynamics research. TENG-based flow velocity and direction sensors offer advantages such as high sensitivity, low-cost fabrication, and the ability to work in various flow conditions.

4.2. Flow Rate Measurement

TENG-based flow rate sensors can be employed to measure the flow rate of fluids in pipelines, channels, or other fluidic systems.[153–162] Various TENG designs, including flapping-based, cylinder-based, and turbine-based TENGs, can be used to capture the mechanical energy from fluid flows and convert it into electrical signals. The electrical output of the TENG can be correlated with the flow rate, providing accurate and real-time measurements.

Wang et al.[153] have developed a magnetic flip-type dual-function sensor (MFTDS) for detecting pneumatic flow and liquid level (**Figure 10**a). It consists of an outer magnetic flip, an inner magnetic float, and a conical cavity, and its working mechanism and output characteristics have been studied. The MFTDS can detect pneumatic flows ranging from 10 to 200 L min^{-1} with a flow resolution of 2 L min^{-1}. Compared with commercial flow switches, the results obtained from MFTDS are satisfactory. Fan et al. have proposed and developed a self-powered and low-pressure drop gas flow meter based on a membrane oscillation-driven frictional TENG, named "TENG flow meter" (shown in Figure 10b).[154] The flow meter consists of a circular pipe with a non-conductive thin film placed at the mid-plane of the pipe, and two copper electrodes fixed at symmetrical positions. When the gas flows through the pipe at a sufficiently high velocity, the thin film will continuously oscillate between the two electrodes, generating a periodic voltage fluctuation that can be easily measured. The experimental results show that the oscillation frequency is linearly related to the mean flow velocity in the pipe, with higher sensitivity and self-powering capability at lower pressure drops for measuring flow rates.

Figure 10c,d shows the rotation of the blades caused by the fluid passing through the pipe radially and axially, respectively.[155,156] The rotation of the blades drives the movement of the friction layer, and ultimately the flow is sensed based on the measured electrical signal. As shown in Figure 10e, in order to convert the flow velocity into vibratory oscillations, a square obstacle-beam structure is designed, where the square obstacle is a beam made of spring steel fixed on the base.[157] The TENG consists of a moving FEP film and fixed interconnect electrodes at the bottom of the obstacle. The vibratory oscillations of the obstacles drive the FEP film across the interconnecting electrodes based on triboelectrification, generating an electrical signal. The pre-compression of the FEP film can be adjusted by installing the position of the electrode plate. When the fluid flows through the obstacle, similar to the principle in Figure 5b, the obstacle will vibrate and drive the TENG to output electrical signals to realize flow sensing.

TENG-based flow rate sensors can be applied in various industrial and environmental applications, such as water distribution systems, wastewater treatment plants, and irrigation systems. These self-powered flow sensors offer benefits such as high accuracy, low maintenance, and the ability to work in a wide range of fluid flow conditions.

4.3. Respiratory Monitoring

Although breathing also involves the flow of fluid, it is often neglected due to the relatively weak airflow. However, as a natural energy source carried by the human body at any time, it should attract more attention. Respiratory airflow energy harvesting involves capturing energy from the airflow generated during breathing. TENGs have been demonstrated to harvest energy from respiratory airflow, which can be used to power wearable or implantable medical devices, such as biosensors, drug delivery systems, or pacemakers, without the need for batteries.[163–175] TENG-based respiratory airflow energy harvesting systems can be designed using various TENG configurations, such as flapping-based or cylinder-based TENGs, and can be integrated into masks, tracheal tubes, or other respiratory devices. These systems offer advantages such as high energy conversion efficiency, biocompatibility, and the ability to work in various breathing conditions.

Figure 11a shows an air-driven TENG for real-time respiratory monitoring signal by converting mechanical energy

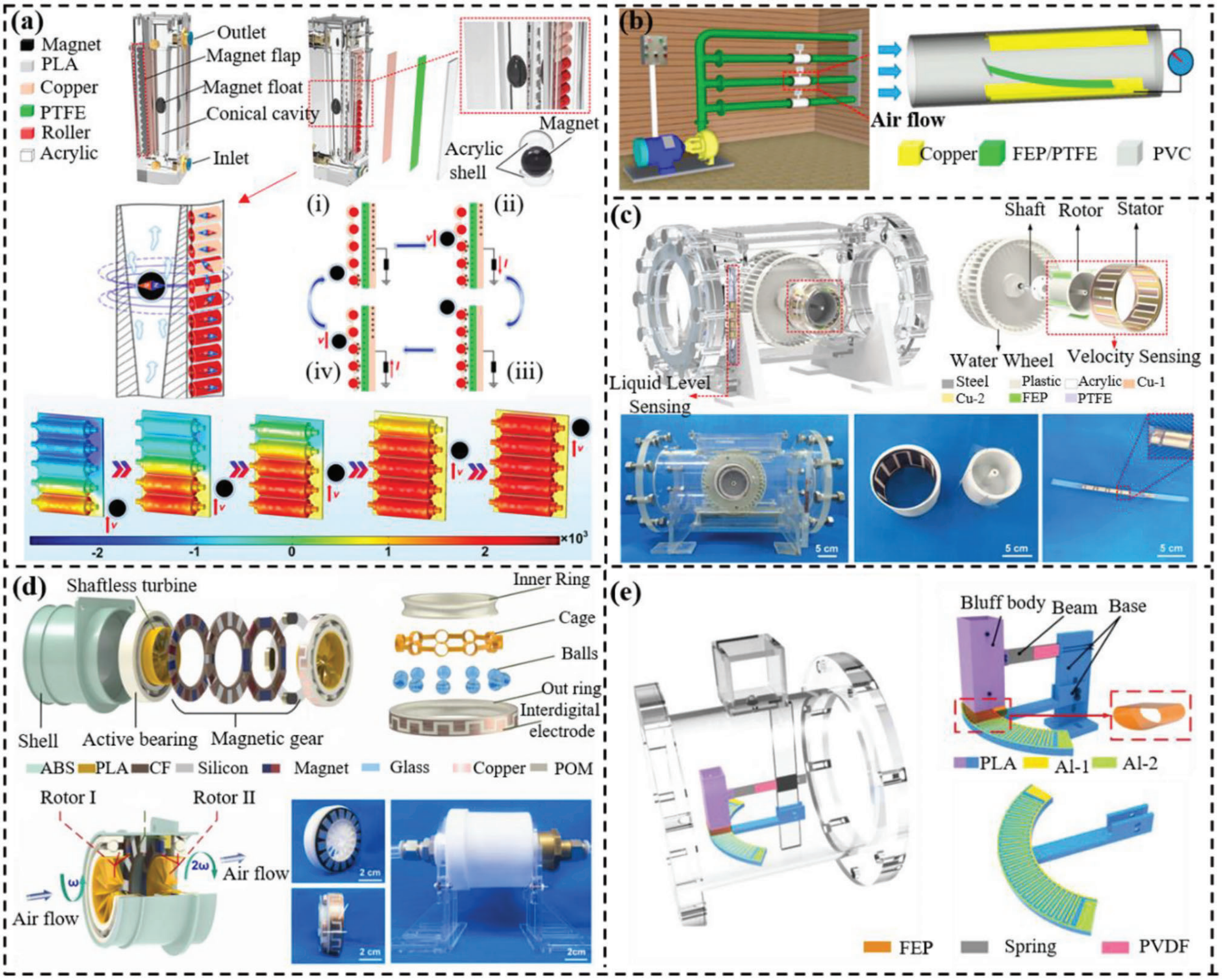

Figure 10. Flow measurement TENG device. a) Magnetic flip-type dual-function sensor for detecting pneumatic flow and liquid level. Adapted with permission.[153] Copyright 2020, American Chemical Society. b) Self-powered low pressure drops gas flowmeter driven by membrane oscillation. Reproduced under the term of CC-BY license.[154] Copyright 2020, The Authors, published by MDPI. c) Fluidic flow monitoring of a non-full pipe. Adapted with permission.[155] Copyright 2022, American Chemical Society. d) Shaftless turbo intake flow sensor. Adapted with permission.[156] Copyright 2023, Elsevier. e) Square obstacle-beam flow sensor. Adapted with permission.[157] Copyright 2023, Wiley-VCH GmbH.

from human respiration into electrical output for self-powered operation.[171] The TENG operates based on the fluttering of a flexible nanostructure-driven film by the airflow. This TENG can generate real-time electrical signals when exposed to airflow from different respiratory behaviors. It was also found that the cumulative transferred charge corresponds well to the total amount of air exchanged during the respiratory process. Figure 11b,c has the same principle as Figure 11a, but the film is placed vertically to make it easier to flutter due to gravity.[163,167] Figure 11d drives the contact and separation of both sides of the TENG through the periodic expansion pressure of an elastic balloon caused by human respiration, outputting the respiratory process as an electrical signal for real-time monitoring.[164] Based on the above TENG devices, an intelligent wireless respiratory monitoring and alarm system was further developed. The system analyzes the TENG signal in real time, and directly triggers a wireless alarm or phone call when the signal is abnormal, and responds quickly to changes in breathing behavior. These studies provide a promising solution for developing self-powered real-time respiratory monitoring devices.

4.4. Water Level and Wave Motion Sensing

TENGs, which can convert mechanical energy into electrical signals with the advantages of small size, light weight, and high sensitivity, have potential for water level and wave motion sensing. By designing TENG-based devices that respond to changes in water levels or wave motion, valuable information can be gathered for various applications such as environmental monitoring, coastal engineering, and marine navigation.[176–186] Here are some possible ways TENGs can be employed for water level and wave motion sensing:

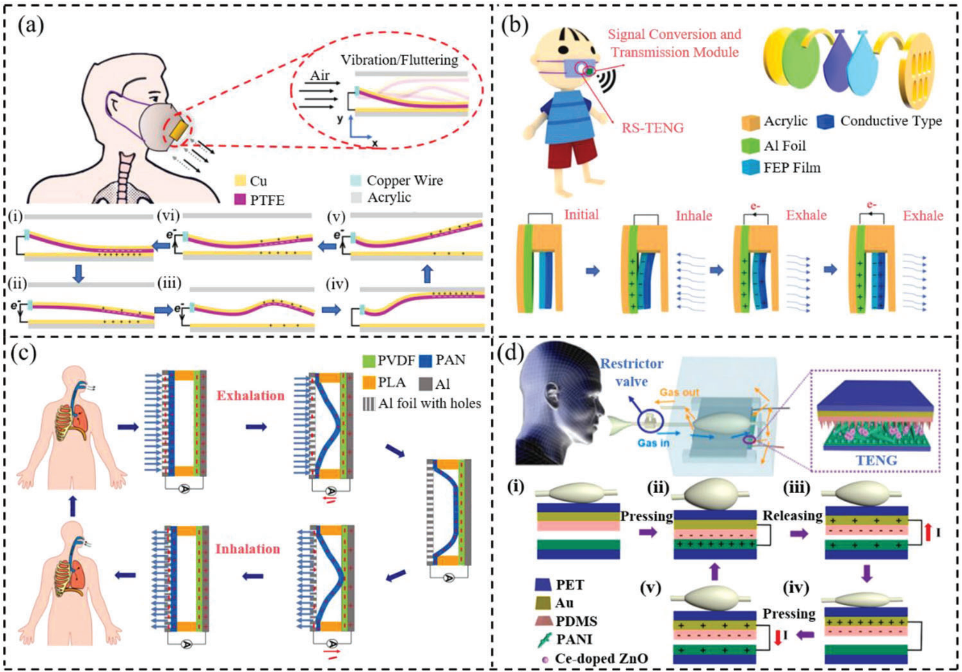

Figure 11. Respiratory monitoring TENG device. a) Flags placed along the direction of respiration to indicate respiration monitoring. Adapted with permission.[171] Copyright 2020, Wiley-VCH GmbH. b) One end is fixed and placed vertically to indicate the respiratory monitoring of the flag. Adapted with permission.[167] Copyright 2021, Elsevier. c) Both ends are fixed and placed vertically to indicate the respiratory monitoring of the flag. Adapted with permission.[163] Copyright 2021, Elsevier. d) Bag-type respiratory monitoring. Adapted with permission.[164] Copyright 2019, Elsevier.

Wave motion sensing: TENG-based wave sensors can be designed to capture the energy generated by ocean wave movement. Using flexible or floating components that respond to wave motion, the mechanical energy from waves can be converted into electrical signals by the TENG device. These signals can then be utilized to determine wave characteristics like wave height, frequency, and direction. **Figure 12**a illustrates a highly sensitive wave sensor based on a liquid–solid interface triboelectric nanogenerator. The sensor comprises copper electrodes and polytetrafluoroethylene film. With wave movement, the output voltage has a linear relationship with wave height.[176] The sensitivity is 23.5 mV mm^{-1}, and the wave height can be detected in the millimeter range. Figure 12b showcases a practical biomimetic jellyfish-inspired TENG using a polymer film as the frictional material.[183] The device features a shape-adaptive, sealable packaging, and a unique elastic rebound structure resembling a jellyfish's behavior. The charge separation in the elastic recovery of this biomimetic structure is based on the contact and separation of friction layers caused by liquid pressure. This design offers high sensitivity, portability, and continuous detection of water level and wave motion. Moreover, as shown in Figure 12c, Zhang et al.[177] proposed a tubular TENG combined with a hollow sphere buoy, which adapts to wave measurements on the ocean surface in any direction while eliminating the influence of seawater on the sensor's performance. Based on TENGs' high sensitivity advantage, ultrahigh sensitivity of 2530 mV mm^{-1} (100 times higher than previous work) and a minimum monitoring error of 0.1% were achieved for monitoring wave height and wave period, respectively. The system can also monitor and sense six basic wave parameters (wave height, wave period, wave frequency, wave velocity, wavelength, and wave slope), wave velocity spectra, and mechanical energy spectra. Figure 12d displays a gradient energy harvesting triboelectric nanogenerator (GEH-TENG) with a dual power generation unit, operating in different transmission states to adapt to wave changes.[182] In small wave environments, the GEH-TENG is always in the primary transmission state, where the initial torque is small, making activation easy. In large wave environments, the two generators work together to improve output performance. Experiments have shown that when the input frequency is 1.0 Hz and the amplitude is 120 mm, the GEH-TENG can generate 0.7 mJ of energy in one working cycle, which is 2.3 times higher than without the gradient structure.

Water level sensing: A TENG-based sensor can detect changes in water levels by incorporating floating components or materials sensitive to water contact. As the water level changes, the TENG device experiences varying degrees of contact or separation between its triboelectric materials, resulting in a change in the generated electrical signal. This signal can be analyzed to determine the water level. Figure 12e demonstrates a water level sensor that can measure ship draft.[178] The sensor consists of multiple copper electrodes uniformly distributed along a PTFE tube. When water flows into the PTFE tube, it causes alternating electron flow between the main electrode and the bottom electrodes distributed along the tube. The distinct peaks in the derivative of open-circuit voltage over time correspond to the electrode distribution. Because the number of clear peaks in the derivative of open-circuit voltage is directly related to the water level, it can be used as a robust and sensitive indicator for water level detection.

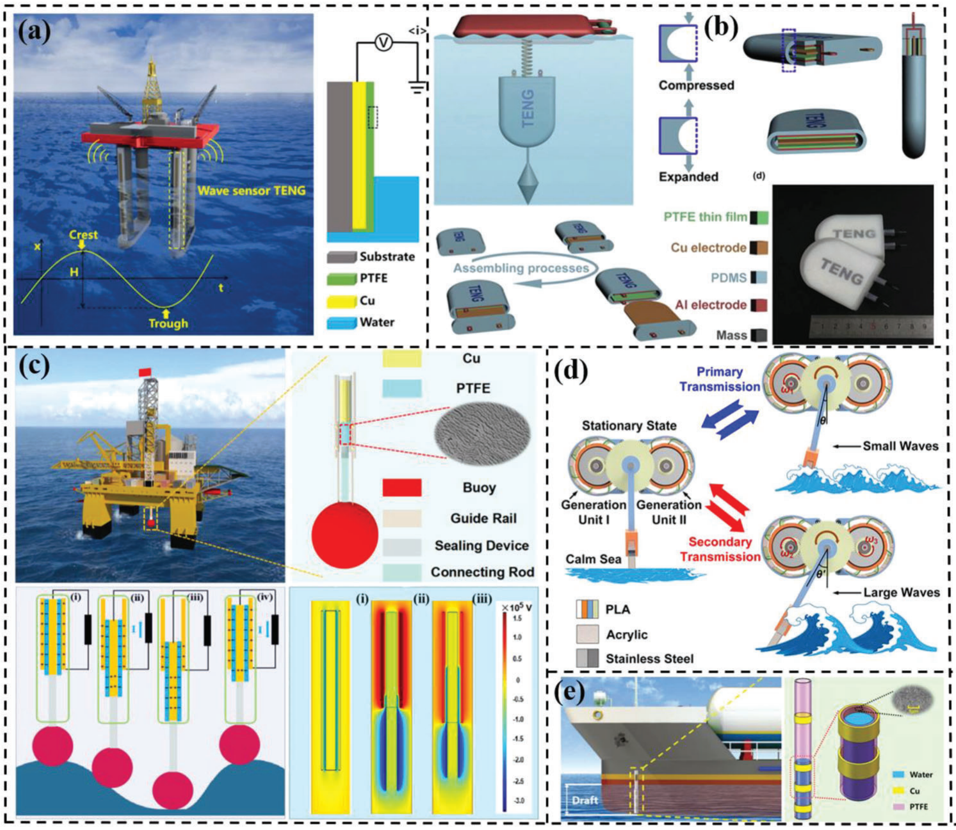

Figure 12. Water level and wave motion monitoring TENG device. a) A highly sensitive sensor for monitoring waves around marine equipment. Adapted with permission.[176] Copyright 2018, Elsevier. b) A practical bionic jellyfish TENG. Adapted with permission.[183] Copyright 2017, Elsevier. c) The TENG combined with a hollow spherical buoy. Adapted with permission.[177] Copyright 2020, American Chemical Society. d) Gradient energy harvesting and sensing triboelectric nanogenerators with dual generator sets Adapted with permission.[182] Copyright 2021, American Chemical Society. e) Tubular ship water level sensor. Adapted with permission.[178] Copyright 2019, Wiley-VCH GmbH.

Possible applications for TENG-based water level and wave motion sensors include: 1) Flood monitoring and early warning systems: TENG-based water level sensors can provide real-time data on water levels in rivers, lakes, or coastal areas, enabling the development of early warning systems for floods and other natural disasters. 2) Coastal engineering and infrastructure monitoring: Wave motion sensors can help assess the impact of waves on coastal structures, such as seawalls, piers, and breakwaters, allowing for better design and maintenance of these structures. 3) Marine navigation and safety: TENG-based wave sensors can provide valuable information on wave conditions, assisting in the safe navigation of ships and other marine vessels. 4) Renewable energy: Wave motion sensors can be used in the development and optimization of wave energy conversion systems, helping to improve the efficiency of these renewable energy technologies. Despite their potential, TENG-based water level and wave motion sensors are still in the early stages of research and development. Further advancements in materials, device design, and signal processing are needed to enhance the sensitivity, reliability, and durability of these sensors for practical applications.

In summary, TENGs have the potential to be employed in various flow sensing applications due to their ability to convert mechanical energy into electrical signals, their self-powered nature, and their adaptability to different environments. **Table 2** summarizes the characteristics of common sensors. However, further research and development are needed to improve the sensitivity, durability, and overall performance of TENG-based flow sensors to enable widespread adoption in practical applications.

5. Challenges and Future Perspectives

TENG-based flow energy harvesting and sensing technologies have shown great potential and attracted significant attention in recent years. However, there are still several challenges that need to be addressed and opportunities for further development. As shown in **Figure 13**, next we discuss the main challenges in the field of TENG-based flow energy harvesting and sensing and how to address them in future work.

5.1. Efficiency and Output Stability

One of the main challenges in TENG-based flow energy harvesting and sensing is improving the efficiency and output stability of the devices. Efficiency and output stability are critical aspects that must be considered in the development of TENG-based flow energy harvesting and sensing technologies. One of the primary

Table 2. Summary of achievements in fluid-based triboelectric sensing.

Working mode	Type	Materials	Structure	Measuring range/Sensitivity	Reference
FT	Speed and direction	Copper/FEP	Rotary	2.7–8.0 m s^{-1}	[111]
FT	Speed and direction	Carbon/PTFE	Flutter	3.6–5.2 m s^{-1}	[119]
FT	Speed	Copper/FEP	Flutter	3–42 m s^{-1}	[147]
V-CS	Speed	Nickel/Eco-flex	Rotary	3–10 m s^{-1}	[148]
V-CS	Speed and direction	Al/PTFE	Flutter	1.5–10 m s^{-1}	[151]
SE	Flow rate	Copper/PTFE	Rotary	10–200 L min^{-1}	[153]
FT	Flow rate	Copper/PTFE	Flutter	5–30 m^3 h^{-1}	[154]
FT	Flow rate	Copper/FEP	Rotary	94–264 L min^{-1}	[155]
FT	Flow rate	Glass/POM	Rotary	300–900 L min^{-1}	[156]
V-CS	Respiratory monitoring	PANI/PNMS	Contact separation	2–6 L min^{-1}	[164]
V-CS	Respiratory monitoring	UHMWPE/ Cotton	Contact separation	N/A	[170]
V-CS	Respiratory monitoring	Copper/FEP	Flutter	5–18 m s^{-1}	[175]
FT	Water level	Water/PTFE	Liquid–solid	10 mm	[178]
FT	Water level	PA66/FEP	Contact separation	4.63 kHz cm^{-1}	[185]
SE	Wave monitoring	Water/PTFE	Liquid–solid	23.5 mV mm^{-1}	[176]
CS	Wave monitoring	Copper/PTFE	Slide	2530 mV mm^{-1}	[177]

challenges in optimizing the efficiency and stability of TENG devices is material selection. The materials used in TENGs can significantly influence their performance, including their output power, output stability, and sensitivity. Researchers are actively exploring various materials to improve the performance of TENG devices, such as carbon-based materials, metal oxides, and polymers. Another factor that can influence the efficiency and output stability of TENGs is surface modification. The surface properties of the TENGs, such as their roughness, surface energy, and hydrophobicity, can affect their interaction with the flow and their ability to generate electrical power. Researchers are exploring different surface modification techniques, such as surface patterning, surface coating, and surface functionalization, to optimize the performance of TENGs. Device design is another critical aspect that influences the efficiency and output stability of TENGs. The design of TENG devices should consider various factors, such as the flow profile, the size and shape of the device, and the electrode configuration. Researchers are exploring different

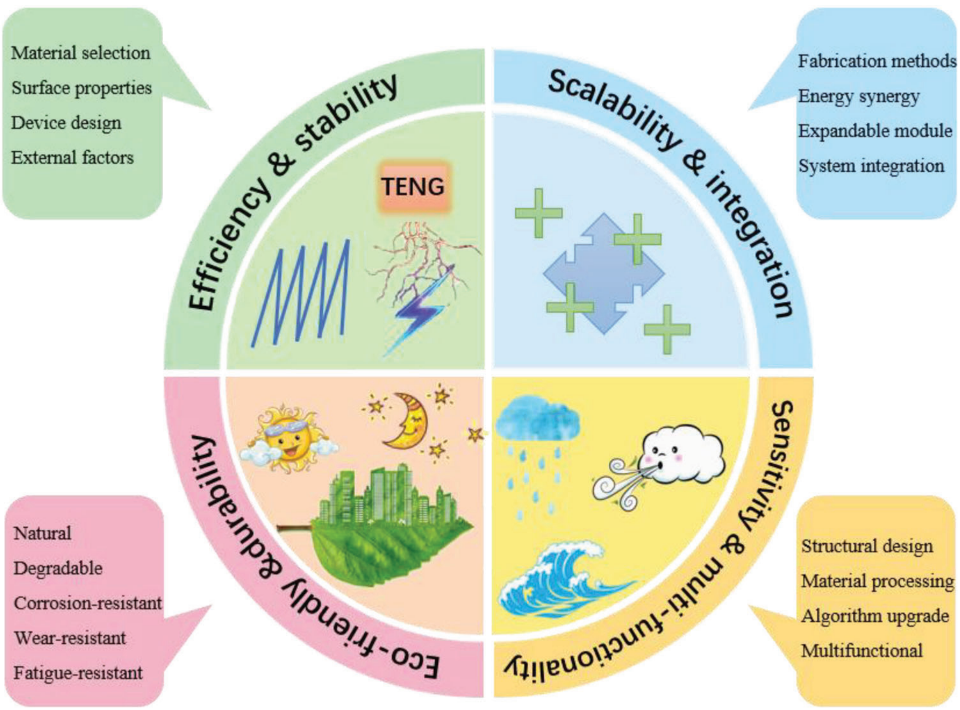

Figure 13. Challenges and future perspectives.

device designs, such as triboelectric nanogenerators, electret-based nanogenerators, and hybrid nanogenerators, to optimize the performance of TENG devices. External factors such as flow conditions can also significantly influence the performance of TENGs. Flow conditions, such as flow velocity, flow direction, and flow turbulence, can affect the interaction between the flow and the TENG device, resulting in variations in the output power and output stability of the TENGs. Researchers are exploring various strategies, such as optimizing the flow path, incorporating flow guides, and controlling the flow rate, to improve the stability and efficiency of TENGs under different flow conditions. In conclusion, improving the efficiency and output stability of TENGs is a critical challenge that must be addressed to enable their widespread adoption in energy harvesting and sensing applications. Future research should focus on optimizing the materials, surface modification, device design, and external factors to enhance the efficiency and stability of TENG devices. By addressing these challenges, TENG-based flow energy harvesting and sensing devices can become a more competitive and viable option for self-powered sensing applications and renewable energy generation.

5.2. Scalability and Integration

To achieve widespread adoption, it is essential that TENG-based flow energy harvesting and sensing technologies be scalable and integrable with existing infrastructure and systems. Scalability refers to the ability of a technology to be mass-produced in a cost-effective manner, which is important for its commercialization. One way to achieve scalability is by developing fabrication methods that can produce large quantities of TENG devices in a reliable and efficient way. This will not only lower the production costs but also ensure the consistency and quality of the devices. Integration is another crucial aspect that needs to be considered. TENG devices can be integrated with existing infrastructure and systems to harness the flow energy and convert it into electrical energy, which can be used for various applications. For example, TENGs can be integrated with water distribution networks to generate electricity from the flowing water. Similarly, wind turbines can be equipped with TENGs to harvest the energy from the wind flow. This integration can lead to the development of self-powered systems that do not require an external power source. Moreover, the integration of TENGs with other energy harvesting technologies, such as solar panels or piezoelectric devices, can create hybrid energy harvesting systems with improved performance and reliability. The combination of different energy harvesting technologies can ensure a continuous power supply, even in fluctuating flow conditions. Hybrid energy harvesting systems can also offer greater energy efficiency, reduce system downtime, and provide a more reliable and stable power output. In summary, the scalability and integration of TENG-based flow energy harvesting and sensing technologies are critical for their commercialization and widespread adoption. Developing scalable fabrication methods and integrating TENG devices with existing infrastructure and systems, as well as exploring the integration of TENGs with other energy harvesting technologies, will accelerate their development and contribute to the advancement of sustainable energy generation.

5.3. Environmental Impact and Durability

When deploying TENG-based flow energy harvesting and sensing devices on a large scale, attention should also be paid to possible environmental impacts. Therefore, it is crucial to develop environmentally friendly materials and fabrication processes for TENGs to minimize their impact on the environment. For instance, using natural or biodegradable materials for the construction of TENG devices can significantly reduce their environmental footprint. Researchers can also explore using recycled materials in the production of TENGs to minimize waste and reduce the carbon footprint of the devices. Another important consideration is the durability of TENG-based flow energy harvesting and sensing devices. The devices are often exposed to harsh environmental conditions, including extreme temperatures, humidity, and corrosive environments, which can affect their performance and lifespan. Therefore, it is necessary to develop materials and fabrication processes that can withstand these conditions and ensure the long-term durability of TENG devices. One approach to improving the durability of TENGs is to improve their corrosion resistance. Corrosion can significantly reduce the lifespan of TENG devices, especially when they are exposed to saltwater environments. Researchers can explore various surface modification techniques to enhance the corrosion resistance of TENGs, such as using anti-corrosion coatings or depositing a layer of protective material on the surface of the device. Wear resistance is also an important factor in the durability of TENGs, especially for devices that are exposed to high flow rates or are subject to frequent use. Wear can result in the degradation of device performance, leading to a reduction in energy output or sensing accuracy. Therefore, researchers can explore various approaches to improving the wear resistance of TENG devices, such as incorporating wear-resistant materials or using surface treatments that can enhance the device's resistance to wear. Finally, fatigue life is another critical factor in the durability of TENG-based flow energy harvesting and sensing devices. The devices may experience repeated stress cycles during operation, which can result in mechanical failure or a reduction in device performance. Researchers can explore various techniques to improve the fatigue life of TENGs, such as designing the device with materials that have a high fatigue limit or incorporating damping materials that can absorb mechanical shock and reduce the risk of fatigue failure. In conclusion, addressing the environmental impact and durability of TENG-based flow energy harvesting and sensing devices is essential for their successful deployment in large-scale renewable energy generation and self-powered sensing applications. Researchers can focus on developing environmentally friendly materials and fabrication processes, improving the corrosion resistance, wear resistance, and fatigue life of TENG devices, to ensure their long-term performance and reduce their environmental footprint.

5.4. Sensitivity and Multifunctionality

Improving the sensitivity and multifunctionality of TENG-based flow sensors is another important aspect for their future development. Improving the sensitivity of TENG-based flow sensors requires optimizing the device design, material selection, and fabrication techniques. For example, increasing the number of

TENG layers or modifying the surface properties of the device can enhance the sensitivity of the TENG sensor. In addition, utilizing advanced signal processing techniques, such as machine learning algorithms, can further improve the accuracy and reliability of TENG-based flow sensing. Enhancing the sensitivity of TENG sensors can enable more accurate and reliable measurements in various flow sensing applications, such as flow velocity, direction, rate, and pressure sensing. Moreover, developing multifunctional TENG sensors that can simultaneously measure multiple flow parameters can provide more comprehensive information for monitoring and controlling fluid systems in industrial, environmental, and biomedical applications. In conclusion, TENG-based flow energy harvesting and sensing technologies have shown great promise in various applications, but there are still challenges that need to be addressed and opportunities for further development. By overcoming these challenges and exploring new opportunities, TENG-based flow energy harvesting and sensing devices can make a substantial contribution to the advancement of sustainable energy generation and self-powered sensing technologies. This contribution helps meet the escalating global demand for clean and reliable energy sources, as well as efficient monitoring and control of fluid systems.

6. Conclusion

TENG-based flow energy harvesting and sensing technologies have shown great potential in a wide range of applications, from renewable energy generation to environmental monitoring and wearable electronics. This comprehensive review has highlighted the fundamental concepts, working principles, and various applications of TENG-based systems in the context of flow energy harvesting and sensing. In addition, the challenges and future perspectives for TENG research have been discussed, providing insights into the ongoing efforts to improve efficiency, stability, scalability, integration, environmental impact, durability, sensitivity, and multifunctionality. As TENG technology continues to advance, it is expected that its adoption will expand across various industries and applications, contributing to the global shift toward sustainable and green energy sources. Further research and development in materials, design optimization, fabrication techniques, and integration strategies will be crucial in unlocking the full potential of TENG-based systems, ultimately leading to more efficient, versatile, and robust energy harvesting and sensing solutions. It is noteworthy that while the article categorizes energy harvesting and sensing into two parts for review, the relationship between TENG energy harvesting and sensing is closely related. Advances in TENG energy harvesting technology directly contribute to the enhancement of TENG sensor performance. For instance, enhancements in TENG design and material selection can increase energy generation, enabling TENG sensors to be applied to sensing tasks with higher power consumption or extending the operating time of sensing systems. Conversely, the development of TENG sensors can positively impact energy harvesting applications. Through the integration of sensing capabilities into TENG devices, the overall efficiency and practicality of TENG-based energy harvesting systems can be improved. Moreover, it is worth discussing future directions and research opportunities to explore the synergistic relationship between TENG energy harvesting and sensing. This can include exploring new materials, designs, or integration strategies that optimize both energy generation and sensing performance simultaneously.

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Conflict of Interest

The authors declare no conflict of interest.

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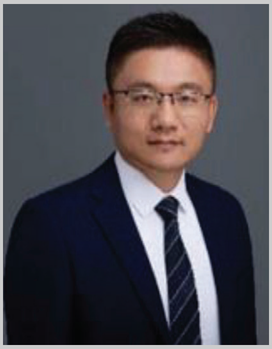

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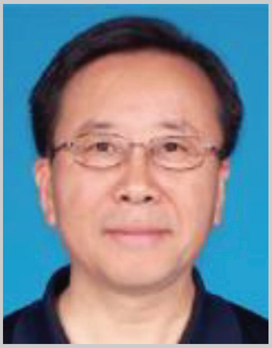

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