

Review

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Recent advances in ocean wave energy harvesting by triboelectric nanogenerator: An overview

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Abstract: A sustainable power source is more and more important in modern society. Ocean wave energy is a very promising renewable energy source, and it is widely distributed worldwide. But, it is difficult to develop efficiently due to various limitations of the traditional electromagnetic generator. In recent years, the newly developed triboelectric nanogenerator (TENG) provides an excellent way to convert water wave energy into electrical energy, which is mainly based on the coupling between triboelectrification and electrostatic induction. In this paper, a review is given for recent advances in using the TENG technology harvesting water wave energy. We first introduce the four most fundamental modes of TENG, based on which a range of wave energy harvesting devices have been demonstrated. Then, these applications' structure and performance optimizations are discussed. Besides, the connection methods between TENG units are also summarized. Finally, it also outlines the development prospects and challenges of technology.

Keywords: energy harvesting, renewable energies, ocean wave energy, triboelectric nanogenerators, TENG networks

1 Introduction

As we all know, it has been proven that energy is the main driving force for the development of the global

economy and also is one of the main causes of disputes between nations. Nowadays, the world's energy is still dominated by conventional fossil energy sources such as oil, coal, and natural gas, accounting for approximately 80% of global energy demand [1]. However, due to increasing energy demand and rising energy prices, the energy crisis will be the number one problem in the world. Ocean energy can be an important way to solve this problem. And the ocean covers 71% of the earth's surface, so ocean energy is extremely rich. It is estimated that global total ocean energy exceeds 75 TW (1 TW = 10^{12} W) [2]. Ocean energy can be classified into the following five forms, i.e., tidal energy, ocean current energy, water wave energy, temperature gradient energy, and salinity gradient energy [3]. Wave energy is an important part of ocean energy, which is not affected by seasons and weather, and it is inexhaustible [4]. And it is estimated that the wave energy around the coastline of the world is about 2–3 TW [3–5]. It will be of great help to solve the energy crisis and environmental protection if ocean wave energy can be fully utilized.

The development of wave energy began in 1799 [6]. However, it was extensively studied and started in 1974 [7]. Wave energy harvesting technology rapidly developed in the late 20th century [8], which especially in countries such as Ireland [9], Denmark [10,11], Portugal, UK, and USA [12]. Nowadays, according to the working principle of these technologies, it can usually be classified into oscillating water columns [13], oscillating wave surge converters [14], point absorbers [15], overtopping systems [16], and bottom-hinged systems [17]. Since these wave energy converters (WECs) often use electromagnetic generators (EMGs), their high cost, high weight, and low efficiency cannot meet large-scale commercial demand [18,19], ocean wave energy has not been widely used. Therefore, need some new methods to achieve cost-effective and high-efficiency wave energy harvesting.

Nanotechnology has a wide range of applications, such as oil and gas industry [20] and medical treatment [21]. Professor Wang's team proposed an innovative

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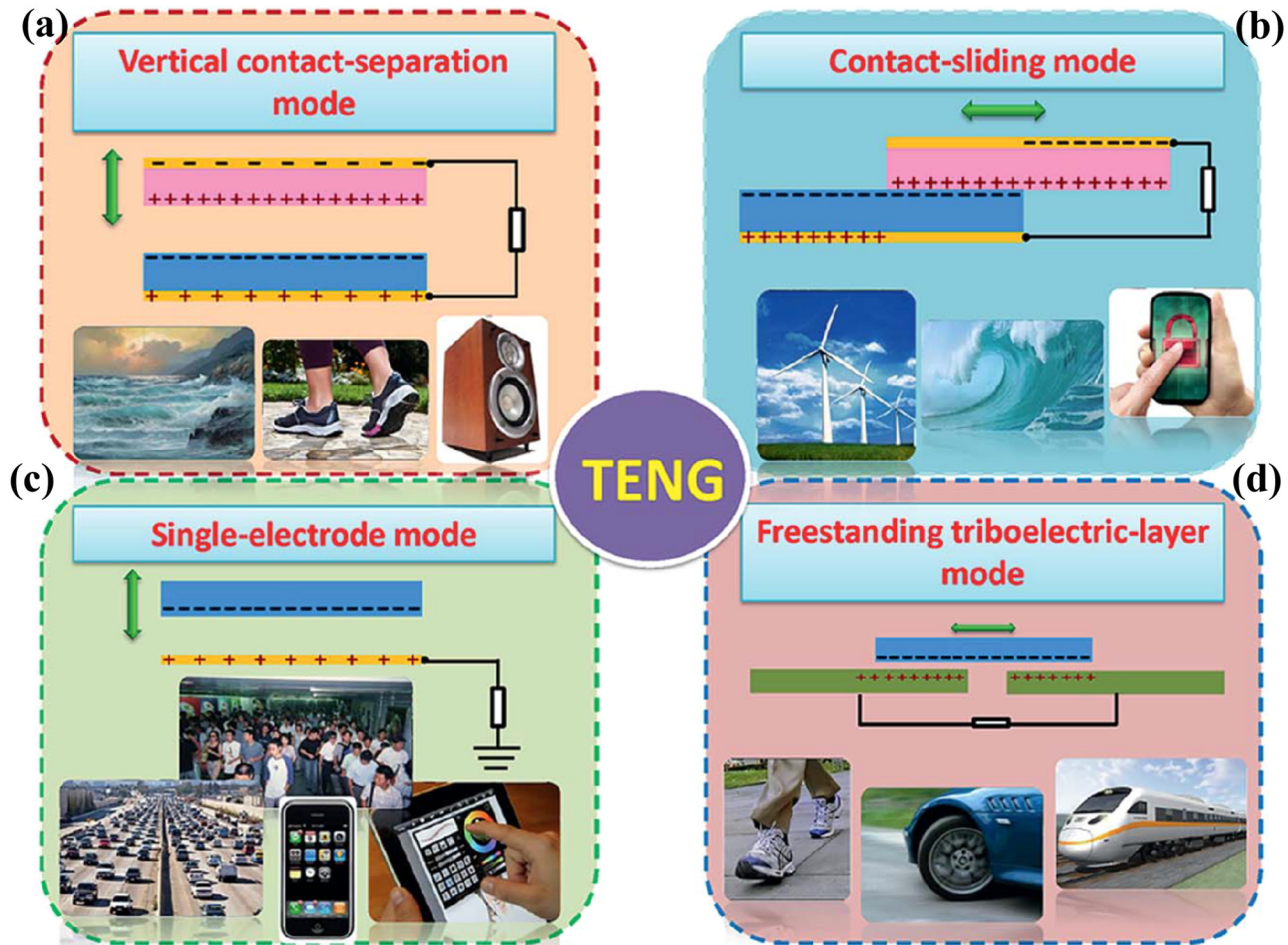


Figure 1: The fundamental modes of TENGs: (a) vertical contact-separation mode, (b) contact-sliding mode, (c) single-electrode mode, and (d) freestanding triboelectric-layer mode [43].

method of energy harvesting in 2012, named TENG [22], which is based on the coupling of triboelectrification and electrostatic induction [23]. In 2014, TENG was first used to harvest wave energy [24]. Compared with EMG, TENG has obvious merits, such as higher power density (as high as $3,200 \text{ W m}^{-2}$), lighter weight (tens of hundreds of grams), higher efficiency (up to 70%), and lower manufacturing costs [25,26]. Therefore, researchers have developed various TENGs with different structures and functions [27], which greatly expands the way of energy harvestings such as human movement [28–30], water flow [31], rotation [32,33], and wind [34,35]. In the past 8 years, with the efforts of more than 40 research groups around the world, such as Wang's team [36] and Zhang's team et al. [37] the output performance of TENG has been greatly improved, the area power density of a single TENG unit can reach $3,200 \text{ W/m}^2$ [38], and instantaneous energy conversion efficiency can be up to 70%, which can meet the needs of many small power

devices [39] and can charge some supercapacitors [40]. In ocean wave energy harvesting, traditional generators are so heavy that they have to float by buoys, while TENG can float easily because of the light weight [41]. The efficiency of traditional WEC is low, only about 30%, but TENG can reach 70%. Because TENG has these advantages when harvesting low-frequency energy [42], TENG has been used to harvest wave energy since 2014 and has got great progress in wave energy harvesting.

This article gives a review of the current development and application of TENG as a wave energy harvesting device. The review is about materials and structural design used in TENG as a wave energy harvesting device. According to the output performance of different TENGs, the structural design and material selection are evaluated. The basic working modes of TENG are introduced in Section 2. Then, the output performance of different structures of TENG in wave energy harvesting is introduced in Section 3.

2 The four working modes of TENGs

Four operation modes of TENGs have been established (Figure 1): the vertical contact-separation mode, the contact-sliding mode or lateral-sliding mode, the single-electrode mode, and the freestanding triboelectric-layer mode [43].

2.1 Vertical contact-separation mode

The vertical contact-separation mode is the first invented operation mode in TENGs. As shown in Figure 1a, two dissimilar dielectric films of different materials are placed face to face, with metal electrodes embedded in the film. Initially, there was a distance between the two films, when the external force makes the two films contact, due to the friction effect, opposite charges are formed on the surfaces of the two films. As the external force decreases or disappears, the two films separate, and an air gap is formed between the two films to form a potential difference, and the surface charge of the film is transferred through the metal electrode to form a current. When the gap between the two films decreases due to external force, the potential difference reverses and the charge flow reverses [44]. Such reciprocating motion forms alternating current.

This type of TENG is usually triggered by an external mechanical shock; it is mainly used in situations where the external excitation is perpendicular to the friction layer, such as waves and man's walk. It has the advantages of convenient preparation, simple design, and easy multilayer integration, whereas the disadvantage is that the separation distance between two friction layers should be considered.

2.2 Contact-sliding mode

The structure of the contact-sliding mode can be regarded as the evolution of the vertical contact-separation mode (Figure 1b). Its structure is the same as the vertical contact-separation mode, but the two dielectric films in the contact-sliding mode are always in contact. The principle is that the two films slide along the contact surface, due to the friction effect, triboelectric charges are generated on the surface. In this way, polarization occurs in the sliding plane, driving

electrons flow between the metal electrodes, and an alternating current is generated by the reciprocal sliding separation and closing of the two thin films.

This mode, which converts the external excitation to a plane or a rotary slide, is mainly used in wave and rotary mechanical equipment. The advantages of this mode over the vertical contact-separation mode is that it does not require air separation to separate the two frictional layers, which is conducive to packaging, and the efficiency can be up to 70%.

2.3 Single-electrode mode

As shown in Figure 1c, the single-electrode mode is used in situations where it is not convenient for both dielectric films to be connected to electrodes. Its structure is that a fixed dielectric film is connected to the electrode, and another moving film is not connected to the electrode. The working principle is similar to the vertical contact-separation mode. Due to the distance between the two films, a potential difference in different directions is generated, which drives the electrons through the electrodes and generates an alternating current.

In real life, if a contact surface of a generator is free to move, such as a car or a walking person, these situations are more suitable for the single-electrode mode. Because it requires only one electrode to be connected to a working surface of the TENG, the other electrode can be arbitrarily placed or even grounded. But the disadvantage of this model is that the overall electrical output of the generator is only half that of the corresponding double electrode.

2.4 Freestanding triboelectric-layer mode

The structure of the freestanding triboelectric-layer mode is shown in Figure 1d, a pair of symmetrical electrodes lay flat under the triboelectric layer. The charged triboelectric layer slides over the symmetric electrode so that the potential difference between the two electrodes changes; to balance the change in the potential difference, electrons will flow back and forth between the two electrodes, thereby generating alternating current. In this mode, the triboelectric layer cannot contact the electrode; therefore, there is no chance of wear between them, which increases the service life. Compared with other operation modes, the

freestanding triboelectric-layer mode has higher conversion efficiency, and its total energy conversion efficiency can be up to 85%.

This model relies entirely on the horizontal sliding of the friction layer to generate electricity, which is suitable for moving objects, such as cars and trains moving on the floor. It does not require the electrode to be plated on the moving part of the device, which facilitates the manufacture and work of the device, and is not interfered by the single-electrode mode shielding effect, which can output higher output performance.

There is no fixed application occasion for each mode, and the key point is to transform the external energy excitation into the corresponding mode through a certain structural design. But, nowadays, vertical contact-separation mode and freestanding triboelectric-layer mode are widely used in ocean wave energy harvesting. Actually, in this paper, all but three of the paper [45–47] used a single electrode, and the others used a contact-separation mode or freestanding triboelectric-layer mode.

3 Ocean wave energy harvesting by the TENG

In 2014, TENG was applied to wave energy harvesting, under the research and development of more than 40 research teams worldwide; TENG has got a great progress in wave energy harvesting. And the output voltage produced by TENGs depends upon such criteria as the triboelectric materials, device geometry, applied force and frequency, and ambient temperature and relative humidity [48]. Many devices for wave energy harvesting have been invented, and their output performance is continuously improved. This section discusses the latest research progress of TENG in ocean wave energy harvesting from the perspective of TENG common structures and TENG network.

3.1 Common structures of TENG in ocean wave energy harvesting

3.1.1 Spherical-shell structure

The spherical-shell structure is very promising in TENG for ocean wave energy harvesting. It has the characteristics of lightweight and simple structure, which can

harvest ocean wave energy in any direction. The spherical-shell structure is easy to connect to a network. Wang et al. [49] first proposed a spherical-shell structure in 2015, which has undergone at least seven times changes and optimizations.

In 2015, Wang et al. demonstrated a TENG with a spherical-shell structure, which is named Freestanding Triboelectric-layer based Nanogenerator (RF-TENG). In this design, under the water wave of 1.43 Hz, this RF-TENG can directly light up several 10 commercial LEDs and has excellent power generation performance (Figure 2a). As shown in Figure 2b, RF-TENG uses a rolling rigid nylon ball to contact the Kapton film in a closed spherical shell. The Kapton film is connected by two curved electrodes on the back to form an independent triboelectric layer structure. When receiving external vibration from the ocean waves, the ball will roll back and forth between the two electrodes to provide AC power to the external load. Experiments show that RF-TENG has a stable output performance between 1.05 and 2.35 Hz in water wave frequency (Figure 2c). Especially, it has an almost consistent output characteristic between 1.23 and 1.55 Hz by systematically optimizing the friction-matching material, rolling ball diameter, and electrode structure of RF-TENG to obtain the maximum output under random water waves. To optimize the friction pairing material, a comparison test was performed using the nylon/Kapton membrane and PTFE/Al. The test results show that the output power density of the nylon/Kapton device is better than that of the PTFE/Al device. Then, from the perspective of theoretical calculations and experimental measurements, the size of the ball is optimized to achieve the maximum output (Figure 2d and e). As the ball size increases, the transfer charge increases and then saturates (Figure 2f). The experimental results agree with the theoretical predictions. The theoretical prediction is that there is an optimal ball diameter with the maximum transfer charge. The optimized RE-TENG can provide a short-circuit transfer charge of 24 nC and a short-circuit current of 1.2 μ A at a wave frequency of 1.43 Hz (the natural frequency of this device).

As they are all hard balls, the obvious disadvantage of these shell structures mentioned above is that the contact area is too small, resulting in low-power generation. And hard balls can greatly reduce the durability of the TENG due to heavy wear.

To solve the small contact area and improve durability, Xu et al. [50] have manufactured a TENG using silicone rubber instead of hard nylon balls (S-TENG); the softness of silicone rubber can increase the

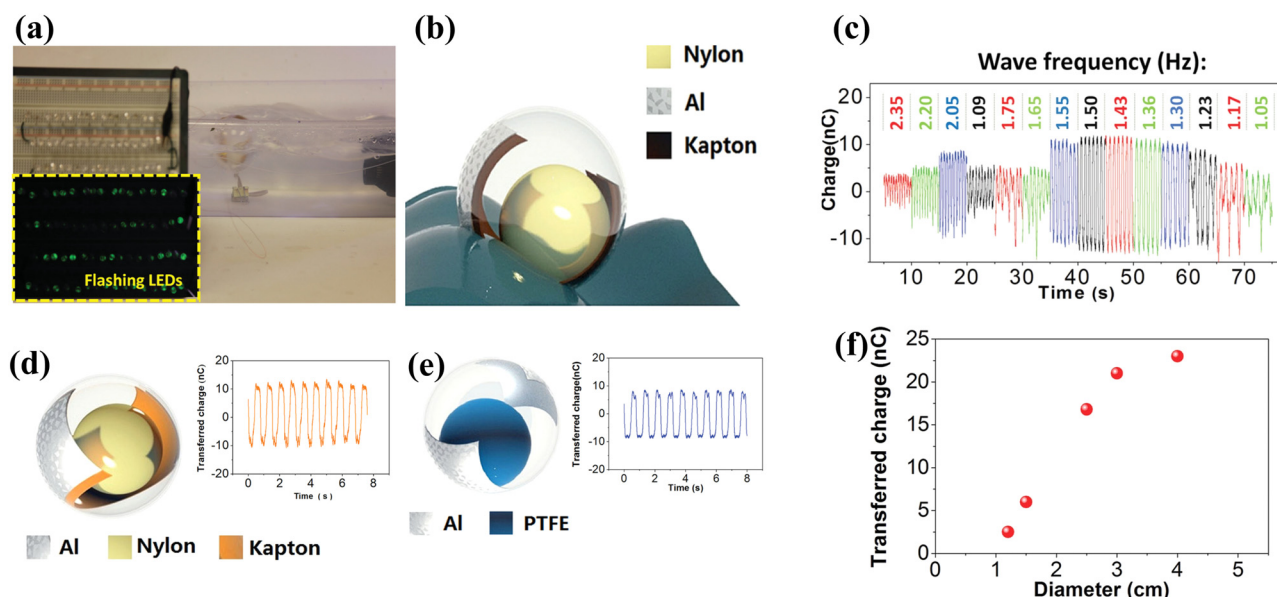


Figure 2: (a) Photograph of the RF-TENG pool test lighting LED, (b) schematic diagram of an RF-TENG device, (c) the relationship between the charge transferred by the RF-TENG device with a diameter of 4 cm and the wave frequency, (d) the schematic of the nylon/Kapton device and measured the transfer charge, (e) the schematic of a PTFE/Al device and measured the transferred charge, and (f) the relationship between the diameter of the experimentally tested ball and the transferred charge [49].

actual contact area and help improve the durability of the device (Figure 3a), and using Ag–Cu alloy can get high performance due to copper alloys and copper-based composites prepared through various strengthening mechanisms, which not only have high electrical and thermal conductivity but also have high strength and plasticity, along with good processing performance [51]. To enhance the contact electrification of silicone rubber, the silicone rubber is UV-treated and mixed with polyoxymethylene particles in the dielectric layer to produce microstructures on the surface, the reinforcement of rubber can be referred to ref. [52]. These two treatments have also reduced the viscosity of the surface so that the dielectric layer has a relatively low damping force and can roll smoothly, which greatly improves the performance of TENG under low-frequency waves. Under the external vibration of 3 Hz, the charge transferred by the short circuit increases rapidly with an initial increase in the amplitude of the harmonic stirring displacement, from 14 nC at 5 mm to 66 nC at 30 mm and then reaches saturation. Similarly, open-circuit voltage and short circuit current reach 1,780 V and 1.8 μ A in the stable region, respectively, and its short-circuit current at 5 Hz can observe a maximum current of about 3 μ A (Figure 3b and c).

To further increase the contact area of the ball, Cheng et al. [53] further optimized the inner ball. By using rolling soft water/silicone as the inner rolling ball

(Figure 3d), a better triboelectric nanogenerator (SS-TENG) was manufactured. This design maximizes the contact area, which can generate more charge and adjust the output performance by changing the thickness of the silicone shell. Compared with the S-TENG, the output of the design is 10 times higher at 5 Hz (Figure 3e and f) and 2 times higher at 2 Hz. Xia et al. [54] also designed a similar internal soft ball structure to harvest ocean wave energy, named multiple-frequency triboelectric nanogenerator based on the water balloon (WB-TENG). The fabricated WB-TENG generates a maximum instantaneous short-circuit current and an open-circuit voltage of 147 μ A and 1,221 V, respectively.

Due to the excellent characteristics of the spherical-shell structure, researchers have proposed different variants on the traditional structure and dig deeper into the structure. Shi et al. [45] created a highly symmetrical 3D spherical water-based triboelectric nanogenerator (SW-TENG) (Figure 4a). In the device, the rolling ball was directly replaced with a liquid, because in a complex water wave environment, a liquid-based 3D symmetrical structure is more desirable and more efficient and not easy to leak. It has a spherical-shell frame with double-layer water-based TENG on its inner and outer surfaces, which is twice the performance of traditional liquid–solid contact power generation. Similarly, Lee et al. [46] made a spherical hybrid TENG (SH-TENG) based on solid–solid and liquid–solid power

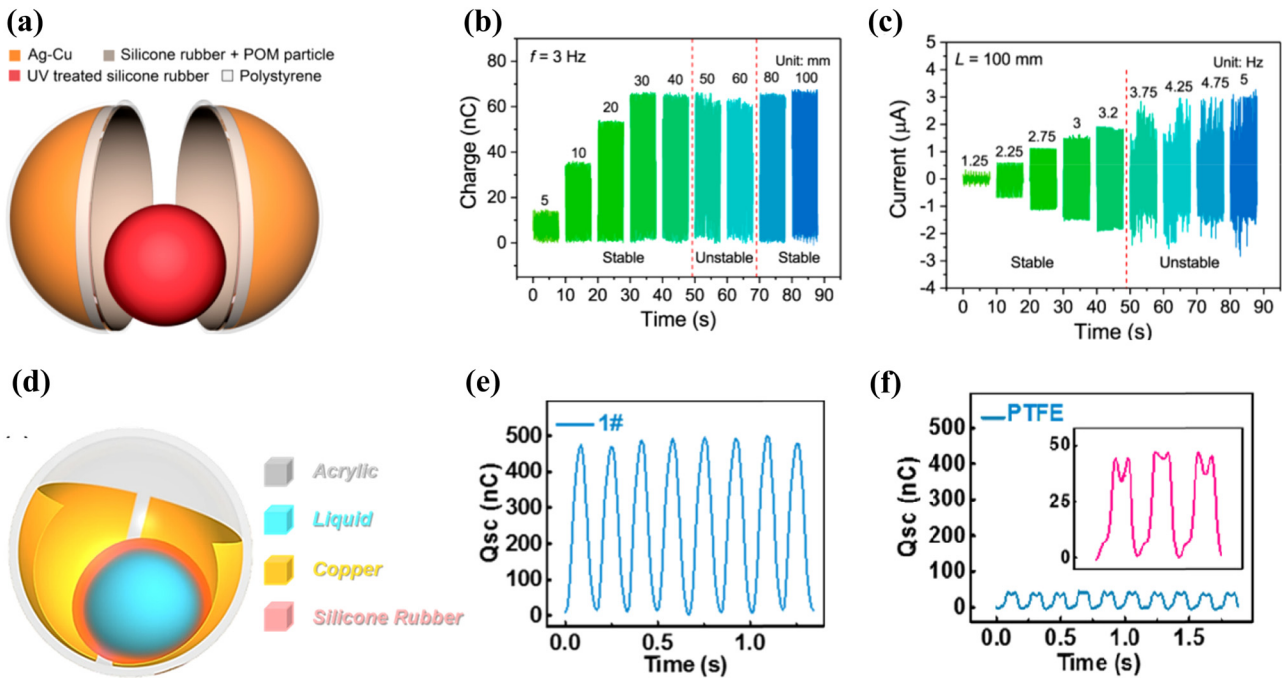


Figure 3: (a) Schematic structure of the S-TENG unit, (b) the relationship between the transferred charge and harmonic stirring displacement, (c) the relationship between the transferred charge and the amplitude of the small ball displacement [50], (d) structure of a soft contact model spherical TENG (SS-TENG) with a flexible rolling spherical surface, and (e and f) maximum transfer charge of SS-TENG and S-TENG (illustration shows an enlarged image) [53].

generation (Figure 4b); in this work, the liquid was replaced with a hardball inside the spherical-shell structure, and solid–solid TENG and solid–liquid TENG were coupled together using a single electrode. But its performance improvement is relatively small. In contrast, Yang et al. [55] obtained greater output performance, the inside of the shell is layered, and multiple TENGs are integrated into each layer (Figure 4c) to achieve the maximum utilization of space. Under external excitation of 1.67 Hz, the power density can reach up to 8.69 W/m^3 , which is the largest performance gain of the current spherical-shell structure. The research also focuses on the self-assembly problem of the TENG network (see Section 3.2 for details). Liu et al. [56] designed the spherical shell into an oblate shape and integrated two kinds of TENG inside, which can perform well in rough seas and relatively calm seas (Figure 4d).

Spherical shell structure is a very promising structure, because using soft ball can increase the contact area, improving durability, and using multilayer structure can provide more power density, which will be the first choice in the future practical applications.

3.1.2 Wavy structure

The wavy structure is one of the earliest structures used to harvest wave energy, and it is also a popular structure in the initial research. The wavy structure was first proposed by Wen et al. [57], and it is based on a wavy structure of Cu/Kapton/Cu film (Figure 5a), which is sandwiched between two flat nanostructured PTFE membranes. When subjected to external mechanical vibration/shock/compression, the membrane will extend the vertical impact transition laterally, which causes the sliding charge between the electrode and the PTFE membrane. After the impact, the TENG will automatically restore the initial position due to the elasticity of the membrane. This repeated pressing and release will allow the charge to flow between the planar electrode and the electrode, thereby generating alternating current. As shown in Figure 5b, the TENG is sealed in a thin rubber bag and then fixed on the side wall of the bathtub to make water waves hit the TENG. The experimental results show that the LED light is lit, which proves that the TENG in the wavy structure can harvest wave energy. According to the experiment, under the artificial wave

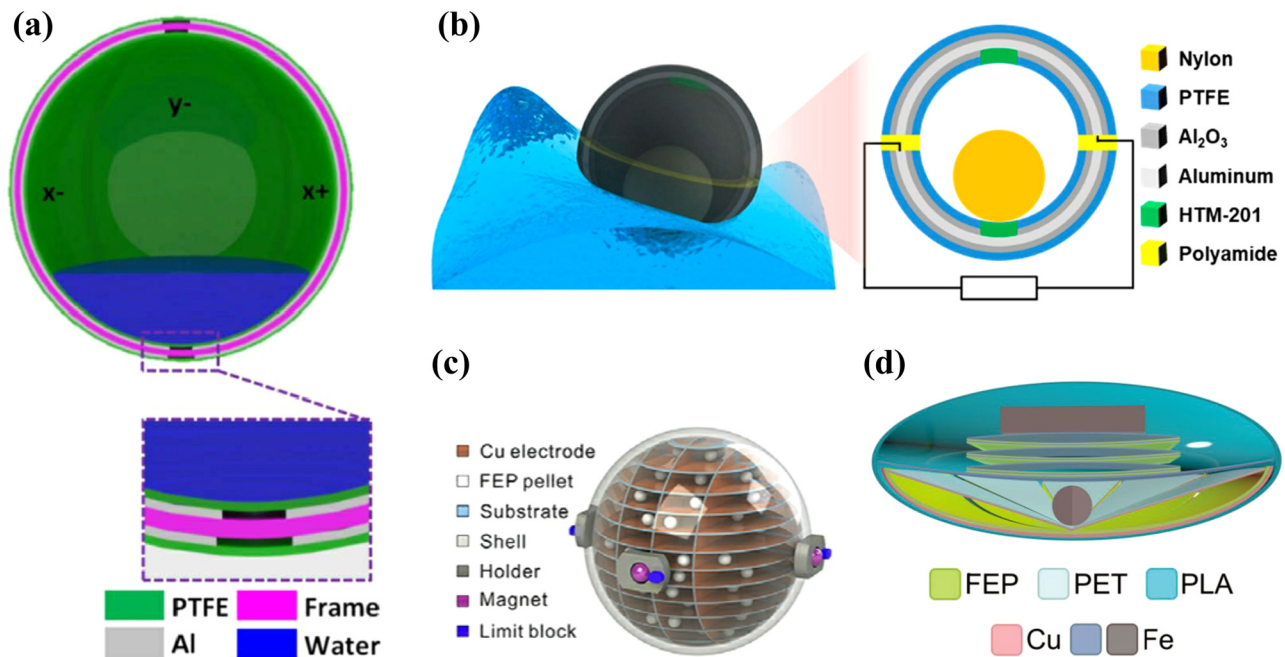


Figure 4: (a) Symmetrical 3D spherical water-based triboelectric nanogenerator (SW-TENG) structure diagram [45], (b) spherical hybrid TENG (SH-TENG) structure diagram [46], (c) spherical multilayer TENG [55], and (d) oblate double-layer TENG [56].

height of 0.2 m and the wave speed of 1.2 m/s, the output of a single TENG can reach up to 30 V and the output current can reach up to 6 μ A (Figure 5c and d).

Wavy structure TENG (WS-TENG) can be used as part of an integrated device, which can more efficiently collect wave energy. Jiang et al. [58] manufactured a boxed TENG consisted of a wavy-shaped TENG wall and a closed ball (Figure 5e). Each WS-TENG consists of a wavy Cu-Kapton-Cu film and two fluorinated ethylene propylene (FEP) films, and the metal electrodes are sputtered into a sandwich structure. This research is mainly based on the theoretical research and experimental verification. A theoretical model of TENG with a wavy structure is established. The size and mass of the box-shaped TENG spheres are optimized to obtain an optimal sphere size and mass, which is proved that the maximum output power and electrical energy can be obtained at this time by experiments. Yao et al. [59] based on ref. [58] used theoretical and experimental research to research the charging characteristics of TENG for a wavy structure to charge the capacitor under the impact of water wave and closed ball collision and calculate the influence of the compressive deformation depth of the film on the output performance. Research indicates that under direct water wave impact, the energy storage and maximum energy storage efficiency are determined by the depth of deformation, which can be optimized by the size of the sphere under the impact of a closed ball. Finally, the theoretical results are verified through experiments. The work of Jiang et al. and Yao et al.

can provide strategies for improving TENG's charging performance for effective water wave energy collection and storage.

To make full use of the inner wall area, Zhang et al. [60] changed the previous box shape to a dodecahedron shape (Figure 5f). Each surface is fixed with a wavy-shaped TENG (WS-TENG). Twelve WS-TENGs are integrated to form a dodecahedron device. Under external vibration, the maximum output voltage and output current of the device reaches 250 V and 150 μ A (Figure 5g and h), and the device can easily form a network, and its power density can reach up to 0.64 MW/km².

Research on wavy-shaped TENG shows that the structure has a good ability to harvest wave energy and will have better performance output in the future. However, the intermediate wave structure requires a great deal of elasticity, and when the elasticity decreases, the performance of the generator will decrease. Therefore, the wave structure faces a great durability challenge. Maybe we can use some composites with more durability [61].

3.1.3 Spring-assisted structure

TENG without assistant components is more effective for harvesting transient mechanical energy. However, the waves provided by the ocean have a lower trigger

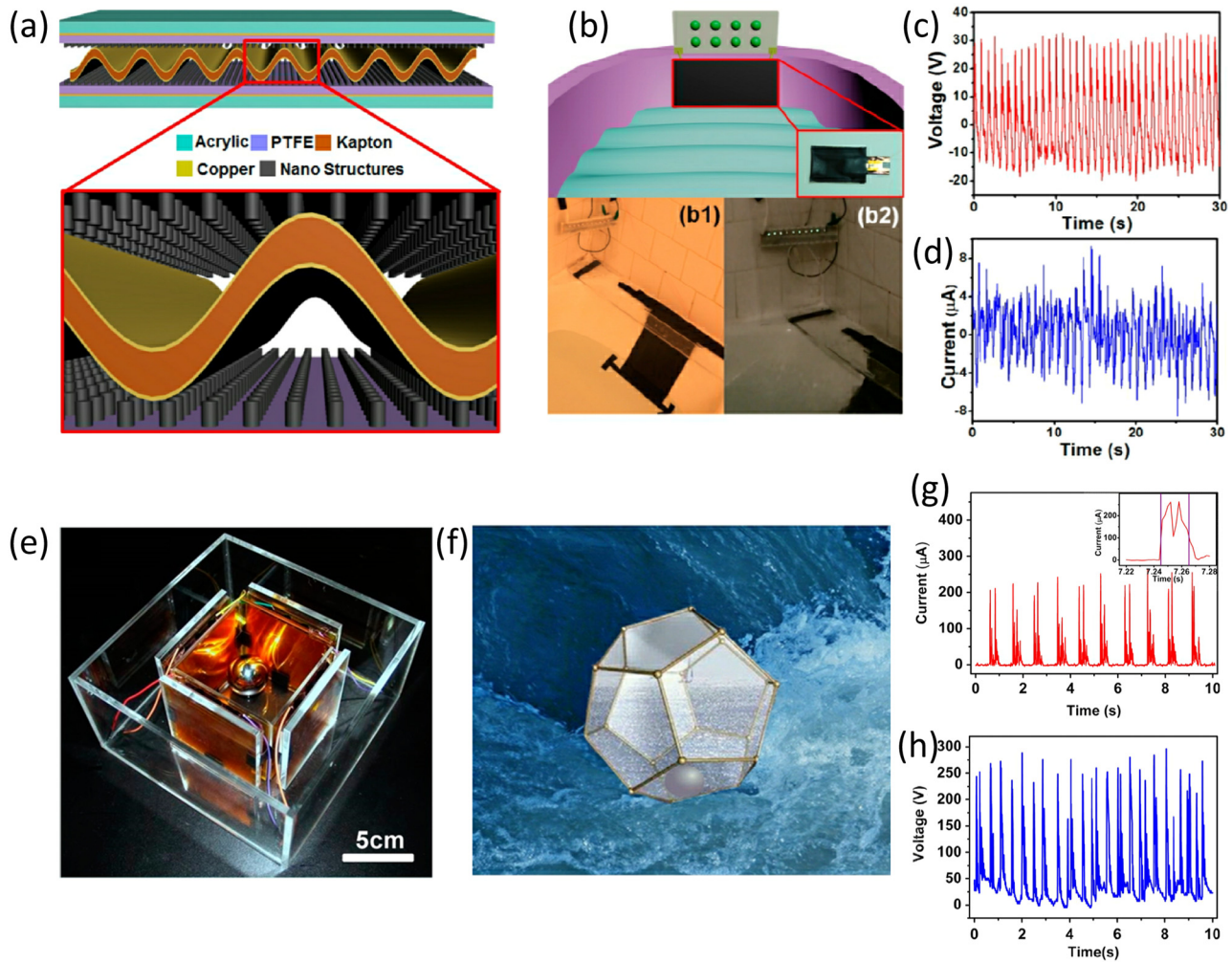


Figure 5: (a) Schematic diagram of the wavy structure TENG, (b) photograph of wavy-shaped TENG lighting LED in pool test, (c and d) output voltage and current of TENG triggered by water wave [57], (e) photo of boxed TENG [58], (f) schematic diagram of dodecahedron TENG, and (g and h) rectified output voltage and current of dodecahedron TENG in water [60].

frequency, causing most of the impact potential energy to dissipate, making themselves face a problem of generating very limited electrical energy in a short time. In some TENGs, using springs to store unstable and discontinuous kinetic energy and then apply these kinetic energies to the TENG unit, which can convert low-frequency water waves into high-frequency oscillations and can act for a longer period, ultimately enhancing energy conversion efficiency.

Xu et al. [62] first proposed a novel design, which was based on an elastic suspension oscillator structure and a mechanism for transmitting and distributing the collected water wave energy using air pressure. A spring as an energy storage element can effectively drive a series of integrated TENG. This design has been proven to store unstable and discontinuous kinetic energy under

the impact of water waves and then further act on the moving components, and then convert low-frequency ocean wave motion into high-frequency oscillations, resulting in higher average output power. The basic structure of the device is shown in Figure 6a. It is mainly composed of an internal oscillator and an outer shell. The elastic bands connect the oscillator and the shell to form a spring-suspended oscillator structure. This device is based on the vertical contact-separation mode. The impact of the water wave causes the spring-suspended oscillation structure to keep the TENG unit in contact-separation, thereby generating alternating current. Experiments have shown that when operating at low frequencies around a resonance frequency of approximately 2.9 Hz, a device integrating 38 TENG units exhibits a high output of 15 μC transferred charge per

cycle, a short-circuit current of $187\ \mu\text{A}$, and an optimum of $13.23\ \text{W/m}^3$ peak power density and can light up to 600 LED lights in real water.

Jiang *et al.* [63] designed a spring-assisted TENG (Figure 6b) and connected a TENG unit based on the vertical contacts separation mode at each end of spring. In this way, the potential energy generated during the mechanical triggering process was spring store and then releases it, causing the TENGs separated with a certain frequent contact, thereby generating alternating current. They optimize the output performance of the basic unit by adjusting the motor acceleration and spring parameters (including stiffness and length). There is a spring stiffness or spring length to get a great performance output. Studies have shown that after using springs, the accumulated charge of TENG can be increased by 113.0% and the converted electrical energy or efficiency can be increased by 150.3%. Compared with Jiang *et al.*, Tian *et al.* [64] using the same spring-assisted structure, but using a silicone rubber/carbon black composite electrode (Figure 6c). Compared to traditional hard copper electrodes, improving 75.2% charge transfer, 60.4% output current, and 103.9% voltage. Compared with the traditional hard copper electrode and no spring-assisted structure, it improves the charge transfer by 188%. Its performance has been greatly improved. To improve space utilization, they designed a TENG array composed

of spherical TENG elements based on elastically assisted multilayer structures [65], the structure shell diameter is 10 cm, and four steel shafts were fixed in the shell (Figure 6d). Four flexible springs attached to the acrylic block at the bottom support the mass. It generates elastic force under the impact of water waves to squeeze multiple layers of TENG, thereby generating alternating current. Due to the use of springs and increased space utilization, the output current of a spherical TENG unit can reach up to $120\ \mu\text{A}$, which is two orders of magnitude larger than the output current of the previous rolling spherical TENG, and the TENG can achieve a maximum output power of 7.96 mW (Figure 6e).

Although the effect of frequency on TENG has been solved, the most significant challenge to this structure is the durability issue, which is associated with friction and wear. This is a mechanism associated with TENG, so the solution to this problem must be to improve the durability of materials.

3.1.4 Bionic structure

Inspired by nature, researchers have invented many TENG devices with bionic structures, which have superior performance. Initially, Ahmed *et al.* [66] were inspired by the famous wave energy harvesting device

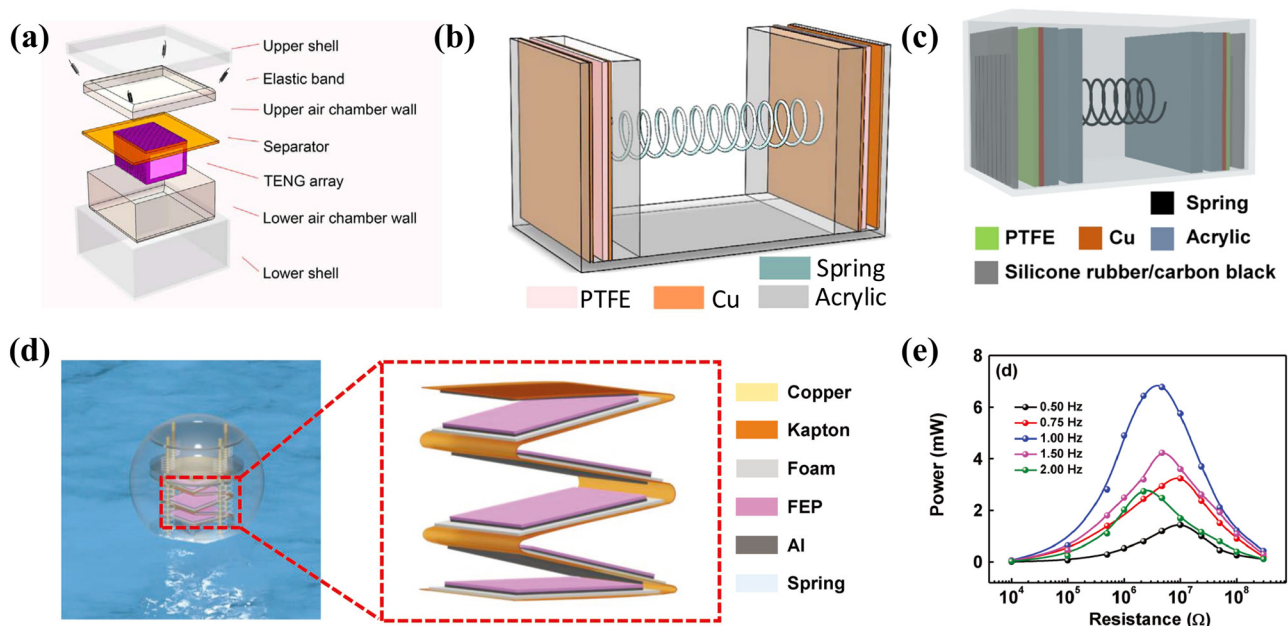


Figure 6: (a) Schematic of the integrated TENG array device based on air-driven membrane structure [62], (b) schematic of spring-assisted TENG structure [63], (c) schematic diagram of a silicon-based spring-assisted TENG device [64], (d) schematic diagram of spring-assisted multilayer TENG structure, and (e) output power–resistance curves of five-element spherical TENG at different water wave frequencies [65].

called the Edinburgh Duck [67]. Ducks have an efficient hydrodynamic structure, and they have been shown to extract 80% of mechanical energy in waves under laboratory conditions [68]. Therefore, a duck-shaped TENG based on freestanding triboelectric-layer mode is designed. Figure 7a shows a schematic diagram of a duck-shaped TENG. The working principle of this design is that the structure repeats pitching motion caused by water waves, causing the inner nylon ball to roll back and forth on the Kapton membrane, thereby generating alternating current. As shown in Figure 7b and c, the frequency response of the output voltage and current of the duck TENG is also characterized. At a wave frequency of 2.5 Hz, the maximum amplitude of voltage and current reaches 325 V and 65.5 μA , and the maximum peak power of the TENG measured can reach up to 1.366 W/m². To further explain the excellent performance of duck TENG, Saadatnia et al. [69] performed a comparative analysis between a TENG device and an equivalent EMG to harvest wave energy. They obtained the electrical output characteristics of the two technologies under various mechanical and electrical conditions. The analysis shows that at low operating frequencies of 2.5 Hz, the peak power densities of TENG and EMG reach 213.1 and 144.4 W/m³, respectively. Harvesting wave energy at low frequencies, the structure has superior performance output than EMG. Subsequently, Ahmed et al. [70] conducted a lot of theoretical research to design the duck-shaped TENG with better performance. Under

different wave conditions, to quantify the performance of the duck-shaped TENG, they introduced a comprehensive hybrid 3D model, and the mechanical and electrical characteristics of the overall structure and internal structure of the duck-shaped TENG are quantitatively analyzed using this model. Furthermore, the duck-shaped TENG's duck radius and mass are optimized. Finally, the effects of different TENG parameters are verified by comparing the performance of several existing TENG wave collectors. This study provides important guidance for the performance improvement of duck TENG.

Inspired by the jellyfish movement, Chen et al. [71] demonstrated a biomimetic jellyfish triboelectric nanogenerator (bi-TENG) based on the contact-separation mode. As shown in Figure 7d, this structure is considered as a priority technology, due to its high sensitivity, portability, and adaptability for continuous detection of water levels and levels. At a low frequency of 0.75 Hz, which outputs 143 V, 11.8 mA/m², and 22.1 $\mu\text{C}/\text{m}^2$ for sustainability and enhanced performance (Figure 7e and f). Inspired by the movement of sea snakes in the water, Zhang et al. [72] produced a sea snake-based triboelectric nanogenerator (SS-TENG). As shown in Figure 8a and b, the interior of the sea snake consists of polytetrafluoroethylene (PTFE) balls, nylon membranes, sputtered copper layers, and soft anti-loosening springs. This spring is an enlarged schematic diagram of the SS cross-section. To increase the frequency of the balls

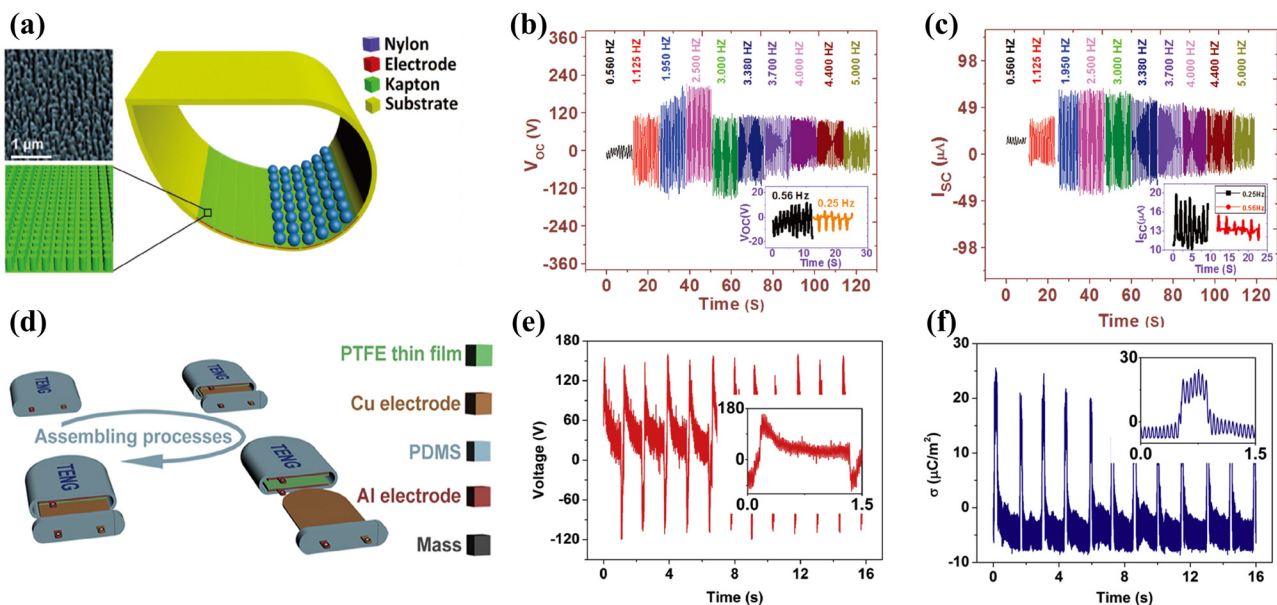


Figure 7: (a) Schematic diagram of duck TENG [66], (b and c) the output response of voltage and current of duck TENG at different frequencies [69], (d) bionic jellyfish TENG, and (e and f) output voltage and output current of bj-TENG at 0.75 Hz [71].

rolling over the electrodes, the copper wires of TENG are also arranged in an interdigitated manner, which will increase the total output current of the device. The sea snake repeatedly shakes under the impact of the waves, causing the nylon ball to roll back and forth, thereby generating alternating current. This structure also solves the problem that the electrolyte affects the output of the generator. Wang *et al.* [73] inspired by seaweed, designed a bio-inspired triboelectric nanogenerator (BI-TENG) to mimic the movement of kelp (Figure 8c). Kelp will sway gently with the waves and use energy in the process. Lei *et al.* [74] inspired by a butterfly, they manufactured a butterfly-type triboelectric nanogenerator (B-TENG) with a spring-assisted four-link mechanism. As shown in Figure 8d, the curved shell can effectively respond to the impact of water waves. To increase the frequency of the contact and separation movement of the TENG module, a four-bar linkage mechanism is internally assisted by springs. Both of these movements allow B-TENG to harvest energy from different types of low-frequency water waves. As shown in Figure 8e and f, the short-circuit current and open-circuit voltage of the B-TENG device can reach up to $75.35\ \mu\text{A}$ and $707.01\ \text{V}$, respectively, the maximum output power density can reach up to $9.559\ \text{W/m}^3$, and 180 LEDs can be directly lit.

The natural world has always been the survival of the fittest, and what is left in nature is the best. We collect energy from the ocean and conform to nature is the best way. Triboelectric nanogenerator imitating the structure of marine life, which can better collect wave energy.

However, the bionic structure is of great uncertainty, because the imitation can be changeable without uniformity, and the structure is relatively complex, which is unfavorable to the future commercialization.

3.1.5 Liquid–solid contact TENG to harvest ocean wave energy

Harvesting wave energy based on solid–solid contact triboelectric nanogenerators requires quite tight sealing, and the influence of the electrolyte in the water wave on the output performance of the generator needs to be considered. TENG based on liquid–solid contact power generation has many advantages, such as the ability to collect wave energy from different directions, a larger contact area, and easy sealing. Li *et al.* [47] have reported a liquid–solid TENG to harvest wave energy, as shown in Figure 9a and b, which manufactures nanowires by etching on the FEP film, increasing the contact area between the FEP film and water (Figure 9c), thereby generating more charge. Therefore, the output of the TENG will be greatly increased. The TENG can produce a maximum output current and voltage of $10\ \mu\text{A}$ and $200\ \text{V}$, respectively, and the performance output is much higher than previously reported [75,76], which has an important guiding role in wave energy harvesting.

To study the effect of liquid properties on TENG performance, Pan *et al.* [77] designed and manufactured a U-shaped tube TENG based on the liquid–solid contact

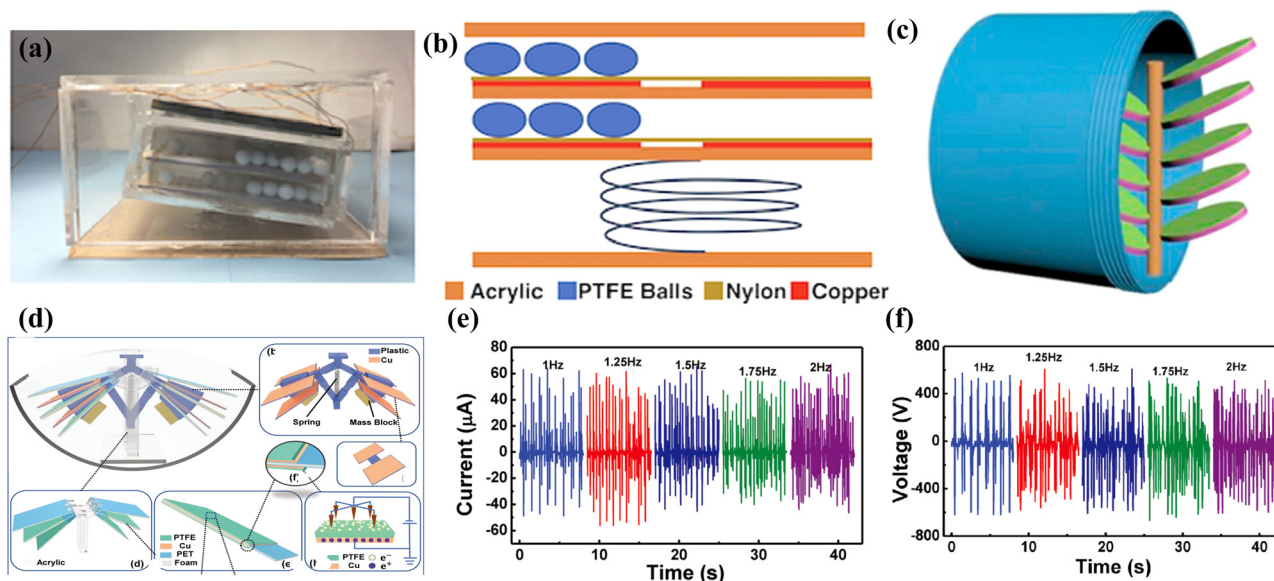


Figure 8: (a and b) SS-TENG structure picture [72], (c) BITENG structure diagram [73], (d) B-TENG structure diagram, and (e and f) B-TENG response diagram of output current and voltage at different frequencies [74].

mode. To study the effect of liquid characteristics on the output performance of TENG, they used 11 liquids as an experimental medium. The experimental results show that the output performance of TENG is the polarity of the liquid, the dielectric constant and the FEP affinity. The pure water U-shaped TENG has the highest output among these 11 liquids. For the vibration mode (0.5 Hz), the open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) are 81.7 V and 0.26 μ A, respectively. For horizontal shift mode (1.25 Hz), it can be further increased to 93.0 V and 0.48 μ A, respectively (Figure 9d). It exhibits quite high-performance output at very low frequencies. Li et al. [78] designed and manufactured a liquid–solid buoy nano-generator (LS-TENG), which has increased 48.7 times compared to the solid–solid TENG performance of the same area. A single LS-TENG can obtain output voltage and output current up to 400 V and 40 μ A, respectively, and has extremely excellent output. As shown in Figure 9e, LS-TENG is made of conventional materials, including two external and internal TENG, which can collect up and down, shaking and rotating motions from waves. It is also easy to form a network. Zhao et al. [79] demonstrated the device of water wave energy harvesting using a sliding freestanding water-TENG device. As shown in Figure 9f, in this device, multiple pairs of electrodes are mounted on top of a flexible substrate. The electrode material was made of

conductive fabric, and the PTFE membrane is used as a hydrophobic coating after dry etching. Its output power can reach up to 1.03 mW, after collecting the wave energy; the author successfully demonstrated the wireless self-powered transmission of important hydrological information. The harvested water wave power is also used to light 60 LED bulbs.

Liquid–solid contact TENG is an effective method of collecting wave energy because of its simple structure, large contact area, and excellent output performance. It is an effective device for collecting wave energy in the future.

3.1.6 Hybrid generator to harvest ocean wave energy

Although traditional EMG is not enough to collect wave energy due to its bulkiness and other characteristics, in recent years, EMG and TENG hybrid generators collect wave energy, which has been loved by many researchers, has achieved very great results, and is an important direction for future development.

In general, these hybrid nanogenerators can be divided into two ways to cut magnetic induction lines. One is to rotate the magnetic induction lines to generate electricity like traditional electromagnetic power generation [80], and the other is to take into account the

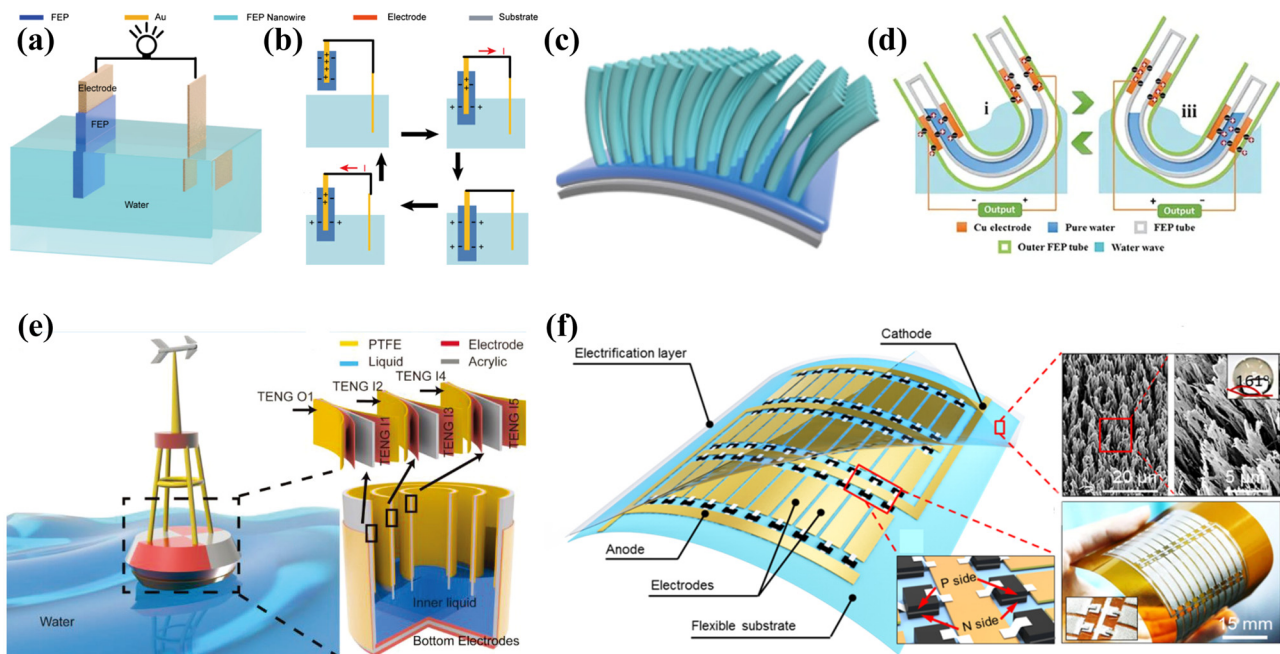


Figure 9: (a and b) The working principle of the nanowire-based TENG, (c) illustration of a bent nanowire-based [47], (d) schematic illustration of the functional components of the U-tube TENG [77], (e) the structure of a buoy nanogenerator [78], and (f) structure of a networked integrated triboelectric nanogenerator (NI-TENG) [79].

characteristics of the ocean waves themselves and cut the magnetic induction lines in wave mode to generate electricity [81,82].

For rotary cutting, Shao *et al.* [80] reported the design of a hybrid generator based on the contact-separation mode TENG (CS-TENG) and the rotating self-supporting EMG (RF-EMG). As shown in Figure 10a, the water wave makes the EMG rotor rotate to cut the magnetic induction line, thereby generating alternating current. During the rotation process, due to the magnetic force, TENG periodically contacts and separates and also generates an alternating current. TENG and EMG can generate output voltages and currents of up to 315.8 V, 0.59 V, 44.6 μ A, and 1.78 mA under 100 rpm trigger conditions, respectively.

The EMG of the existing hybrid nanogenerators is mostly based on the wave mode, and TENG is mainly based on contact-separation and freestanding triboelectric-layer mode. Of course, there are also two modes that integrate power generation [83,84]. Zia *et al.* [85,86] based on the traditional point-absorptive structure for collecting wave energy, a typical TENG hybrid nanogenerator based on sliding mode is designed. As shown in Figure 10b, in this device, TENG is based on the grating structure mechanism and the dielectric–dielectric independent TENG operation. Under the action of high and low waves, the slider moves up and down in the barrel, cutting the magnetic induction wire while sliding across the dielectric layers at different positions so that TENG generates an alternating current. For the TENG hybrid generator based on the contact-separation mode, its

working principle is the same as that of the EMG hybrid generator based on the rotary cutting mode [87–89]. The TENG friction layer is periodically contacted and separated by magnetic force, thereby generating alternating current.

The structure of the hybrid nanogenerator is based on a single TENG integrated with an EMG, but it can obtain more than double the output performance, make full use of the limited space, and be an important way to collect wave energy in the future. But due to add magnets and coils, EMG is relatively bulky when compared with other types of TENG.

3.2 TENG network to harvest ocean wave energy

The concept of using the TENG network to harvest ocean wave energy was proposed by Wang *et al.* [24,90] in 2014; the TENG network consists of thousands of TENG units through a certain connection method (Figure 11a), which can output high-power electrical energy. The connection method of the TENG network will affect the performance output of the entire network. This section will discuss the current research progress on the connection mode of the TENG network in detail.

Xu *et al.* [50] studied the impact of three connection modes of rigid, flexible, and wire connection on the performance output of the TENG network. Research shows that for a group of TENG if the units are not

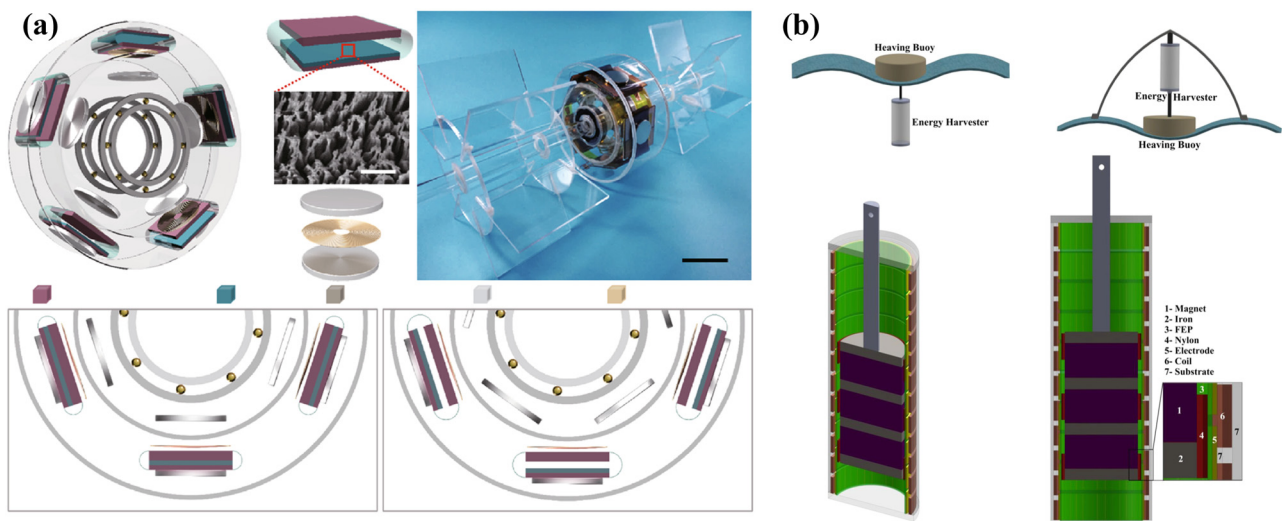


Figure 10: (a) Structure of the triboelectric – electromagnetic hybrid generator (TEHG) [80] and (b) structure of the hybridized triboelectric-electromagnetic generator based on heaving point absorbers [85].

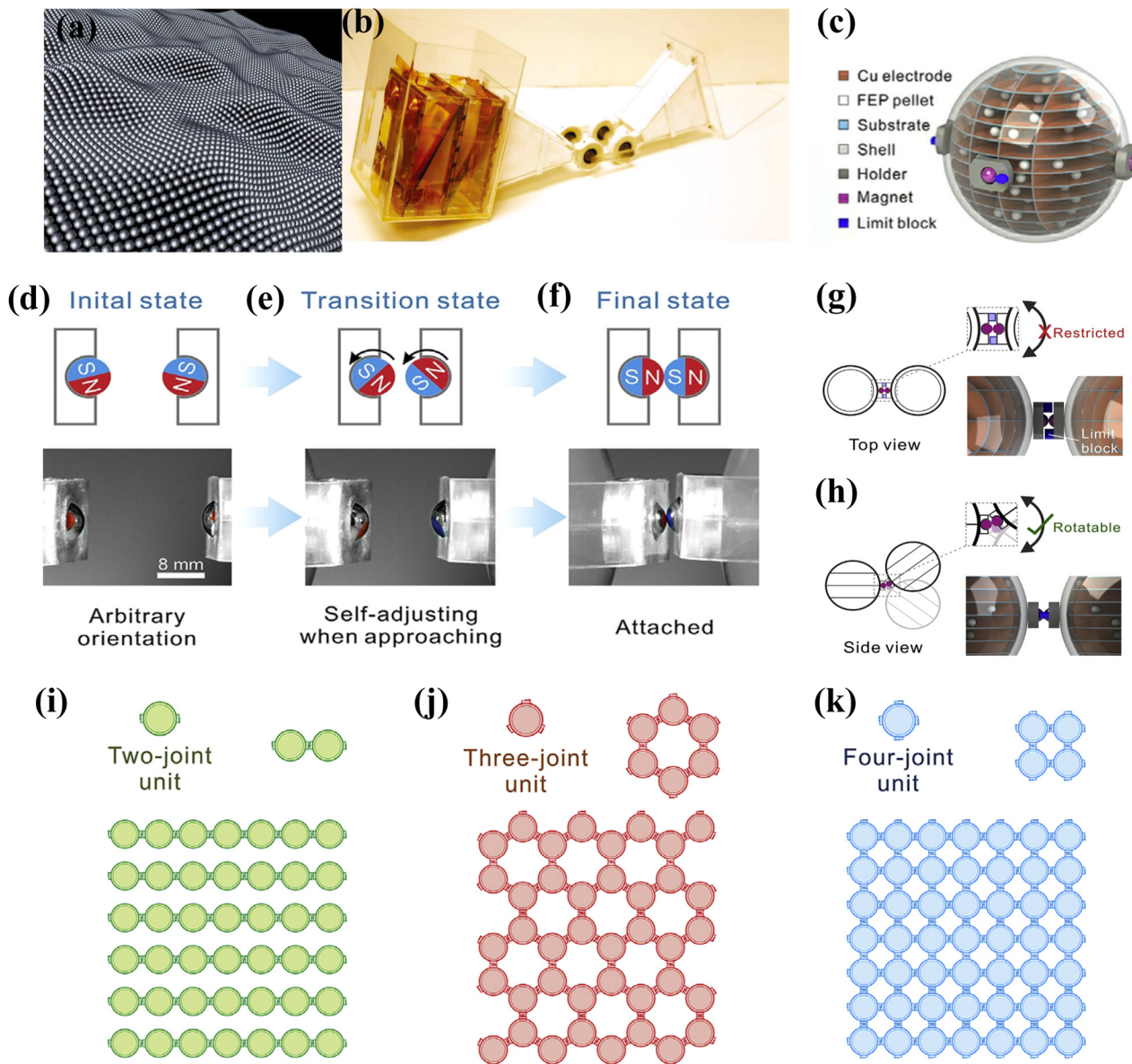


Figure 11: (a) A proposed TENG network composed of tens of thousands of spherical ball based TENG units for harvesting ocean wave energy [25], (b) a hinged connection structure of the TENG network [88], (c) schematic structure of the self-assembly TENG unit, (d–f) principle of SAM-joints transfer without limit block, (g and h) assembly diagram of SAM-joints with limit block, and (i–k) schematic diagram of different assembly shapes [55].

connected to each other, the efficiency will be very low. Therefore, the mechanical connection between the various units plays a vital role in the TENG network, because it can provide a high output by coupling the relevant mechanical motion between them. Finally, experimental research shows that under actual water wave conditions, rigid connections impose too many internal constraints between the units. Compared with rigid connections, flexible connections are a better network strategy. To study the specific connection

structure between units, as shown in Figure 11b, Wang et al. [88] produced a hinged connection structure that could easily link the proposed TENG together to form a network.

The ocean environment is harsh, and the connections between TENG networks may be broken due to natural disasters such as storms and large waves. Therefore, Yang et al. [55] invented a self-assembling structure that can automatically reorganize the scattered TENG units. As shown in Figure 11c, a plurality of self-

Table 1: Summary of studies on different triboelectric nanogenerators (TENGs) in harvest ocean energy

Structure	Year	Author	Trib o-layer used in TENG	The electrode used in TENG	Open-circuit voltage (V)	Short-circuit current (μ A)	Current density	Surface power density	Power density and power	Load resistance (Ω)
Spherical-shell structure	2015	Wang et al. [49]	Nylon 6/6 and Kapton	Al	903	1			10 mW	10 G Ω
	2017	Shi et al. [45]	PTFE/PDMS/Kapton	Al	15.2	0.12			3.04 μ W	56.5 M Ω
Wavy structure	2018	Xu et al. [50]	Polystyrene	Ag-Cu	1,780	1.8			4.47 W/m ³	1 G Ω
	2018	Lee et al. [46]	PTFE	Al	3.3					
	2018	Cheng et al. [53]	Silicone rubber	Cu	350	5			1.8 mW	200 M Ω
	2019	Yang et al. [55]	FEP	Cu		5			8.69 W/m ³	50 M Ω
	2019	Liu et al. [36]	FEP	Cu	281	76				
	2014	Wen et al. [57]	PTFE	Cu	72	32		0.4 W/m ²		5 M Ω
	2015	Jiang et al. [58]	Kapton/FEP	Cu	300	12			1.94 mW	20 M Ω
	2016	Zhang et al. [60]	Kapton/FEP	Cu	250	150		0.64 MW/km ²		
Spring-assisted structure	2016	Xu et al. [62]	FEP	Al	600	187			13.23 W/m ³	
	2016	Jiang et al. [63]	FEP	Cu	755.8	65			2.4 W/m ³	
	2018	Xia et al. [64]	PTFE	Silicone rubber/carbon black	630.7	22.3				
	2018	Xia et al. [65]	Kapton/FEP	Al/Cu	560	120			15.2 W/m ³	
Bionic structure	2016	Ahmed et al. [66]	Kapton	Cu	325	65.5		1.37/W m ²		50 M Ω
	2017	Abdelsalam et al. [70]	Kapton	Cu	390	7.2			213.1 W/m ³	280 M Ω
Liquid-solid contact structure	2017	Young et al. [92]	PET/Kapton	Al	8	200 nA	11.8 mA/m ²			
	2017	Chen et al. [71]	PTFE/PDMS	Al/Cu	143	7.5				
	2018	Li et al. [93]	PTFE	Al	550	1.5			8.23 μ W	120 M Ω
	2018	Zhang et al. [72]	PTFE	Cu/Nylon	300	2			3.5 W/m ³	11 M Ω
	2018	Wang et al. [73]	FEP	Cu	260	10		25 μ W/cm ²		15 M Ω
	2018	Lei et al. [74]	PTFE/PET	Cu	707.01	75.35			9.56 W/m ³	300 M Ω
	2019	Liu et al. [94]	FEP	Cu	83.41	2.6		0.21 W/m ²	72.75 μ W	13.8 M Ω
	2019	Zhong et al. [72]	PTFE	Al	625	0.45 mA			7.45 W/m ³	20 M Ω
	2017	Liu et al. [47]	PEP	Ag	200	10	1061.8 mA/m ²	9.62 W/m ²	16 μ W	
	2017	Yang et al. [95]	PTFE	Cu	350	1.75			2.04 W/m ³	
Hybrid TENG-EMG	2018	Pan et al. [77]	FEP	Cu	600	9				
	2018	Li et al. [78]	PTFE/FEP/FET/PDMS	Cu/Al						
	2018	Zhao et al. [79]	Kapton/PTFE	Conductive textile						
	2016	Wen et al. [83]	FEP	Cu	375	13.5		15.67 μ W/cm ²	1.03 mW	50 M Ω
					1.79	14.12		27.12 μ W/cm ²		
	2017	Shao et al. [87]	PTFE	Al	142	11.57 mA			31.5 μ W	261 Ω
					0.66	23.3			66.9 μ W	100 M Ω
	2018	Saadatnia et al. [86]	PTFE	Cu	100	2.14 mA			120 W/m ³	
					25					

Table 1: Continued

Structure	Year	Author	Trib o-layer used in TENG	The electrode used in TENG	Open-circuit voltage (V)	Short-circuit current (μA)	Current density	Surface power density	Power density and power	Load resistance (Ω)
Other structure	2018	Shao et al. [80]	PTFE	Al	1.5	80 mA			220 W/m ³	50 Ω
					315.8	44.6			90.7 μW	100 M Ω
	2018	Wang et al. [84]	Silicone	Cu	0.59	1.78 mA			79.6 μW	400 Ω
					150	15			850 μW	20 M Ω
	2019	Wang et al. [88]	PTFE	Cu	4.3	15 mA			9 mW	100 Ω
					400	15.3				
	2019	Hao et al. [81]	PMMW	Al/Ag	1.7	5.4 mA			4 mW	100 Ω
					75	1.2			0.08 mW	100 M Ω
					13	2 mA			14.9 mW	1,000 Ω
	2019	Wu et al. [82]	PTFE	Cu	172.95	3.5				
	2014	Xie et al. [94]	PTFE	Al	470		90.6 mA/m ²	42.6 W/m ²	2.7 kW/m ³	
	2015	Chen et al. [96]	PTFE/PET	Cu/Al	569.9	0.93 mA		0.26 mW/cm ²		1 M Ω
	2016	Huang et al. [97]	PDMS	Al	205	30			3 mW	10 M Ω
	2017	Xi et al. [98]	PTFE	Cu	490	24				
	2018	Dong et al. [99]	PTFE	Cu	30	1.2			1.2 μW	100 M Ω
	2018	Cheng et al. [100]	FEP	Cu	240	1.22		0.08 W/m ²		500 M Ω
	2019	Xu et al. [101]	PTFE	Al	105	1.3			10.6 w/m ³	
	2019	Xi et al. [102]	FEP	Cu	250			13.2 mW/m ²		
	2019	Zhang et al. [37]	PTFE	Cu	140	60		4.2 mW/m ²	54	1 M Ω
	2020	Jiang et al. [103]	PTFE	Cu	342	5.9			4.5 mW	50 M Ω

adaptive magnetic joints (SAM-joint) is installed on the closed TENG shell to realize self-assembly. The working principle of SAM-joint is shown in Figure 11d–f. When two nodes of two TENG units are close, the spherical magnet will rotate rapidly and self-adjust to the state of the opposite external magnetic pole and attach due to magnetic interaction. To maintain the flexibility of the energy collection performance while maintaining the assembly structure of the network, a limit block is also designed at the node to limit the anisotropy of the degree of freedom of the unit (Figure 11g and h). As shown in Figure 11i–k, the shape of the network can be adjusted by installing a different number of SAM joints on each unit. This design greatly enhances the autonomy and mechanical robustness of the network, which is conducive to large-scale manufacturing and maintenance.

In the past few years, the TENG device has achieved great success in collecting ocean wave energy. TENG with different structures has been applied, and the output voltage of the TENG device has been greatly improved. The output voltage of TENG harvesting wave energy is now up to 1,780 V [91].

Table 1 illustrates the performance output comparison of TENG devices for capturing ocean wave energy. In Table 1, in the first row of Hybrid TENG-EMG, the first row of its output performance is the performance output of TENG, and the second row is the performance output of EMG. However, the size of the nanomaterials or the frequency or speed of external application is not considered, which also determines the output power of the device. As can be seen from Table 1, tribolayer used in TENG more are PTFE and FEP, the electrode used in TENG more are Al and Cu. From the time dimension of view, the output performance of TENG is increasing for the same structure, and the performance output of TENG is also increasing among different structures. But TENG's output performance stills low.

4 Summary and perspective

This article focuses on a comprehensive review of triboelectric nanogenerators in wave energy harvesting. We introduced the four work modes of TENG and the various structures of TENG. We list the various structure's working mechanisms and compare the output power with various TENG in detail. Through this review, we can see that TENG has a large number of structures for wave energy collection. Different structures have different advantages and disadvantages. Each structure is being

optimized to improve its performance output. Among these structures, spherical-shell structure is more promising due to its more simple and easier to connect the network. From output power view, all structure's single structure TENG's output power was still very low. However, many a mickle makes a muckle, the TENG network constructed by thousands of TENG units through a certain connection method, such as cables, magnets, etc., which will provide a feasible solution for large-scale ocean wave energy harvesting in the future. For the method of the network, we review the different method of the network; from the current view, the magnet connection is a more promising way to connect single structure TENG.

To solve the energy crisis using the TENG network, there are still many technical problems to be solved. According to the development of TENG, the following points are summarized:

The durability of TENG has always been a problem that needs to be solved first, and it is necessary to choose durable materials and reasonable designs to solve this problem.

The connection mode between TENG networks, the sea environment is harsh, and the network connection method is the key link for the final transmission of the collected energy. The network connection method needs to be comprehensively considered.

Management and distribution of TENG output power.

There is no doubt that the blue dream of triboelectric nanogenerators is about to come true.

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