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Review article

Recent advances in ocean energy harvesting based on triboelectric nanogenerators

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ABSTRACT

The ocean contains abundant natural energy resources including several types of clean and renewable energy. Traditional ocean energy harvesting (OEH) systems based on large electromagnetic generators have shown limitations of inefficiency in harvesting irregular, low-frequency ocean energy. Triboelectric nanogenerators (TENG) have emerged as a promising new source of ocean energy, and it has shown significant technical advantages in applying low-frequency ocean energy-efficient harvesting. The self-driven energy system based on TENG has been successfully used in the ocean Internet of Things and distributed sensor systems, and breakthroughs have been made in integrating research and development with traditional electromagnetic power generation systems. In this paper, we systematically review the latest developments in ocean energy harvesting with TENG and analyze and summarize the principle, structure, efficiency, and performance of various types of TENG ocean energy harvesting systems, and the present challenges and future development trends of TENG in ocean energy collection and application are also pointed out.

Introduction

Petrochemical resources are the primary source of global energy supply up to now. With the continuous increase of energy consumption by human activities, the side effects such as resource over-exploitation and carbon dioxide emissions have been emerging[1]. In recent years, most countries have promoted green lifestyles such as low-carbon travel, saving electricity, and rational using natural resources to achieve sustainable development strategies[2]. Therefore, the development and utilization of clean and renewable energy have gradually become a hot research topic [3]. Oceans cover 71 % of the earth's surface and contain a wide variety of natural resources [4]. According to theoretical calculations, the annual power generation of ocean energy can reach 75 TW [5]. If ocean energy's full availability and utilization can be realized, it will bring considerable changes to the existing energy acquisition methods.

There is abundant energy stored in the ocean, including wave energy, tidal energy, temperature difference energy, and ocean current energy. Among many energy forms, wave energy is the most typical and easy to obtain, and most OEH projects aim at wave energy harvesting.

Abbreviations: BJ-TENG, Bionic-Jellyfish Triboelectric Nanogenerator; BS-TENG, Ball-shell Structured Triboelectric Nanogenerator; B-TENG, Butterfly-inspired Triboelectric Nanogenerator; CIT-TENG, Cascade Impact Structure Triboelectric Nanogenerator; DB-TENG, Droplet-based Triboelectric Nanogenerator; EMG, Electro-Magnetic Generator; FEP, Fluorinated Ethylene Propylene; FE-TENG, Fully-Enclosed Triboelectric Nanogenerator; FL-TENG, Flower-Like Triboelectric Nanogenerator; FSHG, Fully-Space Triboelectric-Electromagnetic Hybrid Nanogenerator; FSL-TENG, Fish-Scale-Like Triboelectric Nanogenerator; IE-TENG, Interfacial Electrification enabled Triboelectric Nanogenerator; KPFM, Kelvin Probe Force Microscopy; LS-TENG, Liquid-Solid-based Triboelectric Nanogenerator; MSLT, Mat-shaped Solid-Liquid Triboelectric Nanogenerator; NI-TENG, Networked Integrated Triboelectric Nanogenerator; OEH, Ocean Energy Harvesting; PC-TENG, Parallel-Cell TENG; PMM, Power Management Module; PVDF, Polyvinylidene Fluoride; RF-TENG, Rolling Spherical Triboelectric Nanogenerator; SAM-joint, Self-Adaptive Magnetic Joint; SH-TENG, Spherical Hybrid Triboelectric Nanogenerator; SS-TENG, Soft-contact Spherical Triboelectric Nanogenerator; S-TENG, Stackable Triboelectric Nanogenerator; TENG, Triboelectric Nanogenerator; TENG-NW, Triboelectric Nanogenerator Network; *T*-TENG, Tower-like Triboelectric Nanogenerator; UF-TENG, Underwater Flag-like Triboelectric Nanogenerator; WEC, Waves Energy Converter; WS-TENG, Wavy-Structured robust Triboelectric Nanogenerator; WT-TENG, Water-Tube-based Triboelectric Nanogenerator.

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The wave originates from the movement of wind on the ocean's surface and is essentially formed by the absorption of wind energy by the ocean. Compared with wind energy, wave motion has better continuity and spatial concentration. At different times, it will show different wave energy levels affected by factors such as wind speed and temperature, so the waves show randomness. Ocean waves are composed of many low-frequency fundamental waves in different directions, and the frequency range of natural ocean waves is 0.17–1.25 Hz[6,7].

The transformation of ocean renewable energy into usable electrical energy has undergone long-term attempts and explorations, and many technological signs of progress and scientific research results have been achieved[8]. In the 1840s, Masuda developed a navigation buoy driven by wave energy, which became one of the devices for collecting and utilizing wave energy[9]. Since then, ocean energy harvesting technology based on electromagnetic generators has continued to develop, and various devices and systems have been created. These include attenuators[10], oscillating wave surge converters[11], submerged pressure differential[12], point absorbers[13], oscillating water columns[14], overtopping converters[15], bulge head wave energy converter[16], and more. However, this type of ocean energy harvesting system based on electromagnetic generators has the disadvantages of large volume, complicated structure, and high construction and maintenance costs while gradually improving the energy conversion capability. Moreover, the system exhibits limitations of inefficient conversion when harvesting irregular, low-frequency ocean energy. Therefore, an innovative and efficient device needs to be explored to overcome the technical drawbacks of traditional ocean energy harvesting devices.

In 2012, Wang's team proposed the concept of the Triboelectric Nanogenerator [17], which achieved the conversion of tiny mechanical energy into electrical energy. Moreover, the application of TENG technology has shown very efficient performance in harvesting low-frequency energy[18], including different forms of mechanical energy such as energy in nature[19], energy generated by humans during exercise[20], and vibration energy when mechanical equipment is working[21]. For wave energy, tidal energy, temperature difference energy, and ocean current energy that widely exist in the ocean, different types of TENG energy harvesting and conversion systems have been developed, and the experimental tests have shown excellent performance [6,22–24]. Further, TENG can provide distributed energy in the Internet of Things and may be used to collect blue energy in the ocean on a large scale[25]. As shown in Fig. 1, in future research on ocean energy based on TENG, after solving the large-scale TENG network structure and energy storage technology, this technology can bring colossal application prospects and possibilities to the development of unmanned underwater systems. Therefore, the application of TENG technology in ocean energy harvesting provides a solution that is different from traditional electromagnetic generator-based methods, showing excellent application potential[26].

Fig. 2 illustrates the research steps of ocean energy harvesting using TENG. First, the type and structure of the TENG used are clarified through specific project background or application requirement analysis. In the second step, the energy conversion efficiency of the device is enhanced by experimental testing and optimization of the design method. Finally, the TENG energy conversion device is arranged into application scenarios to achieve continuous improvement and demonstration applications. The paper aims to provide a review of recent research advances in all relevant aspects of TENG technology from the perspective of ocean energy harvesting research. In Section 2, the principles, structures, and output performance of different TENG ocean energy harvesting systems, including liquid-solid contact TENGs, fully enclosed TENGs, bionic structures TENGs, composite TENGs, and TENG networks. The improved structure and energy conversion efficiency of TENGs in the listed literature is reviewed with emphasis. In Section 3, challenges and future development trends in the research field of TENG ocean energy harvesting are presented.

TENGs for ocean energy harvesting

In this section, we discuss the recent research progress of TENG in ocean energy harvesting from the perspectives of liquid-solid contact TENG, fully enclosed TENG, biomimetic structure TENG, EMG-TENG hybrid OEH structures, and OEH-TENG network structures.

Liquid-solid contact TENG

TENGs based on the solid-solid contact mode often need to pay attention to the sealing of the equipment to prevent water from entering the equipment. Researchers developed liquid-solid-based TENG(LS-

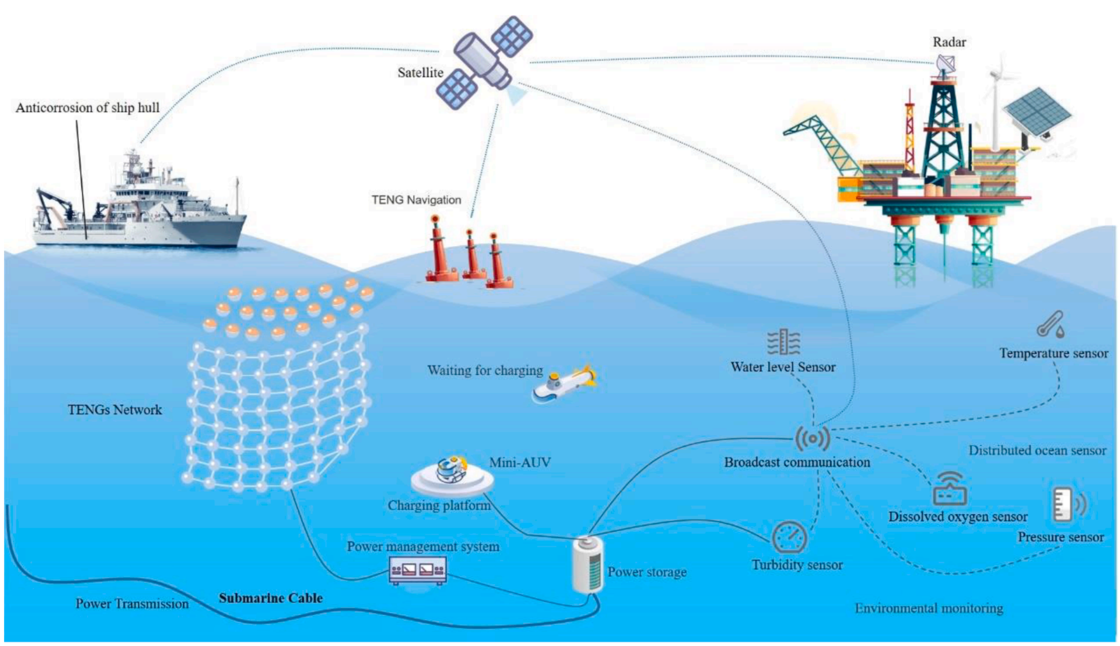

Fig. 1. An application conception of blue energy harvesting system based on TENG. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

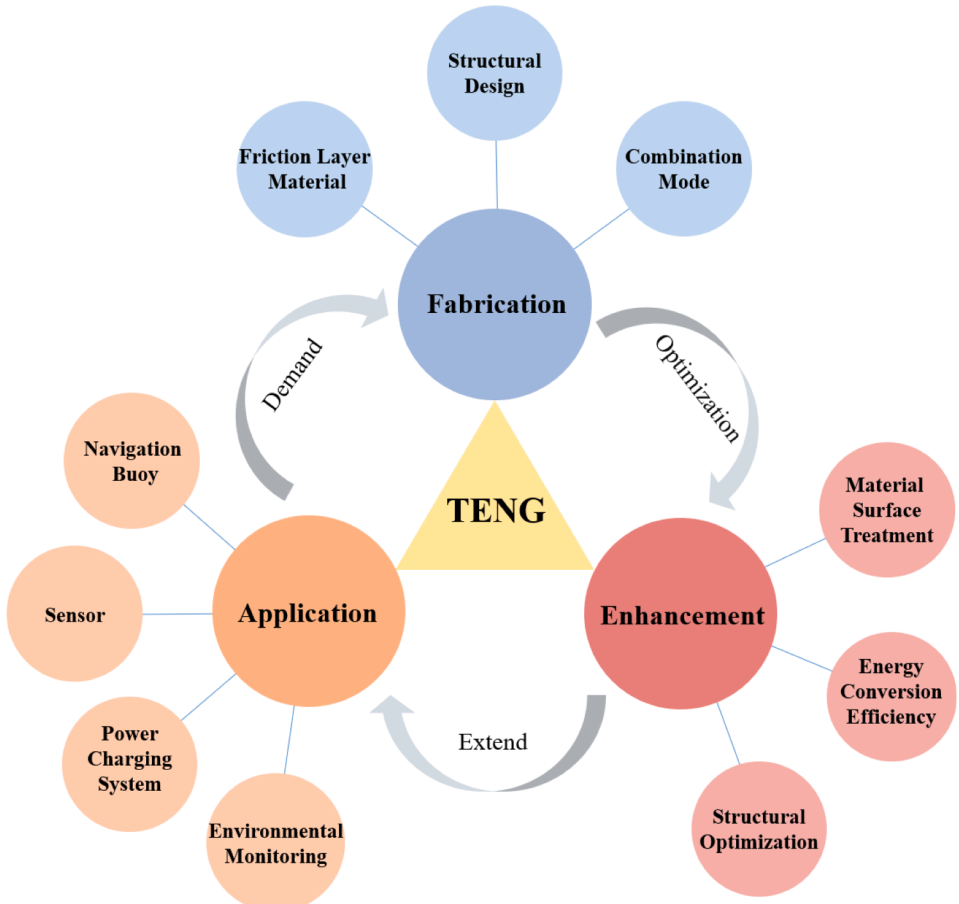

Fig. 2. The research method of ocean energy harvesting system based on TENG.

TENG), which enlarges the contact surface area and avoid the wear problem of solid-solid TENGs. The hydrophobicity of the friction material surface plays an essential role in the liquid-solid contact process, and excellent hydrophobicity can make the friction material have the advantages of self-cleaning and moisture resistance while ensuring the stable operation of the energy harvesting device [27]. When a liquid is in contact with a hydrophobic surface, two different wetting states, the Wenzel state and the Cassie-Baxter state, are exhibited depending on the surface structure and material [28]. In the Wenzel state, the liquid penetrates the microstructure's unevenness on the material's surface. In the Cassie-Baxter state, the gas is trapped in the asperities of the material surface, forming a mixed solid-gas surface. Cassie-Baxter exhibits a larger apparent contact angle than the Wenzel wetted state [29]. On the nanopatterned surface of complex structures, the Wenzel and the Cassie-Baxter states can coexist to form an intermediate state [30]. In this state, increasing the aspect ratio of the surface structure can increase the contact angle and improve the hydrophobicity of the material [31]. These characteristics provide researchers with an optimization design method to realize the design of the hydrophobicity of the material, thus improving the energy conversion efficiency of LS-TENG.

In solid-liquid contact, water has a positive triboelectric charge after friction, so negative friction materials such as fluorinated ethylene propylene(FEP) are usually used as the friction layer. The LS-TENG fabricated based on FEP films for energy harvesting from various water motions are shown in Fig. 3(a) [32]. As soon as the nanowires were modified on the FEP film's surface, the actual contact area was increased, and the electrical output efficiency was increased by 7.7 %. The material nanowire processing method solves the problem of low surface charge density of traditional friction materials, and the hydrophobicity ensures reliability and durability. In Fig. 3(b), Li et al. have the same idea and use the etching method to fabricate nanowires on FEP surfaces[33]. The output voltage of TENG after surface treatment can reach 200 V, and the output current can reach 10μA. The data show that even with low-cost polymer films, after nanowire processing, excellent output results are achieved, significantly reducing the manufacturing cost. On the basis of liquid-solid contact mode, Su et al. proposed an integrated hybrid TENG consisting of an Impact-TENG and an IE-TENG [34]. They simulated seawater in different regions by changing the concentration of NaCl solution. The experiment proved that impact-TENG could maintain a stable output, which solved the effect of seawater concentration on the output of TENG. In addition, embedding the hybrid TENG into the life jacket can power electronic devices and send out a distress signal in time when falling into the water. As displayed in Fig. 3(c), a networked ensemble TENG (NI-TENG) was fabricated by Zhao et al.[35]. Benefiting from its 2D network structure, NI-TENG can harvest energy from various types of water waves and can generate stable electrical output. And the generated electric energy can be stored and released in time, which can solve the power supply problem of the wireless sensor network. Experiments showed that under a water wave with a height of 12 cm, NI-TENG with a contact area of 70 cm^2 could generate an output power of 1.03 mW.

According to Wang et al., an annular liquid-solid interface is utilized to fabricate a TENG[36]. The TENG-based tilt sensor can further improve the sensitivity by optimizing the electrode material and liquid type. After repeated tests, TENG can also work generally to power the sensor in harsh environments with high humidity and high salinity, and the robustness is greatly improved. As demonstrated in Fig. 3(d), Singh and Khare used KPFM to observe the triboelectric phenomenon of water droplets falling on the surface of ferroelectric polymer (ZnO-PVDF film) and finally proposed the electrical mechanism of TENG at the liquid-

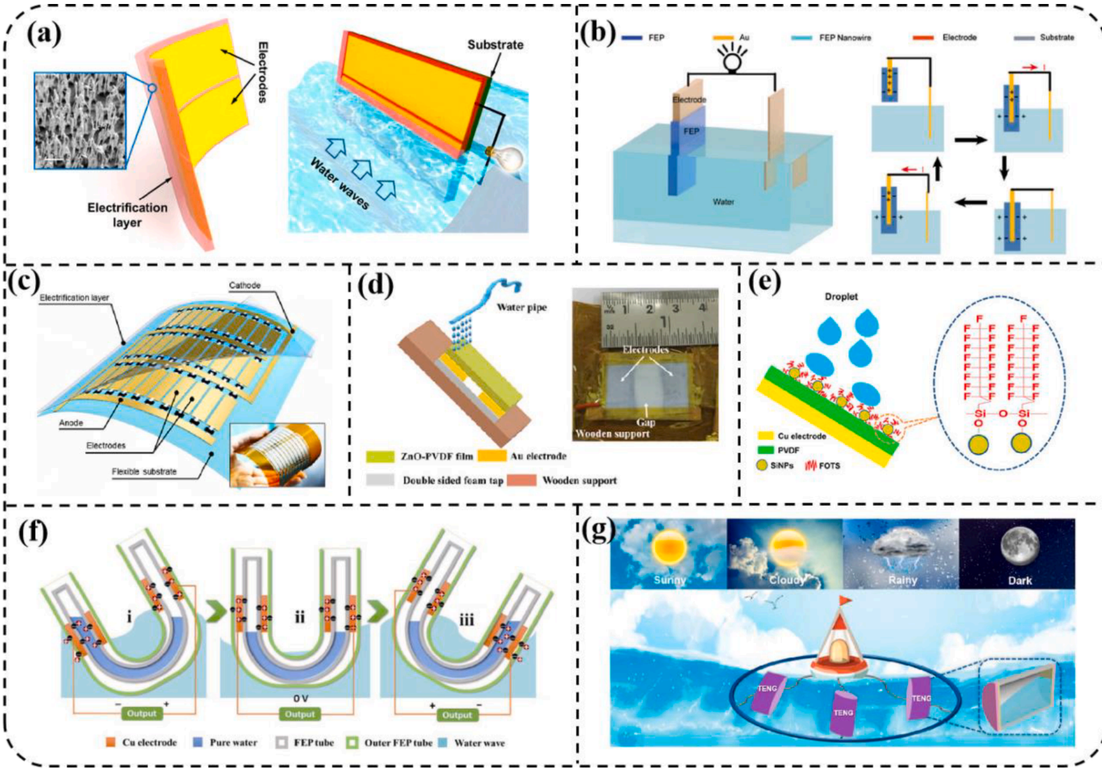

Fig. 3. Liquid-solid structure TENG. (a) Liquid-solid TENG based on fluorinated ethylene propylene films [32], (with permission from American Chemical Society). (b) Schematic diagram of TENG treated with nanowire [33], (with permission from American Institute of Physics). (c) Highly adaptive liquid-solid interface TENG for harvesting multiple water wave energies [35], (with permission from American Chemical Society). (d) Liquid-solid TENG is fabricated based on ZnO-PVDF films [37], (with permission from Wiley). (e) Schematic diagram of Liquid-solid TENG. Tuning surface polarity by epitaxial growth on PVDF membranes to enhance the power generation performance of liquid-solid TENGs [38], (with permission from Elsevier). (f) U-tube TENG of liquid-FEP to harvest water wave energy [40], (with permission from Springer). (g) Novel dual liquid-solid TENG exists for all-weather ocean energy collection and cathodic protection [41],(with permission from Elsevier).

solid interface[37]. This finding provides a theoretical basis for fabricating efficient LS-TENG devices. They manufactured a liquid-solid TENG based on ZnO-PVDF films and achieved a maximum power of 44 nW. Fig. 3(e) demonstrates the fabrication of a new surface-polarity-tuning PVDF film using an epitaxial growth process[38]. This film has excellent dielectric properties and waterproofing. The modified PVDF film's TENG exhibits higher stability and robustness in harsh environments. Wei et al. designed a droplet-based TENG (DB-TENG) [39], which overcomes the shortcomings of previous LS-TENGs that can only work on rainy days and harvests ocean energy in all weather conditions. Under simulated waves, the non-encapsulated DB-TENG can successfully drive the electronic devices to work. As shown in Fig. 3(f), Pan et al. fabricated U-tube TENG to test the effects of 11 sealing liquids[40]. After testing, the pure water-based U-tube showed the optimal effect and was able to light up 60 LEDs. In addition, the U-shaped tube was optimized in structure, adopted a sandwich structure, and successfully powered the thermo-hygrometer. U-tube TENG provides a promising approach to the power supply problem of electronic devices.

In Fig. 3(g), Sun et al. fabricated a novel dual-solid-liquid TENG[41], which achieved adequate cathodic protection of metallic materials and overcame the seawater corrosion problem of metallic materials. The PTFE-based two-device array showed excellent output performance, with the maximum voltage and current reaching 129.63 V and 2.83μA. At the same time, they have developed a self-powered corrosion protection system using the liquid-solid TENG array as the power source, which can inhibit metal corrosion all day long. This system shows great potential for buoy and marine equipment power supply development. By encapsulating deionized water in tubes made of fluorinated ethylene propylene, Wu et al. developed TENG using a water tube (WT-TENG) [42]. The finger-sized WT-TENG unit achieved an output voltage of 233 V. Whether in the rotation mode, the swing mode, the seesaw mode, or the horizontal linear sliding mode, the WT-TENG shows a promising power generation effect. WT-TENG solves the drawback of the limited energy form of a single motion and can realize the multiplication output of multiple energy sources through integration. Zaw et al. fabricated a mat-like liquid-solid TENG (MSLT) using a mixture of PDMS and conductive carbon black as electrodes[43]. MSLT has the advantages of good flexibility, strong corrosion resistance, and no need for packaging. The innovation of MSIT is that it can not only obtain energy from wave energy but also decompose seawater to produce hydrogen, which expands the application field of LS-TENG.

The liquid-solid TENG has a simple structure and does not require sealing, improving the service life and reducing the manufacturing cost. However, it is easily affected by the high concentration of ions in seawater, limiting the transfer of electrons and reducing power generation.

Fully enclosed TENGs

The ocean environment's humidity significantly influences the output performance of the solid-solid contact mode TENG. The fully enclosed structure effectively overcomes the negative impact of the harsh marine environment on TENG. This section reports three typical fully enclosed structures: spherical structure TENG, spring-assisted structure TENG, and multilayer structure TENG.

Spherical structure TENG

The spherical structure TENG has been used as a typical structure when harvesting ocean energy, and the spherical structure is widely used in the fabrication of TENG[44]. First, it is simple to manufacture and lightweight[45,46]. Second, the spherical structure has low motion resistance in water waves and can respond quickly to wave motion [47,48]. Third, thanks to its symmetrical design, the spherical structure can collect water wave energy in any direction[22,49].

Spherical TENGs have been shown to harvest wave energy efficiently. In 2013, Yang et al. proposed a fully enclosed spherical structure [50], which is not affected by the harsh marine environment. Experiments show that the fully enclosed spherical form has potential applications in driving electronic devices and sensors. This structure cannot move free because wires connect the inner rolling ball. To reduce the binding of wires to the inner rolling ball, Zhang et al. designed a three-dimensional TENG consisting of an inner PFA ball and an outer transparent ball[51]. This structure harvests the vibrational energy in space through a single-electrode operating mode. The advantage of the single-electrode mode is that the wired bondage is eliminated, and the inner PFA ball can roll freely for energy harvesting in all directions. On this basis, Wang et al. manufactured an RF-TENG on basis of freestanding triboelectric-layer mode[46]. Because the spherical shell structure has many advantages, researchers have conducted in-depth research on friction materials on this basis. To further enhance the performance of TENG, they increased the area of contact by fabricating nanowire arrays on the Kapton film, which reduced the energy loss due to friction and improved the energy conversion efficiency. In order to alter the surface of the material, Xu et al. manufactured a split ball-shell structured TENG (BS-TENG) by utilizing a soft material method to raise the area of contact [52]. In this work, they demonstrated the treatment of silicone rubber as triboelectric material. BS-TENG can obtain high output power under small external shock. After testing, the voltage and current can reach 1780 V and 1.8μA at the amplitude of 3 Hz. Experiments have proved that using silicone rubber can improve the output effect. At the same time, it can solve the problem of inner and outer ball wear and enhance the durability of the equipment. As displayed in Fig. 4(a), Cheng et al. designed a similar soft spherical TENG(SS-TENG) structure using a flowing liquid and silica gel as the soft inner core[53]. Additionally, the outcome can be varied by changing the softness of the liquid and silicone core to match the impact frequency of different external waves, ensuring efficient work in complex environments. The maximum transfer charge generated by this soft-contact TENG can reach 500 nC, which is ten times that of the ordinary hard-contact TENG. To further optimize SS-TENG, Guan et al. established a contact electrification model, quantitatively analyzed the influencing factors of output performance, and finally obtained the contact electrification model with the highest efficiency[54]. Among soft-contact structures, water balloon structures with increased flexibility, high elasticity, and self-supporting properties also have excellent effects on collecting low-frequency wave energy [55]. It realizes multi-frequency response under low-frequency waves and generates high-frequency electrical output.

To increase the robustness of the working of TENG devices, Shi et al. proposed a highly symmetric 3D water-based TENG[59]. Its inner and outer surfaces are designed with a double-layer water-based structure, preventing the device from leaking and harvesting energy from multiple motion modes. The most important thing is that this structure can significantly improve energy conversion efficiency. Based on previous work, Lee et al. further enhanced the design of TENG and fabricated a spherical hybrid TENG(SH-TENG)[45]. SH-TENG combines the two triboelectric modes to flexibly respond to random water wave energy.

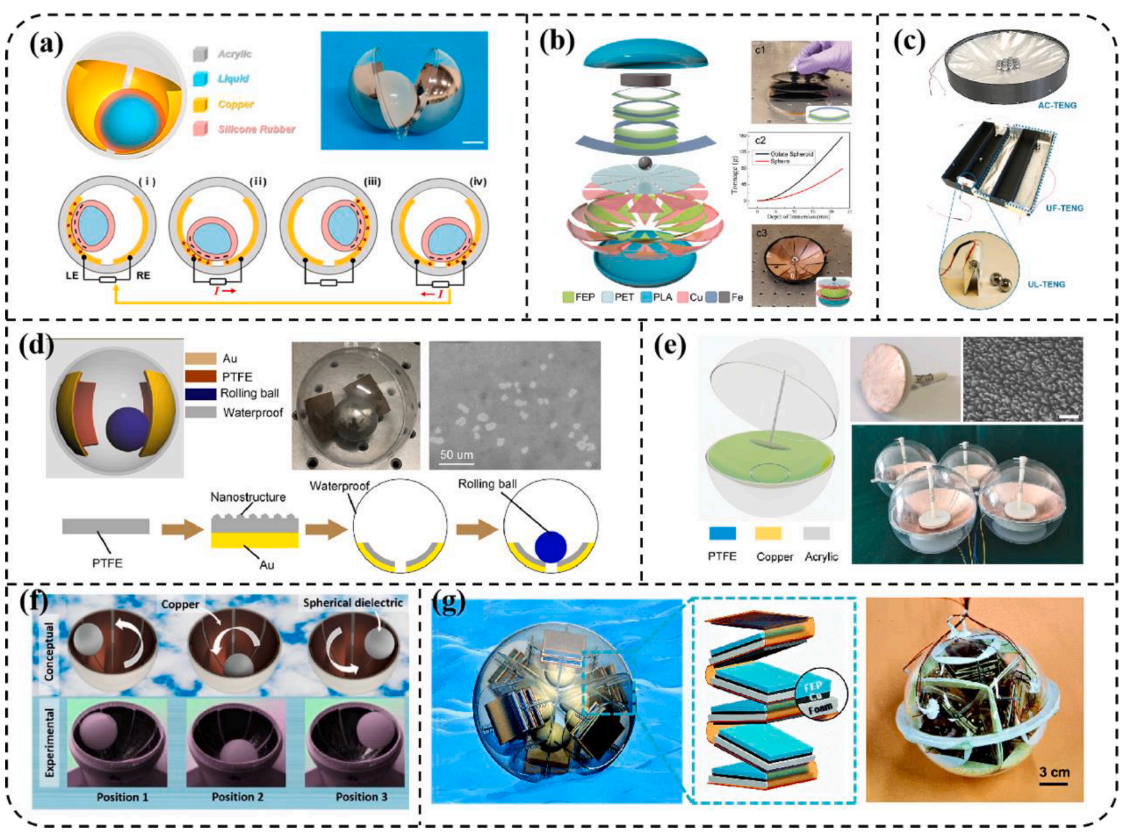

Fig. 4. TENG on basis of spherical structure. (a) TENG is based on a soft contact structure to collect water wave energy [53], (with permission from Elsevier). (b) The oblate spherical TENG harvests blue energy in all weather conditions [56], (with permission from Wiley). (c) Three spherical TENGs are integrated with buoys for harvesting water wave energy from the degrees of freedom [57], (with permission from Elsevier). (d) Rolling TENG is based on nano-microstructures for marine environmental monitoring [47], (with permission from American Chemical Society). (e) Sketch map of the pendulum-like structure TENG based on elastic connection and soft contact [58], (with permission from Wiley). (f) Schematic diagram of rolling spherical TENG [49], (with permission from Multidisciplinary Digital Publishing Institute). (g) Spring-Assisted Multilayer Spherical Structure TENG [22], (with permission from Royal Society of Chemistry). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The inner and outer surfaces of the spherical shell are covered with a double-layer structure composed of Al_2O_3 and PTFE, in which Al_2O_3 is used as the dielectric layer, which solves the problem of charge leakage well. Fig. 4(b) demonstrates the oblate spherical TENG based on two novel components[56]: spring-based steel plates and rolling ball components. The most outstanding contribution of the flat ball TENG is to overcome the problem that the center of gravity of the object inside the TENG is unbalanced, and it is easy to lose the optimal motion posture. Contrasted to the ordinary spherical shell, the flat, spherical shell has the advantages of high stability, fast response, and low consumables.

Fig. 4(c) shows three TENGs based on rolling balls to simultaneously harvest wave energy with 6 degrees of freedom[57]. Incorporating the TENG into the buoy not only solves the sealing problem of the TENG and ensures the stable operation of the TENG in harsh environments but also solves the problem of the power supply of the ocean sensor and realizes the long-term operation of the sensor in the ocean. Chen et al. proposed a nano-micron PTFE-based rolling TENG with enhanced output properties [47], as shown in Fig. 4(d). Nano-micro structure treatment on the PTFE surface can enlarge the real contact area and enhance the friction effect. Lin et al. creatively introduced flexible dielectric villi into TENGs and designed a novel pendulum structure[58], as demonstrated in Fig. 4(e). It mainly adopts elastic and soft contact to collect ultra-low frequency mechanical energy. The soft contact mode can supplement the surface triboelectric charge after being intermittently excited. This design overcomes friction loss and dramatically improves the energy conversion efficiency. As displayed in Fig. 4(f), Wang et al. devised a rolling spherical TENG that can generate electricity even with slight oscillations [49]. Compared to spherical TENGs triggered by springs or lever arms, practical applicability is addressed in this structural design. To better manage the harvested energy, Liang et al. designed a spring-aided multilayer TENG integrated with a Power Management Module(PMM) to manage the output[22], as shown in Fig. 4(g). Integrating with PMM, TENG overcomes the unstable and non-sustainable output voltage across the load resistance, effectively managing the output energy. The TENG can be successfully applied in real-world scenarios such as alarm systems, water level detection, and temperature detection.

The spherical structure has the advantages of lightweight, flexible movement, good sealing, and omnidirectional water wave collection, which has attracted many researchers to fabricate excellent TENG devices. In addition, the researchers conducted a series of in-depth explorations in friction materials, layered design or internal structure, etc., to further optimize the spherical TENG and obtain higher output power. All in all, the spherical structure provides a practical model for ocean energy harvesting.

Spring-assisted structure TENG

The wave trigger frequency in the ocean is low, most of the shock potential energy is dissipated, and the energy collected by TENG in a short time is very limited. By adding a spring structure to the TENG, the spring can be used to store elastic potential energy, which can then be converted into kinetic energy and applied to the TENG. The low-frequency wave energy can be converted into high-frequency oscillation, increasing the oscillation time and improving energy conversion efficiency.

Xiao et al. invented a spherical TENG based on a spring-aided structure for efficient collection of low-frequency, random wave

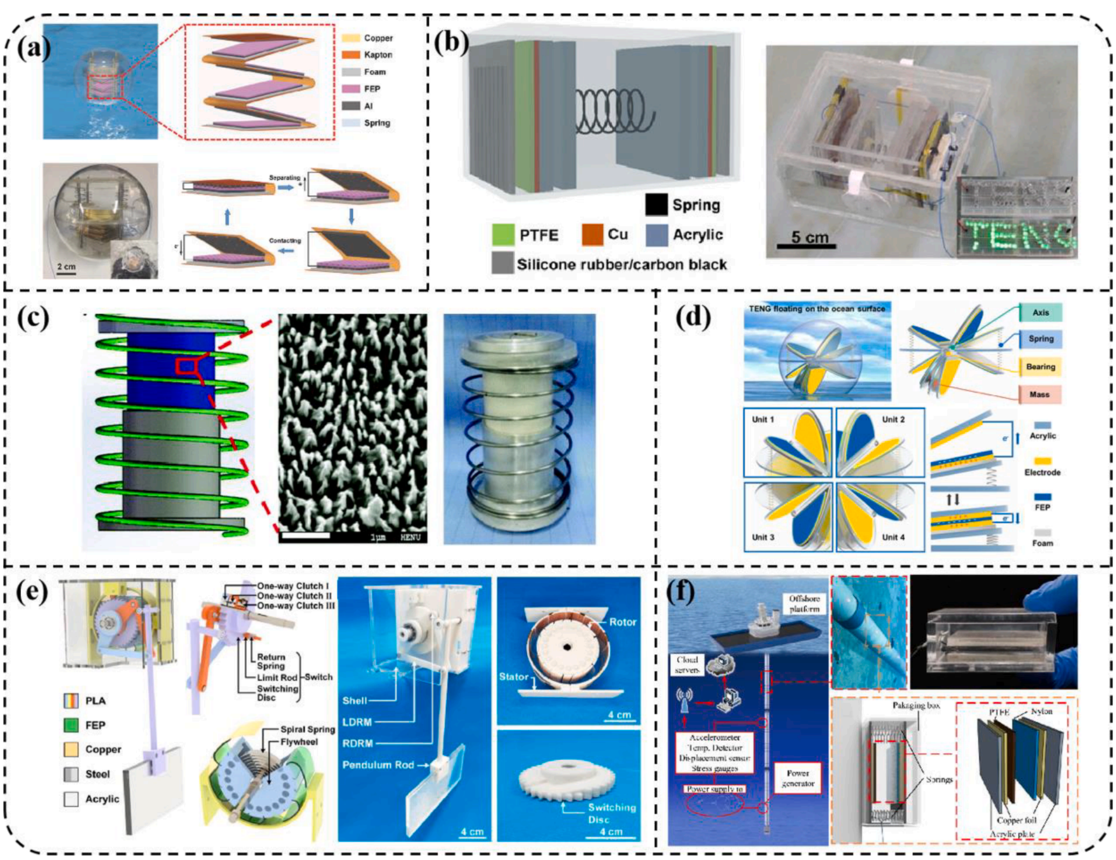

Fig. 5. Spring structure TENG. (a) Schematic diagram of the spring-based spherical TENG structure [60], (with permission from Wiley). (b) A silica-based spring-aided TENG structure for waves energy collection [61], (with permission from American Chemical Society). (c) Sketch map of the hybrid triboelectric-electromagnetic spring-assisted nanogenerator [62], (with permission from Royal Society of Chemistry). (d) Spherical TENG structure coupled with pendulum and spring structure [64], (with permission from Elsevier). (e) TENG structure is designed with a pair rocker structure to harvest extremely low frequency water wave energy [66], (with permission from Elsevier). (f) Contact-separation TENG structure for collecting energy from the vibration of marine pipelines [67], (with permission from Multidisciplinary Digital Publishing Institute).

energy[60], as illustrated in Fig. 5(a). The spring structure inside the spherical shell can convert the slow wave into high-frequency vibration, thereby increasing the output effect of the TENG. Fig. 5(b) demonstrates a silicone-based spring-aided TENG that combines the advantages of spring structures and flexible electrodes[61]. The silicone rubber/carbon black electrode replaces the traditional pure copper electrode and further increases the area for charge transfer to enhance the surface density of the triboelectric material. Driven by waves, the TENG can generate a power density of 2.4 W/m^3, which fully demonstrates the superiority of the structural design of this TENG. Wang et al. developed a unique structurally designed EMG-TENG hybrid nanogenerator[62], as shown in Fig. 5(c). The spring force makes the EMG and TENG operate. During the back-and-forth sliding process, the two energy harvesting units work simultaneously, effectively increasing the power generation performance. To increase the operating bandwidth of TENGs, Bhatia et al. proposed an all-in-one tandem TENG, which adopted a novel continuous collision structure(CIT-TENG)[63]. The CIT-TENG consisted of four layers of TENG, with spring connections between each layer. When an external force moves a TENG, other adjacent TENGs will also work due to the cascading influence. The frequency conversion structure composed of two vibration systems solves the problem that typical TENGs cannot continuously scavenge vibration energy.

Integrating the characteristics of the spring structure and the swing structure, Liang et al. fabricated a spring-assisted swing structure TENG [64], as illustrated in Fig. 5(d). Triggered by waves, the sphere is driven to swing by external forces. At the same time, the spring increases the swing frequency by limiting the swing height to achieve the purpose of increasing the output power. Wang et al. proposed a regular tetrahedron-based TENG structure[65]. The structure consists of a small tetrahedron nested inside a large tetrahedron, and the vertices of the inner and outer regular tetrahedrons are connected by springs. The innovation lies in using surface contact to replace the regular point contact or soft contact in the closed structure, which overcomes the phenomenon that the output performance of TENG is limited due to the small contact area, and finally obtains excellent output performance. Fig. 5(e) shows a schematic diagram of the dual rocker TENG structure for energy collection from intermittent reciprocating motion[66]. The pendulum structure stores the vibrative energy collected from the water waves in the spring via the transmission structure. The accumulated energy drives the flywheel to rotate when the switch disk is turned on, and the TENG device operates. The clever cooperation between the switch structure, flywheel structure, and spiral spring converts intermittent water wave energy into controllable electrical energy. This configuration is capable of generating an open circuit voltage of 450 V. Li et al. attached the TENG to the surface of the ocean pipeline[67], which can efficiently harvest the mechanical energy of the vibrating pipeline, as displayed in Fig. 5(f). When the TENG is excited by the ocean current, the pipeline bends along the flow direction, causing the friction material to contact and separate under the force. This novel design not only realizes the effective harvesting of the vibration energy of the marine pipeline but also solves the power supply problem of the pipeline monitoring system.

The advantage of the spring structure is that it can respond quickly to external shocks and increase the vibration frequency. However, the problem with this spring structure is the durability problem related to friction and wear. The key to solving this problem is to improve the material's durability.

Multilayer structure TENG

In the previous design of fully enclosed TENG structures, many

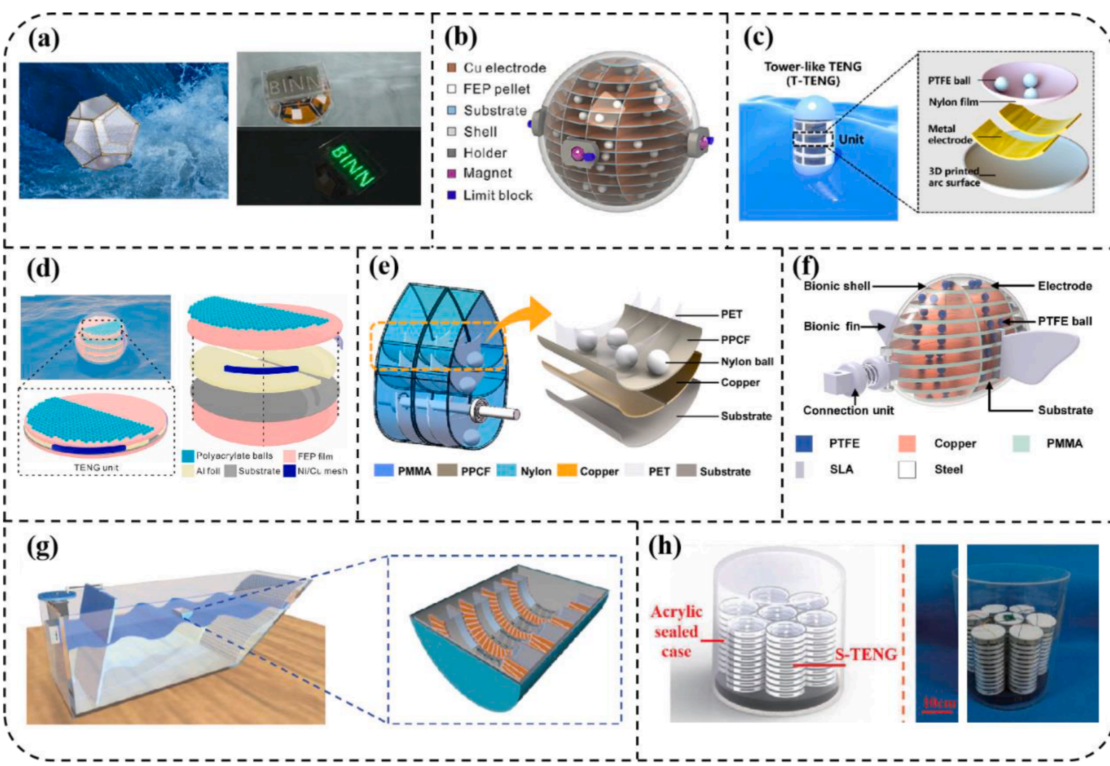

Fig. 6. Multilayer Structure TENG. (a) Schematic diagram of a dodecahedron closed structure device integrating 12 sets of multi-layer wave structure TENG [68], (with permission from Elsevier). (b) Schematic diagram of a closed high-performance spherical TENG [69], (with permission from Elsevier). (c) High-power TENG structure inspired by tower shape [70], (with permission from American Chemical Society). (d) Schematic illustration of a spherical TENG with dense point contacts for collecting waves energy in arbitrary directions [48], (with permission from American Chemical Society). (e) A three-layer multi-track freestanding TENG schematic diagram simulates a duck structure's design [71], (with permission from American Chemical Society). (f) Three-dimensional fully enclosed TENG with the bionic fish structure harvests hydrokinetic energy [72], (with permission from Springer). (g) Arc TENG Based on Internal Rolling Structure [73], (with permission from Wiley). (h) Schematic diagram of stackable TENG [74], (with permission from Author).

designs were wasted due to a lack of reasonable space planning. The advantage of introducing a multi-layer structure into a TENG is that it can make full use of the space utilization and further boost the output power of the TENG.

Zhang et al. designed a multi-layer wavy structure TENG[68], which is a dodecahedral device, as shown in Fig. 6(a). It integrates 12 groups of TENG units with a multi-layer wave structure. The structural design of the dodecahedron can face water waves in any direction and achieve omnidirectional water wave energy harvesting through the impact of the internal mass ball on the TENG unit. Experiments show that a separate WS-TENG unit can measure an output voltage of 250 V. Fig. 6 (b) demonstrates an encapsulated high-performance spherical TENG [69]. The sphere's interior is layered, and each layer integrates multiple TENG units, which maximizes the problem of space utilization. Inspired by the tower-like structure, Xu et al. produced a high power density TENG[70], as illustrated in Fig. 6(c), which can collect ocean energy from arbitrary directions. Each layer of this tower-like triboelectric nanogenerator (*T*-TENG) is composed of PTFE balls and curved surfaces covered with nylon films. The *T*-TENG is completely encapsulated in a waterproof case, which enables multi-directional water wave collection while addressing the effects of dielectric shielding and humidity. Based on the spherical structure, Yuan et al. improved and designed a spherical TENG with dense point contact[48], as shown in Fig. 6(d). The ingeniousness of this structure is that multiple small PA balls are used to increase the point contact frequency while providing appropriate space for the small balls to increase the power density.

As illustrated in Fig. 6(e), Liu et al. combined a multi-track directional structure with a TENG and proposed a three-layer multi-track TENG with a nodding duck structure[71]. The ingenious design of the multi-track avoids frictional energy loss caused by disordered motion and realizes stable and efficient power output. Jing et al. designed a biomimetic fish-like fully enclosed TENG (FE-TENG) [72]. FE-TENG combines the multi-layer structure with the biomimetic fish-like structure, as shown in Fig. 6(f). This structure can overcome the low-velocity water flow energy harvesting in shallow water and utilize the fins and body features to maintain the balance in flowing water to collect wave kinetic energy in a more coordinated posture efficiently. Fig. 6(g) shows an arc-shaped structure TENG[73], which utilizes an inner rolling structure to collect wave energy. Stable power output can be reached by integrating TENG to form a multi-track structure while improving space utilization. In Fig. 6(h), Dong et al. fabricated a stackable TENG (S-TENG) [74]. The S-TENG consists of 10 TENG layers stacked together. Integrating the S-TENG with the buoy can solve the buoy power supply problem, and self-powered ocean monitoring is realized. Based on the stackable structure, after Wang et al. optimized the multi-channel and multi-layer structure, the internal space of the TENG is more fully utilized [75]. The optimized TENG peak power reaches 49 W/m^3, which is 29 % higher than the previous one, and demonstrates excellent power supply capability on ocean sensors and buoys.

The most prominent feature of the multi-layer structure is that it realizes the full utilization of space and, at the same time, guides the inner moving sphere to move with a relatively efficient trajectory, improving the output power of the TENG.

Bionic structure TENG

In nature, many creatures have unique and intriguing structures, and these ingenious and rational structures are gradually being recognized and utilized by people. Researchers usually look for inspiration from biological structures to develop TENG structures with higher output power.

Inspired by the efficient hydrodynamic structure of ducks, Ahmed et al. created a completely enclosed duck-shaped TENG for efficient harvesting of random wave energy[76]. After waves impact the duck-structure TENG, its center of gravity property enables the device to return to its original position. Coupled with its fully enclosed feature, it can show high efficiency even in harsh environments. Experiments show that the power generation efficiency of the new duck-shaped structure TENG can reach 39.1 %. Subsequently, Ahmed et al. further optimized the radius and weight of the duck structure through theoretical research to improve the power generation performance[77]. Liu et al. improved the initial duck structure and added a three-layer multi-track structure internally to avoid mutual influence between TENG units[71]. In addition, the mismatch between the natural frequency of TENG and the wave frequency is solved by adjusting the swing amplitude, which further stimulates the power generation potential of TENG. Chen et al. fabricated a biomimetic jellyfish TENG (BJ-TENG) utilizing a unique elastic rebound structure[78], as shown in Fig. 7(a). It drives the TENG to work by the pressure difference created by moving up and down in the water. The magnetic elastic rebound structure is designed by imitating the characteristics of jellyfish, which overcomes the problem of the low sensitivity of the self-powered water surface fluctuation sensor system and realizes the continuous monitoring of water level and fluctuation.

Due to the flexibility and lightness of the sea snake structure, Zhang et al. manufactured a TENG combining the sea snake structure [79], as shown in Fig. 7(b). The segments are connected by springs for easy flexing, and the inner sphere responds quickly to movement, resulting in higher power output. The air gap structure is used in the design of TENG, which minimizes the electrostatic induction of ions in seawater and solves the effect of the medium on the equipment capability. The maximum power density of TENG can reach 3 W/m^3. Fig. 7(c) shows a kelp-inspired biomimetic TENG[80]. The TENG comprises vertically independent polymer strips and blades fabricated from flexible materials. Its working principle is to simulate the movement of kelp on the seabed, using the ocean current to trigger its blades to swing gently, and the adjacent blades will contact and separate after being stressed. This structure provides an efficient solution for harvesting low-frequency ocean currents and operates stably even at vibration frequencies as low as 1 Hz. In Fig. 7(d), Lei et al. designed a spring-assisted four-link TENG (B-TENG) inspired by butterflies[81]. The advantage of the curved shell is that it can effectively absorb the impact of waves. B-TENG can achieve multiple contact separation actions under one external excitation. The ingenious design of the flower-like TENG structure (FL-TENG) enables six degrees of freedom wave energy collection[82], as displayed in Fig. 7(e). The water wave will continue to trigger the two actions of stretching and folding, driving the FL-TENG to work. FL-TENG can be triggered under different motion forms, such as swing, rotation, and translation, which solves the problem of inefficient energy harvesting in the variable ocean environment.

As illustrated in Fig. 7(f), Zhang et al. fabricated a biomimetic fin structure-assisted multi-layer TENG [85]. Benefiting from the motion control structure of the bionic fin, the TENG can achieve efficient energy harvesting of multi-directional water waves, achieving a maximum power density of 444 W/m^3. To avoid the problem of device energy dispersion caused by the introduction of three electrodes, the bionic fish scale-like TENG (FSL-TENG) was manufactured by Ma et al. [83]. Owing to the regular symmetrical arrangement of the fish-scale structure and the curved structure of the electrodes, the FSL-TENG can smoothly capture the energy generated by the rotational motion and mechanical activity in any direction. Jing et al. proposed a biomimetic fish-like 3D fully enclosed TENG[72]. By imitating the swaying state of fish in water, the non-ideal posture of the TENG device in flowing water is corrected, ensuring that energy is always collected in a perfect posture. Inspired by the arrangement of fish gills, Yin studied a parallel-cell TENG(PC-TENG) [84], as shown in Fig. 7(g). The previous battery series connection method has a large total volume, which will cause the volume power density to decrease. PC-TENG provides a solution for parallel-cell arrangement, successfully reducing the electrical interference between cells by 64.5 %, while increasing the volumetric power density by 8 times, reaching 143.7 W/m^3. Besides, there are many excellent biomimetic structures, including honeycomb three-electrode TENG[86], open-book TENG[87], and seesaw-like hybrid TENG[6].

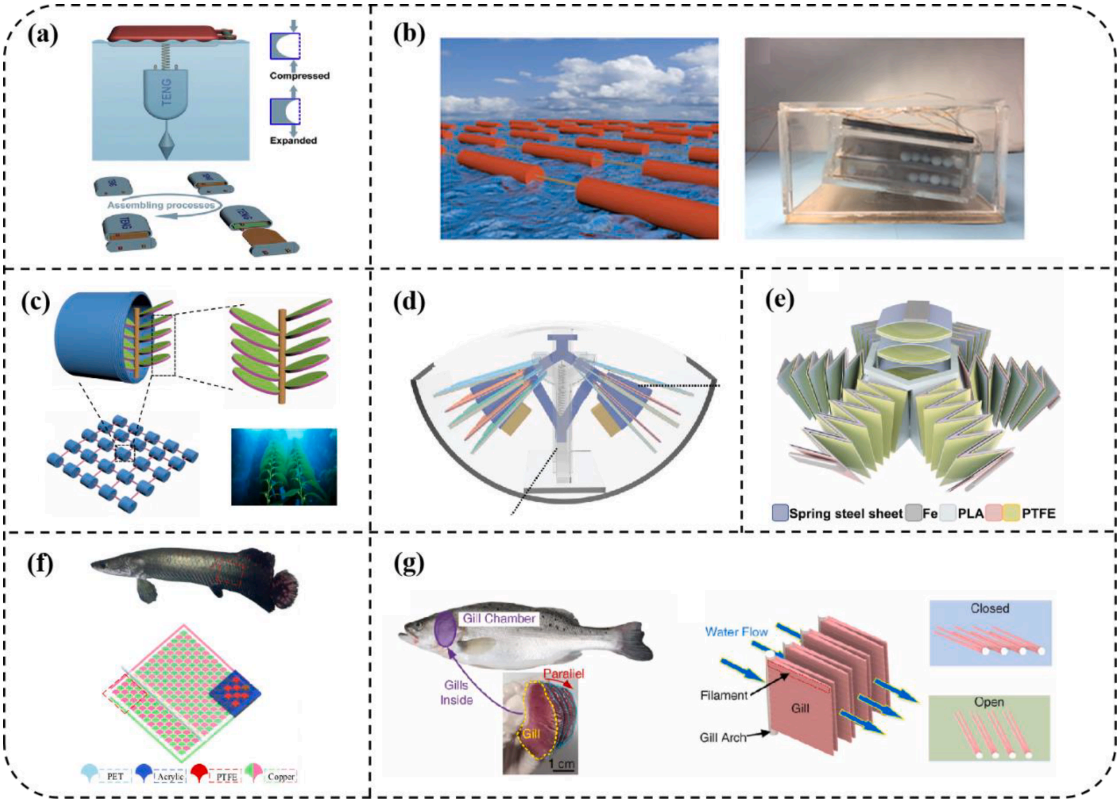

Fig. 7. Bionic Structure TENG. (a) Sketch map of the biomimetic jellyfish TENG with unique elastic rebound structure [78], (with permission from Elsevier). (b) Schematic diagram of TENG based on sea snake structure [79], (with permission from Elsevier). (c) Schematic diagram of a kelp-inspired bionic kelp TENG [80], (with permission from Elsevier). (d) Spring-assisted four-link structure TENG harvests water wave energy [81], (with permission from Wiley). (e) Flower-like TENG collects kinetic energy with six degrees of freedom [82], (with permission from Elsevier). (f) Schematic diagram of the bionic fish scale structure TENG [83], (with permission from Elsevier). (g) Schematic diagram of a parallel battery TENG inspired by fish gills[84],(with permission from Elsevier).

Diverse structures in nature are often a source of design inspiration. In biomimetic design, we need to imitate creatures in shape and function and integrate these excellent structures into the TENG design to achieve higher power density. Although TENG has many advantages, it also has disadvantages, such as relatively complex structure and cumbersome fabrication process. The bionic structure TENG has achieved an exemplary power generation effect. Thus, bionic TENGs have colossal development space in the future.

EMG-TENG hybrid OEH structures

TENG has high voltage and high impedance, while electro-magnetic generator (EMG) has high current and low impedance, which is EMG's strength. The advantage of TENG is that EMG is difficult to work at low frequency, but TENG can work. This conclusion was demonstrated by Zi et al. with a low-frequency mechanical energy harvesting system of TENG and EMG [88]. For water wave frequencies below 3 Hz, the energy harvesting efficiency of TENG is much greater than that of EMG. The combination of TENG and EMG through a reasonable structural design integrates the respective advantages.

A triboelectric-electromagnetic generator based on magnetic spheres was proposed to capture water wave energy by Wu et al. [89], as displayed in Fig. 8(a). Tai Chi-shaped electrodes are used in the structure to reduce the influence of water waves in the direction. Wang et al. designed the hybrid nanogenerator based on the optimized cubic structure and used different topological devices to promote the TENG's output performance [90]. This effectively solves the problem of low energy harvesting efficiency due to the inability of TENG and water waves to move and operate simultaneously. As displayed in Fig. 8(b), Gao et al. designed a hybrid generator with a spinning top structure based on the triboelectric-electromagnetic working principle[91]. This gyroscopic rolling mode has high sensitivity and robustness, which not only makes up for the shortcomings of low sensitivity and high frictional resistance but also solves the limitation of unidirectional motion. It can efficiently remove the wave energy of irregular vibrations. Fig. 8(c) shows a pendulum-structured hybrid nanogenerator [92]. An aspherical magnet is used in the hybrid generator, which can change the center of gravity to respond to wave shocks quickly. Meanwhile, the isolation design between TENG and EMG reduces friction loss. He et al. constructed a 3D full-space hybrid nanogenerator (FSHG) [93], as shown in Fig. 8(d). Under external excitation, the FSHG can translate it into relative motion between different units inside. This complementary operation mode can effectively improve the energy loss when TENG collects energy and shows an excellent output effect in the face of different vibration directions and frequencies. The collected energy can successfully light up 200 LEDs.

Feng et al. put forward a hybrid nanogenerator based on a pendulum structure[94], which consists of a soft-contact cylindrical TENG and an EMG with a pendulum structure, as illustrated in Fig. 8(e). The innovative use of flexible rabbit hair brushes in TENG can significantly reduce the rotational resistance to increase the triboelectric charge density while improving device durability. A similar structure was proposed by Zhao et al. [95], combining a multi-layer soft-brush cylindrical TENG and an undulating point absorber-based waves energy converter (WEC), as shown in Fig. 8(f). Magnetic coupling isolates the TENG from the exterior environment, ensuring smooth output characteristics. This structure has the advantage of low wear and high performance. Zheng et al. fabricated a hybrid wave energy harvester with an oscillating magnetic structure for harvesting multi-directional wave energy[96], as demonstrated in Fig. 8(g). The coil at the bottom is used

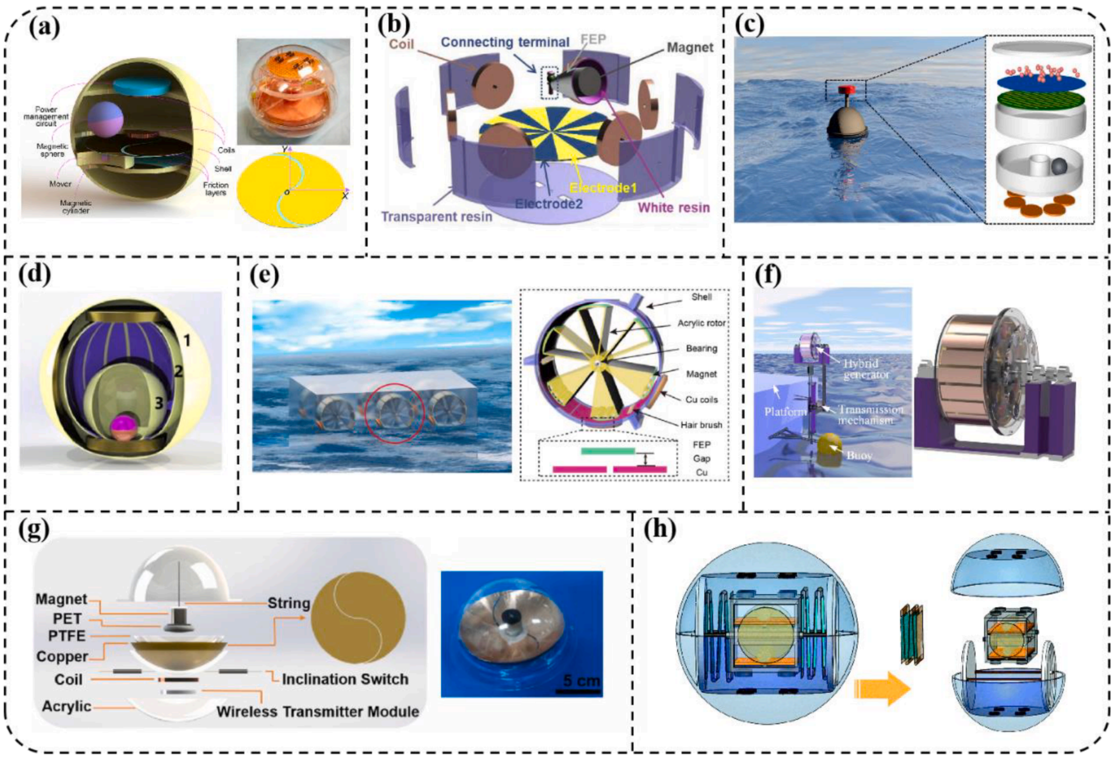

Fig. 8. Composite TENGs. (a) Sketch map of a hybrid triboelectric-electromagnetic generator based on magnetic spheres [89], (with permission from American Chemical Society). (b) Schematic diagram of a mixed generator with a spinning top structure [91], (with permission from Elsevier). (c) A pendulum-structured hybrid nanogenerator collects wave energy [92], (with permission from American Institute of Physics). (d) Sketch map of the 3D full-space hybrid nanogenerator [93], (with permission from Elsevier). (e) Hybrid nanogenerators based on oscillating structures harvest water wave energy [94], (with permission from Elsevier). (f) Schematic diagram of multi-layer soft brush cylindrical hybrid generator [95], (with permission from Elsevier). (g) Hybrid generator with oscillating magnetic structure [96], (with permission from Elsevier). (h) Schematic diagram of spherical hybrid generator with self-powered seesaw structure [98], (with permission from Royal Society of Chemistry).

to remove the magnetic energy in the permanent magnet process. The introduction of the magnet swing structure and the Tai Chi-shaped electrode is beneficial to improving the output performance. In the simulated wave environment at 1.75 Hz, the output voltages of EMG and TENG reached 5.3 V and 90 V, respectively. Liu et al. invented a hybrid triboelectric-electromagnetic nanogenerator utilizing the nodding duck [97]. In practical applications, a high-voltage management circuit is designed, which solves the coupling problem of effective water wave energy harvesting caused by different periods and phases of TENG and EMG, and further improves the coupling output power of TENG and EMG. As shown in Fig. 8(h), Hong et al. proposed a spherical triboelectric-electromagnetic hybrid nanogenerator by integrating multiple operation modes and designing a self-powered seesaw structure [98]. The central module of the stainless steel shaft can merge contact separation and horizontal sliding movement to realize the coordinated operation of the three modules. While making full use of the internal space, it is also necessary to consider the impedance mismatch between the hybrid nanogenerator and the energy storage capacitor. To solve this problem, Hong et al. designed a transistor-controlled power management circuit that increases the charging rate.

The EMG-TENG hybrid OEH structure combines the advantages of each to improve output performance. However, this hybrid structure also has disadvantages. The magnet will increase the overall weight, reducing the entire device's flexibility to a certain extent. Overall, the hybrid OEH structure has excellent application prospects.

OEH-TENG network structures

The power generated by a single TENG is limited after all. Wang proposed integrating multiple TENG units to enhance further the output power to construct a TENG network for large-scale blue energy collection [99], as depicted in Fig. 9(a). According to theoretical calculations, the TENG network (TENG-NW). It performs well and can generate a power of 1.15 MW from 1 km^2 marine area [100].

Liang et al. designed a hexagonal TENG network based on the spring-assisted multilayer spherical TENG[101], as illustrated in Fig. 9(b). The integration of TENG and PMM can generate a stable DC voltage, which solves the problem of inefficient charging of capacitors. Fig. 9(c) displays a buoy-like network structure fabricated with 18 LS-TENG units [102], which can harvest low-frequency energy from movements such as shaking and rotation. LS-TENG combines the advantages of liquid-solid contact mode and buoy structure to solve the low utilization of vibration energy. A single trigger from the outside world can generate multiple consecutive signals. The LS TENG network has an excellent performance in energy harvesting and a wide range of applications in metal anti-corrosion and other fields. Zhao et al. presented a TENG integrated by networked[35]. Benefiting from the highly adaptive design and surface treatment of dense nanowire arrays in the TENG network, the problem of low TENG efficiency caused by random water waves is effectively avoided. Wu et al. paralleled 34 wt-TENG tube units and sealed them in a box [42]. In the design, deionized water is selected as the friction material, which not only solves the problem of the contact tightness of the friction material but also improves the wear problem of the material surface. The WT-TENG unit was integrated with the TENG network and tested in natural ocean waves, and the collected energy successfully lit 150 LEDs.

The way the TENG units are connected plays a vital role in the power output. Three standard methods include magnetic connection, rigid connection, and flexible connection. As presented in Fig. 9(d), Yang et al. designed a self-adaptive magnetic joint (SAM-joint) to connect the

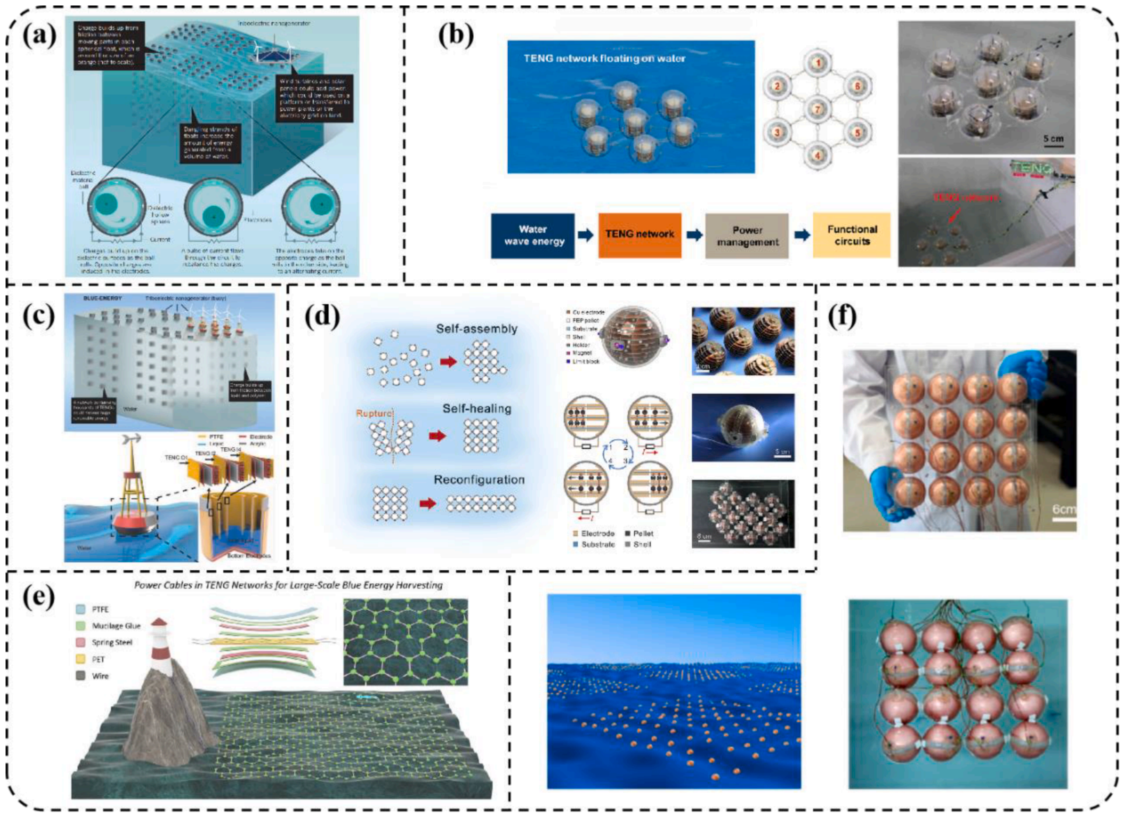

Fig. 9. TENG Network. (a) TENG network has a large-scale collection of ocean energy harvesting ideas [99], (with permission from Springer). (b) Sketch map of a hexagonal network composed of a spring-assisted spherical TENG structure [101], (with permission from Wiley). (c) Buoy-like TENG network based on liquid-solid contact to collect blue energy [102], (with permission from Wiley). (d) TENG network is composed of adaptive magnetic joints with self-healing ability [69], (with permission from Elsevier). (e) Conceptual diagram of the application of a cellular TENG network consisting of a connection topology for ocean energy harvesting [103], (with permission from Elsevier). (f) Schematic diagram of rigid and flexible network based on 4×4 array of spherical structure [52], (with permission from American Chemical Society). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

TENG units[69]. In practical tests, the network exhibits a self-healing ability to re-adsorb after adjacent cells are disconnected. Since the network is easy to reconfigure and self-heal, the independence and robustness of the system are greatly improved. A network of 4×9 arrays network can quickly light up 300 LEDs, power thermometers, and wireless transmitters. Liu et al. assembled a rigid network array with a honeycomb connection topology via cable connections[103], as shown in Fig. 9(e). The rigid cable can prevent the tangle between the TENG units, prevent the collision between the TENG units, and affect the output. As shown in Fig. 9(f), Xu et al. fabricated 4×4 arrays of rigid and flexible networks based on TENG's spherical structure [52]. Through experimental comparison, it is found that the rigid connection can act as a constraint to make the unit move in a relatively synchronous manner. The flexible connection is relatively flexible, has additional internal degrees of freedom, and is highly responsive to slight waves. All in all, the optimized coupled TENG network solves the dilemma of the low output charge of a single TENG, and the output efficiency is greatly improved.

In the future, the OEH-TENG network is expected to be an important way to harvest blue energy. Millions of TENG units will be connected by cables to form an OEH-TENG power generation network, which can float on the ocean surface to collect wave energy and increase the load to maintain it at a certain depth to collect ocean current energy. At the same time, networks floating on the ocean surface can be combined with wind and solar energy harvesting devices to increase access to energy and improve the robustness of continuous energy harvesting. The energy harvested by the OEH-TENG network can be stored in a battery energy management system to power small devices in the ocean. A small distributed OEH-TENG network can be set up around electronic devices such as buoys and ocean sensors to solve the power supply requirements. In addition, the collected electricity can be transferred to a nearby land grid by submarine cable. Overall, the OEH-TENG network provides a way to realize the blue energy dream, which we hope can be realized soon.

Challenges and discussion

Since the theory and method of TENG were proposed, significant progress has been made after more than ten years of development. In applying TENG technology to the development and application of ocean energy, researchers have studied many ocean energy harvesting devices and systems with different structures based on different TENG theoretical models, as shown in Table 1. After fruitful analysis and design improvement, the proposed ocean energy harvesting system has dramatically improved the energy conversion efficiency. Through a review of the research literature in recent years, we believe that several research directions still need to be broken through and resolved.

1. Although a series of ocean energy harvesting devices with superior performance have been proposed, there is still a lack of general models and theories for ocean energy conversion analysis as a guide for system design and performance optimization. In the study of TENG in liquid-solid contact mode, Wang et al. applied the general theoretical formula of energy conversion of TENG. They used the capacitance of TENG, the dielectric constant in a vacuum, the thickness of the film, the distance between the two electrodes, and the electrode area as the influencing factors[24]. However, the effect of waves on the output performance of the system is not introduced

Table 1
Summary of performance output of various structural TENGs in OEH.

Structure	Author	Tribo-layer	Electrode	Open-circuit voltage(V)	Short-circuit current(μA)	Power (density)/Load resistance	Application
Liquid-Solid contact TENG	Zhao et al.[35]	PTFE	Au	—	13.5	1.03mW 22 MΩ	Drive wireless transmitter
	Vu et al.[38]	PVDF	Cu	28.3	5.79	420 mW/m^2 20 MΩ	Light up 120 LEDs
	Wei et al.[39]	FEP	Cu	77	52nA	23.3 μW 500 MΩ	Light up 35 LEDs
	Wu et al.[42]	FEP	Cu	223	0.33	13.1 W/m^3 10 GΩ	Light up 150 LEDs
	Zaw et al.[43]	PDMS	Glass	70	2.4	16.75 W/m^3 50 MΩ	Light up 18 LEDs Power an anemometer
Spherical Structure TENG	Liu et al.[56]	FEP/PET	Cu	281	76	475 μW 8 MΩ	Charges 2.2 μF Capacitor to 5 V in 35 Seconds
	Liang et al.[22]	FEP	Cu	250	80	8.5mW 1 MΩ	Power digital thermometer
	Lin et al.[58]	PTFE	Cu	76	4.4	28 μW/100 MΩ	Light up 80 LEDs
	Yuan et al.[48]	PA/FEP	Al	300	15.5	10.7mW 300 MΩ	Light up 350 LEDs/ Power a timer
	Rodrigues et al.[57]	Nylon6/6 PTFE	Ag	14.6	2.8	230 μW 10 MΩ	Power sensor
Spring-Assisted Structure TENG	Tian et al.[61]	PTFE	Cu	630.7	22.3	3.47 mW/m^2 20 MΩ	Light up 65 LEDs
	Tian et al.[60]	FEP	Al	560	120	15.2 W/m^3 2.21 MΩ	Power thermometer
	Liang et al.[64]	FEP	Cu	419	56.7	4.1mW 10 MΩ	Power wireless signal transmission system
	Wang et al.[65]	PTFE	Al	200	30	14.7mW 10 MΩ	Light up 20 LEDs
Multilayer Structure TENG	Yang et al.[69]	FEP	Cu	—	5.2	32.6 W/m^3 1 GΩ	Light up 300 LEDs
	Xu et al.[70]	PTFE/Nylon	Al	105	5.8	10.6 W/m^3 500 MΩ	Light up 540 LEDs
	Liu et al.[71]	PET/Nylon	Cu	507	1.92	4 W/m^3 800 MΩ	Light up 320 LEDs
	Ren et al.[73]	PTFE	Al	130	9	2.34 W/m^3 40 MΩ	Power thermometer
	Wang et al.[75]	PTFE	Al	—	49	49 W/m^3 250 MΩ	Light up 350 LEDs
Bionic Structure TENG	Ma et al.[83]	PET/PTFE	Cu	63	6.2	175.13 μW 10 MΩ	Light up 30 LEDs
	Jing et al.[72]	PTFE	Cu	520	4.3	7 W/m^3 1000 MΩ	Light up 67 LEDs
	Wen et al.[82]	PTFE	Fe	251	32	31 W/m^3 1MΩ	Light up 400 LEDs
	Yin et al.[84]	Nylon/ Teflon	Al	143	25	143.7 W/m^3 8.8MΩ	Light up 20 LEDs
EMG-TENG Hybrid OEH Structures	Feng et al.[94]	FEP	Cu	640	4.57	2.71 W/m^3 150MΩ	Light up 60 LEDs
				2.9	11.9 mA	7.45 W/m^3 300 Ω	
	Zhao et al.[95]	PTFE	Cu	2600	78	19.2 W/m^3 8 MΩ	Light up 10,080 LEDs
				2.5	30 mA	11.5 W/m^3 100 Ω	Light up 648 LEDs
	Zheng et al.[96]	PET/PTFE	Cu	90	0.61	0.26mW 40 MΩ	Power wave height alarm system
				5.3	6.4 mA	6.2mW 700 Ω	
	Hong et al.[98]	PDMS/ Nylon	Ag	889	1.66	17 W/m^3 10 MΩ	Light up 410 LEDs
				0.78	14 mA	9.6 W/m^3 180 Ω	

into the formula. Through the forced motion analysis of the Flag in water, the influence of various kinetic parameters immersed in flowing water on the critical velocity of the UF-TENG was determined. This method can only optimize the structural parameters and has not conducted in-depth research on the theoretical formula of energy conversion. In the research of fully enclosed TENG, spherical TENG has the characteristics of simple structure and sensitive response to external wave motion and has received extensive attention. Xu et al. used COMSOL software to simulate the electric potential distribution generated by the relative movement of the ball on the friction surface[70]. They did not propose a macroscopic voltage and current conversion formula and did not test the effectiveness of the proposed method. Furthermore, the author assumes that multiple balls in the same arc surface move in the same phase, and the conclusions proposed in low-frequency, one-way periodic wave motion are applicable. However, under the action of high frequency or multidirectional waves, wind, and water currents, the assumption of in-phase motion of multiple balls will no longer apply, and the joint motion and collision of the balls will affect the output of TENG.

2. TENG energy conversion devices need to operate stably for the long term in the harsh ocean environment, which puts forward very high requirements for the stability of system materials and structural reliability. The polymer materials used in the device tend to change their energy characteristics under the combined action of high salinity and high humidity. Moreover, the device floating on the sea will also be affected by sunlight, wind, and waves. Structures that work in the ocean for a long time are subject to the attachment of marine organisms, which may have a fatal impact on the performance of TENG in liquid-solid contact. Therefore, the material selection and hermeticity of the device are critical. In the production process, corrosion-resistant and high-strength waterproof materials can be selected to prolong the service life of the TENG. In liquid-solid contact TENG, the electrode material will be in direct contact with seawater, and while the contact area increases, the impact on the material itself is correspondingly greater. For electrode materials with nanostructured surfaces[33,104–106], the ocean energy conversion efficiency of the device will be significantly reduced. In a closed TENG, the sealed shell acts as a barrier against sea water [49,72,107]. After sea creatures attach the shell, the motion response of the device under the action of waves will also be affected.
3. The application of TENG to power distributed ocean sensors has achieved great technical success. However, there is still no substantial technological breakthrough in the macro energy available for human use. TENG technology is applied to ocean energy harvesting, and the technical advantage is that small-scale devices can achieve efficient collection of low-frequency ocean energy. Then, we have two ideas to increase the magnitude of energy conversion. First, the efficiency of system energy conversion is achieved by increasing the scale of a single TENG device. The proposed large-scale TENG system needs to be more advantageous than the currently widely used wave energy devices or wind power devices in terms of construction, maintenance, and efficiency to have commercial promotion value. The second method is to use small-scale TENG devices to centrally store and transmit the energy collected by each device in a networked manner. Improving small-scale energy transfer and conversion efficiency will be an essential research topic with the increasing number of distributed TENG units.

Summary and future trends

The review summarizes the latest progress of TENG technology in ocean energy collection. The paper introduced the design methods of TENG devices with different structures, including liquid-solid contact TENG, fully enclosed TENG, bionic structure TENG, composite TENG, and TENG network. The advantages and disadvantages of each device are emphasized, and the improvement measures are optimized based on each device to enhance the output performance. TENG can be applied to the power supply of small electronic devices, self-powered sensors, and buoys, showing excellent application value. As a new clean energy technology, TENG has great application potential in ocean energy harvesting and is expected to contribute to the realization of large-scale, efficient utilization of ocean energy.

In future research, one crucial research trend is establishing a general model and theory of ocean energy harvesting to guide energy harvesting system design and performance optimization. Based on the general existing TENG theory, the dynamic characteristics of the marine environment and the interaction of structural parameters should be fully considered, and the theoretical formula of energy conversion should be established and studied in depth. In order to collect ocean energy on a large scale, establishing a TENG network to enhance the ocean energy conversion capability of the system will be another essential research content. Here, it is necessary to focus on the efficiency and durability of a single TENG node. At the same time, it is necessary to consider the issues of energy storage and conversion efficiency after multiple nodes are connected to a network to avoid the loss of the collected trace energy on the transmission line. Going further, it will have an extensive prospect to apply TENG technology to marine devices with long endurance requirements. TENG technology will play an important role in energy conversion systems such as wave gliders, underwater buoys, and ocean bottom systems. Combining traditional ocean energy harvesting methods with TENG technology will significantly improve the efficiency of system energy acquisition per unit time. In this case, these marine devices can better adapt to the changing marine environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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