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Review

Triboelectric and electromagnetic hybrid generators for ocean energy harvesting

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ABSTRACT

Ocean energy is becoming increasingly important as a promising renewable energy source in modern society. Therefore, how to efficiently harvest ocean energy has attracted extensive research attention. In recent years, hybrid nanogenerators consisting of triboelectric and electromagnetic generators (TEHNGs), which compensate for the deficiency of energy conversion efficiency of single type generator, has been proposed and provided a promising way to harvest ocean energy effectively. Therefore, this review provides a comprehensive and in-depth analysis of TEHNGs from the structural design perspective. The characteristics including structural design, material selection, output performance, etc., of the four types TEHNGS are systematically summarized for the first time. The operating characteristics of TEHNGs with different structures in the ocean are elaborated in detail, as well as the significant influence of structural design on the output power of TEHNGs. In addition, the application scenario, environmental adaptability, and mutual assistance between TENG and EMG are discussed deeply. Finally, the existing challenges and development orientation in the aspects of structure design, materials, power management, durability and stability, and large-scale development, of the TEHNGs are put forward. It is believed that this work will be a significant reference for researchers in relevant field and conducive to the development of the TEHNGs in efficient ocean energy harvesting.

1. Introduction

Ocean energy, as a renewable energy source resource [1–3], is regarded as one of the most promising clean energy sources. According to reports, the global ocean energy potential values at 32 TW, which is equal to 18 million petroleum equivalent per year [4–6]. Ocean energy, including wave energy and ocean current energy, have the characteristics of high energy density, stable output power, and wide distribution range [1] as well as wide development prospects [7,8]. Through highly efficient energy conversion technology, wave and ocean current energy can be harvested and converted into electricity [9–12], thus changing the global energy structure and alleviating the growing energy crisis and environmental pollution [13]. Therefore, ocean energy harvesting technology, which obtains energy from the marine environment to generate electricity, has become a research hotspot. Researchers have proposed various energy harvesting technologies for ocean energy harvesting [14], such as electromagnetic generator (EMG) [15], piezoelectric nanogenerator (PENG) [16,17], triboelectric nanogenerator (TENG) [18–20], etc. These different technologies have promoted significant progress in ocean energy harvesting.

EMG is highly efficient in converting mechanical energy into electrical energy with high current, high frequency response and excellent output power. Generally, most of the traditional EMGs for large-scale ocean energy harvesting are relatively complex and takes large space to achieve high output [21]. With the development of the Internet of Things (IoT) era [22–25], micro-nano distributed energy harvesting devices have received widespread attention, which raise challenges for the application of traditional EMGs for large amount of distributed power consumers [26,27]. Meanwhile, TENG stands out due to its simple structural design [28], low material cost [29] and stable power

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output [30–32]. Various methods have been proposed to improve the energy conversion efficiency of TENGs, such as optimizing structural design [33,34], power management circuits [35,36], and charge pumping [33,34,37]. However, low current and high internal resistance characteristics of the TENG still limit its application and hinder its further development in ocean energy harvesting. Moreover, it has been found that the energy harvesting efficiency of a single type of generator is still need to be elevated [38,39]. Structural optimization and hybrid of energy harvesting methods is treated as one of effective methods to solve the problem of insufficient output power of the system. Therein, hybridization of TENG and EMG is proposed and is expected to an effective method to improve ocean energy harvesting [35,40–42]. EMG and TENG are mutually complementary. The material selection and structure of TENG are broad and diversiform, which is capable of integrating well with EMG. At the same time, since the ocean serves as a low-frequency environment and EMG works effectively at high frequencies, the structure of the TEHNGs has to be developed in the direction of low-frequency adaptability. In which, TENG provides high efficiency and stability of power output under weak and low-frequency external excitation [43–46], and EMG has a high energy conversion efficiency under high-frequency external excitation. Therefore, HNG can combine the high efficiency of TENG at lower frequencies with the high efficiency of EMG at higher frequencies, broadening the frequency range for energy harvesting.

Although TENG and EMG are very different in terms of design and fabrication, the combination of the two can dramatically increase the efficiency of ocean energy conversion, and researchers are working to develop and design hybrid energy harvesters to harvest a wider range of environmental energy [47,48]. These hybrid energy harvesting devices are designed to simultaneously harvest energy from different sources and convert it to electrical output through various mechanisms [47,49,50]. Chandrasekhar et al. proposed a spherical hybrid generator (SB-HG) based on TENG-EMG for ocean energy harvesting and real-time position feedback [51]. Chen et al. designed a chaotic pendulum hybrid generator consisting of TENG and EMG units, designed according to the reciprocating motion of ocean waves and can effectively convert wave energy into electrical energy [52]. Zhu et al. proposed a highly integrated tubular triboelectric-electromagnetic wave energy harvester (TEWEH) with innovatively fabricated permanent magnet-polytetrafluoroethylene (PM-PTFE) spheres, which dramatically improves its energy harvesting efficiency [53]. By integrating two energy conversion technologies, they excel in harvesting ocean energy, and the flexible hybridization structure allows them to be more adaptable to variable marine environments [54,55]. Thus, the integration of TENG and EMG to develop a new hybrid energy harvester (TEHNG), which is capable of capturing ocean energy efficiently, has an extensive range of applications.

Recently, researchers have proposed a variety of advanced and efficient hybrid nanogenerators based on TENG-EMG. Therefore, the progress of ocean energy harvesting based on TEHNG need to be thoroughly summarized to promote the development in this field. To this end, a comprehensive review of the development and application of ocean energy harvesting based on TEHNG are outlined on basis of different structures. The advanced structural design allows the TENG and EMG to enhance each other, reducing the size of the unit while increasing the energy harvesting power. In this work, the structural design, material selection, working mechanism, and applications of various types of ocean energy harvesting devices are systematically reviewed. This work is structured as follows. Section 2 briefly describes two typical energy harvesting mechanisms, including EMG and TENG.

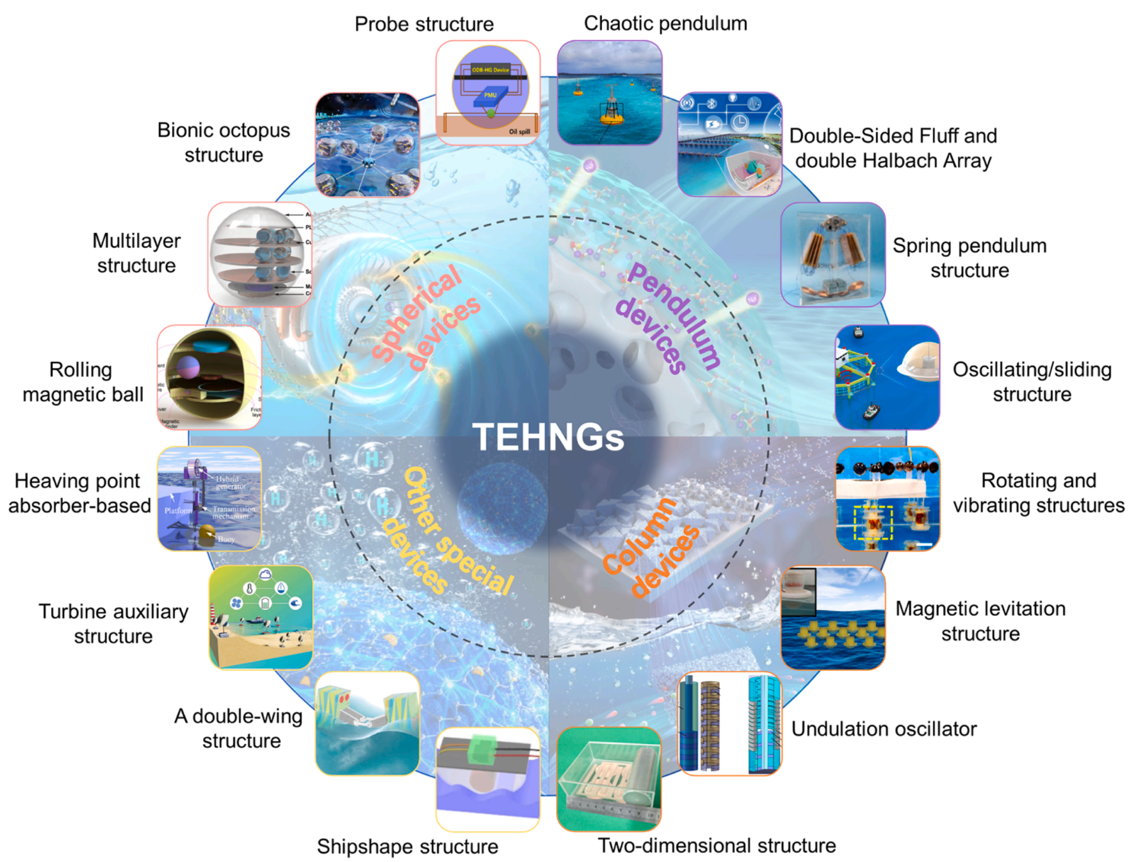

Fig. 1. TEHNGs with different structures, including spherical, pendulum, column and other special structures. Reproduced with permission Elsevier [40,52,56–59]. Reproduced with permission American Chemical Society [60,61]. Reproduced with permission Wiley [62–65]. Reproduced with permission Royal Society of Chemistry [66,67]. Reproduced with permission Springer Nature [68,69].

Section 3 reviews the advances of various types of hybrid generators in detail. As shown in Fig. 1, TEHNGs are mainly categorized into four different structures, including spherical, pendulum, column, and other specialized devices. Each structure of TEHNGs has different characteristics and each has its own advantages for different application scenarios. For instance, spherical device floats well on the sea surface and be benefit from the free motion of the ball, pendulum device can be well combined with sea buoys, column device is treated as one of the most suitable arrangements for arraying to achieve high output, and special types of device is mainly utilized to meet different application requirements. Section 4 highlights the challenges and development orientation of hybrid ocean energy harvesting. Finally, conclusions and perspectives on the future of hybrid ocean energy harvesting systems are discussed in Section 5.

2. Working mechanism of TEHNGs

The ocean typically provides two forms of kinetic energy: current energy and wave energy. Fig. 3 depicts the process of converting ocean energy into electricity, and TEHNG utilizes different modes of motion to collect ocean energy and apply it in different working scenarios. With further development in the field of ocean energy utilization, TEHNG, which consists of TENG and EMG, is expected to achieve a long-term stable power supply.

2.1. Theory of triboelectric nanogenerator

TENG, which is based on combination of triboelectric effect and electrostatic induction, is firstly proposed by Prof. Wang in 2012 [70] and has received widespread attention in recent years. Its theoretical foundation is based on Maxwell's displacement currents (Fig. 2a), and after a decade of development, Wang et al. derived the extended Maxwell's equations [71]:

$$\nabla \cdot D' = \rho_f - \nabla \cdot P_s \quad (1)$$

$$\nabla \cdot B = 0 \quad (2)$$

$$\nabla \times (E - \nu \times B) = -\frac{\partial}{\partial t} B \quad (3)$$

$$\nabla \times [H + \nu \times (D' + P_s)] = J_f + \rho_f \nu + \frac{\partial}{\partial t} P_s + \frac{\partial}{\partial t} D' \quad (4)$$

where, D' is the electric displacement field, ρ_f is the space charge density of the free charge, P_s is the polarization term in the displacement vector, B is the magnetic field, E is the electromagnetic field, vis the translational velocity, H is the magnetization field, and J_f is the local free current density.

The working mechanism of TENG is mainly explained according to the theory of triboelectric effect and electrostatic induction. To well explain the contact electrification and charge retention phenomena of two different materials, Xu [72] and Wang [73] proposed a general electron cloud/potential model (Fig. 2b) based on the basic electron cloud interactions. Until the two materials contact, the surface state electrons cannot migrate due to the trapping effect of the potential well. When the two materials come into contact, their electron clouds overlap, causing electrons transferring through potential wells to strike a balance. When the two materials are separated, due to the potential barrier, some electrons are remained in the material. In this way, there will be the same amount of charges with opposite polarity on the surface of different materials, and the electric field will be formed.

As shown in Fig. 3a, TENGs can be classified into five basic working modes according to the direction of polarization change and electrode arrangements, including i) vertical contact-separation [76,77], ii) 58rolling mode [78], iii) lateral sliding mode [79], iv) single electrode mode [80] and v) freestanding triboelectric layer mode [81]. It can be seen that the generation of TENG electrical signals is directly related to the displacement of the medium in the electric field and can directly convert irregular mechanical motion into electrical energy. Therefore, TENG can convert irregular low-frequency wave motion into electrical energy with high efficiency. Furthermore, together with its diversiform working modes, TENG is very suitable for low frequency and irregular ocean energy harvesting.

2.2. Theory of electromagnetic generator

Electromagnetic generator is based on electromagnetic induction and widely applied in commercial power plants nowadays [82,83]. The basic working principle of the electromagnetic generator involves the rotation of a coil of wire within a magnetic field, which induces an electromotive force (EMF) in the coil [63,84,85], resulting in the generation of electrical energy. As a result, EMGs are available in two main designs: rotary generators and linear generators [86,87].

The rotating generator is shown in Fig. 3b(i), and when a conductor in a closed circuit cuts an induced line of magnetic force in a magnetic field, an induced electromotive force is generated in the conductor,

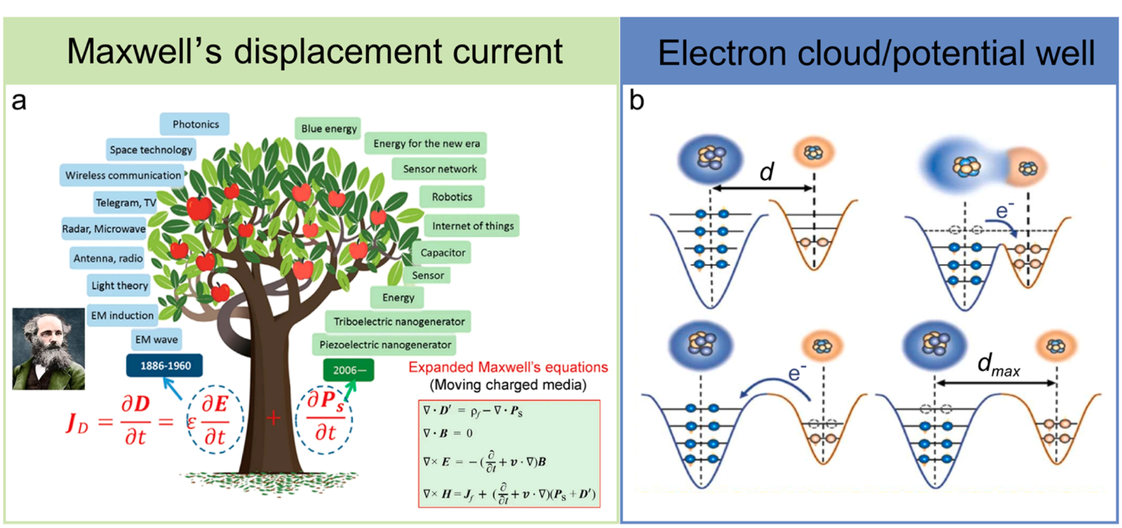

Fig. 2. Theoretical foundations of TENG. a) Theoretical foundation for TENG based on Maxwell's displacement current. Reproduced with permission Springer Nature [74]. b) Electron cloud/potential well model for contact electrification. Reproduced with permission Elsevier [75].

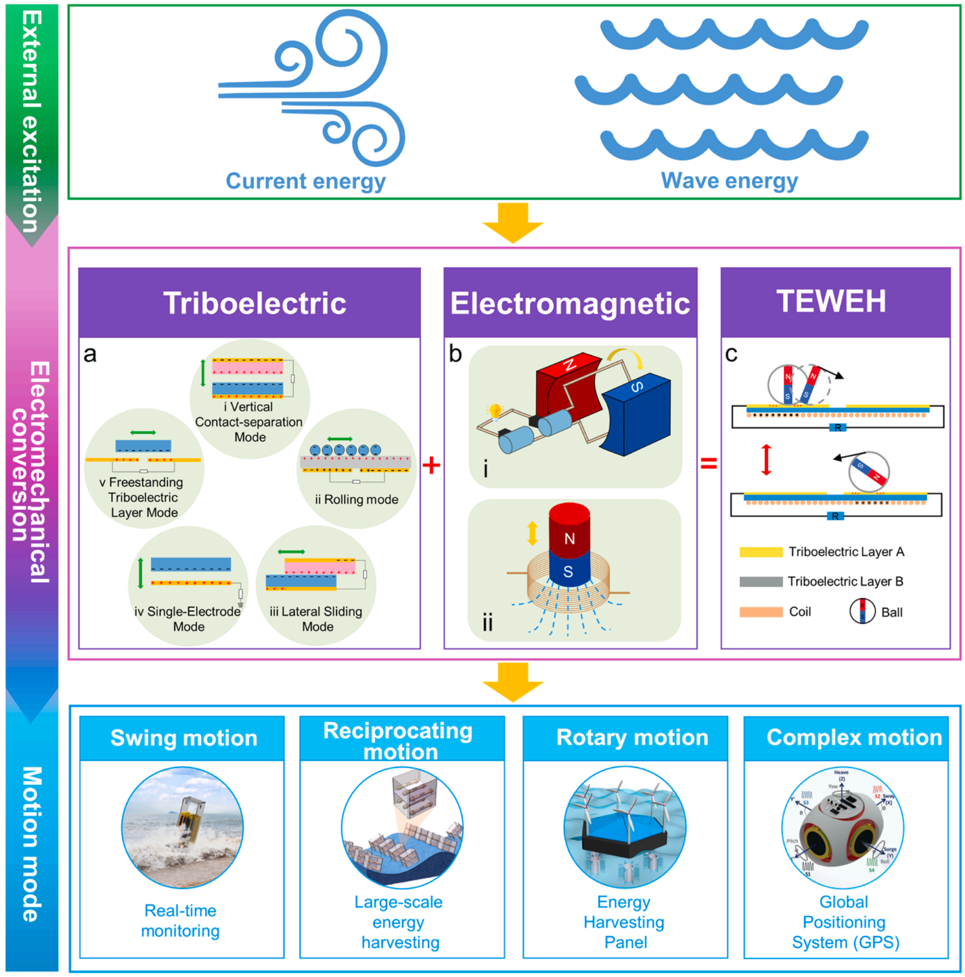

Fig. 3. Flow chart of working principle of TEHNGs with different motion modes work to harvest ocean energy: a) Working modes of triboelectric nanogenerators. i) Contact-separation mode; ii) Rolling mode; iii) Lateral-sliding mode; iv) Single-electrode mode; v) Freestanding mode. b) Working modes of electromagnetic generator. i) Cutting an induced line of magnetic force; ii) Changing magnetic flux. c) Working principle of TEHNG. Reproduced with permission American Chemical Society [67,88]. Reproduced with permission Elsevier [89]. Reproduced with permission Wiley [90].

which drives the electrons in the circuit in a directional motion and produces an induced current. The expression for the induced electromotive force is:

$$E = BL\nu \sin\theta \tag{5}$$

where, B is the magnetic flux density, L is the length of the conductor cutting the magnetic susceptibility, v is the speed at which the conductor is moving through the magnetic field, and θ is the angle between the direction of the conductor's speed and the magnetic field.

The working principle of linear EMG is shown in Fig. 3b(ii), and when the magnetic flux in a closed circuit is varied, an induced electromotive force is generated in the circuit, which leads to the formation of an induced current in the circuit. It can be expressed as:

$$E = n\frac{\Delta\phi}{\Delta t} \tag{6}$$

where, Eis the induced electromotive force, $\Delta\phi$ is the rate of change of magnetic flux, and Δt is the time of change. In order to obtain a larger induced electromotive force, a coil with more turns is usually used, n is the number of turns of the coil. It can be seen that the EMG generates electrical signals by using a coil to cut an induced line of magnetic force or by changing the strength of the magnetic field. Ocean energy harvesting is achieved by utilizing the impact of ocean currents to prompt the coil to cut the magnetic lines of inductance to generate electrical energy. In addition, EMG movement has a higher degree of freedom, which is suitable for the ever-changing ocean environment and can fully absorb energy from all directions of the wave.

Fig. 3c shows a typical operating principle of TEHNG, in which, TENG and EMG are combined together to promote each other, which significantly improves the energy conversion efficiency of TEHNG. According to different external excitation methods, different TEHNG structures are designed so that the TENG and EMG promote each other to form an efficient output and realize the efficient collection of ocean energy. In addition, the structure of TEHNG determines its movement mode, which determines its application scenarios. Therefore, the structural design of TEHNG is crucial, so the advances of TEHNGs for ocean energy harvesting is comprehensively reviewed and discussed in view of different structures adapting to various ocean motions.

3. Different types of hybrid energy harvesting devices

As a prominent renewable energy source, ocean energy constitutes over 70 % of the world's energy supply and holds significant potential in addressing energy shortages and fulfilling global energy demands. However, the irregular and low-frequency nature of ocean waves presents a notable challenge to traditional power generation technologies [91]. Therefore, innovative structural designs and integrated techniques have been developed to overcome these challenges, driving advancements in hybrid energy harvesting. In the development of TENG-EMG devices, three key factors must be taken into account: the selection of TENG materials, the design of TENG-EMG structures, and the optimization of energy management to enhance power output. This section categorizes TEHNGs into four types based on their structure: spherical devices, pendulum devices, column devices, and other special devices. Each type of device is also classified further according to structural and motion characteristics. Moreover, the structure, operation principles and practical applications of various TEHNGs are discussed and analyzed in detail.

3.1. Spherical devices

Spherical structures possess the capability to roll in any direction, enabling spherical devices to effectively adapt to waves from various directions in the marine environment. They are recognized as one of the fundamental structures for harvesting blue energy [92]. Its internal power generating unit utilizes different actuators, which can be categorized into roller ball actuators and ordinary slider actuators. Roller ball actuators can move in multiple degrees of freedom in curved or flat surfaces. The movement of a normal slider actuator is mainly restricted to a track with limited degrees of freedom of movement, which is suitable for special application scenarios, such as oil spill detection [61].

3.1.1. Roller ball actuator structure

When subjected to wave forces, the power generation unit within the spherical device produces electrical energy output, facilitating the conversion of ocean energy into electrical power. Ouyang et al. [93] introduced a magnet assisted triboelectric nanogenerator (MA-TENG). Using the magnetic sphere as a mover makes the TENG establish combination with the EMG. It is both a source of magnetic field and excites the TENG unit to work. In Fig. 4a, a network of MA-TENGs was utilized for harvesting wave energy. MA-TENG system comprises an acrylic spherical shell housing a magnetic ball, two copper coils affixed to the base of the spherical shell, and two symmetrically positioned TENG units on either side of the shell. TENG units are constructed from a negative triboelectric layer material incorporating a PTFE film. The operational mechanism of TENG unit in MA-TENG system is illustrated in Fig. 4b, where the motion of the magnetic ball leads to the separation of PTFE film from the copper electrodes upon contact, resulting in charge transfer. Additionally, EMG unit induces a current in the lower coil as the magnetic field fluctuates due to the movement of the magnetic ball. This device is characterized by its simplicity, cost-effectiveness, and ability to generate substantial electrical output. MA-TENG system (Fig. 4c) demonstrates a maximum power density of 79 W/m^3 under linear motor drive conditions and 26.2 W/m^3 under underwater wave drive conditions.

Wu et al. [60] proposed a hybrid triboelectric-electromagnetic water wave energy harvester (WWEH) utilizing a magnetic sphere. With the magnetic ball as the mover, it is located in the middle layer of the device. The upper layer is EMG and the lower layer is TENG, and the upper and lower layers are combined by means of the magnetic ball. The device differs in that it consolidates all power generation components within the spherical shell, enhancing the space utilization within the shell. WWEH comprises four main sections (Fig. 4d): EMG module, TENG module, the power management circuitry, and the acrylic spherical enclosure. EMG module includes a magnetic ball, a magnetic actuator, and a coil affixed to an acrylic plate. TENG module consists of the actuator, enveloped in a copper mold and embedded with magnetic pillars, and two triboelectric layers designed in a tai-chi shape to accommodate the actuator's movement in any direction. A mechanical analysis of the energy harvester under external excitation is depicted in Fig. 4e. The internal power management circuit of the device optimally utilizes the generated power to establish a self-powered wireless water temperature alarm system (Fig. 4f). WWEH can swiftly charge the supercapacitor to 1.84 V and deliver a consistent and reliable power supply to the sensor. Bhatta et al. [90] developed a novel hybrid self-powered arbitrary wave sensing system (HSP-AWWSS), which is ellipsoidal in shape, featuring coils on six surfaces and additional TENG units on four sides. This design enables the internal magnetic sphere to move freely under external wave action, facilitating energy harvesting

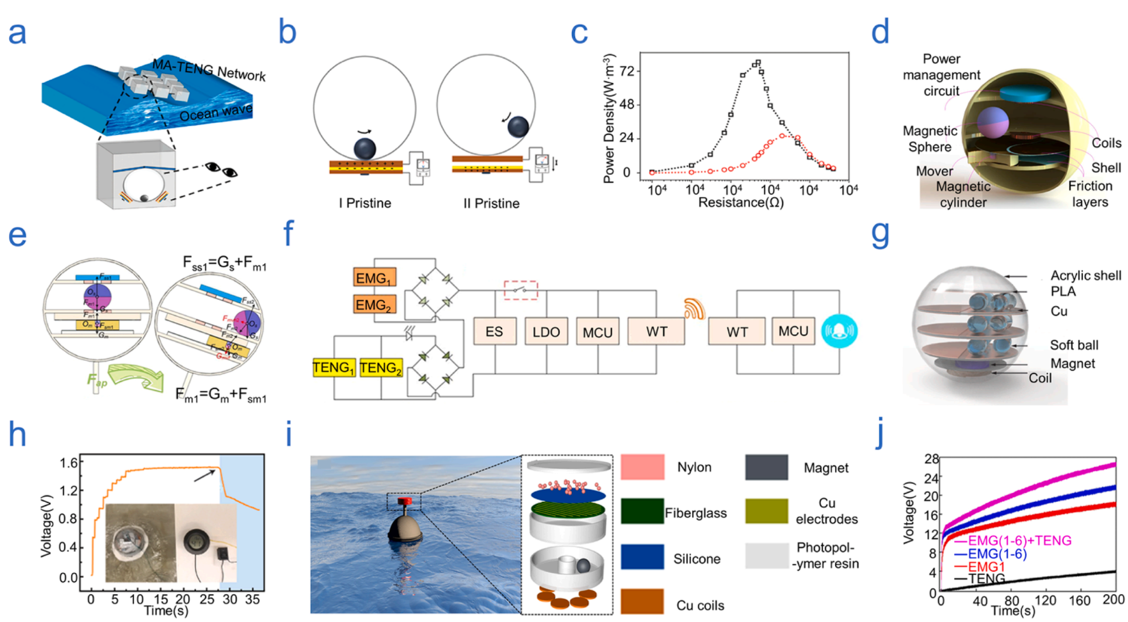

Fig. 4. Detailed structure and functionality of roller ball actuator-based hybrid energy harvesting devices: a) MA-TENG system operating at sea level; b) Working principle of MA-TENG; c) Maximum power density and current density achieved by MA-TENG; Reproduced with permission Wiley [93]. d) Structural schematic of WWEH; e) WWEH undergoing a rocking motion induced by external excitation; f) Schematic of a wireless water temperature alarm system for automatic energy supply; Reproduced with permission American Chemical Society [60]. g) Internal structure of device comprising a SB-TENG and an EMG, with a laminated cavity filled with multiple softballs inside a spherical acrylic shell; h) Charging process of a 100 μF capacitor using TEHG, with an inset photograph of physical TENG unit and associated temperature sensor; Reproduced with permission Wiley [62]. i) Schematic of power generation system integrated with a hydrophone; j) Charging curves of single-generation and hybrid-generation units. Reproduced with permission American Institute of Physics [94].

in 6-degrees-of-freedom (DOF) and enhancing energy conversion efficiency.

Given the limited contact area of a single spherical actuator, researchers have focused on structures that incorporate multiple balls and layers to enhance energy harvesting efficiency. Pang et al. [62] introduced a triboelectric-electromagnetic hybrid nanogenerator (TEHG) based on soft balls to convert mechanical energy into electricity (Fig. 4g). As a proof-of-concept, three layers of soft ball-based triboelectric nanogenerator (SB-TENG) units and an EMG unit are integrated into a spherical acrylic shell. The device is a multilayer structure with EMG in the bottom layer and TENG in the other layers, when it is externally excited, the units in each layer operate simultaneously to increase the output power. The four-layer configuration substantially boosts the device's output power, while enhancing the overall space utilization and volumetric power density. The ball driver of SB-TENG unit is an Eco-flex30 softball filled with liquid material, replacing the conventional hard triboelectric material to enlarge the contact area and increase the electrical charge generation. When placed in a water wave environment, TEHG charges a 100 μF capacitor to 1.5 V in under 10 s (Fig. 4h). At an operating frequency of 1 Hz, TEHG achieves a maximum output power of 0.5 mW and 8.5 mW for its TENG and EMG units, respectively, with further enhancements in the device's output power. Hao et al. [94] developed a multilayer structured triboelectric-electromagnetic hybrid nanogenerator that captures wave energy while delivering a continuous and stable power supply to a hydrophone. The upper layer is TENG and the lower layer is EMG, which work simultaneously and do not interfere with each other. In Fig. 4i, the device features an ellipsoidal hydrophone system at its base and a hybrid generator with a double-layer structure fixed at the top of the hydrophone system. TENG unit is positioned in the upper layer of the power generation unit, while EMG unit is located in the lower layer. The upper TENG unit comprises multiple rolling nylon balls forming the actuator, which can be freely rolled by wave action to facilitate charge transfer and significantly increase the contact area. In contrast, the lower EMG unit consists of 6 coils and a magnetic sphere. The upper and lower isolation structure of the hybrid generator prevents friction losses associated with the traditional contact drive design of the hybrid generator. Experimental results demonstrate the charging curve at a frequency of 1.8 Hz (Fig. 4j) revealing that the hybrid generator not only enhances the charging voltage but also significantly accelerates the charging speed, indicating that the hybrid device can harvest more energy compared to a single type of generator.

3.1.2. Ordinary slider actuator structure

Spherical devices exhibit movement in various directions within the marine environment. Researchers have developed spherical devices with diverse configurations specifically for harvesting energy in marine settings. Kim et al. [61] introduced a triboelectric-slider hybrid generator (TS-HG) for sustainable ocean energy harvesting and self-powered oil spill detection. In the schematic diagram of the device (Fig. 5a), a spherical shell encloses a larger circular tube-shaped hybrid generator, with the energy management unit located at the device's bottom. A magnet block is used as a mover, which reciprocates in a circular tube and simultaneously excites the TENG and EMG to generate electrical energy. The schematic structure of the hybrid generator (Fig. 5b) comprises a TENG unit with Kapton film featuring interdigitated electrode (IDT) as the triboelectric layer, generating electrical output through the movement of a magnetic block inside the circular tube. EMG unit includes the magnetic block and a coil wound around the tube. Apart from energy harvesting from the ocean, TS-HG device can identify oil spills at sea by monitoring changes in seawater conductivity and the output power, as shown in the oil spill detection process map in Fig. 5c. Subsequent oil spill detection experiments conducted in the laboratory (Fig. 5d) demonstrate the device's ability to differentiate the presence or absence of oil in seawater.

Chandrasekhar et al. [51] developed a spheroidal hybrid generator (SB-HG) for a fully encapsulated spherical smart buoy. This device is designed to harness water wave energy for power generation and to

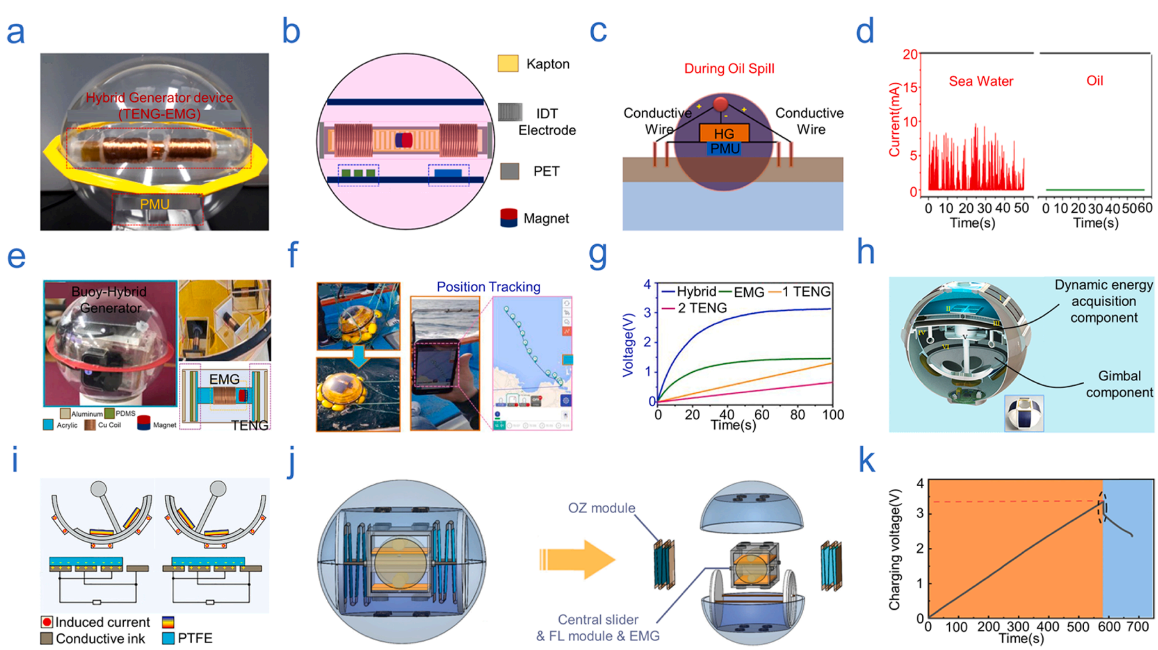

Fig. 5. Structure and applications of ordinary slider actuator-based hybrid energy harvesting devices: a) TS-HG equipment physical image; b) TS-HG in collecting water wave energy and real-time detection of oil spills; c) Working principle of TS-HG for oil spill detection; d) Current output characteristics of TS-HG in seawater and oil environments; Reproduced with permission American Chemical Society [61]. e) Schematic and fabrication of SB-HG; f) Operational depiction of SB-HG at sea, demonstrating its capability to transmit real-time positional information; g) Charging curves for a capacitor using a single power generation unit and a hybrid unit; Reproduced with permission Elsevier [51]. h) Diagram of hybrid nanogenerator; Reproduced with permission Springer Nature [95]. i) EMG unit (i) and TENG unit (ii) operating principle; j) Structural design of SSTE-HNG; k) SSTE-HNG charges commercial capacitors. Reproduced with permission Royal Society of Chemistry [66].

support a position tracker (Fig. 5e). A magnet block is used as a mover, which moves inside a small circular tube to make the EMG generate electricity. At the ends of the circular tube are TENGs, which rely on the impact of the magnets to generate electrical energy. SB-HG comprises eight identical small hybrid generators, each consisting of two TENG units located at the ends of a cylindrical tube and an EMG unit positioned at the center of the tube. TENG assembly features an aluminum positive triboelectric layer on one side and a polydimethylsiloxane (PDMS) layer with an attached aluminum electrode on the other side. The device operates by utilizing the reciprocating motion of a magnet block inside EMG unit when affected by water waves. This motion generates electric current through a coil wound in the middle of the tube. The magnet block also drives both ends of the tube to contact TENG unit in separation mode, enabling its functionality. Experimental validation in a real sea environment demonstrates the device's capability to provide a stable power supply to the position tracker, which can be monitored in real-time through a mobile application (Fig. 5f). In Fig. 5g, the hybrid device, consisting of two TENGs and one EMG, can charge a capacitor to 3 V in 25 s at a motion frequency of 1.5 Hz, outperforming single TENG or EMG units. Maharjan et al. [96] proposed a similar spherical hybrid energy harvesting device that utilizes the motion of an internal magnetic block to activate TENG and EMG units for self-powered environmental monitoring. The research conducted by both groups shows promise for various real-world applications, although the utilization of the space within the spherical shell remains a limitation.

Feng et al. [95] introduced a novel spherical static-dynamic energy harvester designed to cater to the arbitrary motion characteristics of spherical structures and enhance space utilization within the shell. This innovative device serves the purpose of self-powered marine environment monitoring by combining triboelectric and electromagnetic technologies with additional piezoelectric, photovoltaic, and thermotropic units. The core element of the spherical device (Fig. 5h) features a magnetic slider coated with a PTFE film on its surface. Furthermore, a photovoltaic power generation unit and a temperature difference power generation unit are incorporated at the top, while PENG unit is positioned on the lever's top. When deployed in a marine setting, the device's sliding body interacts with the polymerized material at the base due to wave action, resulting in charge transfer. Simultaneously, changes in the internal magnetic field induce currents in the coil at the bottom, as depicted in the working principle of EMG and TENG in Fig. 5i. Experimental results indicate that the device achieves a maximum current of 41 mA and 49 mA for internal and external photovoltaic units, respectively, and 15 mA for thermoelectric units under 3000 Lux illumination. Additionally, the maximum power output of TENG, EMG, and PENG is measured at 0.25, 13.8, and 1.58 mW at 2.4 Hz, showcasing a substantial enhancement in hybrid energy harvesting efficiency compared to single-type devices.

Hong et al. [66] developed a spherical buoy featuring a seesaw structure based on a seesaw triboelectric-electromagnetic hybrid nanogenerator (SSTE-HNG). This device capitalizes on the unrestricted motion of the sphere on the sea surface, enabling intentional flipping, while the symmetrical configuration of the internal power-generating components enhances operational flexibility. In Fig. 5j, SSTE-HNG comprises two OZ modules, two FL modules, and two EMG modules. OZ module, resembling origami components on both sides of the device, consists of four contact-separated TENG units; FL modules contain sliding friction within the central slider, and EMG unit comprises a magnet attached to the exterior of the slider with coils fixed to the inner wall of the spherical shell. Experimental results indicate that the maximum instantaneous power densities of OZ, FL, and EMG modules of SSTE-HNG are 17 W/m^3, 4.8 W/m^3, and 9.8 W/m^3 at 0.7 Hz, respectively, demonstrating high power density. In practical applications, SSTE-HNG is employed in the ocean to charge a 4.7 mF capacitor from 0 V to 3 V (Fig. 5k) activating GPS module to continuously transmit position information at 1-s intervals, with only about 1 V discharge, ensuring continuous and stable operation of the positioning module. These investigations leverage the spherical structure's omnidirectional movement capability, rendering the hybrid generator with a spherical structure highly suitable for ocean energy harvesting applications.

For spherical devices that float on the sea surface moving freely, the main difference lies in the different internal power generation units, which make the devices have different application scenarios. Spherical devices require a symmetrical arrangement of the internal power generation units to facilitate the movement of the actuators.

3.2. Pendulum devices

Considering the continuous nature of waves in the marine environment, the energy harvesting mechanism of the pendulum structure can be effectively stimulated to consistently and reliably harvest ocean energy. Pendulum devices mainly include pendulum center shaft fixed structure and spring assisted structure. The pendulum center shaft fixed structure combines swinging and sliding, using the pendulum fixed on the center shaft as a driving device to generate electricity in marine environment. The other spring assisted structure usually uses a spring to assist the movement of the pendulum, which helps increase the output power and space utilization of the device, and is more suitable for some specific places.

3.2.1. Pendulum center shaft fixed structure

Liu et al. [97] introduced a pendulum hybrid generator enclosed in a waterproof casing, utilizing rolling magnets to enhance the oscillation of the counterweight block in the pendulum structure. Chen et al. [52] designed a chaotic pendulum hybrid generator that combines triboelectric and electromagnetic principles. This device comprises two main components: TENG unit and EMG unit (Fig. 6a). Using the magnetic block as a pendulum, the TENG and EMG are made to generate electrical energy simultaneously when externally excited. TENG unit, designed in an independent layer configuration, secures a PTFE film on the inner pendulum slider along with golden fork finger electrodes positioned in the fan blades area. On the other hand, EMG unit consists of three magnetic spheres attached to the inner pendulum and three internally fixed coils. The magnetic spheres serve as counterweights for the main pendulum, thereby increasing the oscillation frequency of the inner pendulum. When the device is exposed to wave action, the magnetic pendulum oscillates, leading to simultaneous operation of TENG and EMG units to generate electrical output (Fig. 6b).

Zheng et al. [56] proposed a hybridized water wave energy harvester (H-WWEH) is proposed based on a swing magnetic structure with a permanent magnet as the mass block. Using the magnetic block as a pendulum, it also acts as a slider. It is externally excited to oscillate while sliding friction occurs with the bottom, causing the TENG and EMG to generate electrical energy simultaneously. The research team managed to reduce the device's size and weight by integrating TENG and EMG units onto the magnet pendulum. In Fig. 6c, H-WWEH device is structured with TENG unit positioned above EMG unit. TENG unit comprises a polyethylene terephthalate (PET) film attached to the pendulum's base and a copper electrode shaped like a tai-pole covered with a PTFE film at the bottom. Conversely, EMG unit includes a magnet pendulum and a coil affixed to the base. The magnet pendulum is suspended at the device's top and swings freely under the effect of water waves. The power generation principle of TENG unit is depicted in Fig. 6d, which also illustrates the pendulum's trajectory. In a low-frequency wave simulation environment at 1.75 Hz, H-WWEH can achieve output voltages and currents of 90 V and 0.61 μA, and 5.3 V and 6.4 mA for TENG and EMG units, respectively. Fig. 6e illustrates the charging characteristics of TENG and EMG in parallel and series configurations, demonstrating that they can be charged to a higher value at a faster rate when connected in parallel. This highlights the advantages of the hybrid generator, where the high voltage of TENG and the high current of EMG complement each other to enhance the energy

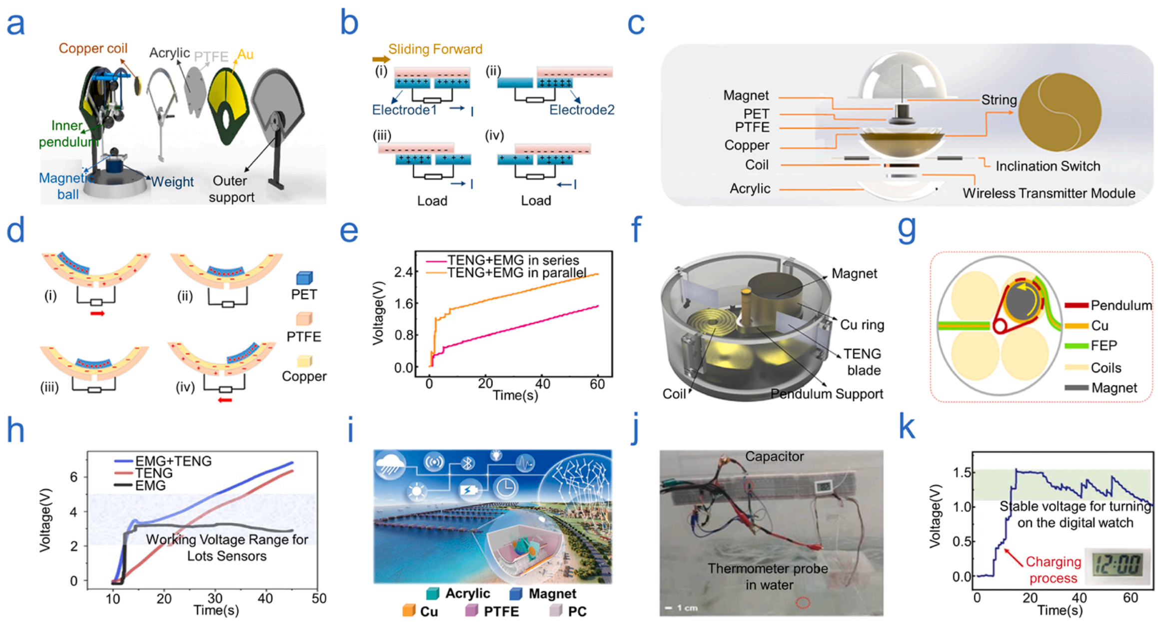

Fig. 6. Structures and functional principles of chaotic pendulum-based hybrid energy harvesting devices: a) Exploded view of chaotic pendulum generator structure; b) TENG module current generation principle; Reproduced with permission Elsevier [52]. c) Exploded structural view of H-WWEH unit; d) Principle of power generation through magnetic pendulum motion; e) Charging curves comparing performance of hybrid units connected in series and parallel; Reproduced with permission Elsevier [56]. f) RPHG equipment structure diagram; g) Top view of RPHG operating principle; h) Charging curves of individual generation units and hybrid generation units of RPHG; Reproduced with permission Elsevier [98]. i) Physical drawing of FH-HG unit and schematic of its self-powered sea surface monitoring system; j) FH-HG powering a sensor under actual water wave conditions; k) FH-HG device charging a capacitor and driving a digital watch. Reproduced with permission Wiley [63].

harvesting efficiency of the device.

A rotating pendulum configuration featuring a stationary rotor at the central axis is a common design for hybrid generators. Hou et al. [98] developed a rotating pendulum hybrid generator (RPHG) to harness low-frequency wave energy utilizing a rotating pendulum. RPHG (Fig. 6f) captures energy from low-frequency vibrations (<5 Hz) in ocean waves. The magnetic rotor, fixed at the central axis, undergoes rotational movement due to inertia or gravity, interacting with the bottom coil to activate EMG unit. A top view of RPHG structure is depicted in Fig. 6g, demonstrating that the contact separation between the copper ring and the FEP film by the rotor stimulates TENG unit. Experimental results indicate that TENG and EMG units achieve maximum power densities of 3.25 W/m^3 and 79.9 W/m^3, respectively, at a driving frequency of 2 Hz and an amplitude of 14 cm. Fig. 6h presents the charging profile of RPHG for the capacitor, revealing that TENG exhibits a higher voltage and lower output frequency. Connecting EMG in parallel enhances the charging speed and level. Gao et al. [99] proposed a hybrid generator based on a rotating gyroscopic structure of a rotating pendulum to harness water wave energy for stabilizing power supply to GPS.

Qu et al. [100] introduced an eccentric pendulum structure of a triboelectric-electromagnetic hybrid generator designed for the collection of low-frequency ocean energy. The rotor is fixed along the central axis to enable swinging motion. Positioned vertically, the device allows the rotor to swing back and forth within a specific angle due to the effect of gravity. However, due to its large volume and the complex marine environment, a certain distance from the application site is still required. Han et al. [63] developed a fluff hybrid generator (FH-HG) for ocean energy harvesting, featuring double-sided fluff and double Halbach arrays (Fig. 6i). This generator also secures the rotor on a central axis, resembling an eccentric structure. FH-HG device comprises a rotary pendulum assembly, an acrylic housing, and a central acrylic strip. The rotary pendulum, composed of two fan-shaped Yak blocks with embedded magnets and double-sided polycarbonate (PC) fluff, is the key component. Copper electrodes coated with PTFE film serve as the triboelectric layer on the bottom and sides of the shell, forming TENG unit with l-TENG on the left side, r-TENG on the right side, and b-TENG on the bottom. The magnets in the rotary pendulum assembly act as optimal counterweights and create a dual halbach-EMG (H-EMG) with a coil attached to the central acrylic strip. Under the effect of a 1.4 Hz frequency, fluff-TENG (F-TENG) and H-EMG of FH-HG achieved maximum power densities of 2.02 W/m^3 and 16.96 W/m^3, respectively. Experimental results demonstrate that FH-HG can efficiently charge a 220 μF capacitor to 1.5 V and provide a stable power supply for electronic devices (Figs. 6j and 5k), indicating promising applications in ocean energy harvesting and environmental monitoring. Feng et al. [101] proposed a hybrid generator comprising an oscillating structure-based soft contact triboelectric nanogenerator and an electromagnetic generator, which operates effectively at low frequencies. This generator achieved a maximum power density of 10.16 W/m^3 for 0.1 Hz water waves, highlighting the high efficiency of the oscillating structure hybrid generator in harnessing energy from low-frequency water waves.

3.2.2. Spring assisted structure

The oscillating structure propels the rotor pendulum within the device to rotate by harnessing the waves, consequently enabling the hybrid generator to operate. However, the device encounters challenges in being stimulated in ultra-low-frequency wave conditions. To address this issue, numerous researchers have integrated spring or spring-like components into the oscillating structure to support the hybrid generator in capturing ocean energy. Xie et al. [102] introduced a non-resonant electromagnetic-triboelectric hybrid nanogenerator that utilizes a spring to bolster the oscillating component, causing it to oscillate spherically around the support position. A magnetic block is used as a pendulum, and the pendulum is surrounded by TENG units, and the collision of the pendulum is utilized to excite the TENG to run. The device (Fig. 7a) comprises a support spring, a magnet, a coil, four TENG assemblies, and a housing. EMG unit includes a pendulum magnet and a top coil, while TENG unit features a double helix structure with

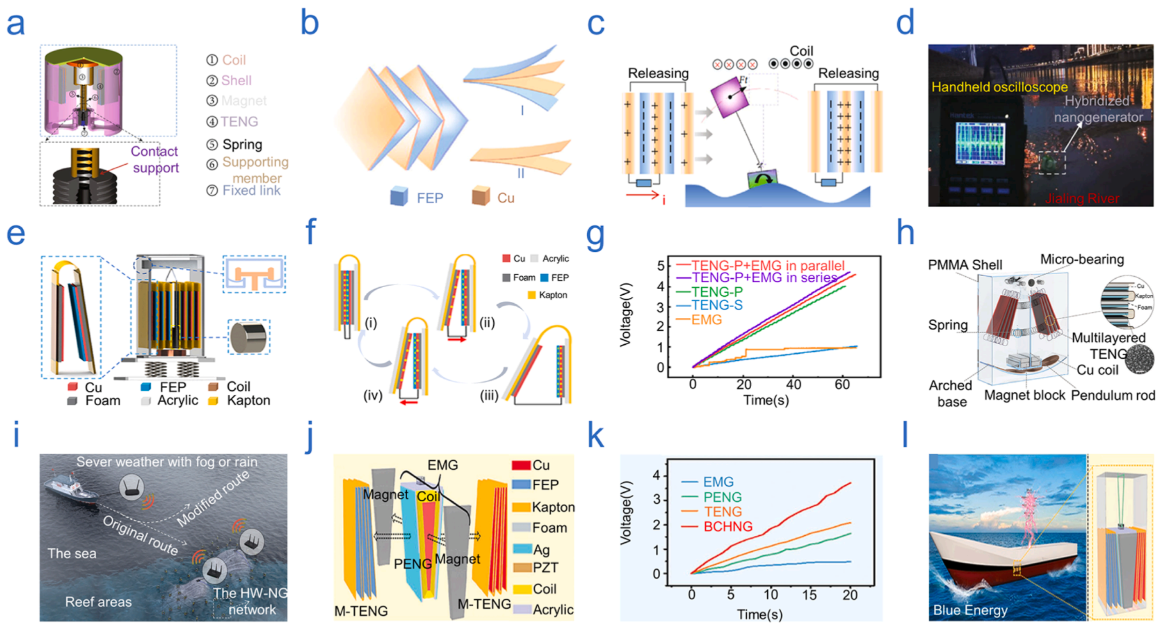

Fig. 7. Structures and operational principles of non-resonant hybrid energy harvesting devices: a) Non-resonant hybrid generator model diagram; b) Oscillation theory; c) Non-resonant hybrid electromagnetic-triboelectric nanogenerator power generation principle; d) Device collecting water wave energy in a real-world environment; Reproduced with American Association for the Advancement of Science [102]. e) Structural design drawing of PT-HNG; f) Current generation principle for TENG unit within PT-HNG; g) Charging curves of PT-HNG device under different conditions; Reproduced with permission American Chemical Society [88]. h) Structural design and material selection for HW-NG; i) Self-powered ship navigation warning system based on HW-NG; Reproduced with permission Wiley [64]. j) Exploded view of BCHNG structure; k) Charging curves for each power generation module of BCHNG; l) Practical application testing of BCHNG. Reproduced with permission Wiley [103].

fluorinated ethylene propylene (FEP) film and copper foil as triboelectric materials, possessing excellent elastic properties (Fig. 7b). This setup leverages the magnetic pendulum to harvest energy and serves as an elastic buffer during pendulum movement to mitigate energy loss from collisions. The power generation mechanism is illustrated in Fig. 7c, where the continuous motion of the magnetic pendulum, connected to the spring and driven by the waves, induces TENG and EMG units to produce electrical power. Experimental results indicate that TENG unit can generate up to 470 μW at a 0.5 MΩ load and 2.2 Hz frequency, while EMG unit can reach a maximum power output of 523 mW at a 280 Ω load, with an energy conversion efficiency of 48.48 %. Real-world testing in water environments (Fig. 7d) demonstrates the hybrid generator's ability to rapidly charge a 2000 μW capacitor to 4 V.

Sun et al. [88] introduced a pendulum-type hybrid nanogenerator (PT-HNG) featuring two multilayer TENGs and a spring-loaded base, which not only enhances stability but also increases the device's oscillation range. PT-HNG (Fig. 7e) comprises two multilayer TENG units, a bottom coil, and a slide structure with embedded magnets. Each TENG unit consists of three contact-separated TENGs with a robust and flexible polyimide film (Kapton) as the connecting backbone, an FEP film, and a copper film adhered to foam as the triboelectric material. EMG units consist of a coil and a slide structure with magnets. When impacted by water waves, PT-HNG oscillates, causing the slide structure to move, leading to contact separation in TENG unit (Fig. 7f). Fig. 7g demonstrates that the hybrid generator can charge the capacitor more rapidly at a frequency of 1.75 Hz, significantly increasing the charging speed.

Ren et al. [64] introduced a hybrid wave nanogenerator (HW-NG) for long-range wave energy harvesting. HW-NG integrates a TENG unit and an EMG unit using a pendulum structure. TENG unit is designed in contact separation mode as a spring-assisted multilayered structure, with springs mounted on both sides of the pendulum to enhance the close contact of the triboelectric layers of TENG (Fig. 7h). HW-NG utilizes Kapton film with copper film and FEP film as triboelectric materials for TENG unit. The movement of the magnetic pendulum in EMG unit propels the power generation unit for electricity production. At a frequency of 2 Hz, HW-NG achieves a maximum output of 580 V and 28 μA, enabling stable power supply for a 433 MHz ultra-high-frequency (Sub-1G) radio transmission. Additionally, it can swiftly establish a long-distance communication node at ocean in less than 1 s (Fig. 7i). This capability facilitates early warning systems for ship traffic in remote ocean areas or islands.

Furthermore, certain hybrid generators can operate independently of springs by utilizing structural design and the elastic properties of materials, known as spring-like structures. It is common practice to design TENG unit of a hybrid generator to function as an analog spring, contributing to electricity generation while supporting equipment operation. Yang et al. [104] introduced a non-encapsulated pendulum hybrid generator that eliminates the need for an additional spring by employing a zigzag multi-layer TENG to mimic spring behavior for harnessing water wave energy. However, the non-encapsulated design is not suitable for harsh ocean conditions and has limitations in practical applications. Zhang et al. [103] developed a two-wire pendulum-coupled hybrid generator (BCHNG), comprising two spring-like structures of TENG and EMG units integrated into a single container. BCHNG structure (Fig. 7j) features a wedge-shaped pendulum cone wound with copper coils and two PENGs for enhanced space utilization. EMG unit includes copper coils with trapezoidal magnets on both sides, while TENG unit utilizes a zigzag Kapton film as a substrate to mimic spring behavior, with copper film and FEP film as triboelectric materials attached to each zigzag Kapton structure. Leveraging the 2-DOF of the bilinear pendulum and the spring-like structure of TENG, BCHNG achieves a peak power density of 358.5 W/m^3. In Fig. 7k, BCHNG charges a 100 μF capacitor, demonstrating a rapid charging rate and offering an efficient approach to ocean energy harvesting. Fig. 7l depicts the installation of BCHNG on a ship, utilizing the ship's auxiliary device to harvest wave energy, thereby creating a more stable operational environment and reducing operational expenses.

Pendulum shaped devices can be tightly integrated with buoys, etc. and are highly adaptable. The pendulum device combines swinging and sliding in order to increase the efficiency of the device's energy conversion. In addition, springs can be added to further improve the performance of the device.

3.3. Column devices

Column devices, such as cylindrical and rectangular columns, are commonly used in the construction of hybrid generators due to the variability of the marine environment. The devices can be divided into two categories based on their different movement. One is rotating mechanical structure, in which the power generation unit rotates under the action of ocean currents and waves to generate electricity. It can better utilize the current energy. The other is rolling/sliding mechanical structure, where the whole device is used as a space for movement, so that it can move effectively under various external excitations.

3.3.1. Rotating mechanical structure

Cylindrical devices are particularly susceptible to rotational movements of internal components when affected by water waves or currents, allowing cylindrical hybrid generators to effectively harness ocean current energy. Wen [67] developed a hybrid generator that integrates a helical fork-finger electrode TENG with a wrap-around EMG to capture ocean energy. TENG unit is enclosed for protection from the external environment and operates through non-contact attraction between magnets, which are linked to EMG unit. In Fig. 8a, hybrid generator comprises three coaxially mounted cylindrical tubes, with the inner and middle tubes movable to create a TENG unit. Copper electrodes are affixed to foam strips cut at various angles and attached to the outer surface of the inner tubes. The foam's elasticity, combined with its super-elasticity for rapid recovery, enhances the device's durability and stability while facilitating the generation of a high density of charges. Additionally, the foam serves as a support material to reinforce the device's robustness and stability during high-density charge generation. EMG unit includes four pairs of magnets fixed to the inner and outer tubes, along with a copper coil on the center tube. The device's unique design enables power generation in both rotating and fluctuating modes (Fig. 8b). Experimental results have shown that TENG unit of the hybrid generator operates at low rotational speeds (<100 rpm) or low motion frequencies (<2 Hz), while EMG unit produces a high-frequency output. The overall output of the hybrid device increases accordingly (Fig. 8c).

Gao et al. [105] conducted a study where they developed a three-mode hybrid generator (TMHG) featuring a water wheel structure. This generator incorporates three power generation units: a solid-solid contact TENG unit (SS-TENG), a solid-liquid contact TENG unit (SL-TENG), and a rotating EMG unit (Fig. 8d). In TMHG water turbine structure, the stator, integrated with the shaft, is designed as a hollow cylinder with a rectangular FEP film attached to its surface to create SS-TENG. Additionally, a nylon with copper film is affixed to the outer stator barrel, and five coils with a strong magnet on the housing form EMG unit. SL-TENG consists of a rotor housing covered with copper and PTFE film, which generates electrical energy upon contact with water. During real-world tests, TMHG was utilized to charge commercial capacitors, exhibiting SS-TENG, SL-TENG, and EMG instantaneous powers of 1.44 mW, 0.15 mW, and 15.9 mW, respectively. The hybrid generator demonstrated the fastest charging rate and achieved higher voltages (Fig. 8e). A practical application of TMHG (Fig. 8f) involved adding a mass block to the device's bottom to ensure full contact with the water flow. Furthermore, the blades on both sides of TMHG were utilized to drive the device's rotation and collect energy from the water flow. Zhong et al. [107] developed a coupling-driven triboelectric-electromagnetic hybrid generator that generates electricity by rotating the rotor to make the FEP film, attached around the rotor, rub against the surrounding copper electrodes. The rotor rotation is facilitated by magnetic coupling drive, and the torque from the device's external impeller drives the coupling drive, leading to power generation for the entire system.

In addition to rotational motion occurring by fixing the rotor to the center axis, constraining the motion trajectory of the actuator to an annular shape is also a method of achieving rotational motion. Xu et al. [106] presented an omnidirectional ocean energy harvesting hybrid generator (iTEHG) based on a guided liquid (Fig. 8g). The device is

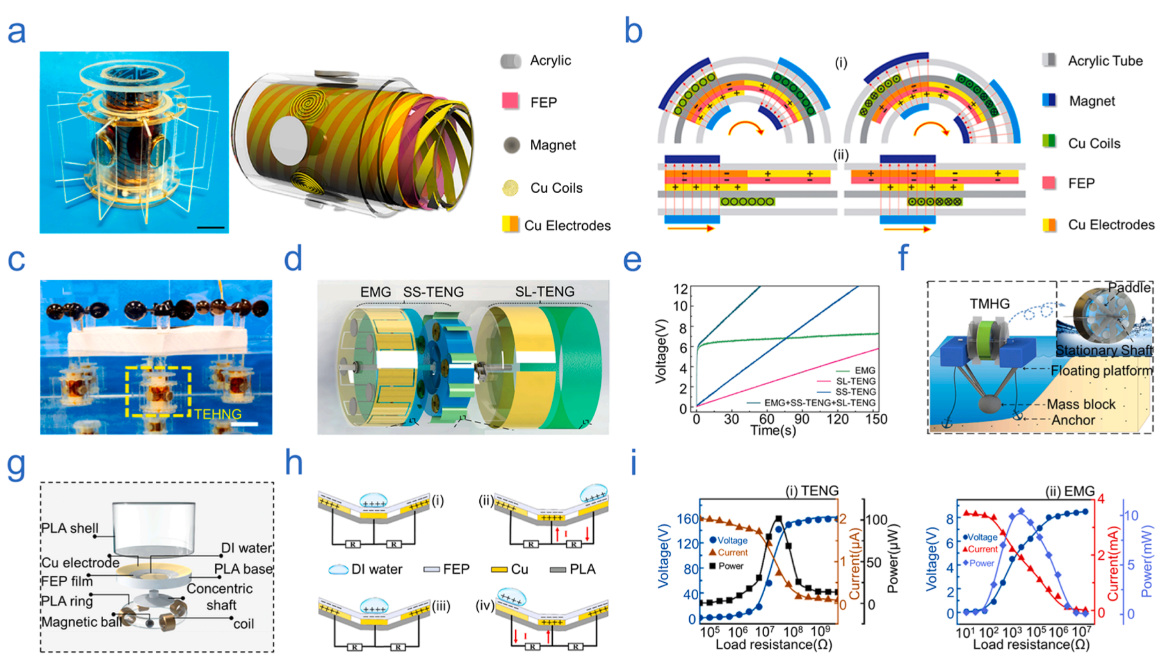

Fig. 8. Design, principles, and applications of hybrid generators for ocean energy harvesting: a) Structural design and material selection for hybrid generators; b) Principle of power generation in TENG modules and EMG modules; c) Multiple hybrid generators forming a power generation platform to harvest ocean energy; Reproduced with permission American Chemical Society [67]. d) Exploded view of TMHG structure (e.g., SS-TENG, SL-TENG, and EMG); e) Charging curves for different generation modules and combined output after mixing all modules; f) TMHG working in marine environment; Reproduced with permission Elsevier [105]. g) Structural design and material selection for iTENG; h) Mechanisms of motion and principles of power generation in TENG modules; i) Energy output curves of TENG(i) module and EMG(ii) module. Reproduced with permission Elsevier [106].

divided into two layers, with TENG in the upper layer and EMG in the lower layer. The movement of the magnetic spheres in the EMG unit will act as a facilitator for TENG. iTEHG comprises a TENG module based on guided fluid and a ring-shaped EMG module, interconnected by a concentric axis in a layered configuration. EMG module is positioned below, reducing iTEHG's center of gravity, resembling a "tilting doll" structure that can withstand irregular wave impacts without toppling. The overall highly symmetrical column structure of the unit ensures stable and synchronous operation of the two modules. TENG module features concentric circular electrode pairs affixed to a substrate, resembling a tilted satellite antenna. Through the interaction of ionized water friction with the electrodes driven by ocean waves, electricity is generated (Fig. 8h). EMG unit is designed as a highly symmetrical hollow ring, with four coils evenly distributed on the ring's circumference, allowing the magnetic ball to rotate around the ring under wave action, causing the coils to cut the magnetic flux and generate electricity. TENG module achieves a maximum power of 101.5 μW at a frequency of 1.33 Hz (Fig. 8i(i)), while EMG module reaches a maximum power of 10.1 mW at a frequency of 1.47 Hz (Fig. 8i(ii)). iTEHG device itself exhibits a maximum power density of 7.25 $\mu W/cm^3$, enabling charging by a 0.1 F capacitor at 3.1 V. Its application in marine environments demonstrates outstanding performance and promising prospects.

3.3.2. Rolling/sliding mechanical structure

Besides the self-rotating structure, a design incorporating a sliding magnet within a circular tube has been proposed by researchers. Saadatnia et al. [108] developed a hybrid energy harvesting device utilizing a circular tube as the outer shell, enabling internal magnetic blocks to move vertically along the tube in response to water waves. This design includes three EMG units with power densities of 170 W/m^3, 220 W/m^3, and 33 W/m^3, respectively, as well as a TENG unit with a power density of 120 W/m^3. Li et al. [109] introduced a wave vibration and undulation energy harvesting device, while Yu et al.[69] presented a novel wave energy harvesting device suitable for embedding in a buoy, both of which are based on the undulating motion of the magnet actuator. To enhance power output and adaptability to marine environments, further enhancements to the device structure were implemented.

Zhu et al. [53] proposed a highly integrated tubular triboelectric-electromagnetic wave energy harvester (TEWEH) designed to efficiently harvest energy across a broad frequency spectrum and under various wave excitations. The internal structure of TEWEH is depicted in Fig. 9a. The innovative design of TEWEH involves the fabrication of PM-PTFE balls, where PM balls are enclosed within a PTFE housing, enabling the movement of the balls within a customized acrylic round tube. Copper coils are wound around the exterior of the tube, facilitating the simultaneous power generation of TENG and EMG components as PM-PTFE balls move. This design significantly enhances the spatial efficiency and volumetric power density of the device. The inherent instability in the motion of the balls enables TEWEH to be activated even by low-frequency and minimal amplitude waves. The power generation mechanisms of TENG and EMG units within TEWEH operate independently, with PM-PTFE ball serving as the mobile component for both power generation units concurrently. The operational principles of TENG and EMG units are illustrated in Fig. 9b(i) and 8b(ii), respectively. The performance of TEWEH was comprehensively evaluated, demonstrating excellent power output even at 0.2 Hz, with maximum power densities reaching up to 13.77 W/m^3 and 148.24 W/m^3 for TENG and EMG units, respectively. In Fig. 9c, TEWEH generates the desired output in tank tests and exhibits the capability to power marine equipment such as navigation lights and thermometers, indicating its potential for diverse applications. Sun et al. [89] proposed a tubular solid-liquid interface triboelectric-electromagnetic hybrid generator (TTEHG) utilizing deionized water (DI) and a magnet block as the kinematic unit, resulting in enhanced excitation and improved power output.

Beyond achieving high output power, a key area of research in engineering is the development of devices that facilitate omnidirectional motion of internal oscillators. Yang et al. [111] introduced a novel

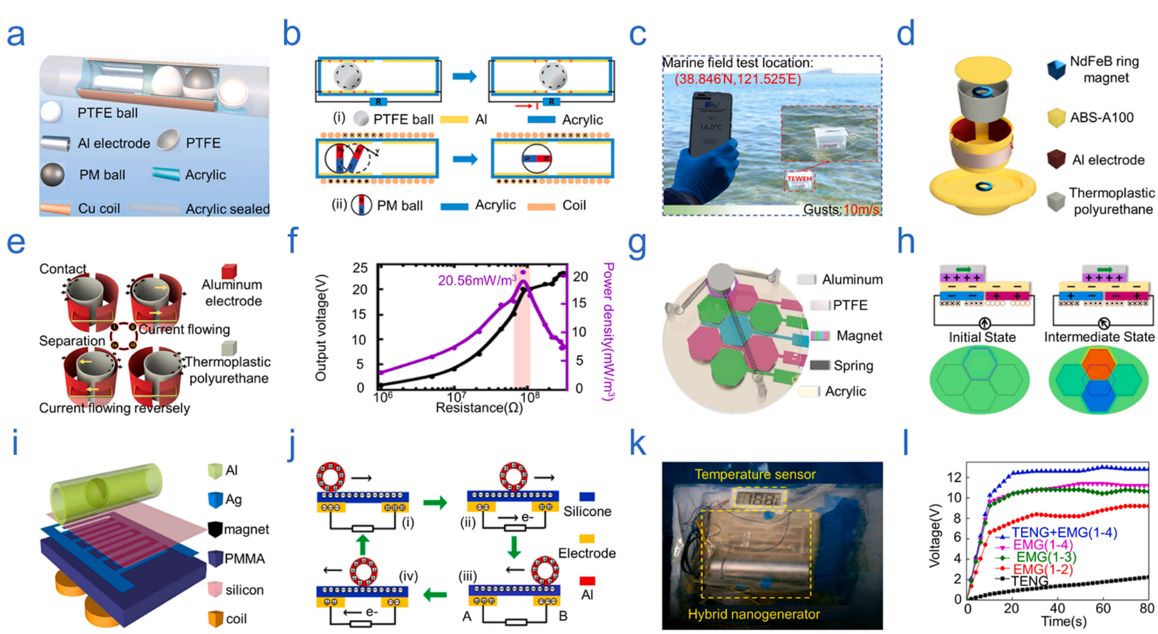

Fig. 9. Arbitrary motion structures of actuator in hybrid energy harvesting devices: a) TEWEH's internal structure and material selection; b) Mechanisms of motion for TENG(i) and EMG(ii) modules, detailing principles of power generation; c) Deployment of TEWEH in an actual ocean area, demonstrating its ability to transmit detection results in real time; Reproduced with permission Wiley [53]. d) Exploded view of structural design for ML-BEHD; e) Principle of power generation by ML-BEHD in presence of water waves; f) Characteristic curves of power density and output voltage of ML-BEHD; Reproduced with permission Springer Nature [68]. g) Structural design and material selection for How-NG's internal power generation unit; h) Principles of current generation and trajectories of How-NG devices; Reproduced with permission Elsevier [110]. i) Design diagram of a 2D hybrid nanogenerator structure; j) TENG module charge generation principle; k) Hybrid nanogenerators powered by water waves providing a steady supply of electricity to thermometers; l) Charging curves for different power generation modules of device. Reproduced with permission Elsevier [40].

hybrid generator aimed at harvesting low-frequency micro-vibrational ocean energy from various directions. To enhance adaptability to multi-directional ocean energy collection, San et al. [68] developed a magnetically levitated blue energy harvesting device (ML-BEHD) inspired by the buoy's shape. ML-BEHD (Fig. 9d) comprises an ML-TENG and an EMG. A levitating magnet is used as the actuator, which moves in multiple directions when it is externally excited to motivate the TENG and EMG to generate electrical energy simultaneously. The ML-TENG includes a freestanding dielectric oscillator (FOD) with two aluminum electrodes attached inside a cylindrical container, along with magnets for levitating FOD to enable omnidirectional oscillation. EMG is composed of coils and magnets wound around FOD. When subjected to wave motion, FOD oscillates, creating electrical energy by separating from the aluminum electrodes (Fig. 9e). Experimental results demonstrated a maximum power density of 20.56 mW/m^3 at an 88 MΩ load (Fig. 9f). Feng et al. [110] proposed a spring-assisted omnidirectional motion honeycomb three-electrode hybrid generator (How-NG) for efficient ocean energy collection in any direction. How-NG device (Fig. 9g) consists of a TENG unit and an EMG unit. TENG unit features aluminum electrodes coated with PTFE film and a sliding magnet block, with honeycomb electrodes serving as the triboelectric layer. EMG unit comprises seven coils with magnets attached to the honeycomb electrode. Three springs connected to the magnet block enable it to slide in any direction under the effect of water waves, generating electricity (Fig. 9h).

In addition to the cylindrical hybrid generators mentioned above, many studies developed hybrid HNGs with a rectangular column structure incorporating a magnet kinematic unit. This design leverages the structural properties of the rectangle to harness ocean energy. Wang et al. [112] introduced a rolling freestanding hybrid nanogenerator for capturing seawater motion energy. Shao et al. [113] proposed an undulating and oscillating multifunctional rectangular device for blue energy harvesting. A notable example is a box-shaped hybrid nanogenerator created by Hao et al. [40] for harvesting water wave energy. This device captures random wave energy in two dimensions through a complementary conversion mechanism. The hybrid nanogenerator comprises two main components: a TENG unit and an EMG unit (Fig. 9i). TENG unit features a hollow acrylic cylinder coated with an aluminum film, silver fork finger electrodes with a silicon film covering. EMG unit includes a magnetic sphere and four copper coils. The sphere is positioned inside a hollow acrylic cylinder that can move freely, while the coils are integrated into an acrylic plate. After rectification and energy management, the hybrid nanogenerator can be deployed in a water wave environment, connected to a temperature sensor. The power generation principle is depicted in Fig. 9j. Experimental results indicate that TENG unit can produce an instantaneous maximum power of 0.08 mW at a 100 MΩ load, while EMG unit can generate an instantaneous maximum power of 14.9 mW at a 1 kΩ load. The hybrid generator demonstrates the ability to deliver continuous and stable power to a thermometer under the effect of water waves (Fig. 9k). When used to charge a 10 μF capacitor, the hybrid generator exhibited faster charging to a higher voltage at a frequency of 1.8 Hz compared to a single generator unit (Fig. 9l). The device can reliably power wireless acoustic sensing systems in marine environments, highlighting its broad potential for ocean energy harvesting.

The cylindrical device utilizes rotor rotation to collect ocean energy. Ocean energy is collected in a specific direction using rolling or sliding by limiting the space in which the actuator moves.

3.4. Other special devices

Significant developments have been achieved in hybrid energy collection devices. However, to enhance ocean energy collection efficiency, addressing the structural design of the devices is crucial. Apart from the commonly used spherical, pendulum, and column structures, there is a necessity to explore and innovate additional specialized structures to accommodate various marine environments. This will enable more effective collection of ocean energy across multiple directions and frequencies. Special devices used for ocean energy harvesting can be categorized as fully enclosed mimic-shaped structure or semi-enclosed mechanism-assisted structure. Fully enclosed mimic-shaped structure utilizes its own structural characteristics to mimic the shapes of small boats [57], biplanes [58], and sea snake [114] for higher energy conversion efficiency. Semi-enclosed mechanism-assisted structure adopts external mechanical aids such as impellers to generate electricity and are adapted to different locations.

3.4.1. Fully enclosed mimic-shaped structure

Encapsulated hybrid generators are known for their enhanced stability when operating in challenging marine environments. The presence of water in the device can lead to short circuits, while humidity levels can diminish the triboelectric effect. Wang et al. [57] introduced a ship-shaped hybrid generator (SHNG) that incorporates two TENG units and one EMG unit. The unique structural design of SHNG facilitates encapsulation and ensures reliable performance even under severe weather conditions. SHNG features a double-deck boat structure with six contact separation mode TENGs connecting the internal hull in a suspended state. Magnets are affixed to both ends of the cylindrical roller inside the hull, with independent rolling TENGs at the bottom (Fig. 10a). This design allows the water waves' action to drive the two TENG units for electricity generation. EMG unit comprises magnets on the rollers with coils on both sides of the hull, enabling SHNG to charge capacitors efficiently and achieve higher voltage levels in a shorter timeframe compared to single TENG or EMG systems (Fig. 10b). Utilizing SHNG as the power source under low-frequency water waves, the rolling and contact-separated TENGs can produce a maximum power of 150 μW and 800 μW at 20 MΩ resistive loads, respectively, while EMGs can generate a maximum power of 9 mW at 100 Ω. This power output is adequate to sustain temperature and humidity sensors (Fig. 10c).

Tian et al. [115] proposed a low-frequency tribo-electric-electromagnetic-piezoelectric hybrid energy harvester (TEP-HEH) with a domed structure. This device integrates TENG and EMG units as its core components and employs a cantilever beam structure to convert vibration frequency from 0.2 Hz to 7.2 Hz, significantly enhancing EMG unit's performance. Furthermore, a PENG unit is incorporated into the cantilever beam to optimize device volume utilization and output power. In Fig. 10d, TEP-HEH configuration includes one TENG module, two EMG modules, and two additional PENG modules, forming a domed arch structure. TENG unit comprises a slider with a nylon film and a housing with a PTFE film, while EMG unit consists of coils and magnets on the cantilever beams. The movement of the vibrator causes the magnets to repel, leading to the vibration of the piezoelectric ceramics (i.e., PENG unit) on the cantilever beam, generating electrical energy. Fig. 10e shows the schematic of the working mechanism of the three power generation modules. The energy harvesting power of TEP-HEH under low-frequency water waves can reach 5.73 W/m^3. When driven at a frequency of 0.5 Hz to charge a 1 μF capacitor (Fig. 10f), TEP-HEH outperforms single modules by achieving higher voltage levels in a shorter duration, demonstrating the effectiveness of this hybrid device for ocean energy harvesting.

A novel duck-shaped structure has been proposed for ocean energy harvesting, enabling the extraction of nearly 80 % of the ocean's energy due to its unique design [116]. The duck-shaped hybrid energy harvester (Fig. 10g) combines TENG and EMG units. TENG unit comprises a rolling freestanding TENG with a nylon ball and a Kapton film covered with copper electrodes at the bottom, allowing the ball to roll freely within the Kapton layer. In contrast, EMG module consists of four fixed magnets at the center and four moving electromagnetic coils mounted on the side. These coils undergo radial motion with the rotation of the duck-shaped structure, leading to the generation of induced current through the change in coil flux. Experimental analysis demonstrates that the peak power densities of TENG and EMG can reach 213.1 W/m^3 and

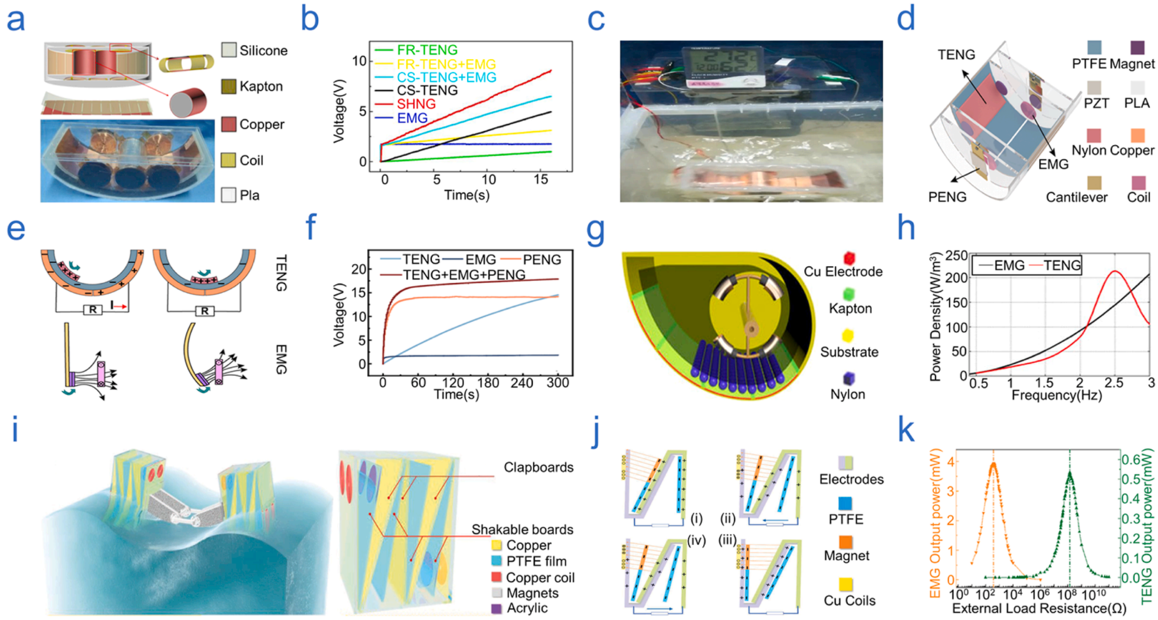

Fig. 10. Structural designs and performance of various hybrid nanogenerators: a) Structural design of SHNG; b) Charging curves for individual power generation modules and different hybrid units of SHNG; c) SHNG providing stabilized power to sensors under external excitation; Reproduced with permission Elsevier [57]. d) Structural design and material selection of TEP-HEH; e) Principle of power generation in TEP-HEH units; f) Charging curves for each power generation module of TEP-HEH; Reproduced with permission Elsevier [115]. g) Structural design of a duck-shaped hybrid nanogenerator; h) Power density of TENG and EMG units at different frequencies; Reproduced with permission Wiley [116]. i) Application scenarios and structural design of hybrid nanogenerators; j) Trajectory of device and principle for current generation(i–iv); k) Maximum output power of TENG and EMG modules. Reproduced with permission Wiley [58].

144.4 W/m^3 at 2.5 Hz (Fig. 10h), respectively. This analysis offers insights for optimizing and guiding the design of the hybrid structure of TENG and EMG. Based on this research, Liu et al. [117] developed a hybrid generator based on a nodding duck structure, which includes a multitrack independent TENG with EMG units. This design enhancement increases the device's adaptability in harsh marine environments and boosts the output power.

The output power of hybrid generators is typically limited. One approach to enhance the output performance of hybrid generators involves employing a special structural design where multiple identical hybrid generators are interconnected without impeding their movement. Wang et al. [58] developed an energy harvesting device with a biplane structure comprising two hybrid generators based on triboelectric-electromagnetic principles connected by a hinge. The biplane-structured energy harvesting device (Fig. 10i) comprises two hybrid generators with an optimized internal topology, each consisting of TENG and EMG units. TENG unit is composed of an acrylic box divided into four separate chambers, each containing swingable plates fixed to the top of the chamber with flexible film. PTFE film is attached to both sides of the plate, and copper electrodes are affixed to the inner wall of each chamber. The contact between PTFE film and copper electrodes separates under the oscillation of water waves, generating electrical energy. EMG unit includes movable magnets and coils within the outermost chamber. TENG and EMG units of the hybrid generator operate in conjunction (Fig. 10j) continuously producing electrical energy through wave action. Experimental results indicated that the peak output power of TENG and EMG units could reach up to 0.5 mW and 4 mW (Fig. 10k), respectively, yielding a more satisfactory output. Cao et al. [114] introduced a serpentine structure energy harvester that mechanically links two hybrid generators. The incorporation of a paper folding TENG unit in the connecting section enhances the electrical energy output, thereby ensuring the suitability of the connecting device in marine environments.

3.4.2. Semi-enclosed mechanism-assisted structure

In the marine environment, the ingress of water into electronics can lead to circuit failures. To address this issue, most hybrid generators are fully encapsulated. However, this design approach can constrain the device's output performance and its suitability for the marine environment. Huang et al. [118] and Guo et al. [119] proposed a semi-closed hybrid generator concept. This design incorporates non-contact forces between magnets as the primary driving force, supplemented by external fan blades. This modification enhances the device's responsiveness to marine environmental stimuli, resulting in increased power generation. Subsequent optimization of the device's structural design further boosts its power output.

Shao et al. [120] introduced a hybrid TEHG, including contact-separated triboelectric nanogenerators (CS-TENGs) and stand-alone rotating electromagnetic generators (RF-EMGs) to harness wave energy and ocean current energy from the surrounding environment. TEHG configuration (Fig. 11a) comprises five CS-TENGs and five corresponding RF-EMGs. Each CS-TENG is constructed with two acrylic plates serving as substrates, aluminum foil attached to the top substrate, and aluminum foil covered with PTFE film affixed to the bottom substrate. The triboelectric effect is achieved by the contact and separation of PTFE and aluminum foil, generating electrical energy through the motion of water waves. In contrast, RF-EMG consists of two magnets and a centrally positioned coil within a sandwich structure. The entire device is encased in a transparent acrylic cylindrical ring, housing five CS-TENGs and coils, with magnets evenly distributed along the central rotating shaft. Large impellers are mounted on both sides to facilitate device operation. The continuous generation of electrical output is enabled by the impeller rotation and the effect of water waves. The electrical energy produced by TEHG is derived from two components (Fig. 11b). The relationship between current and rotational speed is illustrated in Fig. 11c, indicating that TEHG reaches peak output at 100 rpm, with CS-TENG delivering 315.8 V, 44.6 μA, and 90.7 μW, and FR-EMG providing 0.59 V, 1.78 mA, and 79.6 μW. These results serve as a crucial reference for optimizing the structural design of ocean energy harvesting devices. FR-EMG's capacity to supply 0.59 V, 1.78 mA, and 79.6 μW is particularly significant for enhancing the structural efficiency of ocean energy harvesting systems.

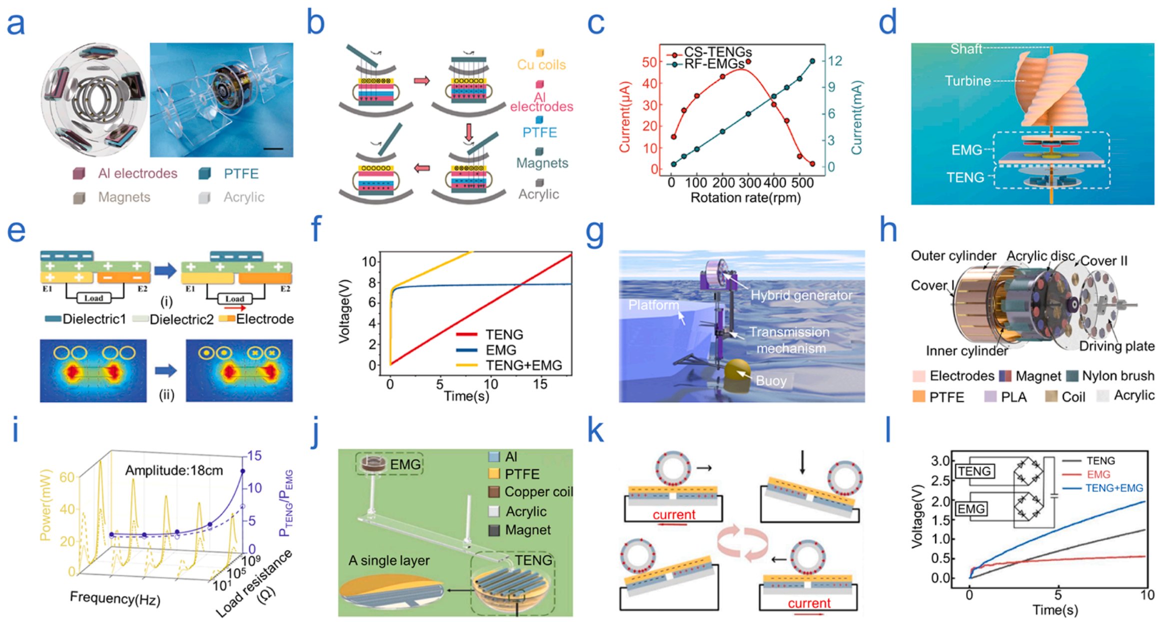

Fig. 11. Structural designs and operational principles of hybrid energy harvesting devices: a) Structural design and material selection for TEHG; b) Power generation principles for CS-TENGs and RF-EMGs; c) Maximum current output of TEHG; Reproduced with permission Springer Nature [120]. d) Structural design of TEHN equipment; e) Current generation principle for TENG and EMG modules; f) Charging curves for different power generation units; Reproduced with permission Wiley [65]. g) Diagram of practical application for undulation energy harvesting device; h) Structural design and material selection for power generation units; i) Output power at different frequencies; Reproduced with permission Elsevier [59]. j) Structural design and material selection for THNG; k) Motion mode and power generation principle of TENG unit; l) Rectification circuit diagram of THNG unit and charging curves of different generation modules. Reproduced with permission Elsevier [121].

Wang et al. [65] developed a turbine-driven triboelectric-electromagnetic hybrid generator (TEHN) designed for harvesting ocean current energy and ocean breeze energy. The structure of TENH is illustrated in Fig. 11d, comprising three main components: the turbine, the connecting shaft, and the hybrid generator. The use of a vertical axis mode turbine enables the device to capture low-grade energy from the marine environment. EMG unit is composed of four magnets in the rotor and four corresponding coils in the stator. Below EMG unit lies TENG unit, which includes a rotor with six pieces of polyvinyl chloride (PVC) film and a stator with a nylon film covered in copper foil. The rotation of the turbine drives both EMG and TENG units to produce electricity. The design and operational concept are depicted in Fig. 11e. TEHN is versatile and can be deployed in various marine settings, such as harvesting near-shore and offshore wind energy and underwater current energy. It achieves a peak power output of 449.74 mW, demonstrating the efficacy of the turbine-assisted configuration. Charging a 10 μF capacitor using this device (Fig. 11f) reveals higher charging efficiency of TENG and EMG hybrid system, indicating superior ocean energy collection capabilities of the hybrid generator.

Apart from the aforementioned mounting of the impeller and external machinery, Zhao et al. [59] proposed a hybrid multilayer soft-brush wave energy converter (WEC) based on a heave point absorber [59]. The device comprises a lifting buoy, a transmission mechanism, and a hybrid power generation module (Fig. 11g). The power generation module is divided into two parts. One part includes a multi-beam contact (MBC)-TENG made up of multilayered nylon soft brushes and copper fork-finger electrodes (Fig. 11h). The other part consists of a radial-disk (RD)-EMG composed of magnets attached to the rotor and coils on the lid. The device is positioned above the water surface, with only the buoy floating on the water, enabling a lifting and lowering motion due to wave excitation, which in turn drives the power generation module to rotate unidirectionally through the transmission mechanism. When subjected to a 1.2 Hz, 18 cm amplitude wave (Fig. 11i) TENG unit exhibits a peak power and power density of 59.5 mW and 19.2 W/m^3, respectively, while EMG unit shows 35.8 mW and 11.5 W/m^3, respectively. The device demonstrates high output, confirming its feasibility. Wu et al. [121] developed a teeter-totter-like hybrid generator utilizing an up-and-down buoy device. This unique device features a buoy-shaped multilayer TENG unit at one end of the seesaw and an EMG at the other end (Fig. 11j). One of TENG units is designed as a hemispherical buoy, internally divided into four layers by an acrylic shell. The bottom of each layer is lined with aluminum fork finger electrodes covered with PTFE film. An acrylic tube, wrapped with aluminum film, serves as a rolling element. When subjected to wave fluctuations, the rolling motion against PTFE film at the bottom generates electrical energy (Fig. 11k). A spacer between each pair of electrodes prevents the pipe from leaning to one side due to gravity, ensuring that the pipe movement covers each pair of electrodes. EMG unit comprises a magnet moving up and down along the acrylic cylinder at the opposite end and a fixed external coil. At the optimal frequency of 0.8 Hz, TENG reaches a maximum voltage of 760 V, and EMG achieves a maximum current of 10 mA. The hybrid generator charges a 100 μF capacitor (Fig. 11l). The hybrid device, combining TENG and EMG, can rapidly charge the capacitor to 2 V, demonstrating its effective ocean energy collection capability. The device's unique design allows it to autonomously adjust the incident wave direction, enabling omnidirectional energy capture.

Special types of devices with a certain specificity in shape. However, whether it is mimic-shaped structure or semi-closed structure utilizing external mechanical assistance, the ultimate goal is to obtain a higher energy conversion efficiency. Therefore, specific needs can be met by unconventional designs.

In summary, different types of hybrid generators, such as spherical, pendulum, column, and other specialized structures, are tailored to suit the challenging marine conditions and diverse application scenarios. The triboelectric nanogenerator produces high voltage and low current, while the electromagnetic generator yields high current and low voltage. Combining these two types of generators in a single device significantly enhances the efficiency of converting ocean energy. The spatial efficiency of the device directly affects its power density, while the selection of materials is crucial in harsh marine environments to ensure consistent and reliable output. Therefore, future research endeavors should concentrate on developing innovative structures, choosing high-performance materials, and achieving better integration with the marine environment.

4. Conclusions and perspectives

Ocean energy is widely distributed globally and is one of the most promising renewable sources. The full utilization of ocean energy in modern society can alleviate the growing energy crisis and environmental pollution. TEHNG can harvest energy in low-frequency environments and is recognized as one of the potential methods of efficiently harvesting ocean energy. TEHNG compensates for the lack of power in energy conversion of traditional single-type generators. The successful application of TEHNG has opened up a new path for ocean energy harvesting over the past period and has produced some remarkable results. In this paper, recent advances in hybrid devices for ocean energy harvesting are comprehensively summarized and systematically discussed from the perspective of four hybrid generators with different configurations.

Table 1 summarizes the structural features and energy output characteristics of several TEHNG with different structures. The different types, structures, materials, operating domain frequency, energy outputs, and application scenarios of TEHNG are systematically demonstrated. As shown in Table 1, TEHNG for ocean energy harvesting are divided into four major types, and each type of TEHNG is further divided into two structures, each of which has its characteristics and can play their respective advantages in different application scenarios. TEHNG has high energy conversion efficiency in low-frequency environment and is suitable for ocean energy harvesting. TEHNG uses TENG as the voltage source and EMG as the current source, both of which assist each other to improve the energy conversion efficiency of TEHNG.

In brief, TEHNG can simultaneously output high voltage and current with high output power, which compensates for the insufficient current or voltage output of a single type of generator. However, due to differences in device structure design, material selection, and application scenarios, they still face some significant challenges in different aspects and need further improvement, as shown in Fig. 12.

4.1. Superior structural design

In order to try to ensure that the TENG and EMG work without interfering and assisting each other, the structural design of the TEHNG needs to be improved to enhance the unique intersection of the integrated devices. Some TEHNG designs simply integrate the TENG and EMG in a separate space, with the two generators operating independently, simply by connecting the output circuits of the two generators in series or parallel. This design not only limits the output of both generators but also significantly increases the device's size in most cases. A high degree of integration of the TENG and EMG [53], where the moving parts work for both generators simultaneously, can effectively utilize the space inside the harvester and significantly increase the output power density of the device. Therefore, the internal structure of the TEHNG need to be optimized and reduced in size to further improve the output performance of it.

4.2. Materials innovation

The energy conversion efficiency and power output performance of the TEHNG is closely related to triboelectric sequence of the materials. Most of the triboelectric materials in the existing TEHNG devices are

Table 1
Summary of the different structures and output properties of TEHNG.

Type	Structure	Triboelectric Material	Frequency	V_{max}	I_{max}	Peak power/ Power density	Application	Ref
Spherical	Roller ball actuator	PTFE/Cu	1.0 Hz	145 V	34.6μA	79 W/m^3	Light up 34 LEDs	[93]
		Silicone/Nylon/ Cu	1.4 Hz	19+14.3 V	0.6μA +1 mA	8.01μW +6.7 mW	Powering hydrophone systems	[94]
	Ordinary slider actuator	Kapton/Cu	/	20 V	100 nA	85nW	Self-Powered Oil Spill Detection	[61]
		Nylon/PVDF/ PDMS/Ag/Al	0.7 Hz	(400+190) +0.78 V	(0.44+0.14μA/ cm^2) + 14 mA	(17+4. 8)+ 9.8 W/m^3	Light up 410 LEDs	[66]
Pendulum	Pendulum center shaft fixed	PET/PTFE/Cu	1.75 Hz	90+5.3 V	0.61μA +6.4 mA	0.26+6.2 mW	A self-powered wireless wave height alarm system for the intelligent fishing ground	[56]
		FEP/Cu	2.0 Hz	230+9.6 V	7μA +5 mA	3.25 +79.9 W/m^3	Light up about more than hundreds of commercial LEDs	[98]
	Spring assisted	FEP/Cu	2.2 Hz	190 +37.42 V	12.4μA +22.45 mA	470μW +523 mW	Wireless temperature sensor powered	[102]
		FEP/Cu	2.0 Hz	580+4.5 V	28μA +1.5 mA	0.41+0.3 W/m^3	A self-powered route avoidance warning system	[64]
Column	Rotating mechanical	FEP/Cu	/	375 +1.79 V	14.12μA +11.57 mA	(1.44+0.15) +15.9 mW	Light up 650 LEDs	[67]
		DI water/ FEP/Cu	1.33 Hz	168.08 +30 V	2.03μA +3.6 mA	101.5μW +10.1 mW	Light up 320 LEDs	[106]
	Rolling/sliding mechanical	DI water/ FEP/Cu	1 Hz	275 V	5 mA/cm^3	0.25 mW/cm^3	Power various electronic devices	[89]
		PTFE/Al	2 Hz	142 +0.66 V	23.3μA +2.14 mA	31.5μW +66.9μW	Light up 60 LEDs	[113]
Other special	Fully enclosed mimic-shaped	Silicone/Cu	2 Hz	(95+150) +4.3 V	(2.8 +15μA) + 15 mA	(165+800μW) +9 mW	Seawater self-desalination and self-powered positioning	[57]
		PTFE/Cu	1 Hz	450+2.5 V	3.7μA +4 mA	0.5+4 mW	Light up 110 LEDs	[58]
	Semi-enclosed mechanism-assisted	PTFE/PVC/ Nylon/Cu	5 Hz	550 +17.61 V	27.35μA +37 mA	449.74 mW	Self-powered marine wireless sensor node	[65]
		PTFE/Al	0.8 Hz	760+2.2 V	4μA +10 mA	55 mW/m^2+/	Powers a rain-drop sensor	[121]

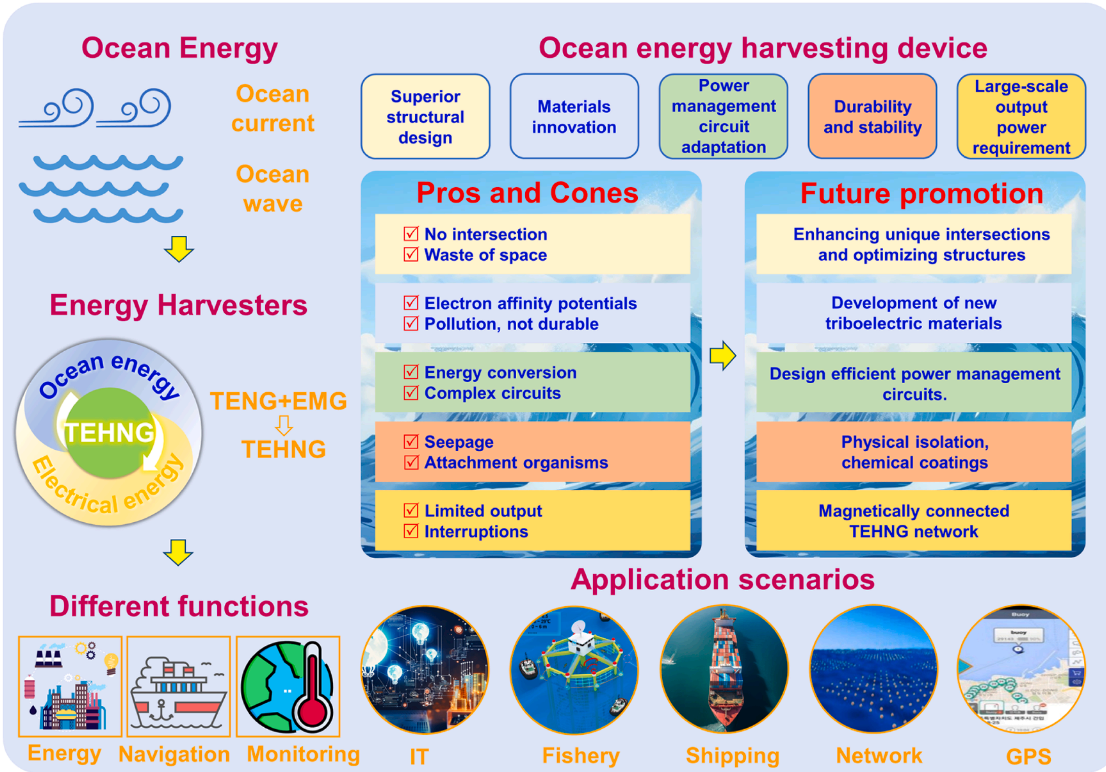

Fig. 12. Challenges and development orientations of the TEHNGs.

commercialized polymer materials, such as PTFE and FEP [64,67,102]. However, the inherent electron affinity of these existing materials limits the further improvement of TEHNG energy conversion efficiency. Therefore, there is an urgent need to exploit novel materials and develop new composites, which require materials with high electronegativity and intense charge trapping and retention capabilities. Environmental-unfriendly and non-recyclable materials should also be avoided, and emphasis should be placed on developing new triboelectric materials that are wear- and corrosion-resistant further.

4.3. Power management circuit adaptation

The electrical energy output of the TENG unit in TEHNG has high-voltage and pulse-output characteristics, which makes it unsuitable for charging batteries directly, as energy storage devices require a stable DC output. Efficient power management circuits can optimize the energy output of TEHNG. Therefore, the development of efficient power management circuits is one of the key factors to improve the energy conversion and energy storage performance of TEHNG. In addition, the TEHNG consists of TENG and EMG with vastly different characteristics, in which TENG is equivalent to a voltage source, and EMG is equivalent to a current source, with a huge difference in output impedance between the two [122]. The ohmic loss caused by complex circuits will reduce the energy conversion efficiency of TEHNG. Therefore, it is of great significance to develop the power management circuits adapting the impedance of TENG and EMG to reduce power loss with optimal design.

4.4. Durability and stability

In actual application, TEHNG should be arranged in the marine environment for a long period with the environment of salt, humidity, pressure, etc., will affect the device to a great extent. Therefore, waterproof strategies must be implemented to prevent seawater from penetrating the device and damaging the internal electronic components. Furthermore, the marine environment is corrosive, so the housing should be made of corrosion-resistant materials or covered with a waterproof structure to enhance the TEHNG corrosion resistance and ensure long-term stable operation of the TEHNG. In addition, marine organisms attached to the TEHNG can also affect the energy conversion efficiency or damage the device. The following methods could be considered to prevent marine organisms from attaching on the device: (1) Design the physical isolation layer on the surface of TEHNG, which can be made of materials with smooth surfaces to reduce the chance of marine organisms' attachment. The physical isolation layer can also be textured to decrease the surface friction coefficient, further reducing the possibility of marine organism attachment. (2) An anti-biotic coating can be applied to the surface of TEHNG, and the coating usually contains active substances inside. The active substances can release reactive ions that prevent the attachment and reproduction of marine organisms.

4.5. Large-scale output power requirement

Researches show that the electrical output of TEHNGs will increase linearly by connecting multiple TEHNGs together to form an energy harvesting array. So utilizing the TEHNG network to collect ocean energy can be used as a large-scale energy supply. TEHNG network consisting of thousands of TEHNG units through a specific arraying method can output high-power electricity. The TEHNG network's connection method will affect the network's performance output, and at present, the main connection method is based on a rigid connection. However, under actual waves, rigid connections have too many internal constraints that may limit the energy conversion of TEHNG networks, so the flexible connections are treated to be a better network connection strategy. Meanwhile, the connection between TEHNG networks may be interrupted under severe ocean conditions such as storms and heavy waves. Self-assembly strategy such as realized by installing multiple adaptive magnetic connectors between the TEHNG may be a promising way to address this problem.

The above challenges are also opportunities for researchers in this field around the world. With growing energy needs, we are confident that TEHNG will play an important role in ocean energy harvesting in the near future after addressing the main challenges.

CRediT authorship contribution statement

Yongjiu Zou: Writing – review & editing. **MINYI XU:** Writing – review & editing. **Dianlong Shen:** Investigation. **Fangyang Dong:** Writing – review & editing, Conceptualization. **Zhixiang Chen:** Investigation. **Hu Cai:** Writing – original draft, Conceptualization. **Taili Du:** Writing – review & editing, Conceptualization.

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.

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Data Availability

Data will be made available on request.

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