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Review

Recent Advances of Hybrid Nanogenerators for Sustainable Ocean Energy Harvesting: Performance, Applications, and Challenges

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Abstract

Ocean energy is an abundant, eco-friendly, and renewable energy resource that is useful for powering sensor networks connected to the maritime Internet of Things (MIoT). These sensor networks can be used to measure different marine environmental parameters that affect ocean infrastructure integrity and harm marine ecosystems. This ocean energy can be harnessed through hybrid nanogenerators that combine triboelectric nanogenerators, electromagnetic generators, piezoelectric nanogenerators, and pyroelectric generators. These nanogenerators have advantages such as high-power density, robust design, easy operating principle, and cost-effective fabrication. However, the performance of these nanogenerators can be affected by the wear of their main components, reduction of wave frequency and amplitude, extreme corrosion, and sea storms. To address these challenges, future research on hybrid nanogenerators must improve their mechanical strength, including materials and packages with anti-corrosion coatings. Herein, we present recent advances in the performance of different hybrid nanogenerators to harvest ocean energy, including various transduction mechanisms. Furthermore, this review reports potential applications of hybrid nanogenerators to power devices in marine infrastructure or serve as self-powered MIoT monitoring sensor networks. This review discusses key challenges that must be addressed to achieve the commercial success of these nanogenerators, regarding design strategies with advanced simulation models or digital twins. Also, these strategies must incorporate new materials that improve the performance, reliability, and integration of future nanogenerator array systems. Thus, optimized hybrid nanogenerators can represent a promising technology for ocean energy harvesting with application in the maritime industry.

Keywords: hybrid nanogenerator; ocean energy; energy harvesting; triboelectric nanogenerator; piezoelectric nanogenerator; electromagnetic generator; maritime Internet of Things; maritime industry

1. Introduction

Ocean energy is the most abundant renewable energy resource on Earth, with a theoretical energy generation of approximately 151,300 TWh per year, depending on the frequency of extreme environmental conditions [1,2]. The oceans are clean and sustainable energy sources that can be harvested using hybrid nanogenerators composed of triboelectric nanogenerators (TENGs), piezoelectric nanogenerators (PENGs), electromagnetic generators (EMs), or thermoelectric generators (TEGs). These generators can integrate eco-friendly systems to harness and store ocean energy, converting it into electricity [3,4]. Thus, these systems can power device networks connected to the maritime Internet of Things (MIoT) for real-time monitoring of different marine environmental parameters. However, the use of hybrid nanogenerators in oceans involves challenges such as performance stability and mechanical durability that can be affected by corrosion and harsh marine environments. To address these challenges, more research on the reliability of hybrid nanogenerators in oceans is required.

Recently, hybrid nanogenerators have been developed for harvesting wave energy and converting it into electrical energy. In addition, hybrid nanogenerators can function as self-powered sensors to measure environmental or wave parameters [5,6]. For instance, Hu et al. [7] designed a hybrid nanogenerator based on the electromagnetic and triboelectric transduction mechanisms. This nanogenerator harvests wind and wave energies, converting them into electrical energy. The electromagnetic and triboelectric mechanisms have power densities of 50 Wm^{-3} and 53 mWm^{-3}, respectively. This hybrid nanogenerator offers an alternative power source for environmental monitoring devices. Tang et al. [8] fabricated a multi-mode hybrid generator that consisted of free-standing and contact-separation TENGs, and an electromagnetic generator. This hybrid device achieved a peak power density of 125.41 Wm^{-3} under a frequency of 0.5 Hz with potential application for self-powered marine sensors. Jia et al. [9] reported a hybrid nanogenerator combining a rotating TENG, two free-standing TENGs, and an EMG for omnidirectional wave energy harvesting. The free-standing TENGs and EMG modules reached a peak power density of 29.92 $Wm^{-3}Hz^{-1}$ and 402.08 $Wm^{-3}Hz^{-1}$, respectively. This nanogenerator integrates a self-powered, real-time ocean currents monitoring buoy system connected to the IoT. This self-adaptive system can estimate the ocean pH, current type, wave direction, and wind direction and speed. Thus, this hybrid system can power distributed device nodes for smart MIoT. Gao et al. [10] developed a hybrid nanogenerator for a smart MIoT network, which incorporated two TENGs, two EMGs, and two PENGs in a vessel. The geometric design of this hybrid device improved its spatial utilization efficiency, reaching a peak power density of 82.4 Wm^{-3}. However, these hybrid nanogenerators require further study to enhance their durability and adaptability to various ocean wave conditions, optimizing wave energy harvesting. Other challenges include maintaining stable performance of the hybrid nanogenerators and ensuring efficient communication within the sensor network.

Herein, we present recent investigations on hybrid nanogenerators that harvest ocean energy and transform it into electrical energy, or function as self-powered MIoT sensors for real-time monitoring of different marine environmental conditions. Furthermore, this review reports the operating principle, materials, electrical performance results, and applications of hybrid nanogenerators in the marine environment. These hybrid devices

comprise various TENG, EMG, PENG, and TEG modules. In addition, the advantages and drawbacks of hybrid nanogenerators for ocean wave energy harvesting are discussed. Also, we present various challenges of the hybrid nanogenerators, considering their design, materials, energy storage and management systems, fabrication processes, reliability, and integration. Thus, the optimal design of hybrid nanogenerators can enable their commercial application as an eco-friendly and cost-effective technology for harvesting renewable ocean energy.

2. Operating Principle of Hybrid Nanogenerators

This section describes the operating principles of various transduction mechanisms that can be utilized in hybrid nanogenerators. These transduction modes include the triboelectric nanogenerators, electromagnetic generators, piezoelectric nanogenerators, and thermoelectric generators. The integration of these transduction mechanisms in hybrid nanogenerators can increase the efficiency of the harvested ocean energy. Figure 1 illustrates various transduction modules for ocean energy harvesting.

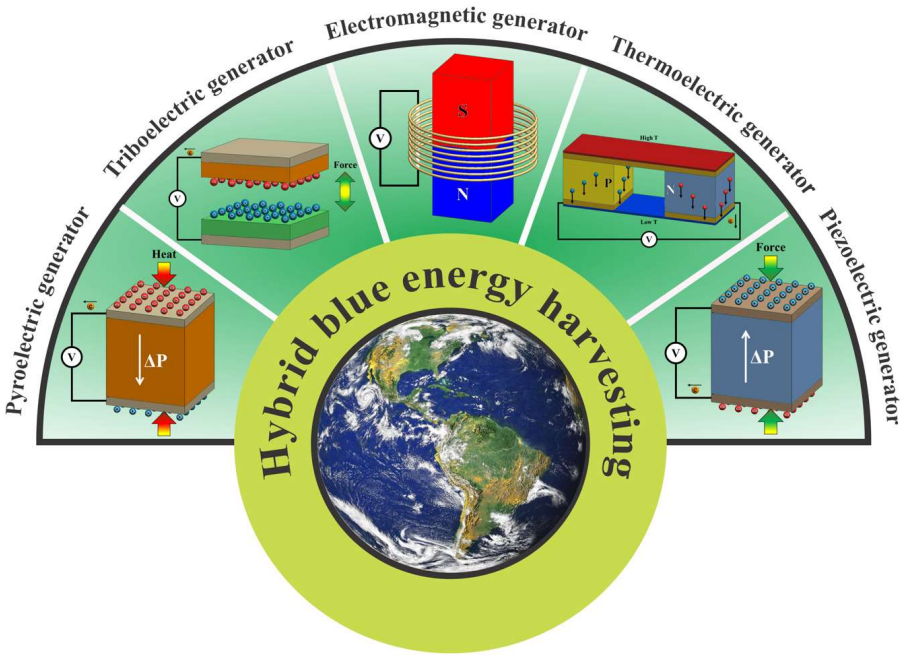


Figure 1. Different transduction mechanisms for ocean energy harvesting.

2.1. Triboelectric Nanogenerators

Triboelectric nanogenerators can harvest kinetic energy and convert it into electrical energy. The operating principle of a TENG is based on contact electrification (CE) and electrostatic induction, as shown in Figure 2. TENGs can perform using four transduction modes: contact-separation, side slip, single electrode, and freestanding triboelectric-layer [11,12]. The side–slip mode of a TENG involves the generation of electrical charges between the surfaces of two triboelectric layers by periodic contact and separation (see Figure 3a). Slip-induced lateral polarization facilitates the flow of electrons between the upper and lower electrodes, generating an alternating current. This side–slip mode of TENGs is suitable for harnessing the variable kinetic energy of ocean waves. In contrast, the contact–separation mode of a TENG occurs when two triboelectric layers generate opposite charges upon physical contact (see Figure 3b). Additionally, the variation in the separation distance between the two triboelectric layers induces electrostatic induction, generating an alternating voltage between the two electrodes of the nanogenerator. This

contact–separation mode allows simple structural designs for TENGs. On the other hand, the single-electrode mode of a TENG generates an alternating voltage due to the contact–separation of a triboelectric layer with respect to an electrode (see Figure 3c). This operating mode of a TENG can serve as a self-powered sensor. The fourth operating mode of a TENG employs a triboelectric layer that slips between two separate electrodes (see Figure 3d). In this mode, the contact and separation of the triboelectric layer with the electrodes can produce an asymmetric charge distribution that generates a voltage difference between the electrodes.

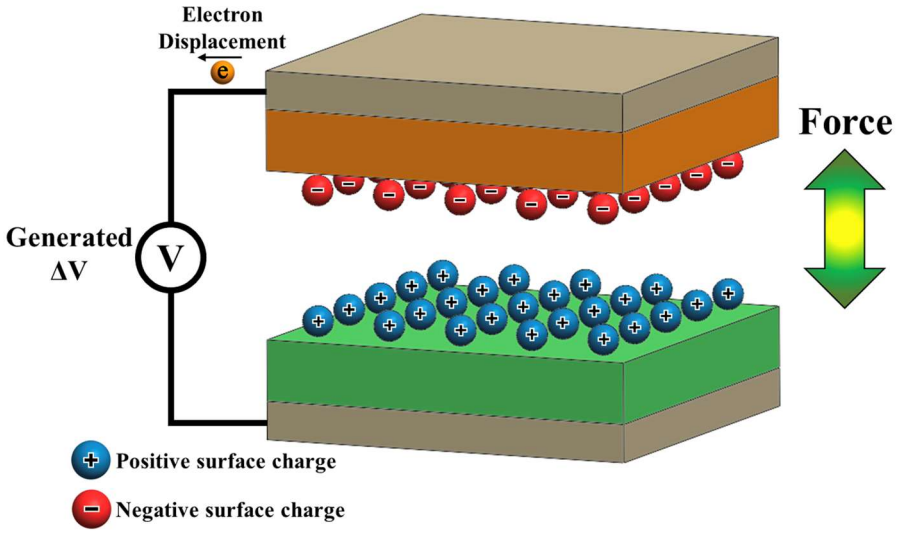


Figure 2. Operating mechanism of a triboelectric nanogenerator with two triboelectric layers.

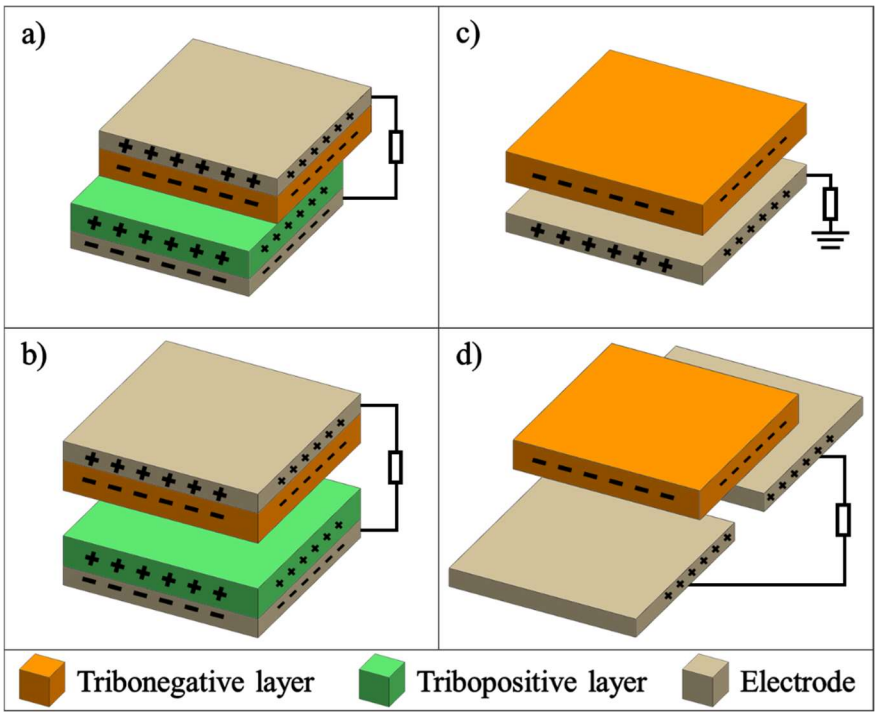


Figure 3. Four working modes of TENGs: (**a**) Side–slip mode, (**b**) contact–separation mode, (**c**) single-electrode mode, and (**d**) freestanding triboelectric-layer mode.

2.2. Piezoelectric Nanogenerators

A piezoelectric nanogenerator can produce an output voltage due to the deformation of a piezoelectric material, as shown in Figure 4. Generally, a PENG uses two electrodes that

are connected to opposite sides of a piezoelectric material. Due to the piezoelectric effect, a piezoelectric material under external oscillating forces can be deformed, causing an electrical potential differential. Researchers have developed piezoelectric nanogenerators based on materials such as $BaTiO_3$, ZnO, polyvinylidene fluoride (PVDF), and copolymers [13–15]. For instance, Figure 5 illustrates a PENG comprising a piezoelectric nanowire and two electrodes. An external oscillating force can be applied in two directions: perpendicular and parallel to the nanowire. In both cases, the upper contact acts as a Schottky contact, while the lower contact functions as an ohmic contact. To optimize the output power of the PENG, it is necessary to integrate several nanowires to ensure that the deformation of each nanowire is synchronized.

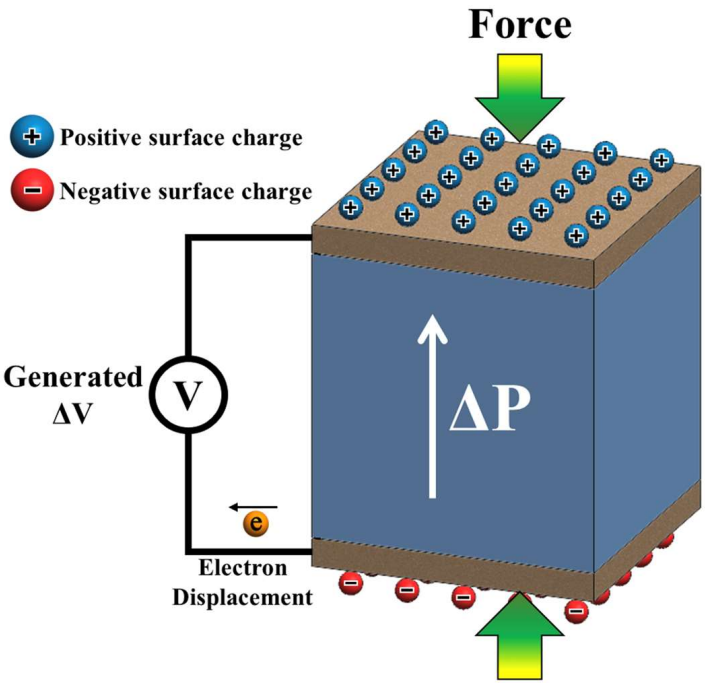


Figure 4. Schematic view of the piezoelectric effect in a PENG.

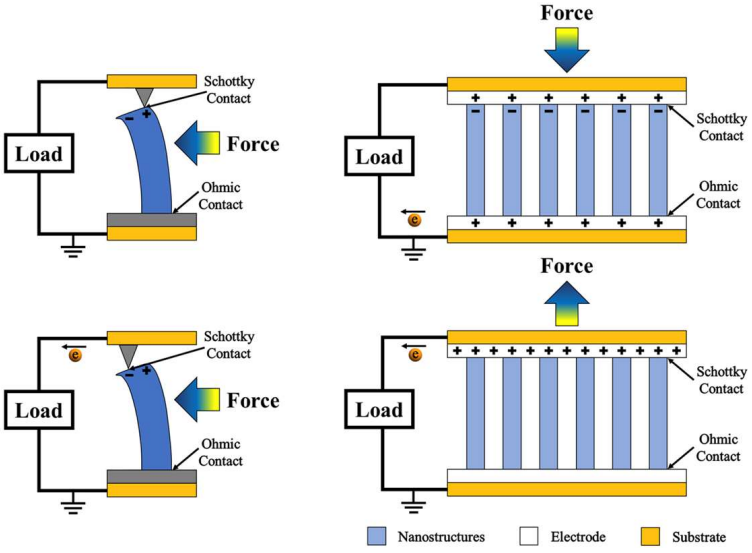


Figure 5. Different operating mechanisms of a PENG: (**left**) force acting perpendicular to the nanowire growth direction and (**right**) force acting parallel to the nanowire growth direction.

2.3. Electromagnetic Generator

Electromagnetic generators operate according to Faraday's law of electromagnetic induction (see Figure 6), inducing an electrical potential difference in a coil when it is exposed to a variable magnetic field [16]. For applications in oceans, EMGs may require a structure that converts water flow into rotational energy. The resulting rotational energy is used to move magnets around the coils of an EMG, facilitating electromagnetic induction [17]. These generators are used to harness ocean waves under variations of amplitude and frequency of the waves [18,19]. However, EMGs face challenges in reducing their fabrication costs, volume, and weight, especially when operating on the surface of the oceans. To address these challenges, more investigations are required to enhance the design and fabrication of EMGs that integrate hybrid nanogenerators.

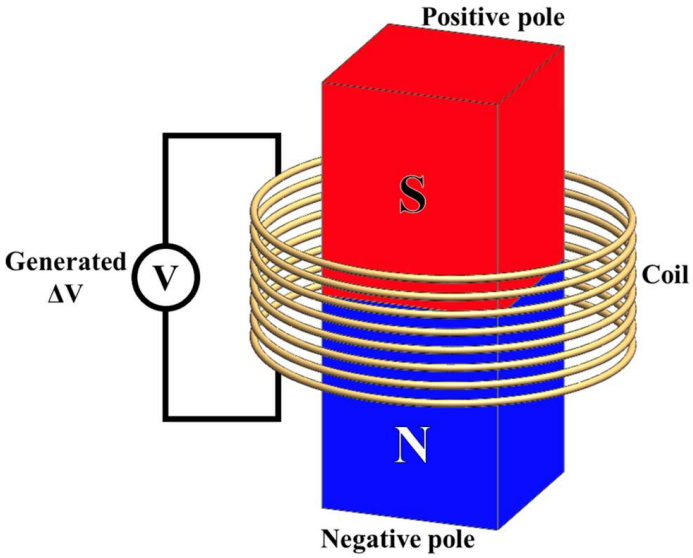


Figure 6. Operating principle of an electromagnetic generator.

2.4. Pyroelectric Nanogenerator

A pyroelectric nanogenerator (PyNG) can convert thermal energy into electricity through the pyroelectric effect [20,21]. These materials change their electrical polarization in response to temperature shifts, generating an electric current (see Figure 7). Commonly, a PyNG is formed by a multilayer structure. The top layer, composed of metal, is combined with the middle layer of pyroelectric material, which generates an electrical charge in response to temperature variations. These temperature alterations induce the reorganization of the electric dipoles in the crystalline structure of the pyroelectric material, causing an imbalance of charges that produces an electric current. Finally, a second electrode is located at the bottom surface of the PyNG. Zinc oxide (ZnO) and potassium niobate ($KNbO_3$) are two materials commonly used to fabricate pyroelectric nanogenerators. These materials can undergo significant changes in their electrical polarization due to thermal fluctuations, which is essential for the efficient performance of pyroelectric nanogenerators. These nanogenerators can be used to harness ocean wave energy and produce self-powered sensors for monitoring ocean wave parameters. Nevertheless, pyroelectric nanogenerators exhibit low energy conversion and dependence on temperature variation, which may limit their application in some ocean environments [22,23].

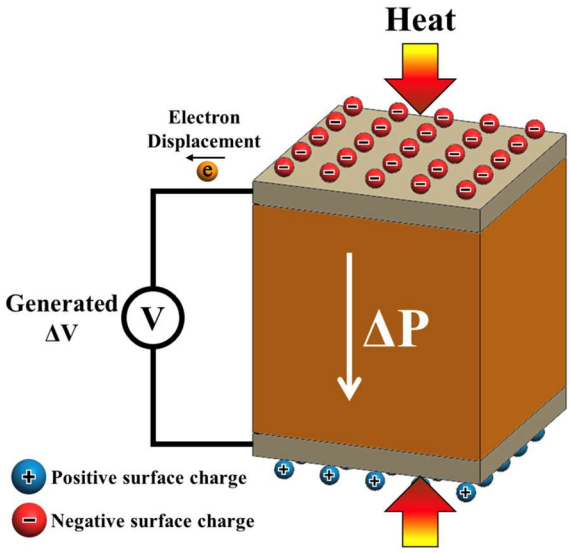


Figure 7. Operating principle of a pyroelectric nanogenerator.

2.5. Thermoelectric Generator

A thermoelectric generator can transform thermal energy into electricity. The operating principle of this generator is based on the Seebeck effect, a thermoelectric phenomenon that generates an electric current in a semiconductor material when a temperature gradient is established across this material [24,25]. Typically, TEGs use n-type and p-type semiconductor materials (see Figure 8). The temperature difference between these materials produces electrical energy. Thermoelectric generators offer advantages such as durability, a simple working principle, and environmental sustainability [26]. However, TEGs have disadvantages such as low efficiency and high-cost fabrication [27,28]. Bismuth telluride and lead telluride are materials employed to fabricate TEGs due to their thermoelectric properties [29,30]. These materials may be useful for harvesting ocean energy and developing self-powered sensors for monitoring ocean environmental parameters. The performance of TEGs can be enhanced when the temperature difference between the outer and bottom surfaces of thermoelectric materials increases.

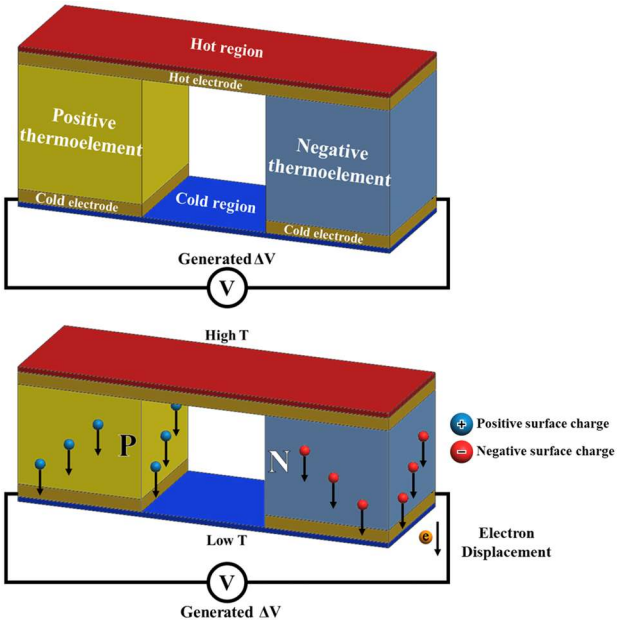


Figure 8. Operating principle of a thermoelectric generator.

3. Applications

This section reports several applications in marine environments of recent hybrid nanogenerators integrated by different transduction mechanisms. Furthermore, the design, performance, and limitations of these hybrid nanogenerators are discussed. Also, a comparison of the main performance results, advantages, and disadvantages of hybrid nanogenerators is included.

To obtain a comprehensive and systematic overview of recent hybrid nanogenerators for harvesting ocean wave energy, we conducted a search of scientific articles in Scopus journals from 2016 to 2025, using the keywords "Ocean energy" and "Hybrid nanogenerator". In this literature search, we only considered scientific articles on hybrid nanogenerators with different transduction mechanisms to harness ocean wave energy. Finally, we identified 50 articles with potential applications for ocean wave energy harvesting, which were included in Table 1. In this table, we described the main transduction modules, materials, performance parameters, potential applications, and advantages of the hybrid nanogenerators. These nanogenerators can capture ocean wave energy and transform it into electrical energy. Thus, these nanogenerators could power sensor networks connected to MIoT for real-time monitoring of different environmental conditions, such as temperature, humidity, wind speed, and current direction and speed. Additionally, hybrid nanogenerators can be designed to serve as self-powered sensors, integrated with signal management circuits, for wireless marine data transmission. For instance, Li et al. [31] developed a hybrid nanogenerator composed of TENG and PENG modules, which can harvest energy from both wind and waves (see Figure 9). In addition, an electronic circuit for energy management was incorporated to improve the efficiency of the harvested ocean energy. This nanogenerator has three transduction modules: a wind energy harvesting triboelectric nanogenerator (WD-TENG), a wave energy harvesting triboelectric nanogenerator (WE-TENG), and a wind energy harvesting piezoelectric nanogenerator (WD-PENG). These three modules can be used individually or in combination, as shown in Figure 10. The maximum power densities of WD-TENG, WE-TENG, and WD-PENG modules were 5.064 Wm^{-3}, 1.478 Wm^{-3}, and 1.092 Wm^{-3}, respectively. This hybrid generator was used to power temperature and humidity sensors, as well as LED lights. Also, this hybrid nanogenerator can be connected to the MIoT. This hybrid nanogenerator exhibited versatility to collect energy from waves and wind. Its coupled design allows the integration of the three modules, which can operate independently or collaboratively. However, this nanogenerator has a complex design that requires precise manufacturing. In addition, the performance of the device depends on environmental conditions, such as wind and wave intensity. Thus, the design of this hybrid nanogenerator can be optimized to improve its performance under alterations in wind and wave amplitudes.

Table 1. Comparison of transduction modules, materials, performance parameters, potential applications, and advantages of recent hybrid nanogenerators.

Ref.	Transduction Modules	Main Components	Performance Parameters	Potential Applications/Advantages
[6]	A large disk-shaped TENG, four small disk-shaped TENGs, and four small disk-shaped EMGs.	Large disk TENG: Rabbit fur, PTFE film, and Cu electrodes. Small disk TENG: Rabbit fur, PTFE film, and Cu electrodes. Small disk EMG: Magnet and coils.	Using all modules: Peak power density of 37.105 Wm^{-3}.	Self-powered corrosion protection systems of ship hulls/long durability and stable output performance.

Table 1. *Cont.*

Ref.	Transduction Modules	Main Components	Performance Parameters	Potential Applications/Advantages
[7]	A TENG and an EMG.	TENG: Fluorinated ethylene propylene (FEP) film and Cu electrode. EMG: Magnets and coil.	TENG: Max. power density of 53 mWm^{-3}. EMG: Max. power density of 50 Wm^{-3}.	Design for large-scale wave energy harnessing/low wear, and improved service life.
[8]	Three free-standing TENGs, two contact–separation TENGs, and two EMGs.	Free-standing TENGs: Polytetrafluoroethylene (PTFE) balls and Cu. Contact–separation TENGs: PTFE film and steel electrode. EMGs: Two coils and magnetic ball.	Using all modules: Peak power density of 125.41 Wm^{-3}.	Self-powered marine sensors/compact structure, easy integration, and cooperative effect of three different module types.
[9]	A rotating TENG, two free-standing TENGs, and an EMG.	Rotating TENG: Nylon ball, polydimethylsiloxane (PDMS) film, and Cu electrode. Two free-standing TENGs: Rabbit fur, polyvinylidene fluoride (PVDF)/$BaTiO_3$ films, and Fe electrode. EMG: Coils and magnets.	Free-standing TENG: Peak power density of 29.92 $Wm^{-3}Hz^{-1}$. EMG: Peak power density of 402.08 $Wm^{-3}Hz^{-1}$.	Self-powered real-time ocean currents monitoring buoy systems, distributed sensor networks for smart MIoT/self-adaptability, versatile structure, and good mechanical robustness.
[10]	Two TENGs, two EMGs, and two PENGs.	TENG: FEP film and Cu electrodes. EMG: Trapezoidal magnet and coils. PENG: Polyvinylidene fluoride (PVDF) film and silver electrodes.	Using all modules: Peak power density of 82.4 Wm^{-3}.	Self-powered MIoT smart sensor networks/simple design, efficient space utilization, and stable output performance.
[31]	A WD-TENG, a WD-PENG, and a WE-TENG.	WD-TENG: PTFE films and Cu electrode. WD-PENG: PVDF films. WE-TENG: PTFE films and Cu electrode.	WD-TENG: Power density of 5.064 Wm^{-3}. WD-PENG: Power density of 1.478 Wm^{-3}. WE-TENG: Power density of 1.092 Wm^{-3}.	Self-sustaining MIoT ocean sensors/stable output performance and adaptability.
[32]	A TENG and an EMG.	TENG: FEP film and Cu electrode. EMG: Magnet and coil.	Using all modules: Instantaneous power density of 0.25 $mWcm^{-3}$.	Self-sufficient ocean monitoring systems/simple design, compact structure, and safe performance in harsh ocean environments.
[33]	A TENG and an EMG.	TENG: FEP film and Cu electrode. EMG: Magnetic ball and coil.	Using all modules: power density of 7.25 μWcm^{-3}.	Self-sufficient ocean sensors for MIoT/self-adaptability for irregular ocean waves, and stable operation.
[34]	An O-TENG and an MTEG.	O-TENG: FEP film and Cu electrode. MTEG: N- type Bi_2Te_3 and P-type Bi_2Te_3.	O-TENG: Max. output voltage of 5.85 V. MTEG: Max. output voltage of 1.821 V.	Self-powered marine mammal condition monitoring system/ease of manufacturing, long service life, and stable operation.
[35]	Two TENGs, two PENGs, and an EMG.	TENG: Kapton substrate, FEP films, and Cu electrodes. PENG: Two lanthanum zirconate titanate sheets, and Cu and Ag electrodes. EMG: Trapezoidal magnets and wedge-shaped coil.	Using all modules: Power density of 358.5 Wm^{-3}.	Self-powered marine sensors/optimized geometric structure, easy maintenance, and stable operation.

Table 1. *Cont.*

Ref.	Transduction Modules	Main Components	Performance Parameters	Potential Applications/Advantages
[36]	Two TENGs and two EMGs.	TENG: FEP and nylon films, and Cu electrode. EMG: Magnet array and coil array.	Using all modules: Average power density of 44.52 Wm^{-3}.	To power sensors at MIoT nodes/adaptable and reliable structure, and stable performance.
[37]	A TENG and an EMG.	TENG: Polyvinyl chloride (PVC) film and Cu electrode. EMG: Magnet and coil.	TENG: Peak power density of 56.7 $Wm^{-3}Hz^{-1}$. EMG: Peak power density of 192.3 $Wm^{-3}Hz^{-1}$.	Self-powered MIoT sensor networks/high efficiency, reliable operation, and low maintenance costs.
[38]	A TENG and an EMG.	TENG: Polyvinyl alcohol (PVA)-based hydrogel with reduced graphene oxide (rGO) and silicone rubber, and Cu electrodes. EMG: Spherical magnet and copper winding.	TENG: Output voltage of 1.20 V. EMG: Output power of 1.47 W.	Sensor for monitoring low-frequency and low-amplitude waves/compact structure, and good durability.
[39]	Four TENGs and two EMGs.	TENG: PTFE film and Cu electrode. EMG: Magnet and Cu coil.	TENG: Open-circuit voltage of 500 V. EMG: Open-circuit voltage of 11.6 V.	To power water quality sensor in oceans/simple design.
[40]	Four free-standing TENGs, three PENGs, and an EMG.	TENG: PTFE film, steel sheet. PENG: Lead zirconate titanate (PZT), Cu and silver electrodes. EMG: Magnet and coil.	Using all modules: Maximum peak power of 15.42 mW.	To power a sustainable MIoT sensing system/good performance under low-frequency, and low-amplitude water waves.
[41]	A TENG and an EMG.	TENG: Rabbit fur, FEP film, and Cu electrode. EMG: Magnet and coil.	TENG: Max. output power of 0.4 mW at R_L = 10 GΩ. EMG: Max. output power of 0.42 mW at R_L = 50 Ω.	Self-powered systems for small marine sensors/optimal structure and simple operating mechanisms.
[42]	Two folded TENGs, a free-standing TENG, and three EMGs.	Folded TENG: PTFE film, stainless steel sheet. Free-standing TENG: Rabbit fur, PTFE film, and Cu electrode. EMG: Magnets and coils.	Folded TENG: Peak output power of 21.7 mW at R_L = 20 MΩ. Free-standing TENG: Peak output power of 0.13 mW at R_L = 70 MΩ. EMG: Peak output power of 2.9 mW at R_L = 1 KΩ.	Self-powered marine sensors/low startup requirements, and good performance for wave low-frequency, and low-amplitude water waves.
[43]	A TENG and an EMG.	TENG: Nylon and FEP films, and stainless steel. EMG: Magnet and coils.	Using all modules: Average power density of 1.69 Wm^{-3}.	Wireless water level alarm system/clever structural design and stable operation.
[44]	Two multilayered TENGs, six PENGs, and nine EMGs.	TENG: PTFE film and steel sheet. PENG: PZT sheet and steel sheet. EMG: Magnet and coil.	Using all modules: Peak power density of 61.4 $Wm^{-3}Hz^{-1}$.	Self-powered desalination technology/simple structure and low-cost fabrication.
[45]	A TENG and an EMG.	TENG: Rabbit fur brushes, nylon and FEP strips, and Cu electrode. EMG: Magnets and coils.	Using all modules: Peak power density of 25.08 Wm^{-3}.	Self-powered wireless sensor networks for marine meteorological monitoring/good durability, and versatile and economical design.

Table 1. *Cont.*

Ref.	Transduction Modules	Main Components	Performance Parameters	Potential Applications/Advantages
[46]	A liquid–solid tubular TENG and two EMGs.	TENG: PFTE tube and Cu electrodes. EMG: Magnetic balls and coils.	TENG: Peak power of 8.8 μW at R_L = 300 MΩ. EMG: Peak power of 2.35 mA at R_L = 12 Ω.	Self-powered ocean sensors/compact structure and stable operation.
[47]	A TENG and an EMG.	TENG: Rabbit fur, nylon, FEP layer, and Cu electrodes. EMG: Magnet and coils.	TENG: Average power density of 141.7 Wm^{-3}. EMG: Average power density of 400.0 Wm^{-3}.	Distributed marine environmental monitoring networks/good durability and stable operation.
[48]	A TENG and an EMG.	TENG: Rabbit fur, FEP film, and Cu electrodes. EMG: Magnet and coils.	TENG: Power density of 32.55 Wm^{-3}. EMG: Power density of 329.78 Wm^{-3}.	Self-powered ocean environment detection systems connected to MIoT/reliable and stable operation.
[49]	Four TENGs, two PENGs, and three EMGs.	TENG: PTFE film, copper, and stainless steel. PENG: Two PZT sheet and silver layers. EMG: Magnets and coils.	Using all the modules: Power density of 250.2 Wm^{-3}.	Self-powered ocean sensing systems/simple design and stable operation.
[50]	A TENG and an EMG.	TENG: FEP film and Cu electrode. EMG: Magnets and coils.	TENG: Peak power of 0.4 mW at 0.8 Hz. EMG: Peak power of 0.12 mW at 0.8 Hz.	Power source of underwater gliders/Optimal design and efficient performance.
[51]	A TENG and an EMG.	TENG: Polyamide and FEP films, and Cu electrode. EMG: Magnet and coils.	TENG: Peak power of 42.68 mW at R_L = 500 kΩ. EMG: Peak power of 4.40 mW at R_L = 40 kΩ.	Self-powered wireless meteorological monitoring system /Optimized structure, self-recovering, strong-anti-wear operation, and large-scale integration.
[52]	Two single-electrode TENGs and two EMGs.	TENG: PTFE film and Cu electrodes. EMG: Magnetic bar and coil.	TENG: Peak power of 85.3 μW at R_L = 20 MΩ. EMG: Peak power of 95.6 μW at R_L = 200 Ω.	Self-powered ocean wave warning systems/Simple design and low-cost fabrication.
[53]	A TENG and an EMG.	TENG: Nylon film, PVDF and PDMS composite film, and Cu electrode. EMG: Magnet and coil.	Using all the modules: Peak power density of 20.9 Wm^{-3}.	Self-powered smart mariculture monitoring and warning systems/optimized design, durable structure, and stable performance.
[54]	A TEG, a TENG, and an EMG.	TEG: P-type Bi_2Te_3 and N-type Bi_2Te_3, silica aerogel, and carbon nanotubes (CNTs). TENG: Nylon film, PTFE film, and Cu electrodes. EMG: Magnet ball and coil.	Using all the modules: Power density of 8.1 Wm^{-3}.	Self-powered marine devices/stable and durable performance.
[55]	A TENG and an EMG.	TENG: Nylon and PVC films, and Cu electrode. EMG: Magnet and coil.	Using all the modules: Peak power of 449.74 mW.	Self-powered marine wireless sensing systems/highly adaptive and simple design.
[56]	A TENG, two PENGs, and two EMGs.	TENG: Nylon and PFTE films, and Cu electrodes. PENG: PZT sheet and Cu electrodes. EMG: Magnets and coil.	Using all the modules: Power density of 5.73 Wm^{-3}.	Large-scale self-powered marine sensors/simple structure and stable performance.

Table 1. *Cont.*

Ref.	Transduction Modules	Main Components	Performance Parameters	Potential Applications/Advantages
[57]	Six TENGs and six EMGs.	TENG: PFTE film and steel sheet. EMG: Magnetic bar and coil.	Six TENGs: Peak open-circuit voltage of 254.96 V. Six EMGs: Peak open-circuit voltage of 7.49 V.	Long-term ocean sensing and monitoring/Simple design and stable operation.
[58]	A free-standing TENG, four PNGs, and seven EMGs TEG.	TENG: PTFE film and conductive ink electrode. PNG: Piezoelectric ceramic and Cu substrate. EMG: Magnet and coils TEG Photovoltaic.	TENG: Peak power of 0.25 mW. PENG: Peak power of 1.58 mW. EMG: Peak power of 13.8 mW. TEG: Output voltage of 5 V.	Self-powered ocean environment monitoring systems/integration of various transduction mechanisms.
[59]	Contact–separation TENGs, free-standing TENGs, and an EMG.	Contact–separation TENGs: PDMS/PVDF/Nylon films. Free-standing TENGs: PDMS/PVDF/Nylon films. EMG: Magnet and coil.	Contact–separation TENG: Peak power density of 17 Wm^{-3}. Free-standing TENG: Peak power density of 4.8 Wm^{-3}. EMG: Peak power density of 9.8 Wm^{-3}.	Self-powered buoy for sea surface wireless positioning/optimized design and stable operation.
[60]	A TENG and an EMG.	TENG: Nylon fibers, PTFE films, and Cu electrodes. EMG: Magnets and coils.	TENG: Peak power density of 15.5 Wm^{-3} at R_L = 8 MΩ. EMG: Peak power density of 6.45 Wm^{-3} at R_L = 100 Ω.	Self-powered marine environment monitoring sensor/stable performance and good durability.
[61]	Two multilayered TENGs and an EMG.	TENG: FEP film and Cu films. EMG: Magnet and coils.	TENG: Peak power density of 0.41 Wm^{-2} at R_L = 10 MΩ and 1.5 Hz. EMG: Peak power density of 0.30 Wm^{-2} at R_L = 2 KΩ and 1.5 Hz.	Self-powered route avoidance warning system for ocean navigation/good mechanical strength and flexibility.
[62]	A TENG and a PENG.	TENG: PDMS-EcoflexTM film, Parylene-C film, and Ti/Au electrodes. PENG: AlN film and molybdenum electrodes.	TENG: Power density of 65 mWm^{-2}. PENG: Power density of 6.5 mWm^{-2}.	Self-powered marine sensors/multifunctional, flexible, and compact design.
[63]	A TENG and an EMG.	TENG: FEP film, rabbit hair brush, and Cu electrodes. EMG: Magnet and coils.	TENG: Peak power density of 2.71 Wm^{-3} at R_L = 150 MΩ. EMG: Peak power density of 7.45 Wm^{-3} at R_L = 300 Ω.	Ocean environment monitoring/good durability and optimized design.
[64]	A TENG and a PENG.	TENG: Polyimide film, copper and aluminum electrodes. PENG: PVDF sheet and carbon conductive ink.	Using all the modules: Max. power density of 0.18 mWm^{-2} at R_L = 8 MΩ.	Self-powered smart sensing systems/simple and compact design, and low-cost fabrication.
[65]	A TENG and an EMG.	TENG: PDMS film and Al electrodes. EMG: Magnet and coil.	TENG: Max. power of 700 μW at R_L = 100 MΩ. EMG: Max. power of 6 mW at R_L = 100 Ω.	Self-powered position tracking systems/simple operation, and inexpensive and reliable structure.
[66]	A multilayered TENG and an EMG.	Multilayered TENG: PTFE film and Al electrode. EMG: Magnet and coil.	Multilayered TENG: Max. power density of 55 mWm^{-2} at R_L = 353 MΩ. EMG: Max. voltage of 1.8 V.	Self-powered marine sensor networks/stable operation, durable and cost-effective structure, and light-weight and reliable device.

Table 1. *Cont.*

Ref.	Transduction Modules	Main Components	Performance Parameters	Potential Applications/Advantages
[67]	A TENG and an EMG.	TENG: FEP films and Cu electrode. EMG: Magnet and coil.	TENG: Max. power density of 3.25 Wm^{-2} at R_L = 10 MΩ. EMG: Max. power density of 79.9 Wm^{-2} at R_L = 100 Ω.	MIoT monitoring systems/simple operation and compact structure.
[68]	A TENG and an EMG.	TENG: PMMA and silicone films, Al layer and Ag interdigitated electrodes. EMG: Magnetic ball and coil.	TENG: Max. power of 0.08 mW at R_L = 100 MΩ. EMG: Max. power of 14.9 mW at R_L = 1 kΩ.	Self-powered wireless acoustic sensing system/simple design and easy operation.
[69]	Three free-standing TENGs, six contact–separation TENGs, and an EMG.	TENGs: Silicone sheet and Cu electrodes. EMG: Magnet and coils.	Three free-standing TENG: Max. power of 165 μW at R_L = 20 MΩ and 2 Hz. Contact–separation TENG: Peak power of 850 μW at R_L = 20 MΩ and 2 Hz. EMG: Peak power of 9 mW at R_L = 100 Ω.	Smart marine rescue system and self-powered environmental electrochemistry/simple and durable structure, stable operation, and low-cost fabrication.
[70]	A TENG and an EMG.	TENG: PFTE and PDMS films, and Cu electrodes. EMG: Magnet and coil.	TENG: Power density of 0.08 $mWcm^{-2}$ at R_L = 60 MΩ. EMG: Max. power density of 0.0295 $mWcm^{-2}$ at R_L = 75 Ω.	To power marine environment sensors/ease to manufacturing and stable operation.
[71]	A TENG and an EMG.	TENG: PTFE film and Al electrodes. EMG: Magnet and coils.	TENG: Max. output energy of 21.7 μJ at R_L = 50 MΩ and 4 Hz. EMG: Max. power of 8.23 μW at R_L = 350 Ω.	Large-scale blue energy harvesting/simple structure and ease fabrication.
[72]	A free-standing TENG and an EMG.	TENG: Nylon balls, Kapton layer, and Cu electrodes. EMG: Magnet and coil.	TENG: Peak power density of 213.1 Wm^{-3} at R_L = 280 MΩ and 2.5 Hz. EMG: Peak power density of 144.4 Wm^{-3} at R_L = 1.5 Ω and 2.5 Hz.	Blue energy harvesting systems/lightweight, eco-friendly, low-cost manufacturing, and stable performance.
[73]	Four TENGs, four EMGs, and a solar cell.	TENG: PTFE film, Al layer, and Cu electrode. EMG: Magnet and coils. Solar cell: Water-proof silicon.	TENG: Max. average power of 31.5 μW. EMG: Max. average power of 66.9 μW. Solar cell: Output power density: of 0.14 mWm^{-2} at R_L = 1.5 Ω.	Multifunctional hybrid power unit/simple design and stable operation.
[74]	A rolling free-standing TENG and an EMG.	TENG: PTFE film, Al rods, and Cu interdigitated electrodes. EMG: Magnet and coil.	TENG: Average power density of 1.05 μWcm^{-3}. EMG: Average power density of 1.32 μWcm^{-3}.	Large-scale blue energy harvesting/compact structure and stable performance.
[75]	A spiral-interdigitated electrode TENG and an EMG.	TENG: FEP film and Cu electrodes. EMG: Magnets and coils.	TENG: Average power density of 15.67 μWcm^{-2} in rotation mode. EMG: Average power density of 27.12 μWcm^{-2} in rotation mode.	Energy harvesting panel floating on the ocean/compact design, cost-efficient fabrication, and stable operation.

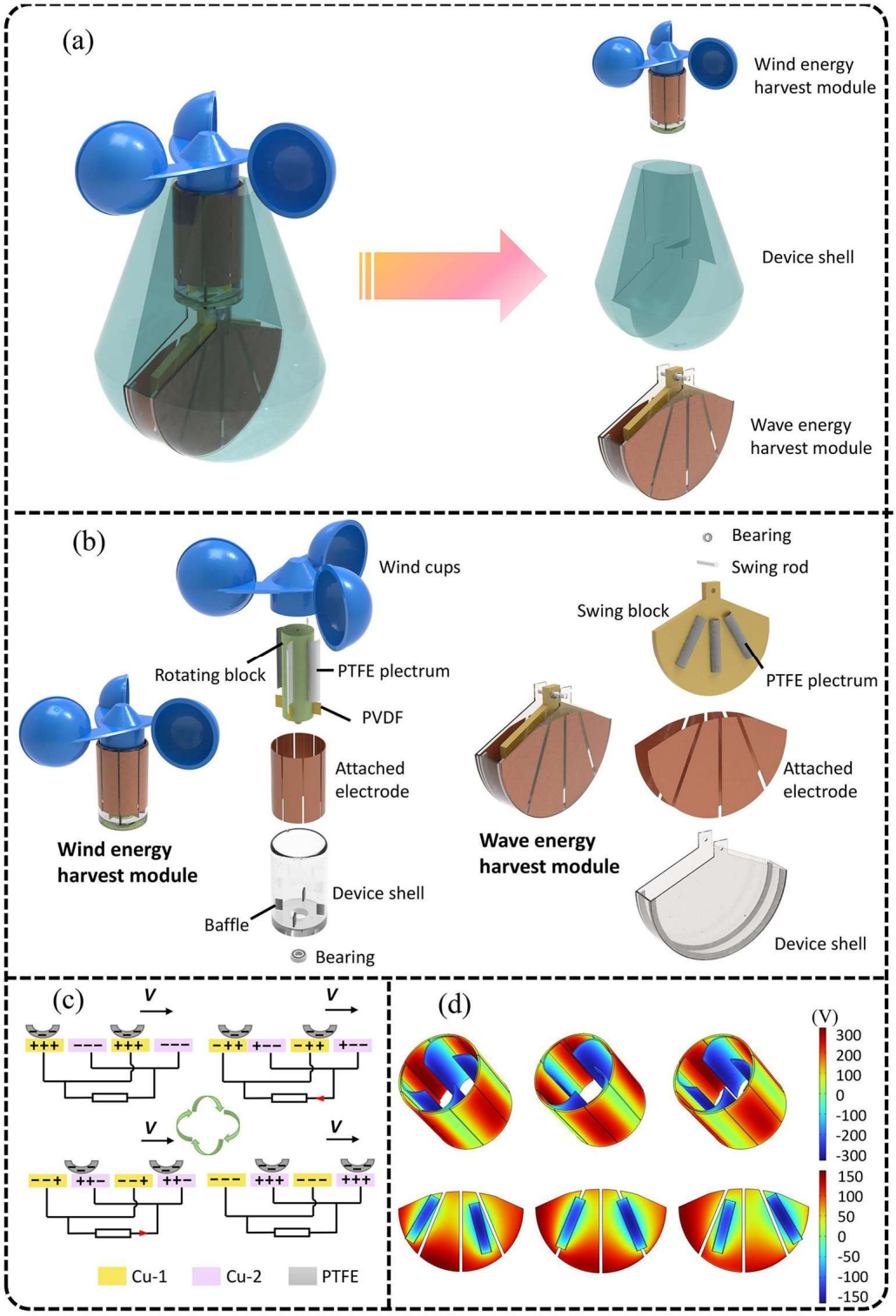


Figure 9. Working principle of a hybrid nanogenerator based on the triboelectric and piezoelectric effects for harvesting wind and wave energy [31]. (**a**) Main components of the hybrid nanogenerator. (**b**) Components of the wind and wave energy harvesting modules of the hybrid nanogenerator. (**c**) Operating mode of the triboelectric nanogenerator. (**d**) Simulation models of the performance of the hybrid nanogenerator. Reprinted with permission from [31]. Copyright ©2023, Elsevier B.V.

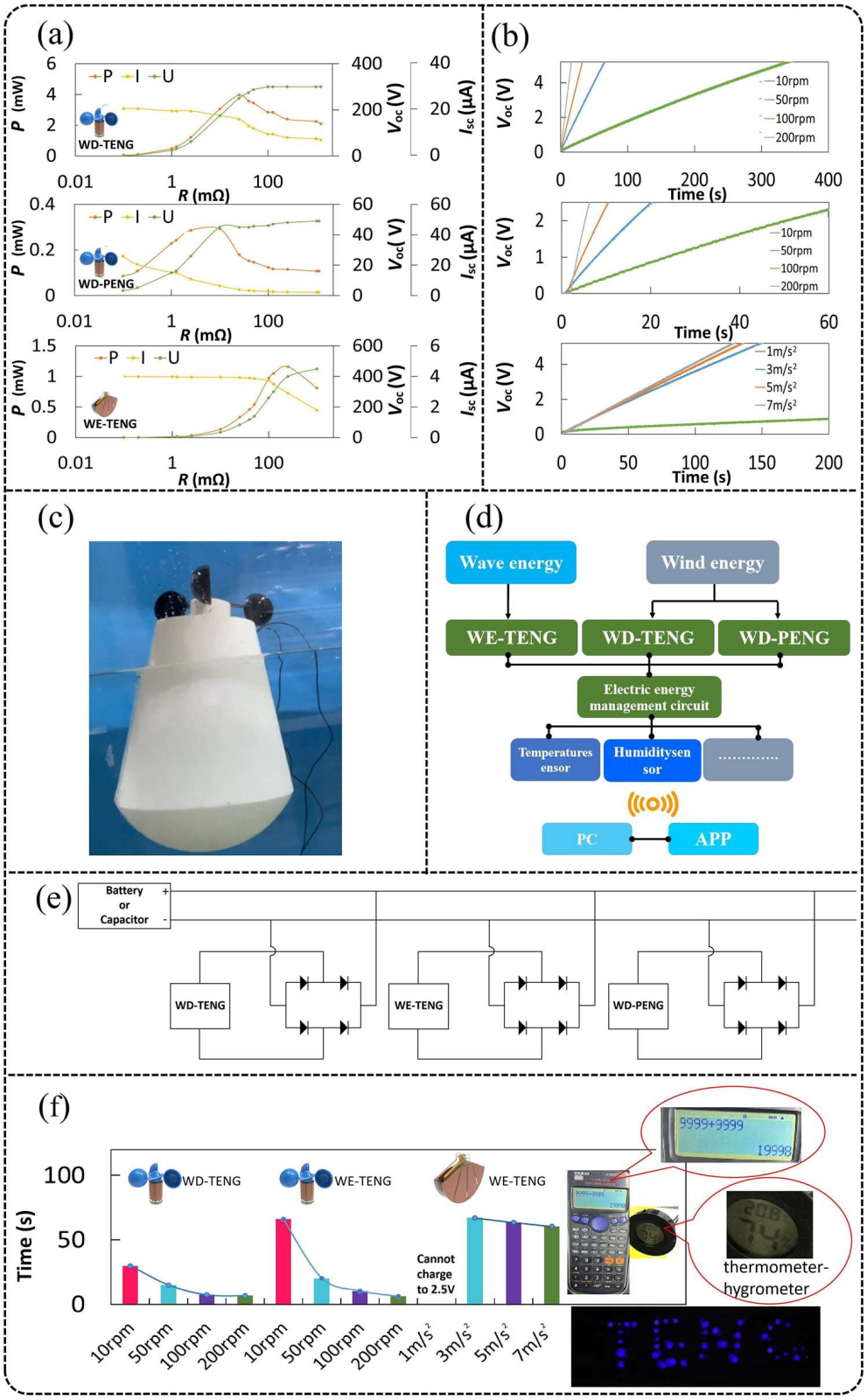


Figure 10. Three modules of the hybrid nanogenerator [31]. (**a**) Performance of the three modules of the hybrid nanogenerator for harvesting wave and wind energy. (**b**) Charging results of the three modules of the hybrid nanogenerator using capacitors of 10 μF. (**c**) Test of the hybrid nanogenerator. (**d**) Schematic diagram of the three modules of the hybrid nanogenerator. (**e**) Energy management circuit of the three modules. (**f**) The calculator and thermometer–hygrometer are powered by a hybrid nanogenerator; the LEDs are also lit by this hybrid device. Reprinted with permission from [31]. Copyright ©2023, Elsevier B.V.

In 2023, Sun et al. [32] proposed a triboelectric–electromagnetic hybrid nanogenerator (TTEHG) to harness wave energy, as shown in Figure 11. This hybrid nanogenerator uses a tube-shaped solid–liquid interface with low friction loss and a wide energy range. This TTEHG achieved an instantaneous power density of 0.25 $mWcm^{-3}$ and a current density of 5 $mAcm^{-3}$ at a frequency of 1 Hz. Even at a shallow operating frequency of 0.2 Hz, the TTEHG had a high output performance with a peak current close to 15 mA. This nanogenerator can power temperature and humidity sensors for monitoring marine environmental parameters. Moreover, this hybrid device can be connected to the MIoT. This TTEHG has several advantages, including efficiency in harnessing energy from sea waves, an effective coupled design at the solid–liquid interface, and good performance at a frequency of 1 Hz (Figure 12). On the other hand, this device has a complex design that requires precise manufacturing. Also, the performance of the TTEHG is affected by variations in the wave conditions and water temperature.

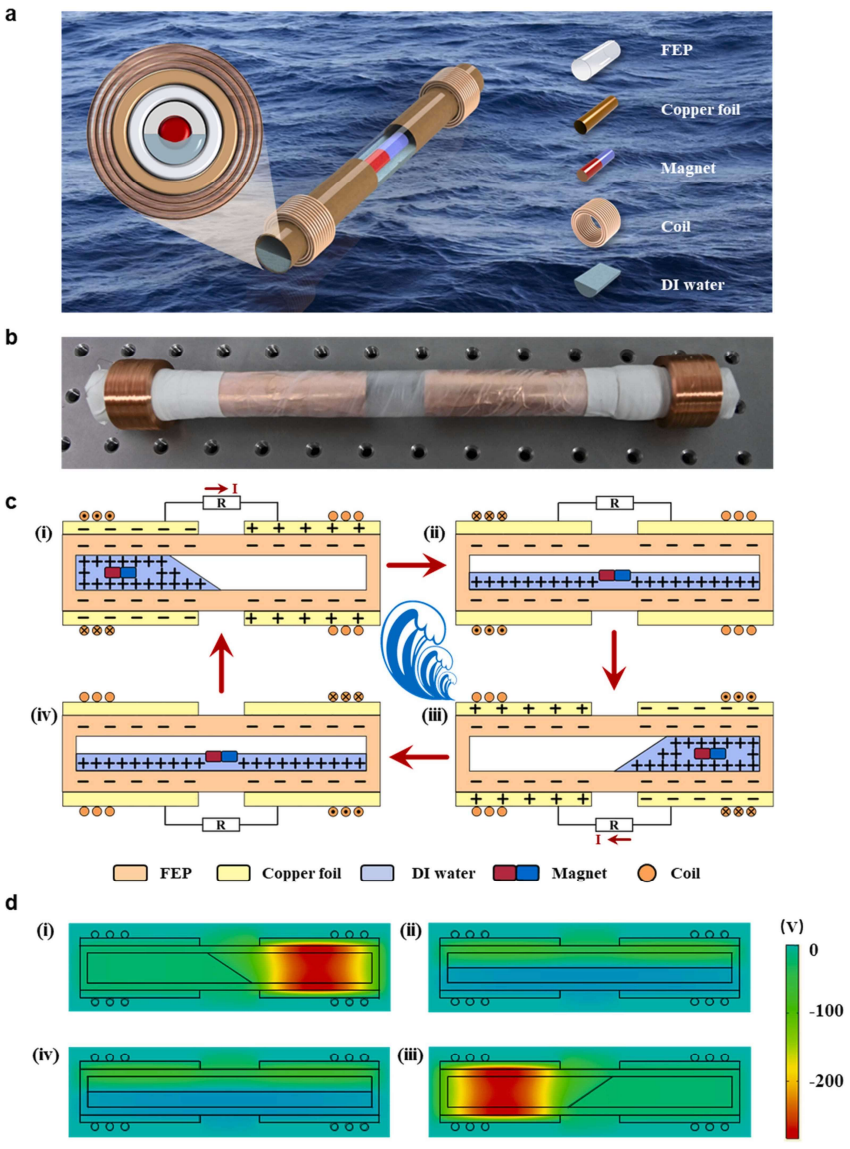


Figure 11. Working mechanism of the hybrid nanogenerator TTEHG [32] for ocean energy harvesting. (**a**) Design of the components of the TTEHG. (**b**) Fabricated TTEHG. (**c**) Schematic diagram of the operating principle of the TTEHG. (**d**) Voltage results of the FEM models of the TTEHG. Reprinted with permission from [32]. Copyright ©2022, Elsevier B.V.

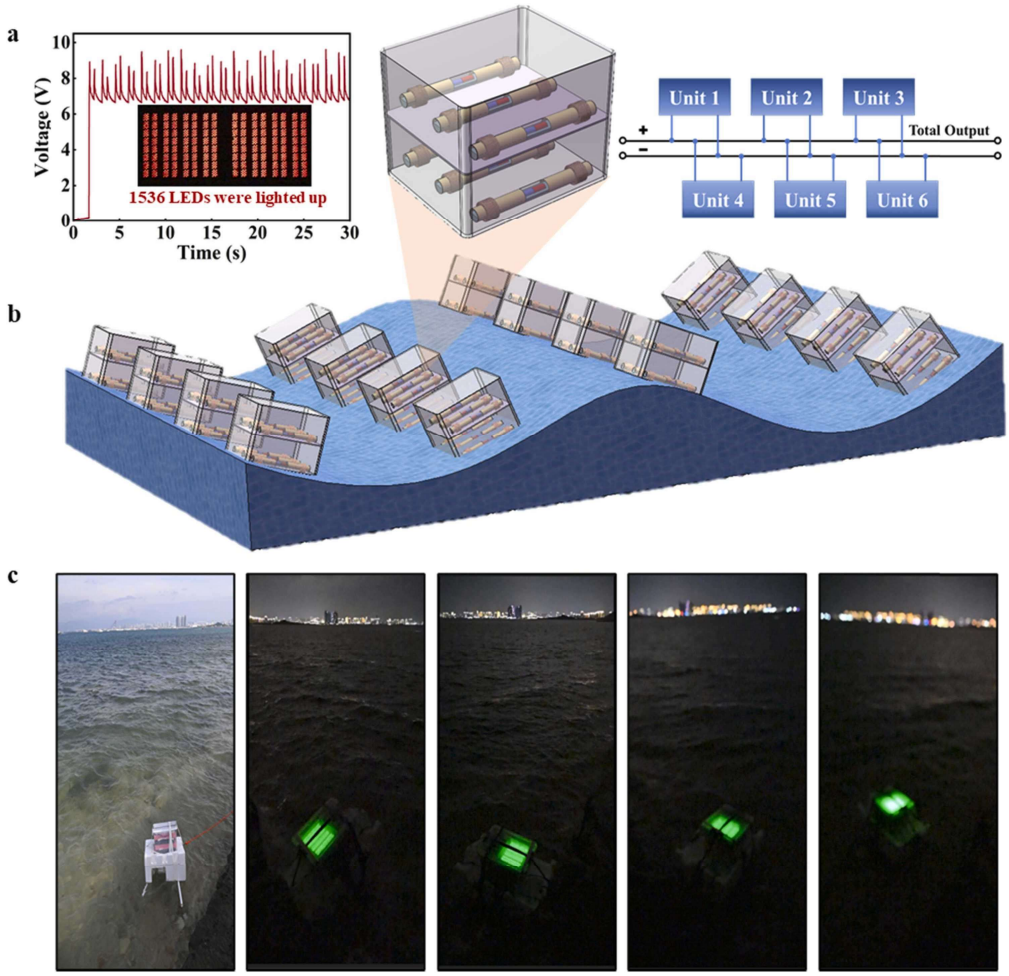


Figure 12. Application of the TTEHG as a sustainable energy source to power electronic devices [32]. (**a**) 1536 LEDs powered using a single TTEHG under a simulated wave at 1.4 Hz. (**b**) The TTEHG network was designed to harness ocean wave energy. (**c**) In Sanya Bay, China, the TTEHG was used to light 336 LEDs. Reprinted with permission from [32]. Copyright ©2022, Elsevier B.V.

Xu et al. [33] proposed an isotropic triboelectric–electromagnetic-hybrid nanogenerator (iTEHG), as depicted in Figure 13. This device employed a pair of concentric circular electrodes, built on a plate shaped like a tilted parabolic antenna, for the gravity-guided movement of the liquid. The iTEHG was designed using a TENG module and a ring-shaped EMG module to collect the omnidirectional energy from the ocean waves. Both TENG and EMG modules were encapsulated in a self-balancing, waterproof, cylindrical housing. This cylindrical housing protects the hybrid device from external moisture and damage caused by wave impact in a marine environment. The design of the iTEHG addressed problems such as wear and insufficient wave contact, which enhanced its lifetime and control. This device has a power density of 7.25 μWcm^{-3} with 360° coverage. This iTEHG charged a 0.1 F supercapacitor at 3.1 V and powered a wireless thermometer for 26 min. In addition, the iTEHG harvested ocean wave energy in Sanya Bay, China, and powered 320 LEDs (see Figure 14). This hybrid device has several advantages, such as efficiency in wave energy harvesting, a unique coupled design, and good performance. However, this hybrid nanogenerator has a complex manufacturing process and a dependence on environmental conditions. These limitations of the hybrid device can be solved by optimizing its design.

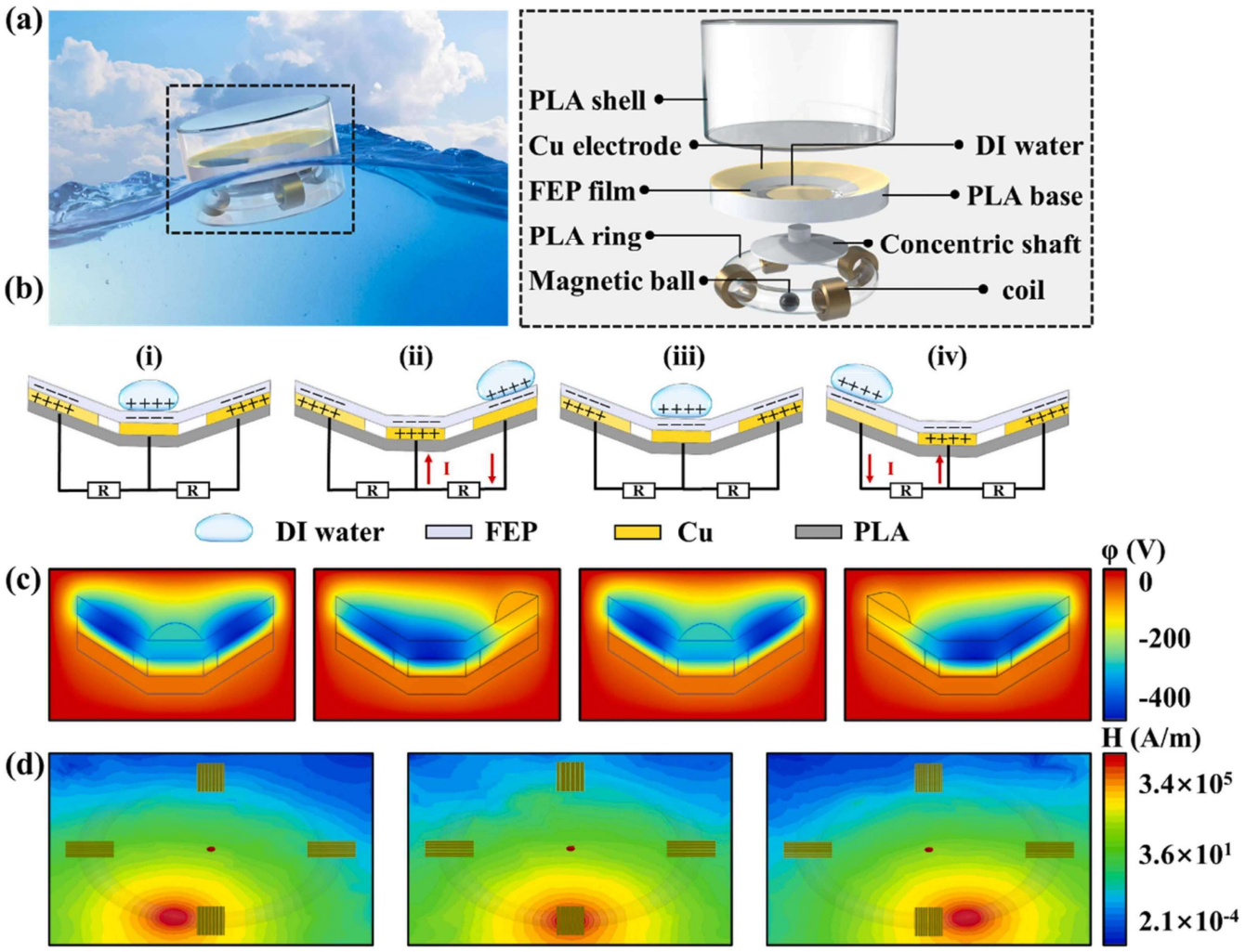


Figure 13. (**a**) Components of the iTEHG were designed to harness ocean wave energy [33]. (**b**) Operating mechanism of the iTEHG. Results of the FEM models of the (**c**) TENG module and (**d**) EMG module. Reprinted with permission from [33]. Copyright ©2023, Elsevier B.V.

Liu et al. [34] proposed a hybrid nanogenerator composed of an oscillating triboelectric nanogenerator (O-TENG) and a micro thermoelectric generator (MTEG), which was used for monitoring marine mammals (see Figure 15). This hybrid device can harvest energy generated by the movement of marine mammals and the temperature difference between the water surface and the surrounding environment. The performance of the device was improved using a power management unit. The O-TENG and the MTEG reached high open circuit voltages of 5.85 V and 1.821 V, respectively. This device has the capability to monitor marine animals in danger of extinction, incorporating the warm-blooded characteristics of marine mammals and the mechanical energy generated during their movement. The MTEG can harness the biological thermal energy of marine mammals, while the O-TENG harnesses their kinetic energy. Thus, this hybrid nanogenerator can monitor the movement of marine mammals and collect energy from the temperature difference between the water and the surrounding environment (see Figure 16). However, this hybrid nanogenerator presents several challenges, including a complex design, dependence on environmental conditions, and limited efficiency.

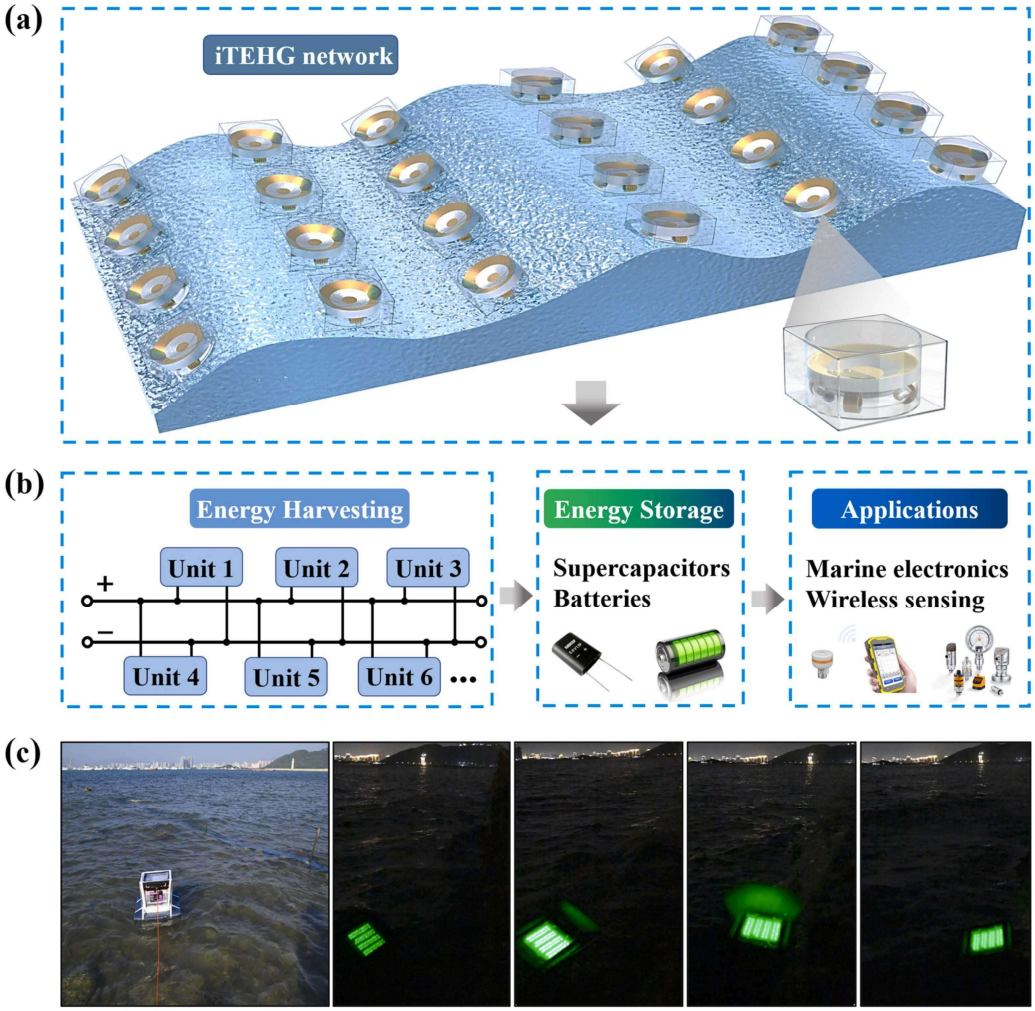


Figure 14. Application of the iTEHG to harvest ocean wave energy [33]. (**a**) Design of an iTEHG network that can harness ocean wave energy. (**b**) Self-sufficient ocean monitoring system composed of iTEHGs, supercapacitors, and batteries. (**c**) Application of the iTEHG to harvest ocean wave energy in Sanya Bay, China. Reprinted with permission from [33]. Copyright ©2023, Elsevier B.V.

Zhang et al. [35] developed a hybrid nanogenerator coupled to a bifilar pendulum called BCHNG (see Figure 17). This nanogenerator incorporates an EMG module, two PENG modules, and two TENG modules, featuring a multilayer structure that integrates a receiving platform to harness wave energy (see Figure 18). As the BCHNG module is embedded in a vessel, the stable environment within the hull platform can facilitate the maintenance of hybrid devices and ensure long-term stable operation. The spring-damped TENG achieved a maximum power density of 1.88 Wm^{-3}, the cylindrical soft-contact EMG-coupled TENG registered an output performance of 10.16 Wm^{-3}, and the load-shifting TENG reached a power density of 30.24 Wm^{-3} in the in-water test. In addition, the TENG with a bifilar pendulum generated a power density of 200 Wm^{-3}. The combination of these three transduction modules increased the power generation capacity from the waves, harvesting the kinetic and gravitational inertia energies of the waves. Based on two degrees of freedom of a pendulum oscillation system, this hybrid nanogenerator reported a peak power of 358.5 Wm^{-3}. However, this hybrid nanogenerator has design and weight-related challenges, which decrease its efficiency.

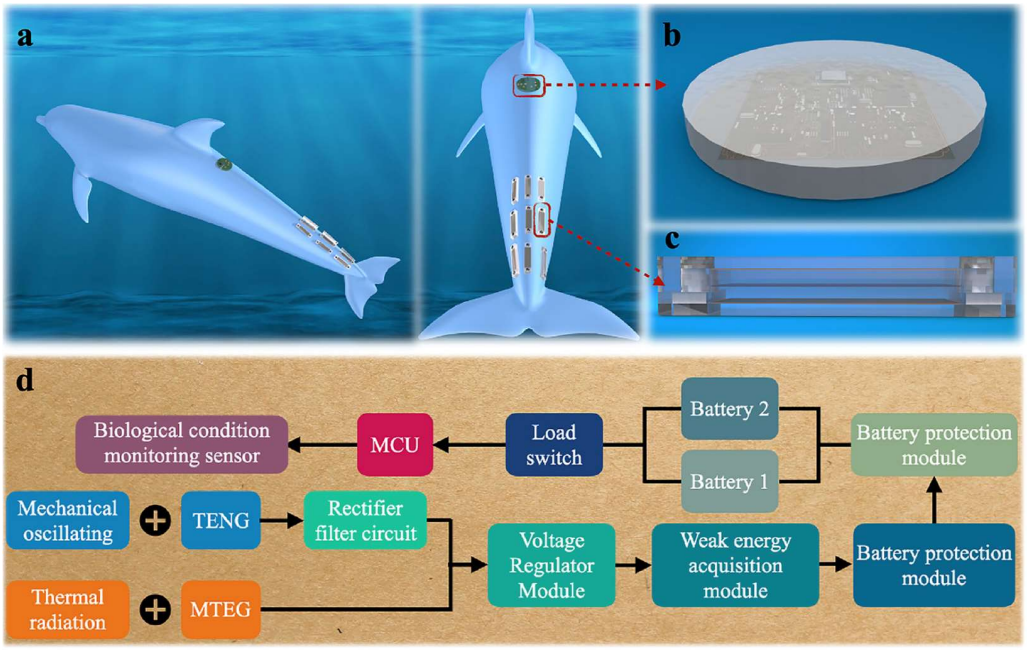


Figure 15. Main components of a self-powered marine mammal condition monitoring system (SMMS) that is integrated with an O-TENG, an EMG, and a power management unit [34]. (**a**) Potential application of the SMMS. (**b**) Schematic view of the power management unit. (**c**) Schematic diagram of a module composed of an O-TENG and an EMG. (**d**) Schematic diagram of the components and working mechanism of the SMMS. Reprinted with permission from [34]. Copyright ©2023, Elsevier B.V.

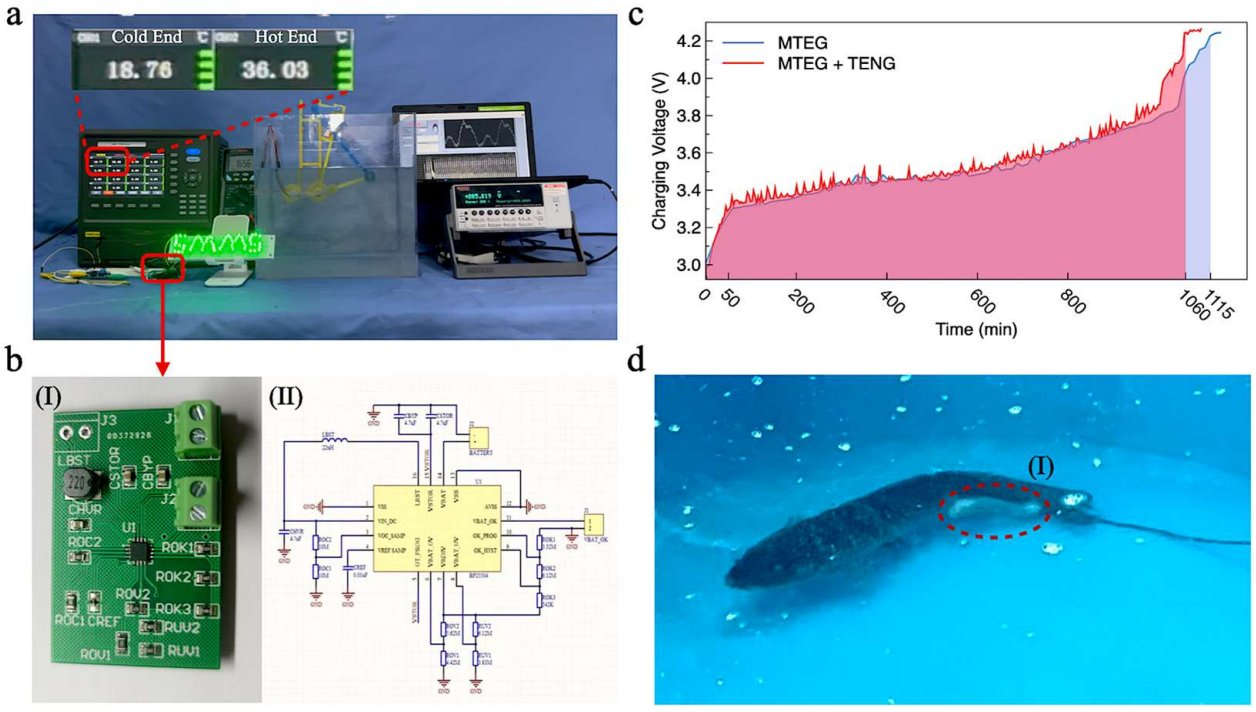


Figure 16. (**a**) SMMS powered 64 LEDs [34]. (**b**) A printed circuit board and its circuit. (**c**) Charging voltage of a battery using the O-TENG and EMG. (**d**) Application of the SMMS in a real fish. Reprinted with permission from [34]. Copyright ©2023, Elsevier B.V.

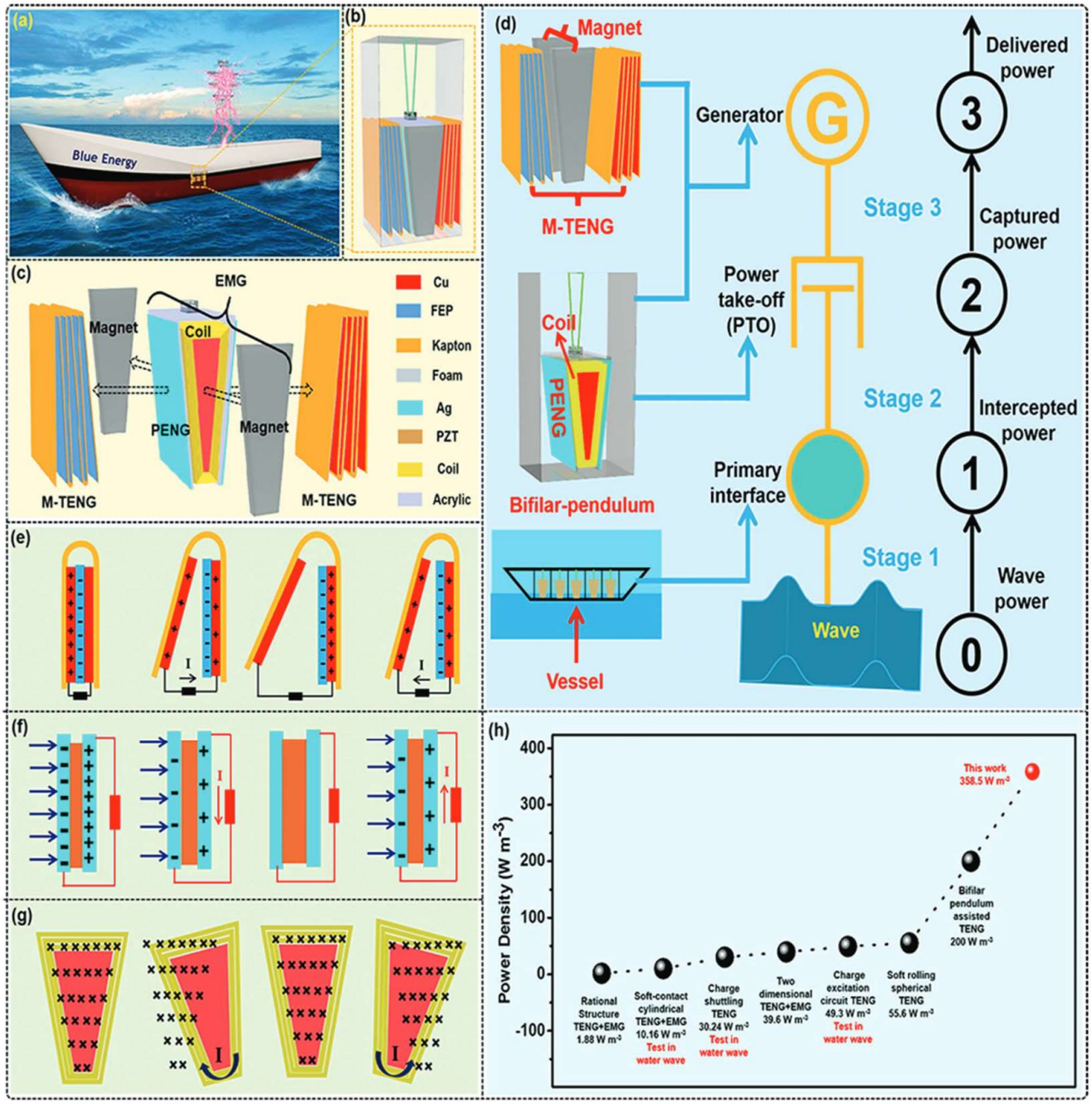


Figure 17. Operating principle and materials of a hybrid nanogenerator coupled to a bifilar pendulum (BCHNG) used in a vessel [35]. (**a**) A vessel with a BCHNG. (**b**) Structural configuration of the BCHNG (**c**) BCHNG composed of EMG, PENG, and M-TENG modules. (**d**) BCHNG components included in a vessel to harvest ocean wave energy. Operating principles of (**e**) triboelectric nanogenerator, (**f**) piezoelectric generator, and (**g**) electromagnetic generator. (**h**) Power densities of the BCHNG and other types of nanogenerators. Reprinted with permission from [35]. Copyright ©2022, Wiley.

Gao et al. [10] developed a spring-pendulum-coupled hybrid nanogenerator (SPC-HNG) incorporated into a vessel, which was composed of two multilayer-structured triboelectric nanogenerators, two electromagnetic generators, and two piezoelectric nanogenerators (see Figure 19). The design of this hybrid nanogenerator enhanced its capability to harness water wave energy, considering the wave kinetic energy in both horizontal and vertical directions. This hybrid nanogenerator has a wide frequency range between 0.5 Hz and 20 Hz and can reach a peak power density of 82.4 Wm^{-3}. The PENG was formed by a PVDF film and two silver electrodes. Additionally, the EMG is integrated with a trapezoidal magnet and annular coils. Finally, the TENG has an FEP triboelectric layer and copper

electrodes. Furthermore, when coupled with a circuit, this nanogenerator can be used as a self-powered ocean buoy that measures ocean parameters, including temperature, wave frequency, and turbidity. This hybrid nanogenerator powered a water quality detector, a hygrometer, and a smart wireless alarm system for real-time monitoring of environmental parameters. Thus, this nanogenerator has potential applications in self-powered smart MIoT networks for measuring environmental parameters and marine investigations.

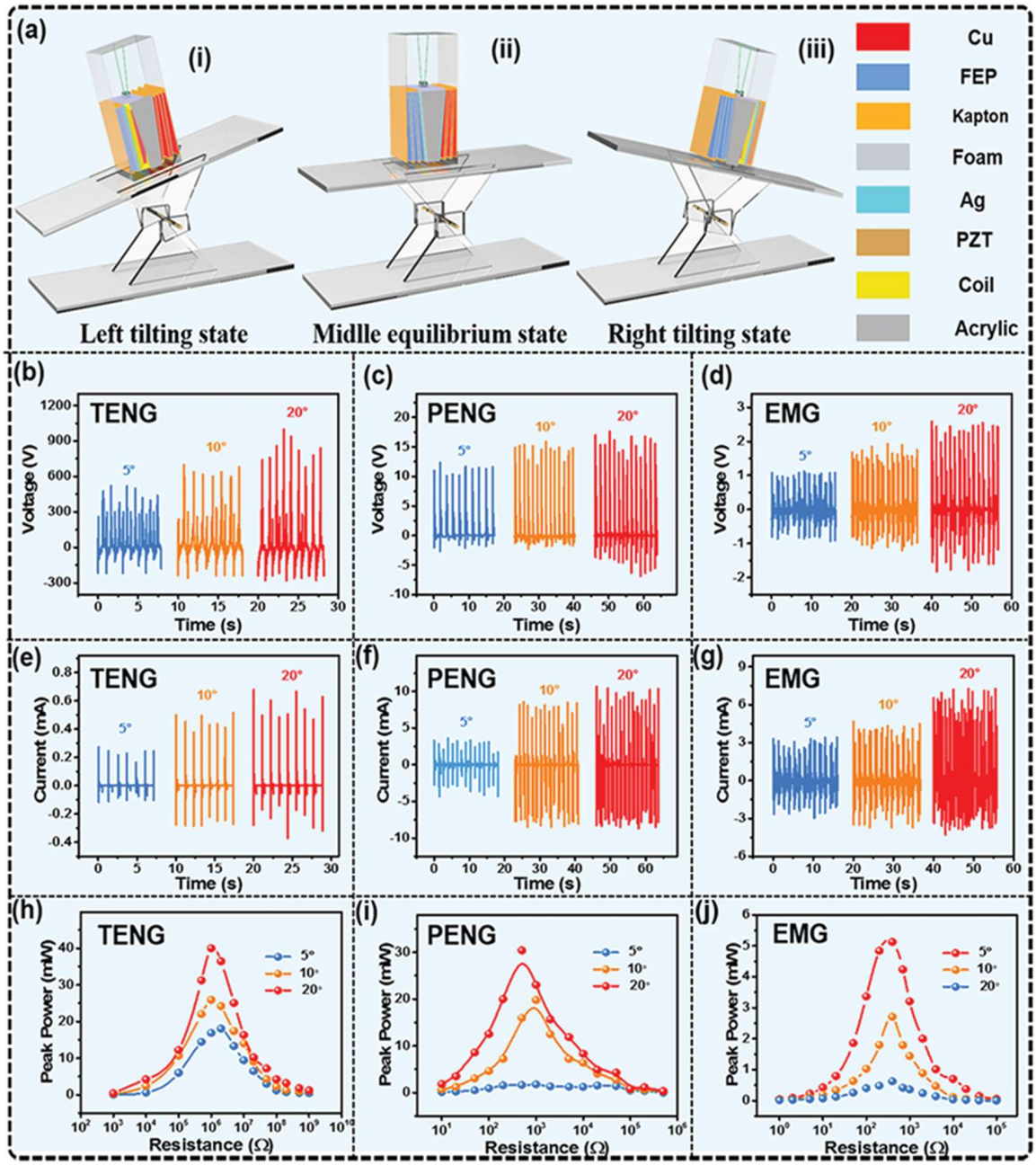


Figure 18. Results of the voltage, current, and power of the BCHNG working in the vertical direction [35]. (**a**) Operating mechanism of the BCHNG driven by a seesaw. The open-circuit voltage of (**b**) a triboelectric nanogenerator, (**c**) a piezoelectric nanogenerator, and (**d**) an electromagnetic generator, considering three values of seesaw angles. The short-circuit currents of (**e**) a triboelectric nanogenerator, (**f**) a piezoelectric nanogenerator, and (**g**) an electromagnetic generator regarding three values of seesaw angles. The peak power of (**h**) a piezoelectric nanogenerator, (**i**) a piezoelectric nanogenerator, and (**j**) an electromagnetic generator under different seesaw angles. Reprinted with permission from [35]. Copyright ©2022, Wiley.

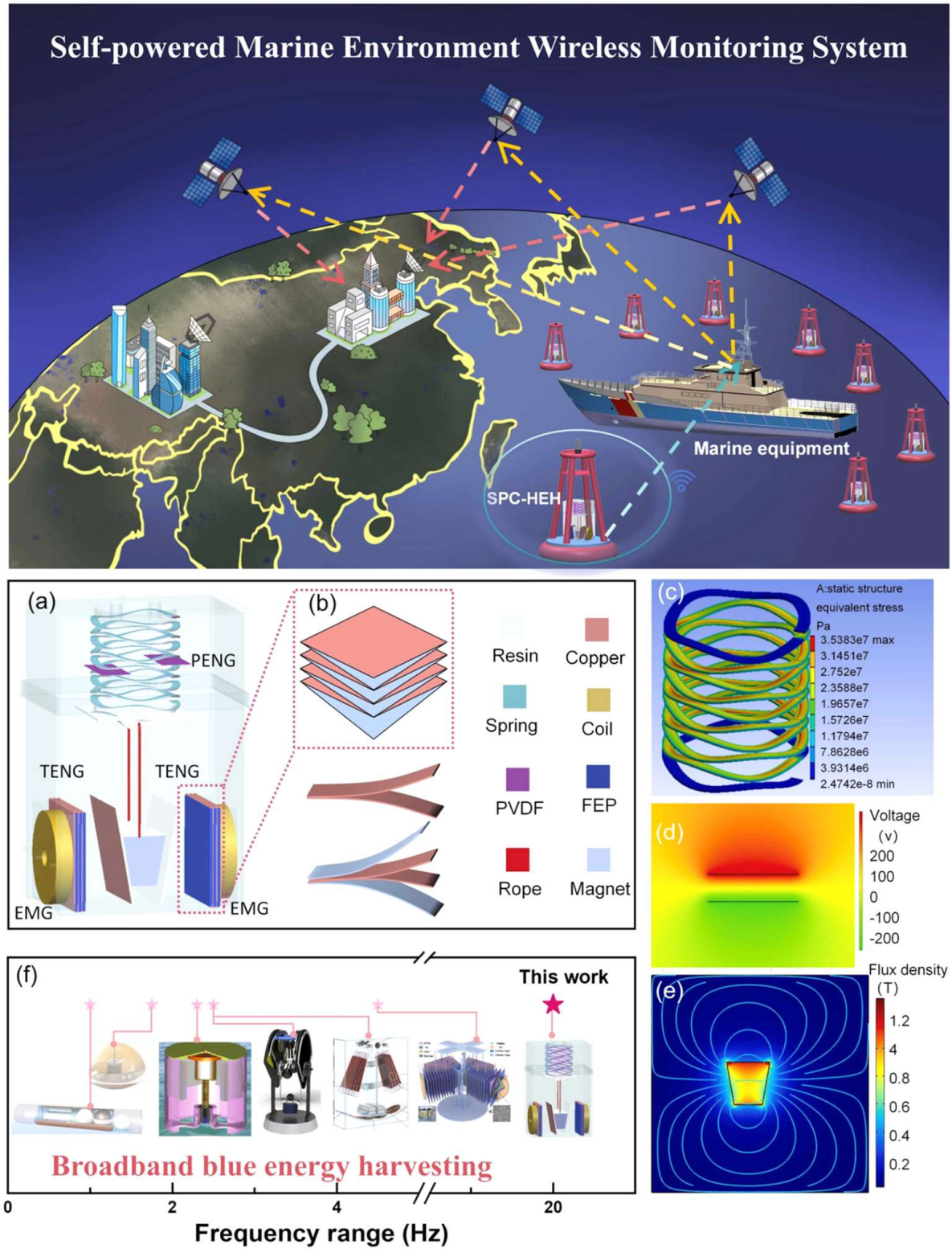


Figure 19. Components, operating principle, and potential application of the hybrid nanogenerator SPC-HNG in self-powered smart ocean IoT networks [10]. (**a**) Modules (TENG, EMG, and PENG) of the hybrid nanogenerator SPC-HNG. (**b**) Configuration of the TENG module of the SPC-HNG. (**c**) Stress of an FEM model of the waveform spring. (**d**) Open-circuit voltage of an FEM model of the TENG module. (**e**) Magnetic flux density generated by an FEM model of the trapezoidal magnet. (**f**) Frequency range of the SPC-HNG compared to other nanogenerators. Reprinted with permission from [10]. Copyright ©2024, Elsevier E.V.

Li et al. [36] developed a hydrokinetic turbine-based triboelectric–electromagnetic hybrid generator (HT-TEHG) to harvest ocean current energy in a wide range of flow velocities (see Figure 20). This hybrid device included two TENGs and two EMGs, as well as a helical hydrokinetic turbine. This turbine enabled self-starting performance and adaptive capability to different flow directions. For a flow velocity of 1.0 m/s, this HT-TEHG achieved an average power density of 44.52 Wm^{-3}. The design of this hybrid generator improved its reliability and adaptability for ocean-current energy harvesting to power sensors at MIoT nodes. Moreover, this hybrid device powered 292 LEDs and two temperature and humidity sensors.

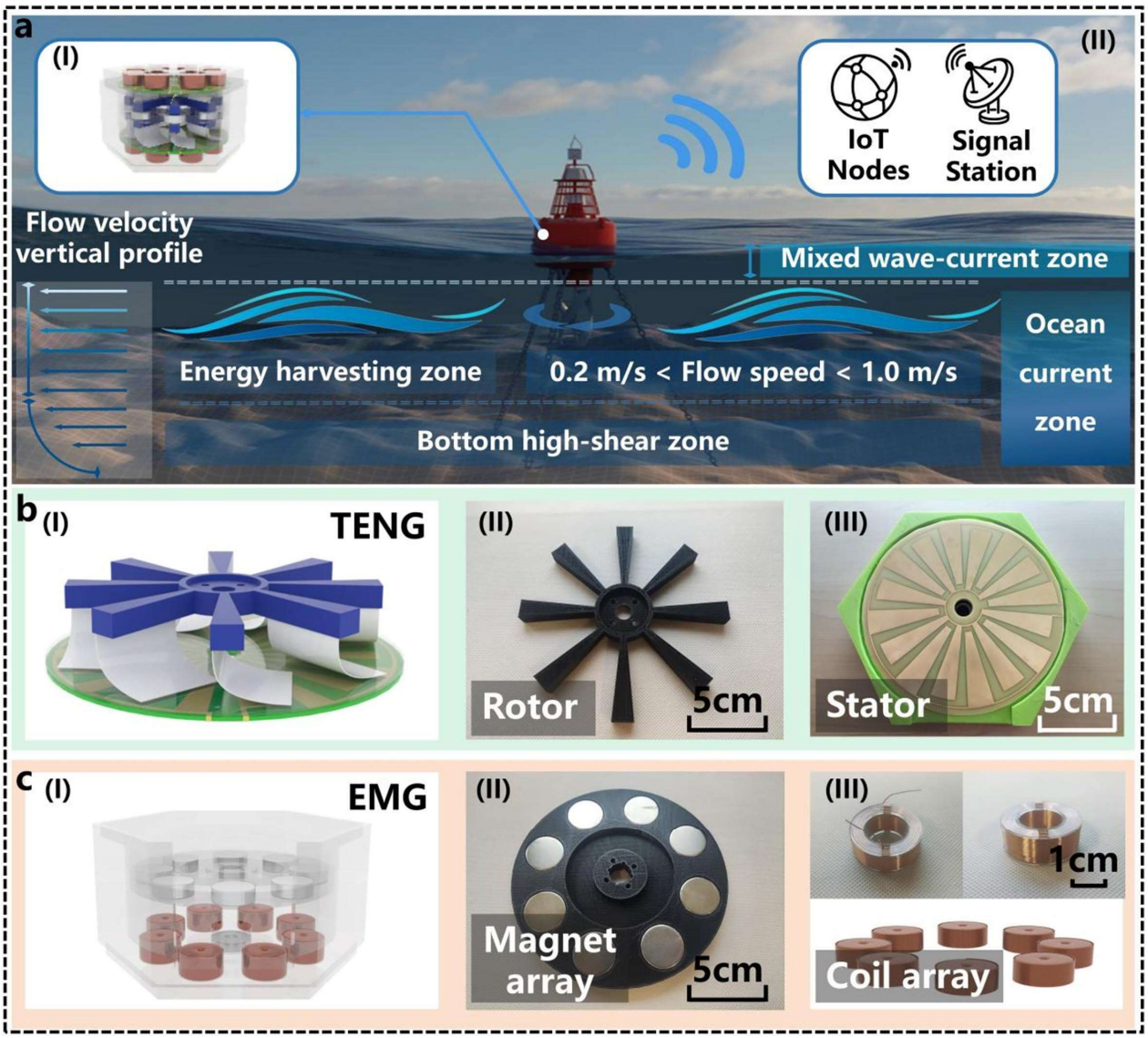


Figure 20. Schematic representation of the application of a hydrokinetic turbine-based triboelectric–electromagnetic hybrid generator (HT-TEHG) [36]. (**a**) (I) Structural configuration of the HT-TEHG and (II) the application of the hybrid generator for real-time monitoring of marine environmental parameters. (**b**) Schematic diagram of the triboelectric nanogenerator, considering (I) structural design, (II) rotor, and (III) stator. (**c**) Schematic view of the electromagnetic generator, regarding (I) structural design, (II) magnet array, and (III) coil array. Reprinted with permission from [36]. Copyright ©2025, Elsevier E.V.

Zhao et al. [37] proposed a hybrid nanogenerator formed by a tower-shaped structure, which integrated a TENG and an EMG (Figure 21). This hybrid device uses a chaotic pendulum mechanism to harvest wave energy. In addition, the tower-shaped structure and charge–excitation circuit improved the harnessed wave energy, with peak power densities of 56.7 $Wm^{-3}Hz^{-1}$ and 192.3 $Wm^{-3}Hz^{-1}$ for the TENG and EMG modules, respectively. Thus, the design of this device allowed it to convert high-entropy wave energy into stable mechanical energy, keeping the stability of the system under irregular waves, as shown in Figure 22. Also, this hybrid nanogenerator can power temperature and humidity sensors for real-time marine monitoring. This device has a reliable self-powered operation and can be used for marine monitoring networks connected to MIoT.

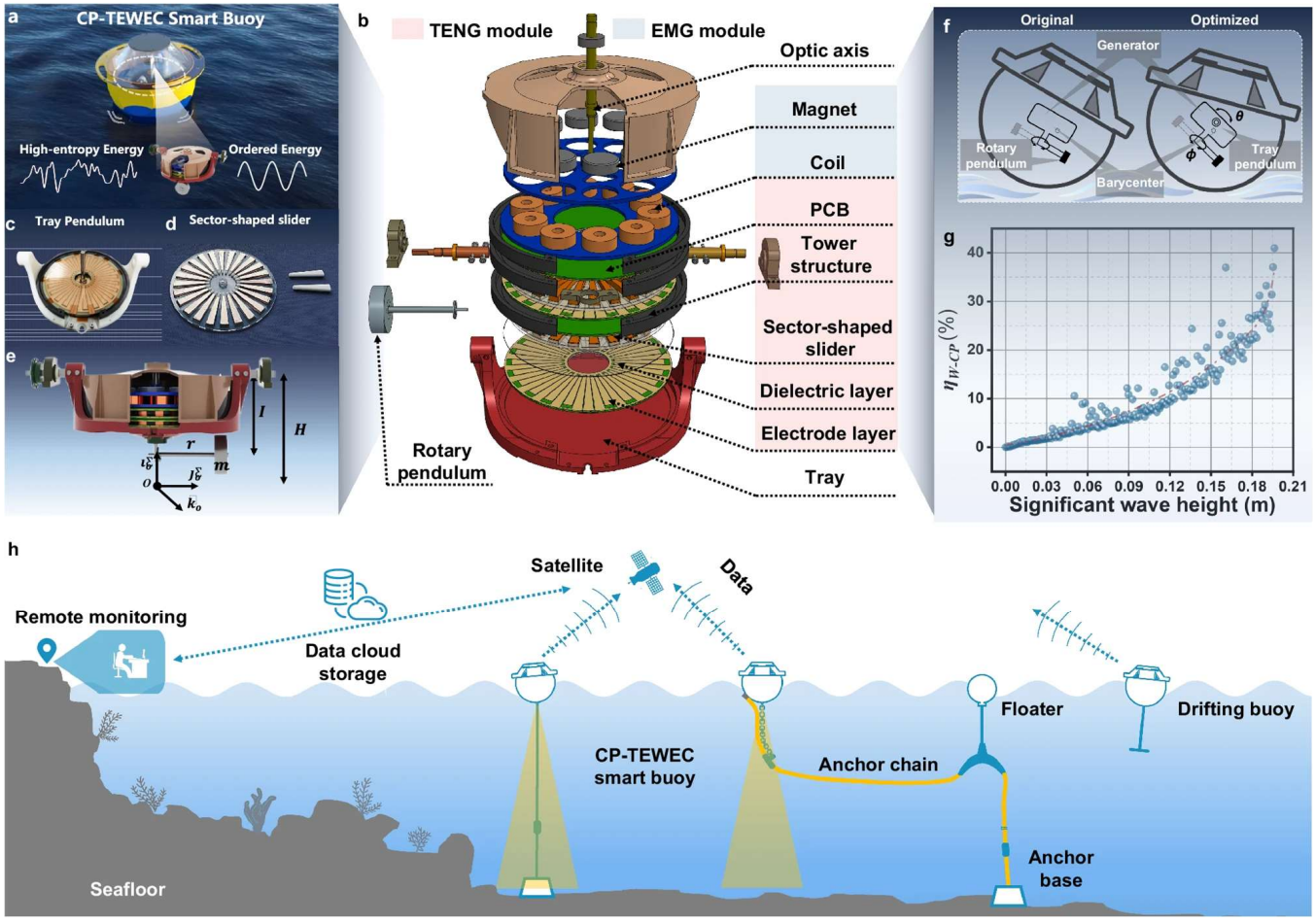


Figure 21. Illustration of the design and application of a hybrid nanogenerator developed by Zhao et al. [37]. (**a**) Design of the hybrid nanogenerator to harvest high-entropy wave energy. (**b**) Elements of the TENG and EMG modules. (**c**) The tray pendulum, (**d**) sector-shaped slider, and (**e**) model of the chaotic pendulum of the hybrid device. (**f**) Schematic diagram of the hybrid device using a rotatory pendulum in comparison with a tray pendulum. (**g**) Results of simulation models of the average energy conversion efficiency of the hybrid nanogenerator. (**h**) Scheme of the application of the hybrid device in the ocean. Reprinted with permission from [37]. Copyright ©2025, Springer Nature Limited.

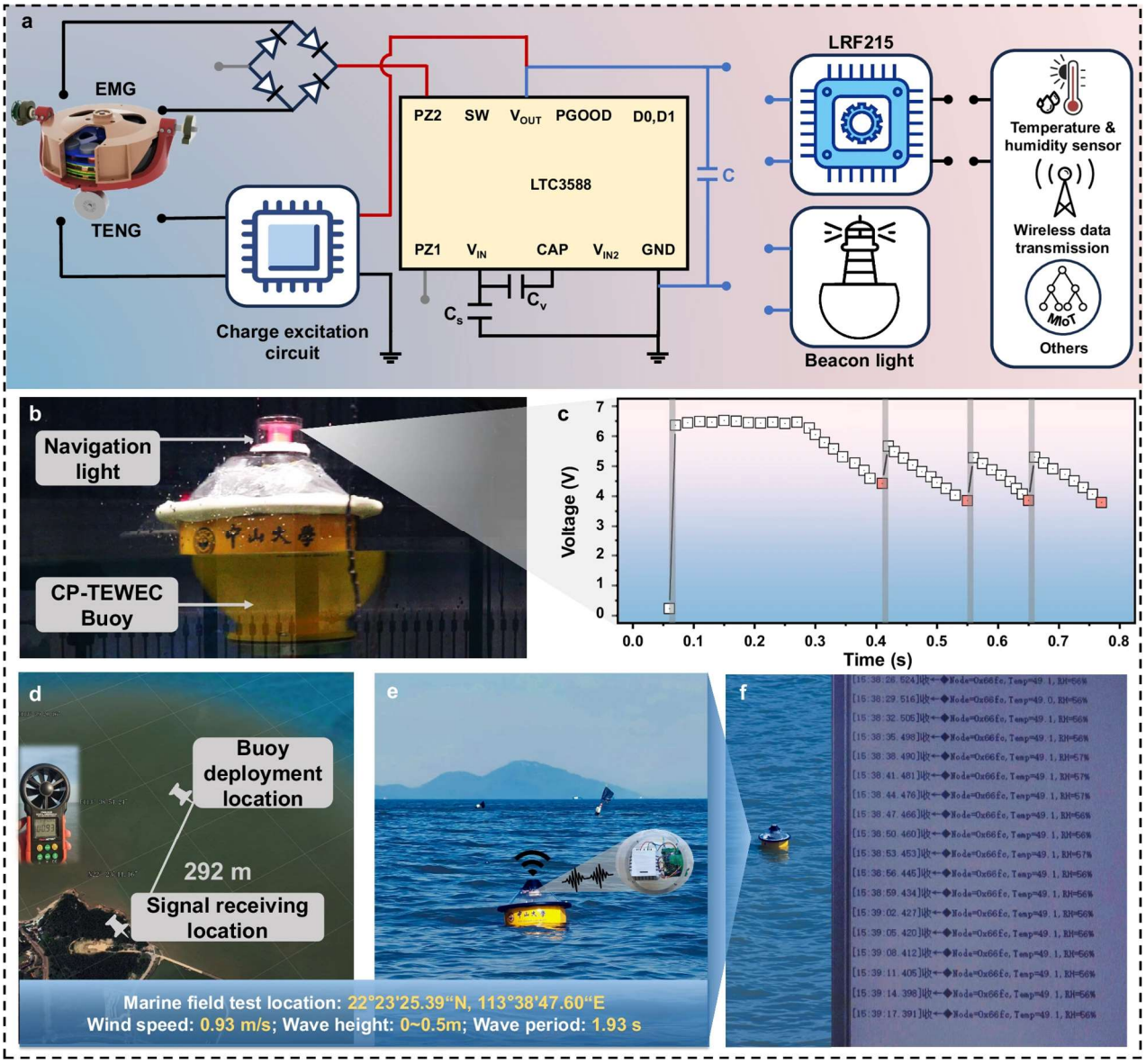


Figure 22. Application of a hybrid nanogenerator fabricated by Zhao et al. [37]. (**a**) Schematic diagram of the energy management circuit. (**b**) Hybrid nanogenerator driving a navigation light, and (**c**) the voltage shift of the capacitor. Location of the (**d**) receiver and (**e**) buoy for potential sustained oceanographic monitoring. (**f**) Transmission of temperature and humidity data to a PC. Reprinted with permission from [37]. Copyright ©2025, Springer Nature Limited.

4. Challenges

Ocean wave energy is an abundant, sustainable, and natural energy resource, which can be harvested using hybrid nanogenerators to power marine environment monitoring systems or serve as self-powered MIoT devices. However, the success of the future commercialization of hybrid nanogenerator technology depends on overcoming important challenges associated with marine environmental conditions, such as low-frequency and irregular ocean waves, extremely corrosive conditions, sea storms, the durability and reliability of electrical and mechanical components, optimization of the output performance, efficient power management modules, and integration of nanogenerator array networks. Therefore, more research to address these challenges is essential to achieve the commercial success of hybrid nanogenerators.

Many challenges of hybrid nanogenerators can be addressed through optimal design strategies that enable improvements in their electrical and mechanical performance, durability, and reliability for each specific application, considering the different and harsh marine weather conditions. Thus, the use of digital platforms, such as digital twins and advanced simulation design software, can help designers and researchers optimize the performance and reliability of hybrid nanogenerators, including the best transduction mechanism array, materials, electrical and structural configurations, power management circuits, control systems, and packaging. These advanced simulation models can provide virtual environments of ocean regions under a wide range of key parameters, including wave frequency and magnitude, impact loads, temperature, wind speeds, and ocean salinity. Thus, designers can replicate real marine environments using these simulation models, allowing them to understand the performance and reliability of new materials, electrical and mechanical configurations, and MIoT sensor arrays based on hybrid nanogenerators.

Sea storms can cause variations in the frequency and amplitude of ocean waves, resulting in strong impact loads on the outer structure or packaging of the hybrid nanogenerators. These extreme marine environments can damage the electrical and mechanical parts of the nanogenerators. In this case, an alternative solution could include high-strength materials for packaging the nanogenerators. Furthermore, these materials must have high resistance to marine corrosion. However, these materials must also have cost-effective manufacturing processes that enable their commercial application in large-scale ocean energy harvesting.

Moreover, the integration of nanogenerator array networks into power grids poses an important challenge for the efficient storage and management of electrical energy for long-distance transmission. To address this, the design of robust nanogenerators is fundamental to the development of MIoT sensor networks using different transduction mechanisms. The fabrication of low-cost and reliable nanogenerators can help facilitate their integration into real marine infrastructure that can revolutionize ocean wave energy harvesting. In the future, research will need to address these challenges to enable the commercial use of hybrid nanogenerators in MIoT sensor networks for real-time monitoring of various ocean environmental variables, including water temperature and pH, wave current amplitude and direction, wind speed, and the proximity of marine species, ships, or submarines.

5. Conclusions

In this review, we discussed the transduction mechanisms and performance results of recent hybrid nanogenerators used to harvest ocean wave energy and convert it into electrical energy. Furthermore, we presented the integration of various nanogenerators, including triboelectric nanogenerators, piezoelectric nanogenerators, electromagnetic generators, thermoelectric generators, and pyroelectric nanogenerators. A comparison of the main transduction modes, materials, performance parameters, advantages, and potential applications of hybrid nanogenerators was reported. These applications included the use of nanogenerators to power devices in maritime infrastructure or serve as self-powered MIoT sensor networks for real-time monitoring of marine environmental conditions. Also, key challenges related to the design, performance, durability, reliability, and integration of hybrid nanogenerators in extreme marine environments were introduced. These challenges can be addressed through the optimal design of hybrid nanogenerators that utilize cost-efficient materials and packages with anti-corrosion coatings. Thus, optimized hybrid nanogenerators could have future commercial success to power ocean environmental monitoring sensors.

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