

Review

Recent Advances in Piezoelectric and Triboelectric Nanogenerators for Ocean Current Energy Harvesting

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Abstract

Ocean current energy, owing to its predictability and stability, is regarded as an ideal power source for distributed marine observation networks and underwater intelligent equipment. However, conventional ocean current energy devices that rely on rigid turbines and electromagnetic generators generally suffer from high cut-in flow velocity, bulky size, high maintenance costs, and significant environmental disturbance, making them unsuitable for deep-sea, miniaturized, and long-duration power supply scenarios. These limitations highlight the urgent need for flexible and low-speed energy harvesters capable of autonomous, long-term operation. In recent years, nanogenerator technology has provided new opportunities for distributed and low-power ocean current energy harvesting. PENGs and TENGs can directly convert weak mechanical energy into electricity, enabling energy harvesting in small-scale and low-velocity flow fields. PENGs offer high durability and mechanical robustness, whereas TENGs exhibit superior output performance in low-speed and intermittent flows. This paper provides a comprehensive review of structural designs, material innovations, interface engineering, hybrid energy-conversion architectures, and power-management strategies for PENG- and TENG-based ocean current energy harvesters. Overall, future progress will rely on the integration of intelligent materials, multi-field coupling mechanisms, and system-level engineering strategies to achieve durable, scalable, and autonomous ocean current energy harvesting for distributed marine systems.

Keywords: ocean current energy; piezoelectric nanogenerator; triboelectric nanogenerator; distributed marine systems



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1. Introduction

The ocean is the largest reservoir of energy and information on Earth, containing vast amounts of kinetic, thermal, and chemical energy, and serving as a key component of the climate system and biogeochemical cycles [1–3]. With the growing demands for global marine resource exploitation, polar and deep-sea scientific exploration, carbon sink monitoring, and ecological protection, the construction of distributed and long-term ocean sensor networks has become one of the essential infrastructures for advancing the “Digital Ocean/Smart Ocean” framework [4,5]. However, underwater nodes deployed over multi-year timescales face a critical energy bottleneck: conventional batteries have limited endurance, incur high maintenance and replacement costs, and pose potential

environmental risks, which severely restrict the scalability and long-term operation of such networks [6–9]. Consequently, the development of sustainable and self-powered micro-energy systems has emerged as a crucial direction for marine observation and engineering equipment.

Among various forms of “blue energy,” ocean current energy—driven jointly by large-scale circulation and monsoon/geostrophic effects—features strong continuity and high predictability. Compared with wave and tidal energy, it is more suitable for providing stable power to low-power distributed nodes (typical flow velocity $< 1 \text{ m s}^{-1}$, with long duration and relatively mild spatiotemporal fluctuations) [10–12]. These intrinsic characteristics make ocean current energy uniquely valuable for building self-powered marine sensing networks and have stimulated research on energy harvesting techniques tailored for low-speed, low-frequency, and weakly disturbed flow fields. The emerging nanogenerator (NG) technology offers new material and structural pathways for this purpose [12–15]. Current nanogenerator technologies mainly include two categories: piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs). PENGs convert mechanical energy into electrical energy based on the piezoelectric effect, which occurs in certain crystals or ceramics where mechanical stress induces charge separation and consequently generates voltage. At the microscale, PENGs exhibit efficient energy conversion and show great potential for harvesting the low-speed kinetic energy present in ocean currents [16–20]. TENGs, on the other hand, operate based on the triboelectric effect: when two materials of different triboelectric properties undergo repeated contact and separation, electrical charges are generated. Through this cyclic contact–separation process, TENGs effectively harvest mechanical energy from ocean currents. Their high sensitivity to low-speed flows and vortex-induced motions makes TENGs another promising solution for ocean current energy harvesting [21–25]. Furthermore, recent developments have demonstrated the feasibility of integrating TENGs with marine propulsion systems for auxiliary power generation, as well as deploying buoy-based or broadband TENG (BB-TENG) configurations for dual-mode energy harvesting and flow sensing, underscoring their versatility in marine environments [26]. However, while nanogenerators have demonstrated significant potential in wave energy and other fluid-energy-harvesting scenarios and have been widely reviewed in the literature [13,14,24,27–29], no systematic review has yet focused on ocean current energy. Compared with wave energy, ocean current energy offers greater stability and directional consistency, and its harvesting requirements and structural optimization mechanisms differ substantially. Therefore, a systematic summary and assessment of ocean-current-oriented PENG- and TENG-based energy harvesting technologies will not only fill an existing research gap but also provide new perspectives for the development of self-powered systems in marine observation and intelligent underwater equipment.

As illustrated in Figure 1, this review provides a systematic summary and comparative analysis of recent advances in PENGs and TENGs for ocean current energy harvesting. The key developmental pathways and technical characteristics are outlined from the perspectives of material fundamentals, structural design, surface/interface engineering, and energy management circuits, followed by an evaluation of future development trends. This work aims to offer a comprehensive overview and theoretical support for the continued progress of this field, promoting in-depth exploration of nanogenerator technologies for ocean current energy harvesting, distributed underwater sensing, and self-powered marine observation. It also lays a scientific and engineering foundation for achieving green, low-carbon, and sustainable utilization of marine energy. Looking ahead, nanogenerator technologies are expected to play an increasingly critical role in the frameworks of the “Smart Ocean” and “Clean Energy.” Through ongoing advances in new material design, biomimetic structural innovation, multimodal energy coupling, and intelligent power man-

agement, PENGs and TENGs are poised to enable efficient, reliable, and environmentally friendly distributed marine energy harvesting networks.

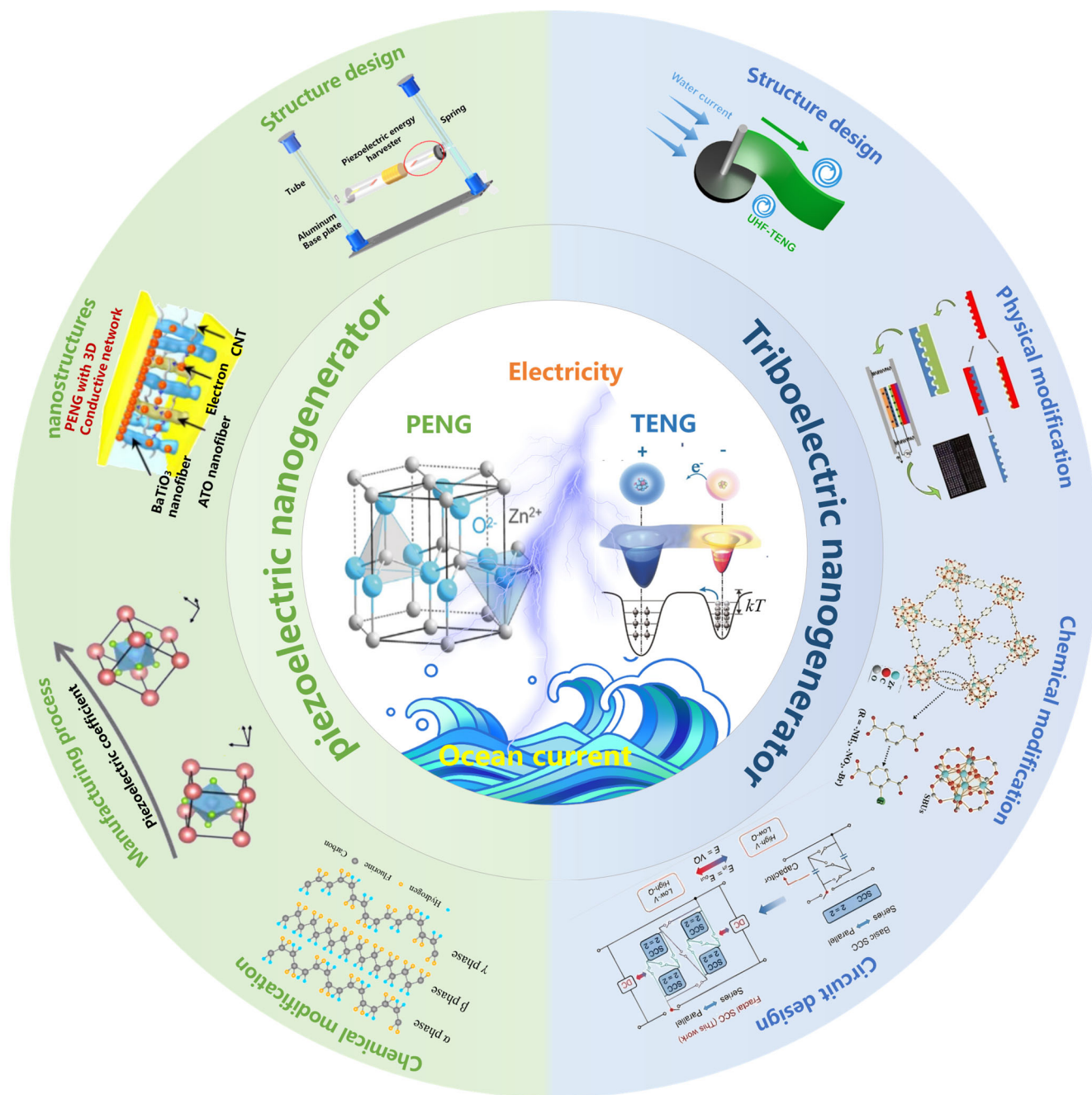


Figure 1. Schematic illustration of the overall strategies for ocean current energy harvesting using piezoelectric and triboelectric nanogenerators (Adapted with permission from [30–38]).

To provide a clear overview of the manuscript structure, the paper is organized as follows: Section 2 introduces the formation and distribution characteristics of ocean current energy and analyzes the limitations of traditional harvesting methods as well as the background for the emergence of micro/nano energy harvesting technologies; Section 3 systematically reviews the applications of piezoelectric nanogenerators (PENGs) in ocean current energy harvesting, covering their working principles, structural designs, and performance optimization strategies; Section 4 focuses on recent advances in triboelectric nanogenerators (TENGs) for ocean current energy harvesting, including material selection, structural innovations, and integrated designs; Section 5 discusses the challenges

and future directions of this technology in terms of new material development, system integration, environmental impacts, and long-term stability; Section 6 concludes the review and provides an outlook on the application prospects of nanogenerators in the context of the “Smart Ocean” and clean energy initiatives.

2. Formation of Ocean Current Energy and Traditional Harvesting Methods

2.1. Formation and Velocity Distribution of Ocean Current Energy

The formation of ocean currents is a complex natural process influenced by multiple geophysical factors. These factors include the Earth’s rotation, wind forcing, spatial variations in temperature and salinity, as well as seafloor topography [39–41]. The Coriolis effect, induced by the Earth’s rotation, exerts a significant influence on the direction of ocean currents, resulting in characteristic global flow patterns. Wind, as the primary driving force of surface currents, is closely linked to the Earth’s thermal circulation and plays a decisive role in determining the speed and direction of ocean flows [42,43]. At the same time, differences in water temperature and salinity affect the density and movement of deep currents, thereby shaping the overall dynamical structure of the ocean [44,45]. In addition, seafloor topographic features—such as seamounts and trenches—play an important role in the formation and evolution of ocean currents by altering flow direction and velocity, further increasing the complexity of the ocean dynamic system.

These characteristics of ocean currents, particularly variations in velocity and direction, directly determine their potential as a renewable energy resource. In specific regions, such as straits and coastal zones, relatively high flow velocities correspond to higher ocean current energy potential. From an energy development perspective, the velocity characteristics of ocean currents directly determine their energy density and exploitable potential. Theoretically, the power of ocean current energy is proportional to the cube of flow velocity, meaning that even small velocity changes can markedly affect energy output [46–48]. However, it is worth noting that traditional electromagnetic generators designed for harvesting ocean current energy require very high flow velocities to start. According to global ocean velocity distribution data (MyOcean Light, 2026) [49], as shown in Figure 2, at a depth of approximately 200 m, the mean current velocity in all regions is below 1 m/s. In order to clarify the challenges of energy acquisition in the deep-sea environment, especially in the large-scale low velocity ($v < 1$ m/s) area related to distributed sensor networks, Table 1 summarizes the average energy density and key characteristics of typical ocean current energy, wave energy and sea surface solar energy. As shown in Table 1, compared with the peak potential of wave energy or sea surface solar energy, the current energy density (approximate to the lower limit of its range) of most deep-sea environments in practice is significantly limited. This indicates that conventional tidal energy devices relying on high-speed rotating turbines operate inefficiently in most medium- and low-speed marine environments, whereas flexible nanogenerators adapted to low-speed, multidirectional flow fields show clear advantages.

Table 1. Typical Characteristics of Energy Density and Distribution of Marine Energy Types.

Energy Type	Energy Density (Average)	Depth Distribution Range	Characteristics	Ref.
Current energy	0.5–2.5 kW/m ²	Underwater (10–200 m)	Energy stable and predictable	[50]
Wave energy	1–50 kW/m	Water surface to below surface (0–15 m)	Large regional gap, irregular fluctuation and seasonality	[51]
Sea surface solar energy	0.5–2.5 kW/m ²	Above water surface	Power generation in daytime and sunny days	[52]

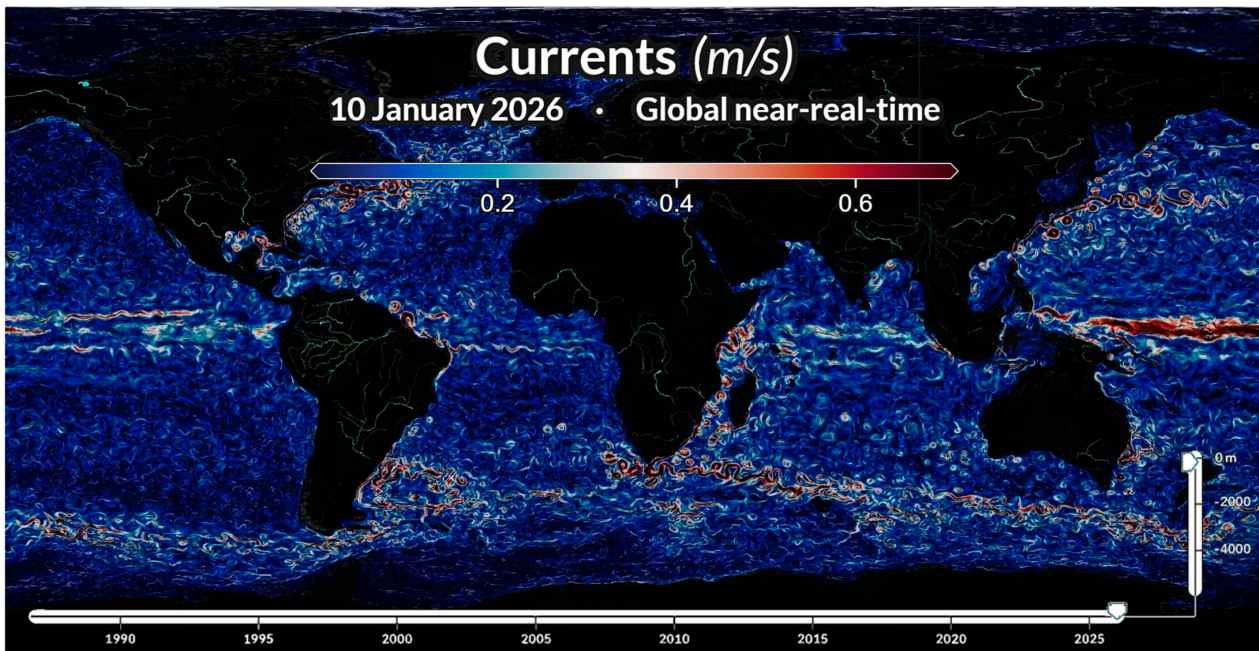


Figure 2. Global distribution of ocean current velocities (200 m depth, January 2026) (Adapted from Copernicus Marine MyOcean Viewer (accessed on 10 January 2026) [49]).

2.2. Traditional Methods for Ocean Current Energy Harvesting

At present, devices designed for high-power ocean current energy harvesting are predominantly rigid structures. They typically convert ocean current energy into mechanical energy through water turbines or propeller-type rotors, which is then transformed into electrical energy via electromagnetic generators. According to structural characteristics, these systems can be categorized into horizontal-axis, vertical-axis, oscillating hydrofoil, underwater kite types, and others. Horizontal-axis current turbines are currently the most widely applied type of ocean current energy device, offering high energy capture efficiency and stable power generation. A typical structure is shown in Figure 3a. Internationally, countries such as the United Kingdom, France, and Canada are at the forefront of research, development, and commercialization of ocean current power technology [53–55]. Among them, the MeyGen project led by SAE Renewables in the UK is the world’s first ocean current energy project to achieve 50 GWh of electricity output, adopting a horizontal-axis configuration (Figure 3b) [56]. In China, significant progress has been made by institutions such as Zhejiang University, Ocean University of China, Harbin Engineering University, and Northeast Normal University in developing horizontal-axis current turbine systems [57]. Notably, the team of Prof. Wei Li at Zhejiang University achieved China’s first grid-connected operation of a horizontal-axis ocean current turbine. Their 650 kW floating unit was deployed and grid-connected in 2017, further advancing the demonstration of megawatt-scale array systems (Figure 3c) [58].

Vertical-axis turbines generally have lower energy capture efficiency than horizontal-axis turbines; however, they are not affected by flow direction and feature compact structural designs, offering greater flexibility in installation location. A typical structure is shown in Figure 3d. Research on vertical-axis ocean current turbines began relatively early in countries such as the United Kingdom, France, Italy, and the United States, with several achieving notable progress [59,63–67]. Among them, Sea Power in Italy successfully deployed the world’s first grid-connected vertical-axis ocean current device—the Kobold turbine—in the Strait of Messina in the Mediterranean in 2000 (Figure 3e) [59]. In China, Harbin Engineering University was the earliest institution to conduct research on

vertical-axis ocean current turbines, developing the country's first vertical-axis turbine, the "Wanxiang II" 40 kW seabed-mounted experimental power station. Subsequently, the "Hai Neng" series was developed. As shown in Figure 3f, the "Hai Neng III" vertical-axis ocean current energy device achieved an annual electricity output exceeding 650,000 kWh [60].

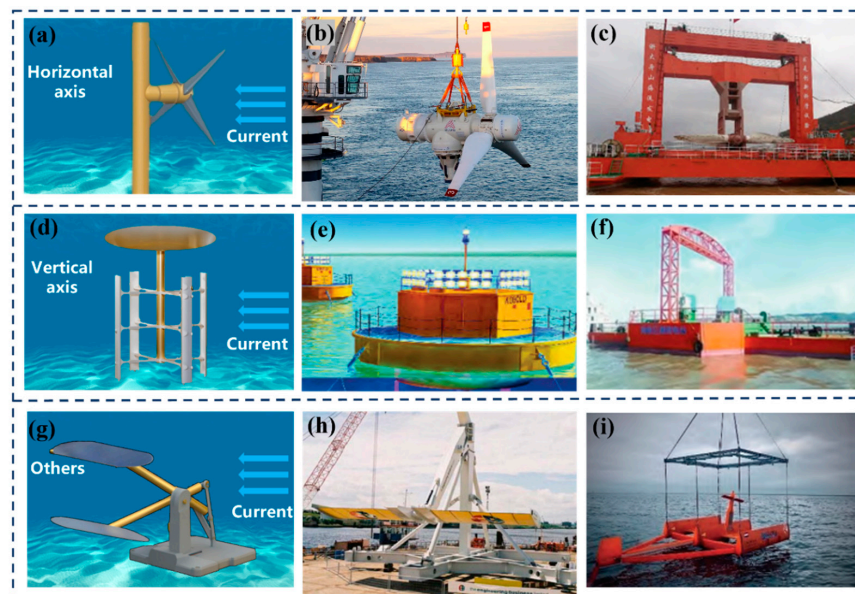


Figure 3. Rigid ocean current energy harvesting structures: (a) Schematic of a horizontal-axis turbine. (b) Turbine used in the MeyGen project [56] (Source: Ampeak Energy, 2025). (c) Floating ocean current power station at Zhai Ruoshan Island (Zhejiang University) (Reproduced from [58], with permission from Elsevier). (d) Vertical-axis turbine. (e) Kobold turbine (Reproduced with permission from [59]). (f) "Hai Neng III" vertical-axis ocean current energy device (Harbin Engineering University) (Reproduced with permission from [60]). (g) Schematic of a flapping-wing generator. (h) Stingray oscillating hydrofoil device (Reproduced from [61], with permission from Elsevier). (i) TidalKite underwater kite system [62] (Source: SeaCurrent.com, 2019; accessed 17 November 2025).

In addition to horizontal-axis and vertical-axis turbines, emerging ocean current energy devices—represented by oscillating hydrofoils and underwater kites—have also attracted widespread attention. A schematic of an oscillating hydrofoil structure is shown in Figure 3g [61,68]. Figure 3h [61] shows Stingray, the first oscillating hydrofoil device built by Engineering Business in the United Kingdom in 2002. Its average output power reached 117.5 kW at the rated flow velocity; however, the project was discontinued due to excessively high costs [69]. Underwater kite power generation systems have similarly received considerable interest. These devices typically move in a figure-eight trajectory underwater, pulling a hydraulic system that drives the generator [70]. As shown in Figure 3i [62], the 500 kW underwater kite system TidalKite, designed by SeaCurrent in the Netherlands, is a representative example of this technology. However, traditional turbine-based ocean current energy devices generally require ideal operating conditions with flow velocities of 2.57–3.6 m/s, whereas in most nearshore regions the current velocity typically ranges from only 0.5–1.5 m/s. This mismatch limits power generation efficiency and may even prevent the devices from starting [71]. Furthermore, with increasing water depth, ocean current velocity decreases significantly, and flow direction becomes more complex and variable, imposing stricter performance requirements on such devices.

2.3. Distributed Power Demand Drives the Emergence of Nano-Scale Energy Harvesting

Underwater distributed observation nodes form the core components of three-dimensional ocean observation networks and are widely used in environmental moni-

toring, scientific research, and resource investigation [72]. With increasing demands for long-term and stable ocean monitoring, these nodes have become even more critical for safeguarding national defense, advancing the marine economy, and protecting national maritime rights and interests. However, because such nodes are typically deployed in deep-sea environments, achieving a long-term and stable energy supply remains a key challenge. These nodes are generally equipped with sensors, communication modules, and data processing units, all of which require stable electrical power [73]. Traditional energy supply methods—such as batteries and external power cables—face numerous limitations. Although batteries offer convenient short-term power, they require frequent replacement, incur high maintenance costs, and pose potential environmental pollution risks [74]. External cable-based power delivery can provide continuous energy but requires complex seabed cabling and is susceptible to extreme environmental conditions such as high pressure, low temperature, and seawater corrosion [75]. Conventional electromagnetic ocean current energy devices are more suitable for high-power generation and demand favorable hydrodynamic conditions, which limit their applicability for powering underwater distributed nodes. Moreover, underwater distributed nodes are often deployed over large spatial scales. To ensure the stable operation of the entire network, each node must possess a highly autonomous energy system that minimizes reliance on traditional power infrastructure. Therefore, the development of efficient, reliable, and sustainable energy supply technologies is urgently needed to expand the deployment range and enhance the monitoring capability of underwater distributed sensor nodes.

As shown in Figure 4, large-power supply over short time scales still relies on batteries, power cables, and high-power electromagnetic generators. However, with advances in materials science, nanogenerator technologies—represented by piezoelectric and triboelectric mechanisms—have gradually been applied to in situ ocean current energy harvesting, providing a new technical solution for distributed power supply to low-power underwater sensors [28,76]. Owing to their inherent advantages in capturing and converting low-frequency, low-amplitude mechanical energy, nanogenerators exhibit significant application potential in harvesting the highly entropic mechanical energy available in marine environments [77].

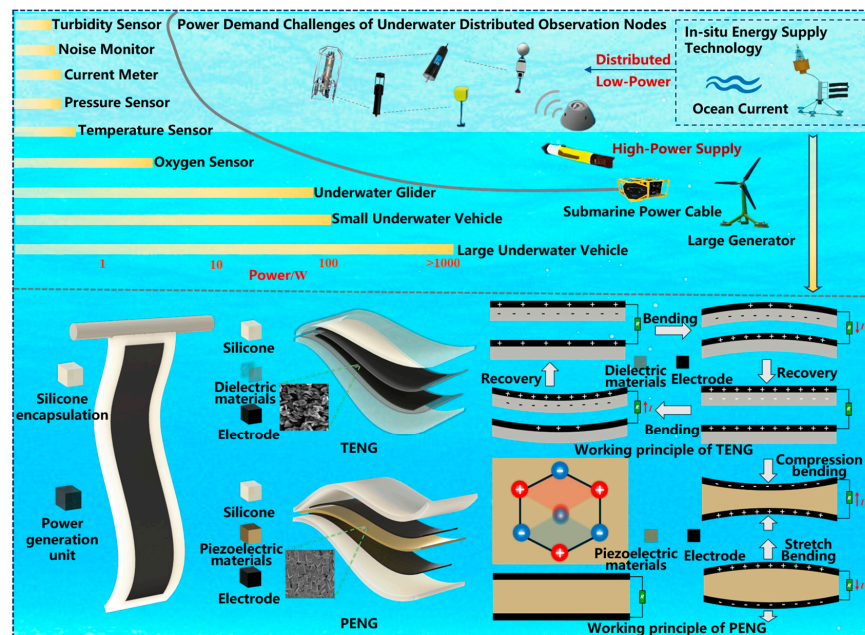


Figure 4. Application scenarios of ocean current energy and the operating principles of nanogenerators.

3. Applications of Piezoelectric Nanogenerators (PENGs) in Ocean Current Energy Harvesting

3.1. Principles and Development of PENG Technology

Piezoelectric nanogenerators are an energy conversion technology based on the piezoelectric effect, first discovered by Pierre and Jacques Curie in 1880 [78]. As shown in Figure 5a, when specific crystalline or ceramic materials are subjected to mechanical stress (such as tension, compression, or bending), their internal dipole moments undergo reorientation, resulting in charge accumulation at the two ends of the material and generating a measurable potential difference. At the macroscopic scale, common piezoelectric materials include PZT ($\text{Pb}(\text{Zr}, \text{Ti})\text{O}_3$), BaTiO_3 , ZnO, and others [79–81]. Under external mechanical loading, the crystal lattice of these materials experiences ionic displacement, leading to the separation of positive and negative charge centers and thus polarization (Figure 5b). For example, in the wurtzite structure of ZnO, when stress is applied along the axial direction, Zn^{2+} and O^{2-} ions shift in opposite directions, forming dipole moments and inducing an electric field at both ends [82,83].

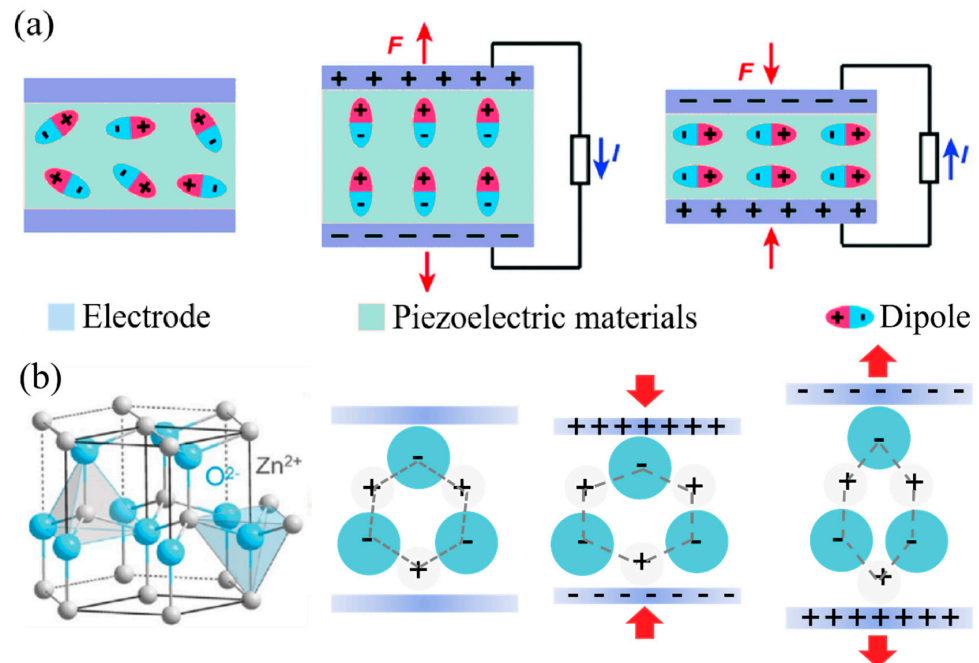


Figure 5. Operating principles of piezoelectric nanogenerators. (a) Schematic diagram of piezoelectric device under mechanical stress. (b) Ion displacement mechanism under stress.

In 2006, the team led by Zhong Lin Wang first proposed and experimentally demonstrated the concept of a nanowire-based piezoelectric generator (ZnO nanowire PENG), achieving direct conversion of micro-/nano-scale mechanical energy into electrical energy [84]. This pioneering work marked the advent of the piezoelectric nanogenerator era and provided a new pathway for energy harvesting in low-frequency and weak-energy environments such as ocean currents, waves, and vibrations. Compared with traditional macroscopic piezoelectric devices, nanoscale PENGs exhibit significant advantages in sensitivity, flexibility, and integrability. Through material modification—such as incorporating BaTiO_3 or ZnO nanoparticles into PVDF and its copolymer P(VDF-TrFE)—structural optimization involving thin films, nanowire arrays, and multilayer composite membranes, as well as interface polarization engineering, researchers have substantially improved output performance and durability [80,85–87]. Meanwhile, flexible polymer-based PENGs can

generate stable electrical outputs under low-velocity fluid excitation, demonstrating unique potential for ocean current energy harvesting and underwater sensing applications.

3.2. Structural Designs of PENGs for Ocean Current Energy Harvesting

The structural design of PENG is a key factor determining their energy conversion performance and environmental adaptability. In response to the characteristics of low-velocity, multidirectional, and high-pressure marine environments, researchers have proposed a variety of structural schemes based on biomimetic flexible bodies, flow-induced vibrations, and inertial coupling, gradually forming a multi-level design framework ranging from macroscopic flexible structures to micro-/nano-scale arrays [16,88–90]. Figure 6 provides a concise summary of representative PENG configurations in recent years and their corresponding energy harvesting mechanisms. As shown in Figure 6a, Taylor et al. proposed in 2001 an eel-inspired flag-type piezoelectric energy harvester, which represents one of the earliest concepts for flexible biomimetic devices for ocean current energy harvesting [91]. The device consists of a PVDF thin-film flag placed in the wake of a flow; the periodic pressure differences induced by the von Kármán vortex street drive the membrane to oscillate, generating charges during cyclic stretching and compression. Its rotation-free design significantly reduces maintenance requirements and has become a foundational prototype for subsequent flexible harvesters. Because cylindrical bluff bodies naturally exhibit typical and stable vortex-induced vibration (VIV) responses under fluid loading, VIV-based energy harvesting has become one of the most systematically developed approaches. Such devices usually integrate piezoelectric patches onto beams connected to the vibrating cylinder, effectively converting periodic transverse strains into electrical energy. As a result, VIV-based designs constitute the most extensively studied and structurally mature class of piezoelectric ocean current harvesters [89,92,93]. As shown in Figure 6b, Zhao et al. [94] placed a cylinder within the wake of a downstream bluff body and conducted a series of studies by varying the bluff-body geometry and spacing. Their results showed that the energy harvesting performance of the piezoelectric device in the wake region increased significantly, by up to 43.2 times.

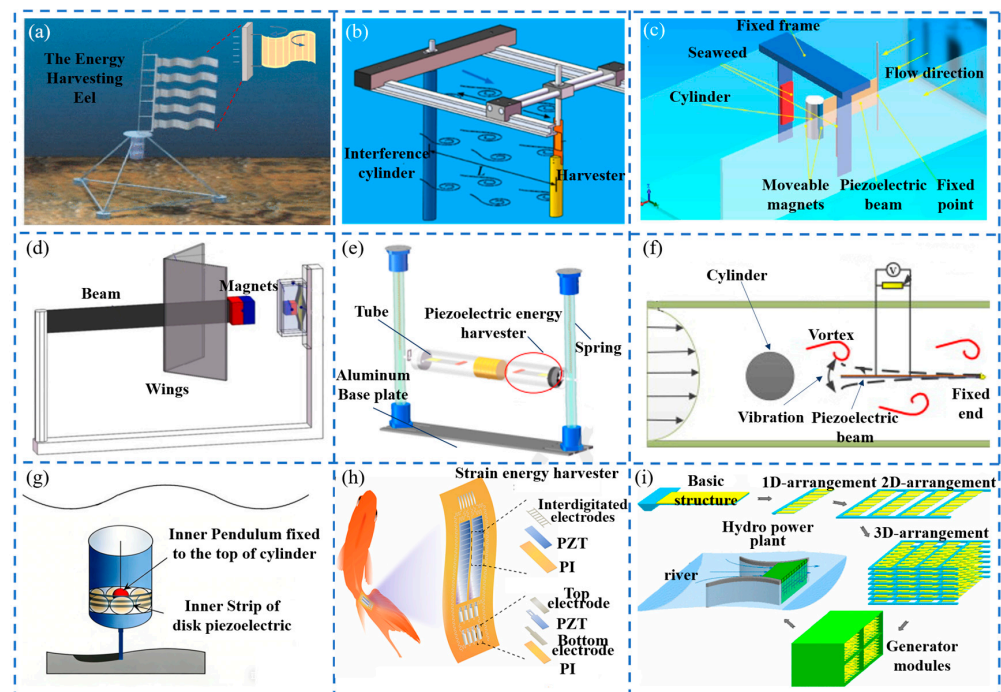


Figure 6. Common structural designs of piezoelectric nanogenerators in ocean current energy collection: (a) Flag-shaped piezoelectric energy collector imitating eel (Adapted with permission from [91]).

(b) Blunt body-beam structure (Adapted with permission from [94]). (c) Magnetic-elastic coupling structure (Adapted with permission from [95]). (d) Non-contact magnetic-elastic coupling structure (Adapted with permission from [96]). (e) Non-stable piezoelectric cantilever beam energy collector inside the tube (Adapted with permission from [30]). (f) Vortex-excited cantilever beam piezoelectric energy collector (Adapted with permission from [97]). (g) Pendulum impact piezoelectric energy acquisition system (Adapted with permission from [98]). (h) Fish tail movement-induced flow field impact-driven piezoelectric thin film power generation (Adapted with permission from [99]). (i) Three-dimensional arrayed piezoelectric micro-module system (Adapted with permission from [100]).

Magnetic assistance is another widely adopted strategy for enhancing structural vibration. Magnetic-elastic coupling has been employed to increase vibration amplitude and improve energy conversion efficiency [101,102]. As illustrated in Figure 6c, Cao et al. [95] proposed and experimentally investigated a magnetically enhanced piezoelectric vibration energy harvester (PVEH), composed of a piezoelectric beam, a cylindrical bluff body, and magnets, achieving a performance enhancement of up to 225%. Figure 6d shows a novel magnetically coupled bistable piezoelectric energy harvesting method for underwater applications proposed by Zou et al. [96]. This method uses a flexible piezoelectric transducer, where magnetic coupling enables harvesting of vibration-induced energy. Because the mechanical energy transfer is non-contact, critical fragile components can be encapsulated without affecting their operation. As shown in Figure 6e, Guan et al. [30] installed a piezoelectric cantilever-beam energy harvester inside a pipe and designed an inclined converter structure to capture inertial vibration energy. At a flow velocity of 0.351 m/s, the system generated a peak-to-peak voltage of 41 V and a maximum power of 57.3 μ W, demonstrating its potential for stable operation in low-velocity ocean currents.

Another common category is the VIV cantilever-beam piezoelectric energy harvester (Figure 6f), a representative example being the MFC-PVC composite cantilever structure reported by Shan et al. [97]. It consists of a macro fiber composite material (MFC) beam and a polyvinyl chloride (PVC) layer. Positioned within the wake of a cylinder, the device leverages periodically shedding vortices to induce oscillations of the beam. In addition, several novel and unconventional designs have been explored by many researchers. For example, Toma et al. [98] proposed a pendulum-impact piezoelectric energy harvesting system (Figure 6g), which demonstrates an alternative nonlinear energy harvesting approach. In this configuration, a pendulum is suspended inside a buoy-shaped housing and periodically impacts eight PZT-4 bimorph disks mounted on the inner wall as the buoy undergoes wave-induced reciprocating motion, thereby generating impact-induced electrical output. Other studies have utilized biomimetic structures to achieve energy harvesting under localized flow disturbances. For instance, Sheng et al. [99] demonstrated a fish-tail-inspired structure in which flow impacts induced by tail-like oscillation drive a piezoelectric thin film to generate electricity, showcasing the feasibility of flexible nanogenerators in underwater fluid-structure interaction scenarios (Figure 6h). Finally, concepts of arraying and modularization have promoted the scaled development of piezoelectric energy harvesting systems. Pobering et al. [100] proposed a three-dimensional arrayed piezoelectric micro-module system (Figure 6i), in which individual bimorph cantilever units are stacked in one, two, or three dimensions, achieving a theoretical power density of 68 W m⁻³. In order to facilitate an intuitive comparison of the performance characteristics and improvement effects of different PENG structural designs, Table 2 summarizes the output performance of the aforementioned representative designs and compares the performance improvement ratios of these designs relative to the benchmark design or the traditional design. These data further confirm the significant role of structural innovation in enhancing energy conversion efficiency, environmental adaptability, and system reliability, and provide a quantitative reference for the subsequent structural optimization and

system integration of PENG. In summary, from biomimetic flexible flags to magnetically coupled vibrating beams, inertial–spring hybrid systems, and arrayed micro-modules, the structural designs of piezoelectric energy harvesters have evolved from passive response to active coupling and from single-degree-of-freedom mechanisms to multimodal synergistic configurations. These structural innovations not only enhance output performance under low-flow-velocity conditions but also improve adaptability and scalability in complex marine environments, thereby laying an essential foundation for developing efficient and stable underwater self-powered systems.

Table 2. Performance comparison of various piezoelectric nano generators in ocean current energy collection.

Structural Designs	Performance Output	Performance Improvement	Ref.
Flag-shaped piezoelectric energy collector imitating eel	-	Underwater environment with low velocity and complex flow direction	[91]
Blunt body-beam structure	0.8–1.2 $\mu\text{W}/\text{cm}^3$	Output power increased by about 3–5 times	[94]
Magnetic-elastic coupling structure	0.15 mW	Output power increased by about 50%	[95]
Non-contact magnetic-elastic coupling structure	0.48 mW	Significantly improved durability and more stable output	[96]
Non-stable piezoelectric cantilever beam energy collector inside the tube	40 μW	It can work effectively at low flow rate (<0.5 m/s)	[30]
Vortex-excited cantilever beam piezoelectric energy collector	25 μW	MFC is more fatigue-resistant and has longer service life	[97]
Pendulum impact piezoelectric energy acquisition system	-	Simple structure	[98]
Fish-tail motion-induced flow-driven film	1.2 $\mu\text{W}/\text{cm}^2$	Biocompatibility and flexible integration	[99]
3D arrayed piezoelectric micro-module	-	Increased energy collection density, suitable for large-scale marine energy utilization	[100]

Note: if the power density of the device is not clearly given in the quoted original document, the power value is reserved in the table for reference.

Although the aforementioned structural design demonstrated excellent energy collection potential in the laboratory environment, PENG still faces several severe challenges in real marine field applications. Firstly, during long-term underwater operation, piezoelectric materials are prone to be eroded by humidity and salt fog, resulting in polarization attenuation and performance drift. Secondly, under low-speed and irregular ocean currents, the vibration response of PENG is often unstable, with large fluctuations in output power, making it difficult to meet the actual load requirements. Furthermore, the structure is prone to fatigue damage under long-term alternating loads, especially brittle piezoelectric ceramics may develop cracks or delamination in impact or vibration environments. Additionally, when PENG is actually deployed, it also faces limitations such as difficulty in integrating with marine structures, high maintenance costs, and environmental friendliness. Therefore, future research should focus on aspects such as material durability, structural reliability, environmental adaptability, and system integration to further promote the transition of PENG from the laboratory to real marine applications.

3.3. Design, Material Selection, and Performance Enhancement Strategies for PENGs

In the process of harvesting ocean current energy, the material selection and structural design of PENGs play a critical role. To achieve efficient energy conversion, an ideal PENG

material should possess a high piezoelectric coefficient to enhance energy conversion efficiency, favorable mechanical properties to withstand long-term cyclic mechanical loading, and excellent chemical stability to ensure durability in marine environments. Figure 7 provides a concise overview of fabrication approaches for piezoelectric materials and several emerging strategies for improving power-generation performance. Tian et al. [103] conducted a comprehensive review of additive manufacturing strategies for nanogenerators (Figure 7a), covering commonly used techniques such as digital light processing (DLP), direct ink writing (DIW), stereolithography (SLA), and fused deposition modeling (FDM). Their review systematically discussed these methods in terms of working principles, performance metrics (e.g., output voltage, current, and power density), theoretical foundations, and application areas. The authors emphasized that additive manufacturing offers unique advantages in material versatility, structural topology optimization, microstructural tuning, and integrated fabrication. These advantages contribute significantly to enhancing key performance characteristics of nanogenerators.

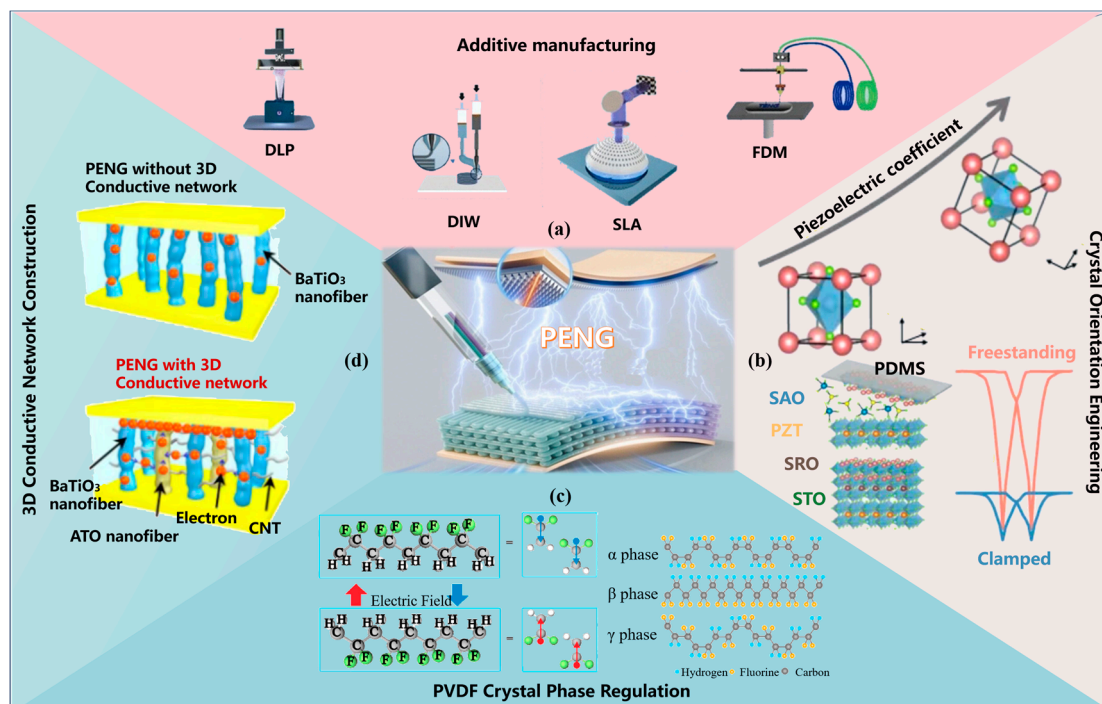


Figure 7. Main ways to increase the output power of piezoelectric nanogenerators (Reproduced with permission from [31–33,103]). (a) Additive manufacturing. (b) Crystal Orientation Engineering. (c) PVDF Crystal Phase Regulation. (d) 3D Conductive Network Construction.

Furthermore, as shown in Figure 7b, Ren et al. [31] successfully fabricated free-standing (111)-oriented $\text{PbZr}_{0.52}\text{Ti}_{0.48}\text{O}_3$ single-crystal thin films to meet the power requirements of flexible electronics. By introducing a soluble sacrificial layer to release substrate clamping effects and employing crystal-orientation engineering to enhance the piezoelectric response, the material exhibited a high output power density ($\sim 63.5 \text{ mW}/\text{cm}^3$), excellent flexibility (withstanding $> 3.4\%$ strain), and outstanding cycling stability ($> 60,000$ cycles). These characteristics indicate its potential applicability in future flag-type ocean current energy harvesters. As shown in Figure 7c, PVDF is one of the most piezoelectrically active polymer materials known, and its multiple crystalline phases arise from different spatial arrangements of molecular chain segments. PVDF mainly contains five crystalline phases— β , α , δ , γ , and ϵ —among which increasing the β -phase fraction has been demonstrated to significantly enhance its electricity-generation performance [32,104,105]. In addition, as

illustrated in Figure 7d, Yan et al. [33] constructed a three-dimensional conductive network within piezoelectric nanofibers and successfully developed a high-performance PENG whose output was enhanced by up to 12.7 times. Table 3 systematically summarizes the common strategies, performance outputs and applicable scenarios for PENG energy enhancement. In summary, the effective application of PENGs in ocean current energy harvesting relies on advances in material system optimization and structural innovation. These technological developments are not only crucial for improving ocean current energy capture efficiency but also provide fresh impetus for the evolution of renewable energy technologies. With continued progress in related research, PENGs are expected to play an increasingly prominent role in future ocean current energy systems.

Table 3. The main ways to increase the output power of piezoelectric nanogenerators.

Optimization Strategies	Implementation Method	Electrical Output	Ref.
Additive manufacturing	FDM	8.17 V/cm ² 108.15 nA/cm ²	[106]
	DIW	242 μW/cm ²	[107]
	SLA	10 V Sensitivity 30 mV/kPa	[108]
	DLP	36 nW/cm ²	[109]
Crystal Orientation Engineering	Introducing soluble sacrificial layer to release substrate clamping effect + crystal orientation regulation	63.5 mW/cm ³ (record-breaking)	[31]
PVDF Crystal Phase Regulation	Electrospinning	4.07 mW/cm ²	[110]
	3D printing	-	[111]
	Filler doping	2.2 μW/cm ²	[112]
	Copolymer Modification	16.41 mW/cm ²	[113]
3D Conductive Network Construction	Building 3D conductive network inside piezoelectric nanofibers	BaTiO ₃ -based: 128.82 mW/m ² (at 5.15 × 10 ⁶ Ω load)	[33]

Note: for the case that the effective area or volume of the device is not clearly provided in the quoted original literature, so the standard power density cannot be calculated or obtained directly, the output voltage, current or absolute power values are retained in the table and marked after the data (such as “V”, etc.) for reference.

4. Applications of Triboelectric Nanogenerators (TENGs) in Ocean Current Energy Harvesting

4.1. Principles and Development of TENG Technology

Triboelectric nanogenerators (TENGs) are a novel energy harvesting technology based on Maxwell’s displacement current and the coupling of contact electrification and electrostatic induction. The core operating principle is that when two materials with different triboelectric properties come into contact, and subsequently separate, static charges are generated on their surfaces; relative motion then drives charge transfer, enabling the conversion of mechanical energy into electrical energy. Wang et al. [34] explained the fundamental mechanism of TENGs using an electron-cloud/potential-well model based on basic electron cloud interactions, as illustrated in Figure 8a. Since TENGs were first introduced in 2012, the technology has made remarkable progress in the fields of materials science and nanotechnology [114–117]. Depending on the electrode configuration and the relative motion between friction layers, TENGs operate in four fundamental modes: the vertical contact-separation mode, the lateral sliding mode, the single-electrode mode, and the freestanding triboelectric-layer mode, as shown in Figure 8b. In the first two modes, periodic contact, separation, or sliding between dielectric layers generates a potential difference that drives electron flow for energy conversion. The single-electrode mode replaces one electrode

with ground, making it suitable for scenarios where wiring is difficult, such as human motion monitoring. The freestanding triboelectric-layer mode generates induced currents through the reciprocating motion of an insulating layer between symmetric electrodes, resulting in low wear and long operational lifetime. These four modes together constitute the fundamental working mechanism of TENG-based energy harvesting. The diversity of these operating modes enables TENGs to efficiently convert mechanical energy to electrical energy across a wide range of applications. TENGs show enormous potential for harvesting energy from low-speed and irregular mechanical motions, making them highly suitable for ocean current energy harvesting environments.

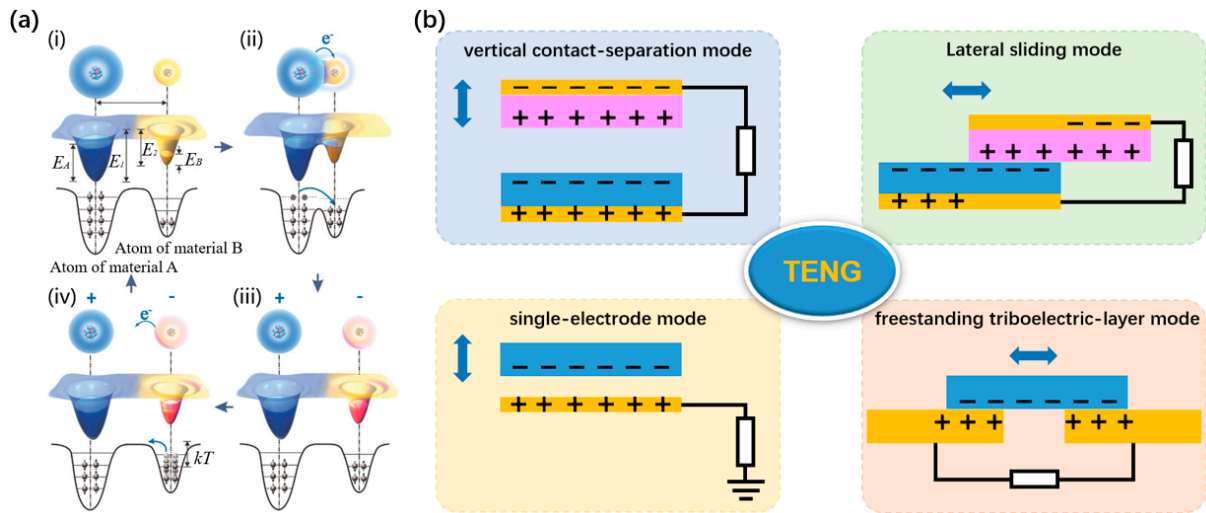


Figure 8. Basic principle and fundamental working models of TENG. (a) The electron cloud/potential model. Schematic of the electron cloud and potential energy profile (3D and 2D) of two atoms belonging to two materials A and B, respectively, when they are: (i) before contact, (ii) in contact, and (iii) after contact, showing electron transfer from one atom to the other after being forced to have electron cloud overlap. (iv) Charge release from the atom at an elevated temperature T once kT approaches the barrier height. (Reproduced with permission from [34]). (b) Four fundamental working models.

4.2. Structural Designs of TENGs for Ocean Current Energy Harvesting

Triboelectric nanogenerators, owing to their excellent energy conversion performance in low-frequency and low-velocity fluid environments, have become an important technological pathway for ocean current energy harvesting. In recent years, researchers have proposed a variety of underwater TENG structures tailored to different flow conditions through innovations in structural design, material optimization, and biomimetic strategies, as illustrated in Figure 9. These designs encompass multiple energy conversion modes—including contact–separation, sliding, and hybrid coupling—demonstrating the evolutionary trend of TENGs from flexible biomimetic units to integrated array systems. As shown in Figure 9a, Wang et al. [118] developed an algae-inspired stacked S-TENG, in which a multilayer flexible structure composed of polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), and conductive-ink-coated polyethylene terephthalate (PET) serves as the basic generating unit. The bending-induced vibration triggers periodic contact–separation even at an ultralow flow velocity of 0.133 m s^{-1} , exhibiting excellent responsiveness under weak hydrodynamic excitation. Figure 9b,c illustrate the potential application scenarios of seaweed-inspired or flag-like TENG structures, including powering deep-sea sensor platforms such as moored buoys through large-scale arrayed devices, or forming extensive seabed energy-harvesting stations via wide-area deployment [119]. Similarly, Huang et al. [35] constructed an energy-harvesting device using a high-permittivity

BaTiO₃/PVDF composite film, which exhibits an ultrafast self-polarization effect under an electric field, thereby ensuring superior output performance in extremely slow-flow environments (Figure 9d). This device can harvest energy from water flows as slow as 0.02 m/s and generate an open-circuit voltage of 44.5 ± 5.3 V and a short-circuit current of 3.2 ± 0.7 μ A.

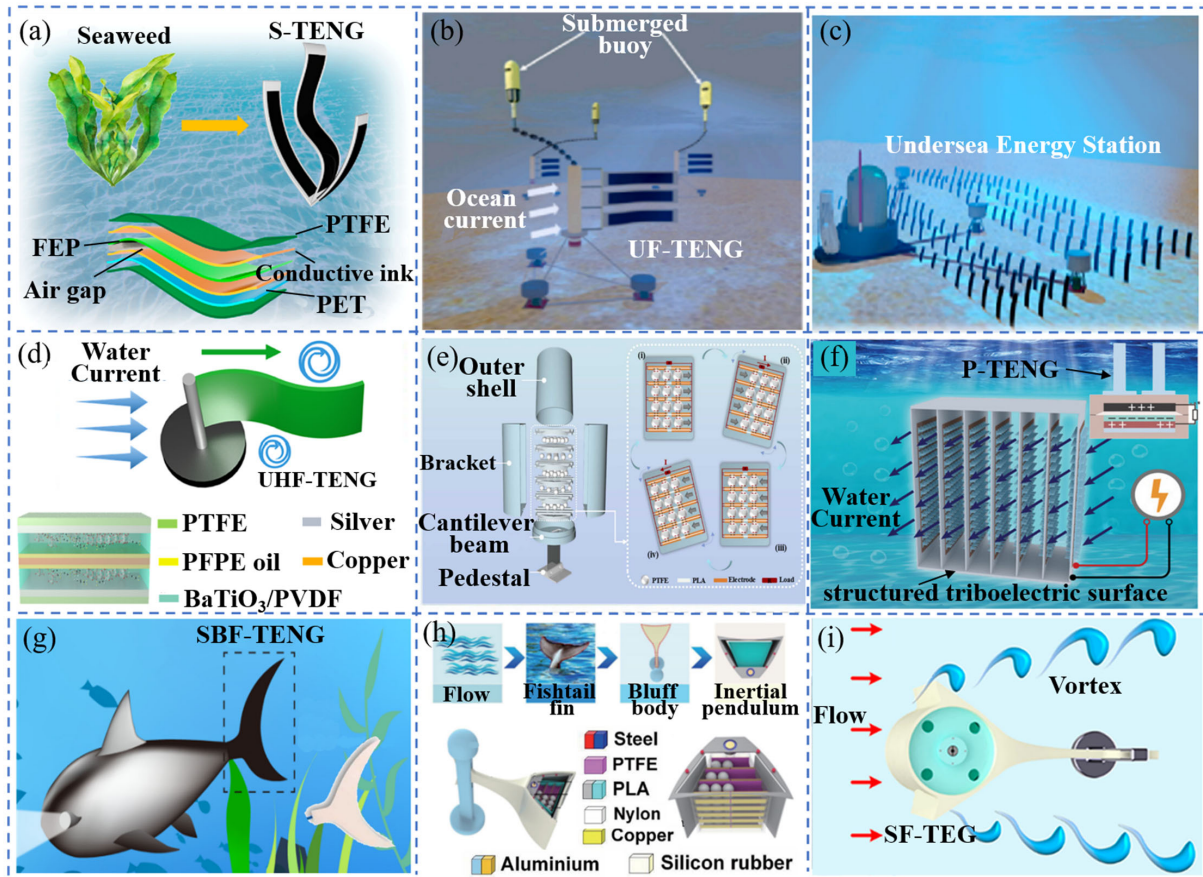


Figure 9. Common structural designs of triboelectric nanogenerators for ocean current energy harvesting: (a) algae-inspired stacked S-TENG (Adapted with permission from [118]). (b,c) potential application scenarios of seaweed-/flag-inspired energy-harvesting structures (Adapted with permission from [119]). (d) BaTiO₃/PVDF composite-film flag-type TENG (Adapted with permission from [35]). (e) columnar cantilever-type triboelectric structure (Adapted with permission from [120]). (f) schematic of a flow-induced vibration seabed energy wall (Adapted with permission from [121]). (g–i) three representative fish-tail-inspired ocean current energy harvesting devices (Adapted with permission from [122–124]).

Figure 9e,f illustrate energy-harvesting devices designed based on the VIV mechanism. As shown in Figure 9e, Zhang et al. [120] developed a columnar cantilever-type UBF-TENG structure incorporating multilayer tubular channels and PTFE rolling-ball arrays. Under ocean current excitation, the rolling balls move periodically to generate electricity. The device exhibits an ultralow cut-in flow velocity of 0.14 m/s, and at 0.76 m/s, the UBF-TENG achieves a maximum open-circuit voltage of 250 V and a maximum short-circuit current of 2.2 μ A. Figure 9f presents the modular application concept of an STS array proposed by Deng et al. [121], where multiple STS units can be connected in parallel to form a seabed “energy wall,” providing power for underwater sensing nodes. Figure 9g–i show three representative fish-tail-inspired ocean current energy harvesters. In Figure 9g, a biomimetic fish-tail-structured triboelectric nanogenerator, encapsulated with anti-corrosion coatings, demonstrates excellent structural controllability, environmental stability, and mechanical

robustness, highlighting its strong potential for blue-energy harvesting applications [122]. Figure 9h presents a device inspired by the geometric features of fish tail fins. The bluff body is designed with a fish-tail-shaped cross-section, and fluid dynamic simulations indicate that this geometry enhances the wake vortex street formation. In the energy-conversion module, researchers adopted a hybrid design combining rolling beads and geometric confinement, configuring the TENG unit as an inertial-pendulum mechanism to improve trigger sensitivity and energy conversion efficiency in low-speed flow environments [123]. Figure 9i displays a flexible biomimetic fin generator featuring a swing-rotation coupling mechanism. The system consists of a flexible biomimetic fin and a composite energy-harvesting module, in which a triboelectric nanogenerator and an electromagnetic generator are integrated to achieve multi-mechanism synergistic energy conversion [124]. In order to more clearly compare the performance characteristics of the above types of Teng structures in marine current energy collection, this paper summarizes and compares their output performance, as shown in Table 4. The table covers the data of key start-up flow rate, power density or absolute output of different designs, and briefly describes the performance improvement or application advantages brought by its structural optimization, which can provide reference for the selection and optimization of Teng for different flow rate conditions and deployment scenarios.

Table 4. Performance comparison of various triboelectric nanogenerators in the collection of oceanic flow energy.

Structural Designs	Performance Output	Performance Improvement/Advantages	Ref.
Algae-inspired Stacked S-TENG	0.33 W/m ²	Multiple units connected in parallel can increase the output	[118]
Flag-like Structures	52.3 μW (0.461 m/s)	Critical flow velocity: 0.133 m/s, Performance output increased by 170% with cylinder (0.461 m/s)	[119]
BaTiO ₃ /PVDF Composite Film Flag-type TENG	27.78 W/m ³	Critical flow velocity: 0.02 m/s, Output has increased by more than 3 times	[35]
Columnar Cantilever-type TENG	0.21 μW/cm ³	Critical flow velocity: 0.14 m/s, The charging speed of the capacitor has been increased by 4.6 times with PMS	[120]
Flow-Induced Vibration Seabed Energy Wall	0.3357 W/m ²	Increase by more than 100 times	[121]
Sealed Bionic Fishtail-Structured TENG	1.67 mW/m ²	Biomimicry, sealing, and anti-corrosion	[122]
Soft Bionic Fishtail-Structured TENG	5.56 W/m ³	The performance will remain at 96.81% after 30 days	[123]
Bionic-Fin Swing-Rotation Hybrid TENG-EMG	TENG: 203 V EMG: 0.41 mA	Output is increased by approximately 2–3 times Working bandwidth is wider	[124]

Note: for the case that the effective area or volume of the device is not clearly provided in the quoted original literature, so the standard power density cannot be calculated or obtained directly, the output voltage, current or absolute power values are retained in the table and marked after the data (such as “V”, etc.) for reference.

Although the TENG structure exhibits excellent low-frequency energy collection performance under laboratory conditions, it still faces a series of challenges in the real marine environment. Firstly, long-term underwater contact-separation or sliding friction is prone to cause material wear, surface charge attenuation, and a decline in output stability; secondly, salt corrosion, biological adhesion, and high-pressure penetration in the seawater environment can cause irreversible damage to the sensitive friction layer and electrode interface; moreover, the complex and variable flow field conditions make it difficult to

maintain stable vibration triggering and motion synchronization of the TENG, affecting the phase consistency of the array units and the overall output efficiency. At the same time, the aging of encapsulation materials, mechanical fatigue, and interaction with environmental organisms also pose challenges to the reliability and environmental compatibility of the TENG for practical long-term deployment. Therefore, developing wear-resistant materials, optimizing environmental adaptability encapsulation, enhancing the robustness of the structure in unsteady flows, and conducting long-term offshore field tests are the key to promoting the application of TENG technology.

4.3. Material Selection and Performance Enhancement Strategies for TENGs

Triboelectric nanogenerators possess a unique advantage in ocean current energy harvesting, as they can directly convert low-frequency mechanical energy into electricity. However, their output performance is constrained by factors such as limited surface charge density, imperfect interface contact, and inherently high internal impedance. To address these challenges, researchers have implemented systematic optimization strategies across three key dimensions: physical structural design, chemical interface modification, and circuit-level energy management. These efforts have led to significant improvements ranging from enhanced output at the device-unit level to increased energy utilization efficiency at the system level (Figure 10).

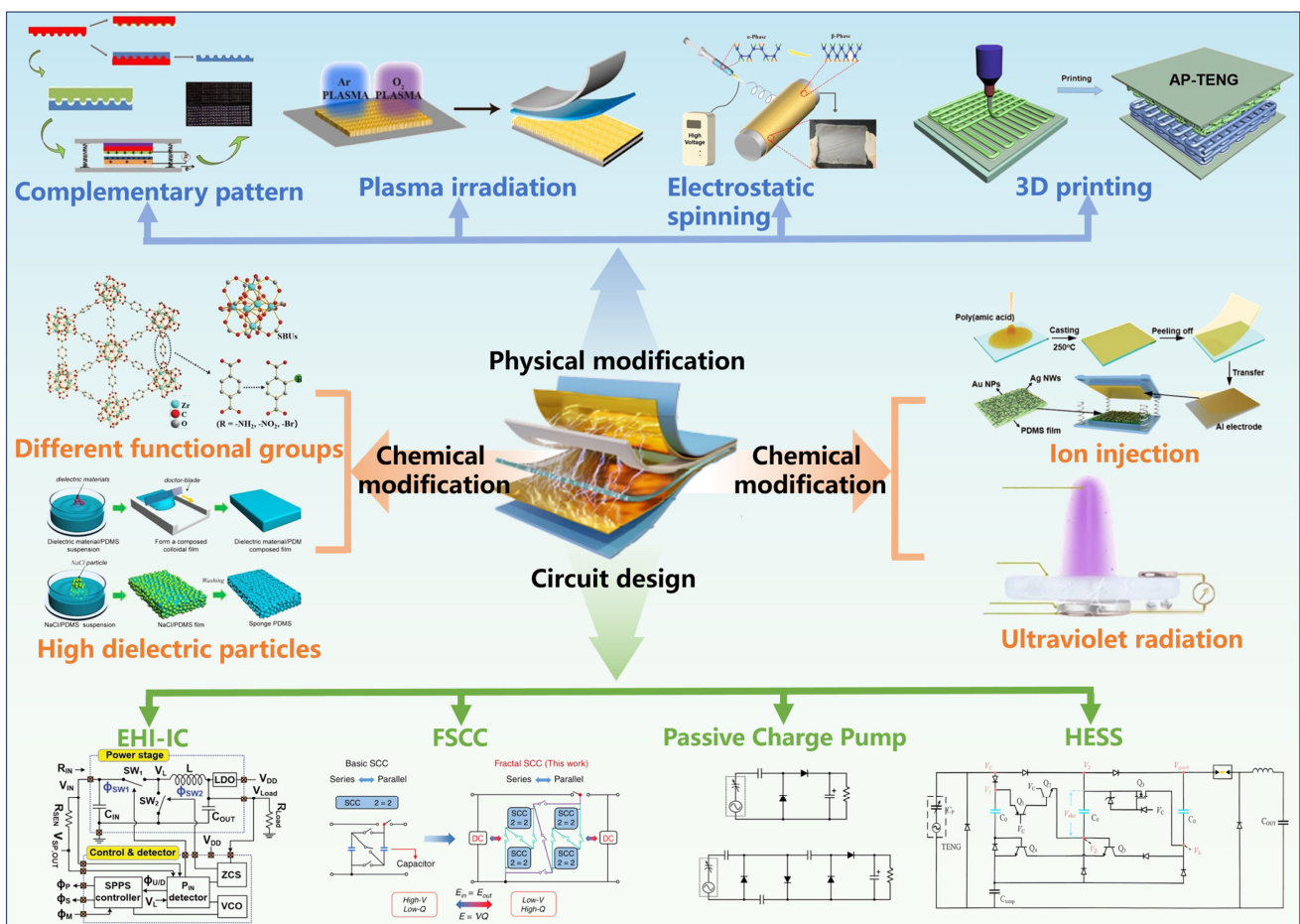


Figure 10. Main strategies for enhancing the output performance of TENGs (Reproduced with permission from [36–38,125–133]).

At the physical level, the structural morphology and micro/nanotopography directly determine the effective contact area of the triboelectric interface and the charge-transfer

pathways. Cao et al. [134,135] systematically reviewed various high-output TENGs enabled by structural optimization. Micro/nanostructured surfaces fabricated through template replication or laser etching can significantly enhance the charge density per unit area [36]. Sun et al. [125] applied a two-step reactive ion etching (RIE) process to PI films, resulting in 3.1-fold and 5.65-fold increases in open-circuit voltage and short-circuit current, respectively, compared with untreated samples. In addition, the integration of 3D printing and electrospinning technologies has further expanded the design freedom of TENG architectures. Yoon et al. [136] constructed a BV-TENG mimicking intestinal villi using 3D printing, achieving a substantially larger contact area and a nearly five-fold increase in output charge compared with flat structures. Sun et al. [127] fabricated a flexible and lightweight triboelectric nanogenerator (PMC-TENG) via electrospinning, where a MoS₂/carbon nanotube (MC)-doped PVDF membrane serves as the triboelectric substrate. Such morphology-controlled multilayer or array structures effectively improve the efficiency of “contact–separation” cycles and provide crucial support for developing flexible and encapsulable ocean current energy harvesters.

Chemical modification is a key strategy for enhancing the surface charge density and interfacial stability of triboelectric layers. Common approaches include the introduction of functional groups, incorporation of high-permittivity nanofillers, and surface-activation techniques such as ion implantation [37,128–130]. Grafting halogen, amine, or silane functional groups onto polymer surfaces can effectively tune the interfacial electron affinity, enabling controlled enhancement of the material’s triboelectric ability. Doping with high-permittivity nanoparticles or constructing nanocomposite systems leverages interfacial polarization effects to improve charge-separation efficiency and carrier stability. Meanwhile, plasma etching, ion implantation, and UV activation can further modify surface energy-level structures, enhancing charge-trapping capability and environmental robustness. These chemical modification strategies, when combined with physical structural optimization, provide a critical material foundation for achieving high-output, long-lifetime TENGs under demanding marine conditions.

Beyond material and structural optimization, electrical matching and power management circuits are essential for converting the high-voltage, low-current output of TENGs into usable electrical energy. Figure 10 illustrates four representative categories of TENG-oriented circuit designs. First, the Energy Harvester Interface IC (EHI-IC) integrates adaptive impedance matching and maximum power point tracking (MPPT), enabling series/parallel switching of multiple TENG units and efficient energy rectification. It represents one of the most advanced and highly integrated interface solutions to date. Representative studies include dual-parameter MPPT-controlled energy harvesting chips, which can achieve over two orders of magnitude improvement in harvested energy [131]. Second, Fractal Switched-Capacitor Converters (FSCC) utilize a fractal-series/parallel switching topology of capacitors. By reducing the effective output impedance and enabling multi-stage voltage boosting or reduction, FSCC significantly enhances charge-transfer efficiency, making it well suited for the high-voltage, low-current characteristics of TENGs [38]. Third, the Passive Charge Pump employs diode–capacitor arrays for charge accumulation and self-rectification. This fully passive mechanism requires no active control and represents the simplest energy-boosting technique, commonly used in small-power wearable TENG systems [132]. Finally, the Hybrid Electronic–Spark Switch power management system (HESS) uses a combined electronic-trigger and spark-discharge mechanism to rapidly release high-voltage transient energy, achieving a 4.69-fold improvement in charge-transfer efficiency [133]. By overcoming the voltage withstand limitations of traditional electronic switches, HESS is particularly suitable for managing the kilovolt-level peak signals typical of TENGs. Overall, these four circuit architectures from left to right reflect a progres-

sive technological pathway: integrated optimization—topological enhancement—passive rectification—high voltage transient modulation. With appropriate adaptations, these circuits are poised to offer robust support for power management in future ocean current energy harvesting systems.

Table 5 systematically summarizes the energy enhancement strategies and performance comparisons of TENG. In comparison, circuit design methods (especially FSCC and HESS) perform best in terms of energy enhancement. The power density of 954 W/m² of FSCC is much higher than that of other methods, which is attributed to its efficient fractal structure and switching capacitor technology, which can effectively manage the high-impedance TENG output. HESS has achieved precise control and high-voltage applicability through a hybrid switching system. Therefore, for applications that pursue extremely high energy output, the circuit design strategy is the preferred choice. Although physical and chemical modifications can enhance the performance of materials, their overall output is limited, and they are more suitable as auxiliary optimization methods. Future work can combine material innovation with advanced circuit design to further enhance the energy conversion efficiency and application scope of TENG.

Table 5. Main strategies for enhancing the output performance of TENGs.

Optimization Strategies	Implementation Method	Triboelectric Material	Electrical Output	Ref.
Physical modification	Complementary pattern	Cu, PDMS	4.36 W/m ² 431 V	[36]
	Plasma irradiation	Irradiation PI, PA11	11.64 μA 68.97 nC	[125]
	Electrostatic spinning 3D printing	PVDF-MoS ₂ /CNT composite nanofibers, Nylon PTFE powder, Ag	134 mW/m ² -	[127] [136]
Chemical modification	Different functional groups	PDMS@UiO-66-R composite film, Cu	191 V 17.3 μA	[37]
	High dielectric particles	Composite sponge PDMS film, Cu	6.47 W/m ²	[128]
	Ion injection	6FDA-APS PI film + Al, Ag NWs-Au NPs/PDMS film	2.82 mW	[130]
	Ultraviolet radiation	p-Si, n-GaN	60 nW	[129]
Circuit design	EHI-IC	Silicone rubber, Al	2.23 mW/m ²	[131]
	FSCC	PTFE, Al	954 W/m ²	[38]
	Passive Charge Pump	PI, Al	-	[132]
	HESS	PTFE/Cu composite film, Al	29.8 mW Hz ⁻¹ m ²	[133]

Note: for the case that the effective area or volume of the device is not clearly provided in the quoted original literature, so the standard power density cannot be calculated or obtained directly, the output voltage, current or absolute power values are retained in the table and marked after the data (such as “V”, etc.) for reference.

Overall, physical structural optimization primarily enhances contact electrification through morphology control, chemical modification strengthens interfacial polarization and durability, and power management circuitry addresses the bottlenecks of energy transfer and storage. The synergy of these three dimensions forms a complete performance-enhancement pathway for ocean-current-driven TENG systems, spanning from materials to fully integrated devices. Future development will focus on an integrated direction combining flexible biomimicry, multimodal energy conversion, and intelligent energy management. Through programmable interfacial material design and adaptive circuit algorithms, it will be possible to achieve stable self-powered node networks even under weak ocean-current conditions.

5. Future Perspectives and Conclusions

With the rapid evolution of ocean current energy harvesting technologies, nanogenerators based on PENG and TENG mechanisms are gradually transitioning from laboratory demonstrations toward engineering-level applications. As illustrated in Figure 11, future development pathways can be summarized into four interrelated key directions. First, continuous innovation in new material systems and structural designs will provide the fundamental basis for improving energy conversion efficiency and environmental adaptability. Second, advancements in system-level integration, energy storage, and power transmission strategies will support large-scale deployment and practical engineering implementation. Third, comprehensive consideration of ecological impacts, regulatory frameworks, and sustainable governance will offer institutional support for long-term technological development. Fourth, long-term durability, operational stability, and multimodal synergistic mechanisms of devices under real marine service conditions will become critical research themes. Taken together, future ocean current energy harvesting technologies will progress along a multi-dimensional pathway encompassing materials, structures, systems, and environmental considerations. This will enable a shift from isolated performance enhancement to whole-lifecycle optimization, ultimately providing more reliable and sustainable solutions for renewable energy systems.

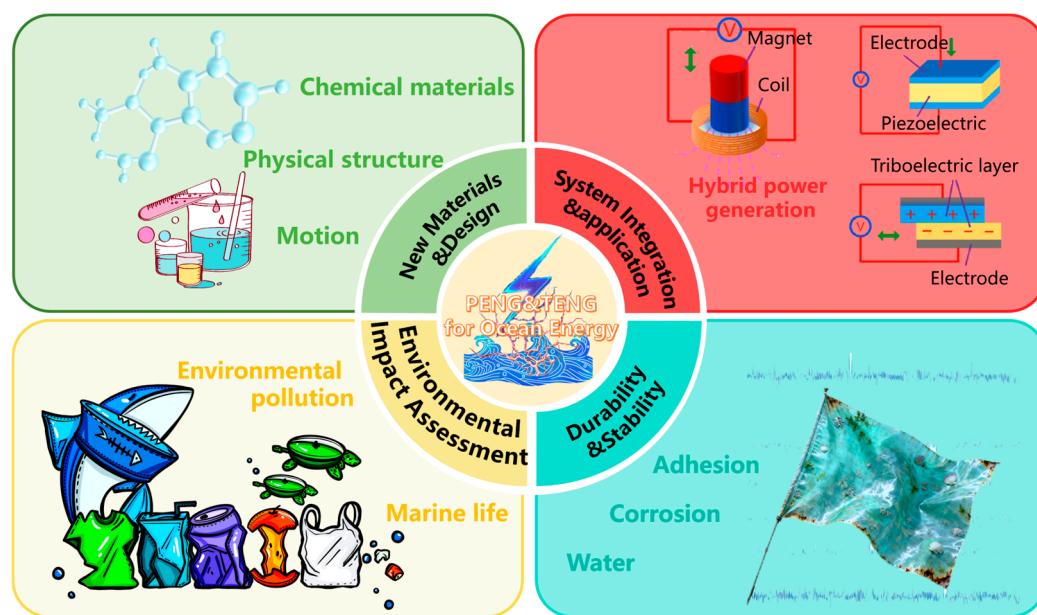


Figure 11. Challenges and Future Development Trends.

5.1. Innovation in New Materials and Structural Design

In recent years, the rapid development of ocean current energy harvesting has been driven by significant breakthroughs in materials science and engineering design. In particular, the continuous advancement of nanotechnology has made the development of novel nanomaterials a key factor in improving the efficiency of piezoelectric nanogenerators and triboelectric nanogenerators. For example, the use of high-performance piezoelectric materials—such as modified zinc oxide (ZnO) or polyvinylidene fluoride (PVDF)—can substantially enhance energy conversion efficiency. From the perspective of microstructural design, strategies such as introducing nanoscale textured surfaces can effectively increase the contact area and triboelectric interactions, thereby improving the electrical output of TENGs in ocean current energy harvesting. These innovations not only reflect a deeper understanding of nanomaterial characteristics but also demonstrate a persistent pursuit of optimized energy-harvesting performance. From an engineering design standpoint,

modularization and compactness have become important trends for future ocean current energy systems. Modular designs reduce maintenance costs, improve system reliability and flexibility, and facilitate installation and servicing. Additionally, more effective energy capture mechanisms (such as optimized flow-guiding structures and advanced dynamic regulation strategies) can further enhance the overall performance and efficiency of ocean current energy conversion devices. As these technologies continue to mature and undergo refinement, ocean current energy is expected to play an increasingly important role in the global renewable energy landscape, providing critical support for the sustainable transformation of the energy structure.

5.2. System Integration and Challenges for Large-Scale Applications

Although nanogenerators have demonstrated significant potential in ocean current energy harvesting, the transition from single-device proof-of-concept demonstrations to large-scale marine deployment still faces multiple challenges at the system-integration level. First, future ocean current energy systems will inevitably evolve from single-mechanism devices to multi-mechanism hybrid energy conversion architectures, such as PENG–TENG or even PENG–TENG–EMG hybrids. However, the substantial differences among these mechanisms in terms of output waveform, impedance characteristics, frequency response, and power density make their co-design and unified rectification highly complex. This calls for the development of new integrated power management strategies capable of adaptive cross-mechanism energy consolidation and high-efficiency energy scheduling. Second, as applications expand from single-point harvesting to multi-node array deployment, system-level fluid–structure interaction issues become increasingly prominent. Wake interference, modal coupling, and nonlinear vibrations among array elements may lead to spatially non-uniform power output, and in some cases, performance degradation or detuning of individual units. Moreover, as the array grows, the parallel/series combination of multiple high-impedance sources introduces significant challenges such as impedance mismatch, backflow of energy, and rectification losses, which place higher demands on the power combining circuits, energy storage units, and communication interfaces. Third, in practical engineering systems, nanogenerators must form a fully autonomous, long-term operational architecture together with sensors, energy storage modules, communication units, and data-processing circuits. The challenges of scaling up ocean-current nanogenerator systems are therefore concentrated in four major areas: (1) cross-mechanism energy integration, (2) flow–structure interference control within array systems, (3) electrical matching of high-impedance energy sources, and (4) long-term reliability of the complete device. Overcoming these bottlenecks requires deep interdisciplinary integration across materials science, fluid mechanics, ocean engineering, and power management electronics, laying the foundation for deployable, scalable, and engineering-ready ocean current energy harvesting networks.

5.3. Environmental Impacts and Regulatory Considerations

In advancing ocean current energy technologies, it is essential to carefully consider their potential impacts on marine ecosystems. Particularly when large-scale deployment is envisioned, ocean current energy devices may interfere with the migration pathways and habitats of marine organisms. Moreover, the long-term operation of triboelectric nanogenerators (TENGs) introduces an additional environmental consideration: the wear of friction layers may lead to the release of microplastics or nanoparticles into the surrounding water. This potential source of marine pollution warrants attention in both material selection and device lifecycle management. To ensure the health and sustainability of marine ecosystems, comprehensive environmental impact assessments and the development of effective mitigation measures are indispensable components of ocean

current energy development. Future designs should prioritize the use of biodegradable, highly wear-resistant, or environmentally benign tribomaterials to minimize such risks. As ocean current energy technologies continue to evolve, relevant legal, regulatory, and policy frameworks must also be updated and refined. This includes establishing clear permitting procedures for device installation and operation, formulating environmental protection standards, and defining mechanisms for interaction between ocean current energy systems and traditional energy markets. To attract investment, stimulate technological innovation, and support the sustainable development of this emerging field, it is crucial to build a regulatory system that is clear, transparent, and equitable. Through continuous technological innovation, improved system integration, the adoption of eco-conscious material strategies, and thoughtful consideration of environmental impacts and regulatory policies, ocean current energy technologies can not only contribute to the global transition toward cleaner energy structures but also hold promise to become an important component of future energy supply. Therefore, taking into account technological, environmental, and policy factors in a holistic manner is vital for ensuring the healthy development and broad adoption of ocean current energy technologies.

5.4. Durability and Stability

In the progression of nanogenerator-based ocean current energy technologies toward real marine deployment, durability and long-term stability represent some of the most significant engineering challenges. Compared with controlled laboratory environments, the marine setting imposes multiple simultaneous stressors—including high salinity, high humidity, temperature gradients, seawater erosion, biofouling, and long-term low-frequency cyclic loading—which collectively accelerate the aging of flexible structures, electrode interfaces, and encapsulation systems. Biofouling, in particular, poses a major hurdle for sustained operation, as the accumulation of organisms can increase hydrodynamic drag, impede mechanical movement, degrade surface properties, and insulate active electrical interfaces. While antifouling strategies such as fouling-release coatings, surface patterning, and functional hydrogel layers have been explored for marine devices, their compatibility with the soft, often charge-sensitive materials used in TENGs and PENGs remains largely unverified. The development of integrated antifouling solutions that preserve triboelectric/piezoelectric performance while resisting biological adhesion represents a critical research gap that must be addressed. For TENGs, the core triboelectric interfaces are prone to wear, surface charge decay, and material fatigue under prolonged vibration, leading to inevitable output degradation. PENGs, on the other hand, face failure risks such as degradation of the polarized layer, electrode delamination, and crack propagation induced by strain concentration. Therefore, future advancements require the development of highly stable interfacial materials with enhanced resistance to wear, corrosion, and hydrolysis, and biofouling, as well as the introduction of novel designs such as self-healing polymers, ionically stable interfaces, biofouling-resistant surface treatments, and fully encapsulated flexible electrodes to extend device lifetime under deep-sea operating conditions. Moreover, with the emergence of hybrid PENG–TENG architectures and arrayed systems, structural fatigue and coupled instability become even more pronounced. In complex flow fields, vortex-induced vibrations, flapping responses, or stochastic turbulent excitations may cause mode-shape drift, localized strain concentration, and disruptions to phase alignment and synchronization among array units, ultimately reducing the uniformity of energy output. Achieving long-term fatigue-resistant structural design, synchronized and stable array operation, mechanically robust encapsulation, effective biofouling mitigation, and compensation for electromechanical output drift will constitute key scientific and technological issues that must be addressed for successful engineering-scale deployment.

6. Conclusions

Nanogenerator-based ocean current energy harvesting has progressed rapidly in recent years, benefiting from advances in materials science, structural innovation, and interface engineering. Synergistic optimization across flexible piezoelectric or triboelectric polymers, nanostructured and biomimetic flow-induced vibration architectures, multidimensional interfacial modifications, and multistage power-management circuits has enabled a transition from proof-of-concept demonstrations to practical energy conversion efficiency in low-velocity marine environments. These developments provide a feasible technological pathway for long-term, low-power, and self-sustained underwater sensing nodes within distributed marine observation systems.

Despite these advancements, several key challenges hinder engineering-scale deployment in real marine environments. These include ensuring long-term structural reliability under immersion, scouring, and biofouling; achieving system-level integration with sensing, communication, and energy-storage modules; minimizing ecological impacts through environmentally benign materials; and establishing unified testing conditions and performance evaluation standards. Addressing these issues will require coordinated progress in new materials, new structures, new circuits, and new system architectures, ranging from corrosion-resistant and degradable piezoelectric/triboelectric materials to multimodal biomimetic energy-conversion structures, hybrid PENG-TENG-EMG mechanisms, and adaptive MPPT-enabled power-management strategies. Looking forward, the deep convergence of materials science, fluid mechanics, ocean engineering, and low-power electronics is expected to drive nanogenerator-based ocean current energy harvesting toward durable, scalable, and autonomous deployment. As these technologies mature, they hold strong potential to contribute to smart ocean observation, distributed marine sensing, and sustainable blue-energy applications.

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