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# Hybrid Nanogenerators for Ocean Energy Harvesting: Mechanisms, Designs, and Applications

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**The ocean holds vast potential as a renewable energy source, but harnessing its power has been challenging due to low-frequency and high-amplitude stimulation. However, hybrid nanogenerators (HNGs) offer a promising solution to convert ocean energy into usable power efficiently. With their high sensitivity and flexible design, HNGs are ideal for low-frequency environments and remote ocean regions. Combining triboelectric nanogenerators (TENGs) with piezoelectric nanogenerators (PENGs) and electromagnetic nanogenerators (EMGs) creates a unique hybrid system that maximizes energy harvesting. Ultimately, hybrid energy-harvesting systems offer a sustainable and reliable solution for growing energy needs. This study provides an in-depth review of the latest research on ocean energy harvesting by hybrid systems, focusing on self-powered applications. The article also discusses primary hybrid designs for devices, powering self-powered units such as wireless communication systems, climate monitoring systems, and buoys as applications. The potential of HNGs is enormous, and with rapid advancements in research and fabrication, these systems are poised to revolutionize ocean energy harvesting. It outlines the pros and cons of HNGs and highlights the major challenges that must be overcome. Finally, future outlooks for hybrid energy harvesters are also discussed.**

## 1. Introduction

Ocean energy is among the most efficient energy sources accessible, with the potential to add value to future renewable power requirements.[1–3] The mechanical energy present in the waves and tides of the ocean can be harnessed and utilized by advanced technologies.[4–6] Unquestionably, the employment and harvest of ocean energy are increasingly considered a vital solution to the critical energy shortage.[7–9] Capturing large-scale wave energy will eventually lead to modifying the world's energy structure to end the energy crisis.[10–12] Ocean energy sources are being explored to provide large-scale electricity, typically over a few watts, to meet the energy demands of commercial and residential areas that face power shortages.[13–15] In parallel, there is a growing interest in energy harvesting technologies that can generate small amounts of power from nanowatts to milliwatts to replace conventional batteries in portable and wearable electronics. Renewable energy-based self-powered systems have progressed remarkably over the last decade.[16–18] The current method of ocean energy harvesting is based on electromagnetic generators (EMGs) or triboelectric nanogenerators (TENGs).[19,20] The TENGs can be an alternative power unit as they can convert various energy vibrations from the ocean into electrical output.[21,22] TENGs often produce a high voltage

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output, but their current output is relatively low, restricting their applicability.

On the other hand, EMGs have a high energy harvesting efficiency at high frequencies but are weak at low frequencies. Besides, low frequencies account for most of the wave motion; therefore, the active research of methods capturing wave energy is becoming more crucial.[23–26] For instance, piezoelectric (PENG), electromagnetic, and triboelectric energy harvesters scavenge kinetic energy from the surroundings.[27–29] However, most sustainable energy sources such as ocean energy, might not always be reliable or accessible. Since the capacity to produce energy depends on the energy source accessibility, an individual type of nanogenerator cannot constantly satisfy the power requirements of electronic devices.[30]

Thus, HNGs can solve the energy-insufficiency issue of individual energy harvesters.[31] These energy systems are designed to meet the requirements of harvesting energy from diverse sources and converting it into electricity by utilizing multiple mechanisms.[32–34] Self-powered electronic devices require various energy sources for optimal performance, and hybrid devices are a promising solution for harvesting multiple types of energy simultaneously. While PENGs and TENGs have distinct differences in design and operation, researchers have found that combining these technologies can significantly improve energy conversion efficiency.[35,36] By utilizing the strengths of both PENGs and TENGs, researchers are working to develop hybrid energy harvesters that can generate more power from a wider range of environmental conditions.[37,38] By leveraging the strengths of various mechanical energy harvesters, TENG/EMG hybrid harvesters offer distinct advantages over other energy harvesting methods.[39–41] They excel in scavenging vibrational energy due to the high voltage output of TENGs and the high current output of EMGs.[37,42] Their flexibility allows for customization to meet specific application requirements.

Additionally, TENG/EMG hybrids can extend the operating range of NGs by combining TENG's high efficiency at lower frequencies with EMG's improved performance at higher frequencies and amplitudes. However, scaling downsize comes with technological challenges, such as EMG facing difficulties in dealing with high magnetic flux gradients and assembly issues. Similarly, TENG encounter surface potential decay due to imperfect dielectric insulation and stray electric fields at the edges, which can impede their performance. Overcoming these obstacles can unlock new possibilities for powering small-scale devices sustainably and efficiently. Various types of state-of-the-art ocean harvesters, applications, and their power generation capabilities are summarized in **Table 1**.

Over the past few years, numerous researchers have revealed efficient and cutting-edge methods for hybrid energy harvesters.[43–45] Since there are not as many publications as there are single-source harvesters, these studies have not been thoroughly examined and summarized. Our study provides a comprehensive overview and highlights the current advancements in self-powered hybrid energy harvesting devices for ocean energy in response to the increasing demand. The body of this review is structured as follows. First, Section 2 provides a brief introduction of various typical energy harvesting mechanisms, such as piezoelectric, electromagnetic, and triboelectric. The unique hybrids of TENGs with PENGs and EMGs are particularly discussed. Then, Section 3 discusses the hybrid energy harvesters focused on various device structures (Circular/spherical, cylindrical/ rectangular, pendulum/swing, advanced structures), covering the working mechanisms and output performance from recent research. Section 4 presents the performance comparisons and analyses of the pros and cons of different hybrid devices. On this foundation, Section 5 highlights the potential future improvements for hybrid systems to overcome the present issues. Lastly, the conclusions and perspectives regarding the future of the hybrid system are discussed in Section 6. To promote research from the laboratory to practical application, this review will address the reader's knowledge of a potential platform for ocean energy harvesting using self-powered hybrid systems. **Figure 1** summarizes the aspects of hybrid systems, cutting-edge layouts, and power management units for ocean energy harvesting and its diverse applications.

## 2. Working Principle of Various Nanogenerators

Hybrid energy harvesters offer a promising approach to effectively harvest energy by creating enormous currents by accumulating all available energy (tidal/wave) from the ocean. Effectively combining different energy conversion mechanisms can boost power output while improving the effectiveness of space use. Different types of nanogenerators and their working modes are illustrated in **Figure 2**.

**Table 1.** Comparison of state-of-the-art ocean harvesters, their applications, and power generation capabilities.

| Type of wave energy harvesters | Applications | Power | References |
|---|---|---|---|
| Oscillating water columns | Power generation | 450 kW | [118] |
| Overtopping devices | Grid-scale electricity, Desalination | 4 MW | [119] |
| Wave absorbing devices (point absorbers) | Environment monitoring, offshore power generation | 2.52 MW | [120] |
| Wave absorbing devices (Wave attenuators) | Aquaculture, Research in the ocean environment, power generation | 250 kW | [121] |
| TENG-EMG-PENG hybrid nanogenerators | Powering of sensors and smart IOT, Offshore communication, Marine navigation, Desalination | µW-mW | This work |

 

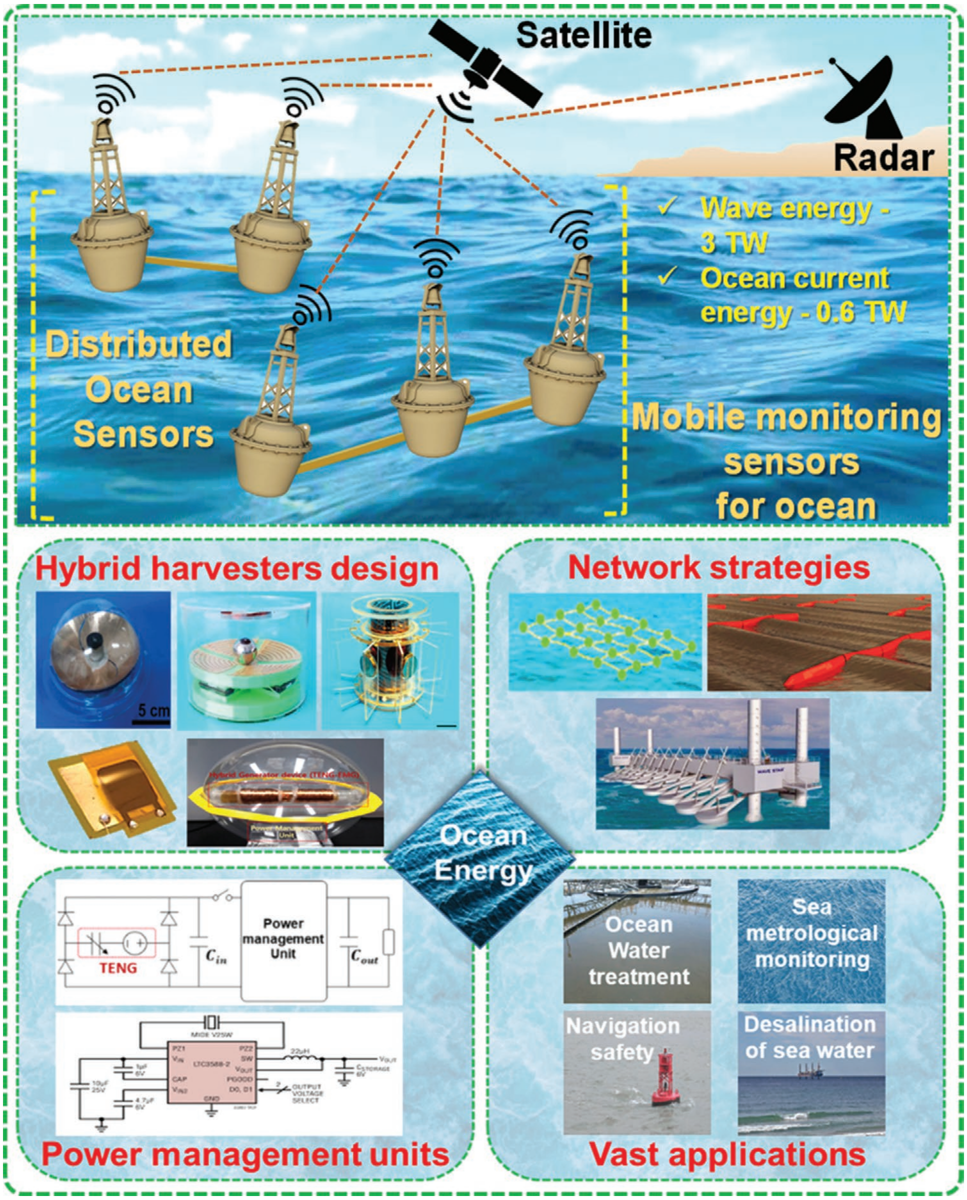


**Figure 1.** Perspectives of hybrid nanogenerators for ocean energy harvesting and its application.

### 2.1. Piezoelectric Nanogenerator (PENG)

A PENG utilizes the applied force on a piezoelectric material to generate electricity.[46,47] This technology could generate a significant amount of useful electrical energy from waste energy. The direct piezoelectric effect is the main mechanism upon which PENG operates. The surface of the piezoelectric material generates charge when the PENG is subjected to stress or deformation. The charges flow in the form of current through the load as the PENG is attached to an external load. Hence, the piezoelectric material is essential as it affects the voltage, current, charge, and power output.[48] The power generator is another term used for a piezoelectric harvester. Force, pressure, and acceleration are basic effects that can produce a direct piezoelectric effect in PENG.[49,50] Reducing carbon footprints and the energy crisis is the major recent concern and the call for sustainable, green energy for a healthy future.[51,52] There is an increase in health and environmental issues owing to rapid industrialization. The smart device demand has expanded quickly, and its adaptation is widespread.[53,54] Most of these devices use low or powerless operations in device applications such as medical and remote monitoring, where battery replacement can create inconvenience, inaccessibility, and high labor cost. PENG is an energy harvester that relies on piezoelectric materials.[55] It has many benefits ranging from a long lifetime to flexible structures and small-scale energy harvesting.

PENG has two working principles: direct and indirect piezoelectric phenomena, as shown in Figure 2(a1). The electrical output in the direct mode is produced by applying mechanical stress to a piezoelectric material, whereas in the indirect

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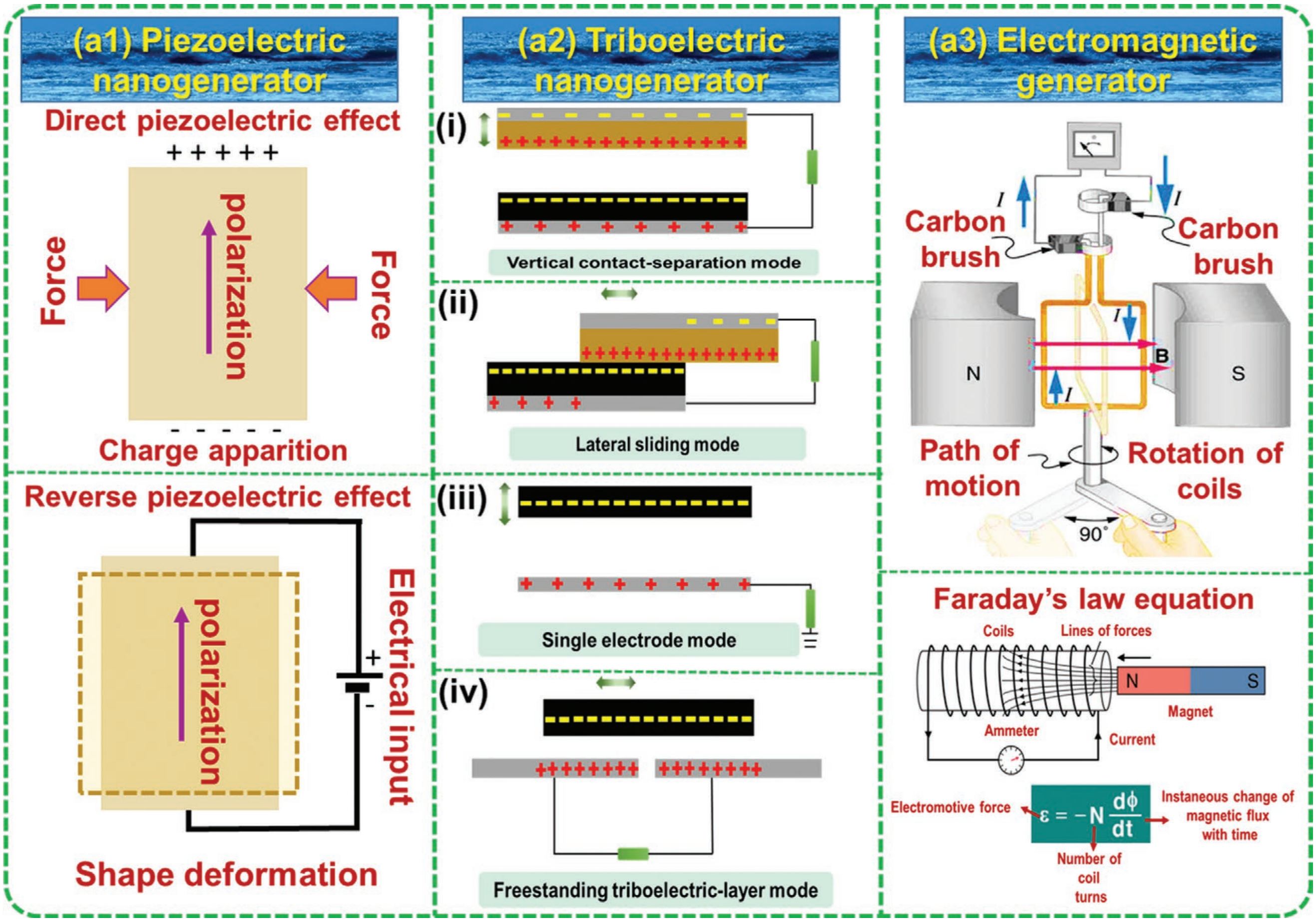


**Figure 2.** The working mechanism of different types of nanogenerators. a1) piezoelectric nanogenerator. a2) Triboelectric nanogenerator (i) vertical-contact separation mode, (ii) lateral sliding mode, (iii) single electrode mode, (iv) freestanding triboelectric-layer mode. a3) Electromagnetic generator.

mode, the mechanical deformation in the material is enabled by an electrical field.[56] The direct piezoelectric effect is given by the formula: $D = \varepsilon E$ ($D$ is the electrical displacement, $E$ is the strength of an electric field, and $\varepsilon$ is the permittivity of the material). Hooke's principle shows linear elastic material as $S = sT$ ($S$ is the strain, $s$ is compliance, and $T$ is the stress). In the direct piezoelectric effect, the electric displacement is directly proportional to $T$ and expressed by: $D = Q/A = d \times T$ (expressed in coulomb/Newton), where $d$ corresponds to the piezoelectric coefficient. The few $d$ components, such as $d_{33}$, $d_{31,}$ and $d_{15,}$ decide the device output. The charge generation under mechanical vibration is responsible for PENG devices' open circuit voltage and short circuit current.[57]

Regarding the flexible PENG device, there are three major procedures during the generation of electrical output: (i) initial state, (ii) under applied force, and (iii) under force-removed condition. In the initial state, the dipoles are randomly oriented, and as the force is applied, there is deformation in the piezoelectric composite films. The dipoles are polarized, and electric charges are generated on both sides of the electrodes, leading to current flow across the load. After the force is removed, the piezoelectric effect gradually diminishes, causing the dipoles to revert to their random state, reversing the current direction. This periodic motion results in the generation of alternating output of PENG.[58]

### 2.2. Triboelectric Nanogenerator (TENG)

The contact electrification and electrostatic induction process enable TENG to transform mechanical vibrations into electrical energy.[59,60] It offers benefits such as high-power output, wide selection of materials, and flexible working modes. When two materials consisting of different work functions touch or rub each other, one will lose electrons and the other will accept electrons due to varied electron affinity, creating a potential difference between the two layers.[61] The AC output is generated as the electrons flow between the electrodes.[62] TENG has four working modes: contact separation mode, freestanding mode, single electrode mode, and lateral sliding mode.

#### *2.2.1. Vertical Contact Separation Mode*

The vertical contact separation mode of TENG is a simple configuration, as illustrated in Figure 2(a2-i). The opposite charges are generated upon a triboelectric layer backed by an electrode concerning their polarity. The potential drops between the two layers as the external force is removed. Half of the electrical AC output is formed when both triboelectric layers tend to separate, leading to the flow of electrons between the electrodes through the load until the equilibrium position. The other half of AC output tends to generate as the two triboelectric layers approach each other leading to the flow of electrons in the reverse direction. Thus, the periodic contact and separation generate the AC output from TENG.[63,64]

#### 2.2.2. Lateral Sliding Mode

The lateral sliding mode produces electrical output by sliding one triboelectric layer over another, as shown in Figure 2(a2-ii). Both layers have different polarities per their position in the triboelectric series. At the initial stage, an equal number of charges are generated, which have opposite polarity when two triboelectric layers are in full contact. The charges are separated when the contact area between the two triboelectric layers reduces while they slide outward. This generates electrical output by electron flow from the bottom to the top electrode until the top layer completely slides out. As the top layer tends to move in the opposite direction, an opposite flow of electrons occurs. Thus, this process produces AC output from the TENG.[65]

#### 2.2.3. Single Electrode Mode

The single-electrode mode offers a large flexibility for operation since the opposite triboelectric layer can be moved freely without any connection, as illustrated in Figure 2(a2-iii). A single-electrode mode can be constructed using a ground electrode and a moving triboelectric layer. An electronic current flow between the electrode and ground due to the periodic separation of the contacts of the moving layer. Single electrode mode also supports the ability to operate in contact separation mode and lateral shift mode.[66]

#### 2.2.4. Free Standing Mode

The freestanding mode also includes a simple operation where the moving layer is not connected to any electrode or wire. It provides higher output performance than the single electrode mode TENG and operates in a non-contact mode. Also, two symmetric electrodes are separated by a small gap below the dielectric layer having less distance, as shown in Figure 2(a2-iv). The dimensions of both the dielectric and electrode are the same. By leveraging the triboelectrification process, the mobile layer acquires charges, and when it moves across the electrodes, an asymmetric charge distribution is created. This imbalance causes electrons to flow from one electrode to the other, establishing equilibrium and generating AC output.[67]

### 2.3. Electromagnetic Generator (EMG)

The core of EMG is electromagnetic induction, which is characterized by Faraday's law of induction as the development of an electromotive force in a conductive wire changes the magnetic flux, as shown in Figure 2(a3). EMGs often have a moving and stationary component that consists of coils and permanent magnets. Magnetic fields can be generated using current-fed coils or permanent magnets. Electromotive forces are generated in the coil by time-varying magnetic fields in addition to displacement or distortion of the coil relative to the magnetic fields.[68,69] EMGs have two designs, linear generators and rotating generators.[70] The relative motion between a magnet and conductor creates electromotive force based on Faradays law of electromagnetic induction.[71] The linear generators can create the relative motion of the magnet through the coil leading to the generation of potential difference induced between the coil ends. Lenz's law states that the magnetic fields produced by the generated electric currents prevent the magnetic flux from changing. This provides a force that prevents its relative motion since momentum conservation applies. To produce electrical energy in the form of currents and voltages in an external circuit, generators transfer kinetic energy from their moving parts. Important parameters that decide the performance of the EMG are the magnet composition material (magnetic field intensity) and coil parameters such as coil area, wire diameter, length, and turns.[72,73]

Today, most commercial large-scale power plants use EMGs as their electrical generator.[74–76] The different forms of EMG are categorized as follows: mechanically into rotational, linear, or multidimensional kinetic input and electrically into direct current or alternating current.[77,78] When the EMG operates, a slight movement of the permanent magnet with respect to the coils ($\delta x$) causes a change in the magnetic flux ($\Phi B$) flowing through the coils, leading to the creation of voltage and electromotive force ($\xi$), electromagnetic induction change ($\delta V$), and the free charge flow ($\delta I$) through the external circuit. Consequently, the voltage and current changes are reversed when the magnet moves in the opposite direction.

Performance comparisons of major energy harvesting devices such as TENG, PENG, and EMG are discussed in **Table 2**.

## 3. Different Types of Hybrid Device Structures

The vast potential of ocean energy to meet our energy requirements is limited by the difficulty in harnessing it. The low frequency and unpredictable nature of wave directions pose a significant challenge to conventional energy plants. Nonetheless, with innovative ideas, designs, and integration techniques,

**Table 2.** Comparison of major energy harvesting devices: TENG, PENG, and EMG.

| Energy Harvesters | TENG | PENG | EMG |
|---|---|---|---|
| Working Mechanism | Triboelectrification and electrostatic induction | Piezoelectric effect | Electromagnetic induction |
| Voltage | High | Medium | Low |
| Current | Low | Low | High |
| Power | low | low | High |
| Power characteristic | AC | AC | AC |
| Internal impedance | MΩ | kΩ | Ω |

substantial strides have been made in improving the efficiency of hybrid energy-harvesting systems. Despite the development of several hybrid NGs, the fundamental hurdle in ocean energy harvesting is to capture the micro mechano-vibrational energy across a broad operational bandwidth and from multiple directions.[79] Additionally, power generation is a crucial component of most self-powered systems based on hybrid NGs, and combining the multi-units into one paves the way toward creating a self-powered system.[80] This section discusses various types of device structure, device performances, and applications. **Table 3** summarizes the different types, shapes, and applications of hybrid modules in the ocean energy harvesting field, the working mechanism of various devices, and electrical outputs such as voltage, current, and power densities.

### 3.1. Circular/ Spherical Structures

Since spherical TENGs or circular-driven TENGs can be easily adapted to any direction of waves, they are regarded as a typical structure for harnessing ocean wave energy.[81,82] From point contact to surface contact, numerous modes, especially the contact-friction mode, have emerged to improve their output performance.[83] Recently, a hybrid TENG-EMG water wave energy harvester (WWEH) based on a magnetic field that could harvest the energy of ocean waves in any direction was introduced by Wu et al.[84] A TENG module, an electric generator module, a power management circuit, and a circular acrylic shell made up the device, as shown in **Figure 3**(a1-a2). A mover was positioned between two collision layers to build the TENG module. The mover was a copper-film-covered acrylic plate magnetically affixed to the shell. The magnetic sphere (NdFeB, N38) was positioned between two acrylic discs that had two coils inserted within them. Two acrylic discs had two friction layers bonded to them, and the area in between served as the mover's moving area. The mover contained a magnetic cylinder (NdFeB, N38) attracted by the magnetic sphere. The friction layer electrode was defined as a Tai Chi posture to ensure that the TENG module had good output performance without limiting the operator's movement. The magnetic field used to create the EMG module excited the wave, forming a flexible magnetic field on the coils and causing the converter to slide through collision layers while being pulled by gravity. Figure 3(a3) depicts the magnetic system's mechanics analysis diagram. Even in bright light, the white LED was lightened up by the hand pressure applied to the device as shown in Figure 3(a4). Based on this, the WWEH was mounted on a buoy and tested in Lake Lanier to show how well it could capture water wave energy. Figure 3(a5) displays a schematic of a self-powered wireless water temperature alert system.

For ocean energy harvesting and oil spill prevention, Kim et al. and colleagues designed a spherical energy harvesting device made of a tubular-shaped TENG-EMG enclosed hybrid generator.[85] This device's negative triboelectric layer comprised a Kapton film interdigitated (IDT) electrode structure. The magnet traveling across the Kapton film might produce the triboelectric output. On both sides of the tube-shaped unit, copper coils were used as EMG units with the same mechanical motion that activated the device and generated the output. The electromagnetic and triboelectric components were triggered when the magnetic moment shifted within the coil and across the Kapton. A schematic of a buoy-like device with a bridge rectifier circuit, a rechargeable battery or capacitor, and housings for power management and energy harvesting components is shown in Figure 3(a6). The engineered buoy-based energy harvester is also depicted in the digital photograph. The HNG used a triboelectric component to generate an electrical output of 20 V, 100 nA, and 85 mW at 1 m/s$^2$. It was built like a tube. A single EMG system delivered a specified 3 V and 11 mA output power of 4 mW. The hybrid structure produced an output of 7 V and 20 mA, higher than the other components. Afterward, the device was used as a power source with a bridge rectifier circuit, PMU, and various LEDs to power electronic components. When the conductivity of the water under normal conditions was compared to that under oil spill conditions, this equipment was also employed for oil spill detection. Figure 3(a7) shows the schematic layout of the oil leak detection and operation procedure of the TS-HG device. An emulsion method was used to carry out this procedure, in which oil and water were completely immiscible. The TS-HG device was used to conduct an oil spill experiment in a laboratory environment, as shown in Figure 3(a8). Oil leak detection testing using different water samples is shown in Figure 3(a9). Therefore, this device served as a prototype showing how quickly and cost-effectively the hybrid energy harvester can be used in marine rescue systems and climate monitoring.

Recently, Chandrasekhar et al. developed a TENG-EMG hybrid generator-equipped spheroidal buoy to capture ocean wave energy effectively.[86] The device was powered by a wave energy harvester and contained a position-tracking long-range device. Under low-wave circumstances, a solar panel mounted on the buoy acted as a backup power source for the position-tracking equipment. A cylindrical tube connecting the two units facilitated mobility in both the forward and reverse directions and was used to activate the TENG units at both ends. The EMG component used the same motion by winding a coil on the tube's surface and permitting the magnet to rotate inside. The TENG-EMG hybrid configuration allowed the two elements to individually provide electrical output while performing the same mechanical motion, as shown in **Figure 4**(a1). Electrical outputs as high as 100 V/2 µA and 20 V/15 mA were produced. The devices functioned together to effectively transform the kinetic energy of the waves into usable electrical energy, which was then utilized to charge a lithium-ion battery and a commercial capacitor. The powered position tracking device showed that the manufactured device was a low-cost and trustworthy candidate for maritime navigation and energy harvesting systems. Figure 4(a2) shows how the floats were tied around the buoy to support it in the water. The buoy was towed a few kilometers offshore to test its ability to track its position while being tracked by a mobile app. Onshore and offshore position tracking analyses were performed, and data were recorded. These studies, analyses, and immediate tests have shown that the SB-HG has the potential for self-powered location tracking, all-weather environmental monitoring, and IoT-based signaling.

A seamless navigation tracking solution is possible through a comprehensive integration of GPS and compass. Considering

 

**Table 3.** Different types of hybrid modules, designs, applications, working mechanisms, and outputs.

| Hybrid Module | Device shape | Application | Mechanism | Materials | $V_{max}$ | $I_{max}$ | Frequency | Peak power/ Power density | Ref |
|---|---|---|---|---|---|---|---|---|---|
| TENG-EMG | Duck-shaped | Efficient offshore energy converter/ terminator type harvester | Rolling freestanding TENG + Electromagnetic induction | Nylon balls, Kapton layers, copper electrodes, Neodymium N42 magnet series | 390 + 0.18 V | 7.2 µA + 0.12 A | 2.5 Hz | 213 W m$^{-3}$ + 144 W m$^{-3}$ | [122] |
| TENG-PENG-EMG | Bifilar pendulum shaped | Ocean wave energy harvester and self-powered marine sensing device | Piezoelectricity, contact-separate mode TENG, electromagnetic induction | Lanthanum zirconate titanate (PZT), trapezoidal magnets, FEP, Kapton, copper electrodes, foams, sliver electrode | 600 + 12 + 1.2 V | 0.27 mA + 2 mA + 3.5 mA | NA | 358.5 W m$^{-3}$ | [103] |
| TENG-EMG | Cylindrical slider type | Ocean wave energy harvester and hydrodynamic sensor | Grating-structured freestanding TENG + Electromagnetic induction | Fluorinated ethylene propylene (FEP), copper electrode, nylon, iron, magnets | 1500 + 30 V | 59 µA | 3 Hz | 271.1 W m$^{-3}$ | [123] |
| TENG-PENG | Arc-shaped | Coastal wave impact energy harvesting system | Dielectric-metal contact separation mode AND water-dielectric contact mode TENG, piezoelectric effects | PVDF, copper electrodes, carbon conductive ink, aluminum, polyimide | 631 V | 314.13 µA | 0.7 –3 Hz | 15.92 mW + 0.99 mW cm$^{-2}$ | [116] |
| TENG-EMG | Honeycomb | Multi-angle range wave energy harvester | In-plane sliding mode and vertical contact-separation mode, electromagnetic induction | Aluminum, PTFE, magnet, spring, acrylic | 550 + 3 V | 1.25 µA + 4.65 mA | 4 Hz | NA | [109] |
| TENG-EMG-PENG | Cantilever beam structure | Wave energy harvester | Contact-separation, sliding mode TENG, electrostatic induction, piezoelectricity | PTFE, nylon (PA66), PZT, coils, magnets | 1078 + 2.62 + 7.4 V | 8.2 µA + 0.2 mA + 74 µA | 0.2 - 7.2 Hz | 5.73 W m$^{-3}$ | [124] |
| TENG-EMG | Ship-shaped | Wave energy harvester with self-desalination and self-powered marine rescue systems. | Freestanding rolling and contact-separation modes, electromagnetic induction | Silicone, Kapton, copper, coil, PLA, NdFeB magnet, flexible magnet | 105 + 4.3 V | 1.5 µA + 15 mA | 2 Hz | 9 mW | [112] |
| TENG-EMG | Sphere with inner rows (Tai Chi shaped) | Wave energy harvester | In-plane sliding mode TENG, electromagnetic induction | Acrylic disc, NdFeB, N38 magnets, PTFE, copper electrodes | 120 + 0.75 V | 1.5 µA + 2 mA | NA | NA | [84] |
| TENG-EMG | Cylinder with an axis (rotational pendulum) | Ultra-low frequency energy harvester, arbitrary human motion sensor | Contact-separation mode TENG, electromagnetic induction | Fluorinated ethylene propylene (FEP), copper ring, magnets, pendulum, coils | 180 + 13 V | 7 µA + 50 mA | 2 Hz | 3.25 W m$^{-2}$ + 79.9 W m$^{-2}$ | [125] |
| TENG -EMG | Chaotic pendulum | Low-frequency wave energy harvester | Freestanding TENG, electromagnetic induction | Copper coil, acrylic, PTFE, inner pendulum, magnetic ball, gold electrode | 197.03 + 1.08 V | 3 µA + 4 mA | 2.5 Hz | 15.21 µW and 1.23 mW | [95] |
| TENG-EMG | Tube shaped | Ultra-low frequency ocean wave energy harvester | Solid-liquid interface in conjunction with the coupled TENG and EMG | FEP tube, DI water, copper foil electrodes, coils, magnet | 200 V | 1.832 µA | 0.2- 1.4 Hz | 0.25 mW cm$^{-3}$ | [126] |
| TENG-EMG | Flexible pendulum structure | Irregular and ultralow frequency blue energy harvesting | Contact-separate mode TENG, electromagnetic induction | FEP, hollow cylindrical shell, adjusting stud, NdFeB magnet, coil, locking screw | 53.89 + 3.16 V | 2.12 µA + 11.57 mA | 2.2 Hz | 470 µW + 523 mW | [127] |
| TENG-EMG | Double-sided fluff and double Halbach array structured | Ultra-low frequency wave energy harvester and self-powered hydrological monitoring system | Contact-separation mode TENG, electromagnetic induction | Steel shaft, PTFE, acrylic shell, copper coils, PC fluff | 382.3 + 6.4 V | 1.8 µA + 14.7 mA | 1.4 Hz | 2.02 W m$^{-3}$ + 16.96 W m$^{-3}$ | [128] |

 

**Table 3.** Continued.

| Hybrid Module | Device shape | Application | Mechanism | Materials | V max | I max | Frequency | Peak power/ Power density | Ref |
|---|---|---|---|---|---|---|---|---|---|
| TENG-EMG | Pendulum shaped | Ocean wave energy harvester and hydrophone-based wireless sensor | Contact-separate mode TENG, electromagnetic induction | Photopolymer resin, copper coils, fiberglass layer, silicone film layer, rolling nylon balls, rolling spherical magnet | 72 + 14.3 V | 1.7 µA + 1 mA | 2 – 2.6 Hz | 8.01 µW + 6.7 mW | [96] |
| TENG-EMG | Buoy shaped | Ocean energy harvester | Freestanding TENG, electromagnetic induction | Hollow cylinders, Al electrodes, NdFeB ring magnet, thermoplastic polyurethane, ABS-A100 | 50 V + 9 mV | 200 nA + 30 µA | 1 – 8 Hz | 20.5 mW $m^{-3}$ + 0.57 mW $m^{-3}$ | [129] |

the TENG-EMG hybridized ocean energy harvesting system, Gao et al. designed a self-regulating and self-monitoring system based on energy harvesting.[87] The technology could successfully collect energy from low-frequency waves and peculiar vibrations owing to the gyro's distinctive circular form. Triboelectric and electromagnetic energy were consecutively produced during the rotating movements of the gyro-structured nanogenerator, as shown in Figure 4(a3). The cylindrical structure was constructed using 3D printing technology with an inner diameter of 110 mm and a height of 40 mm. The digital

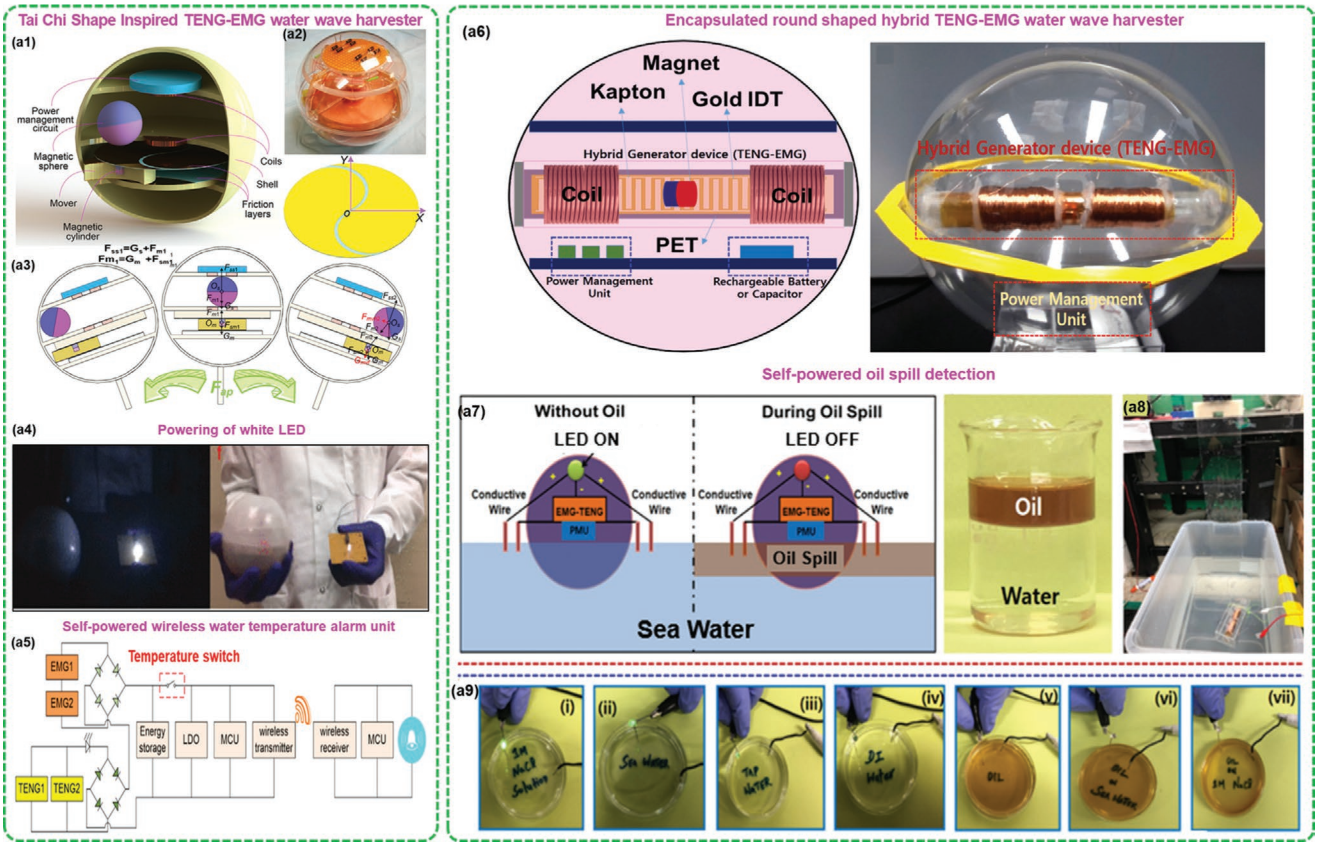


**Figure 3.** a1) Schematic diagram of the water wave energy harvester (WWEH). a2) Photograph of WWEH, schematic diagram of the friction electrodes with Tai Chi shape. a3) Mechanics analysis diagram of the WWEH. a4) LED was lightened up by the hand pressure applied to the device. a5) Schematic diagram of a self-powered wireless water temperature alarm system. Reproduced with permission.[84] Copyright 2019, the Americal Chemical Society. a6) Arrangement of the encapsulated triboelectric-electromagnetic hybrid generator (TS-HG) device into the buoy device for scavenging water wave energy and utilized for performing the real-time applications, digital photographic image of the TS-HG device. a7) Schematic diagram of oil spill detection with oil and without oil, emulsion behavior of pouring oil into the water. a8) Real-time testing of the TS-HG device under laboratory scale with the water wave generator setup. a9) Testing of oil spill detection with different water samples. Reproduced with permission.[85] Copyright 2020, American Chemical Society.

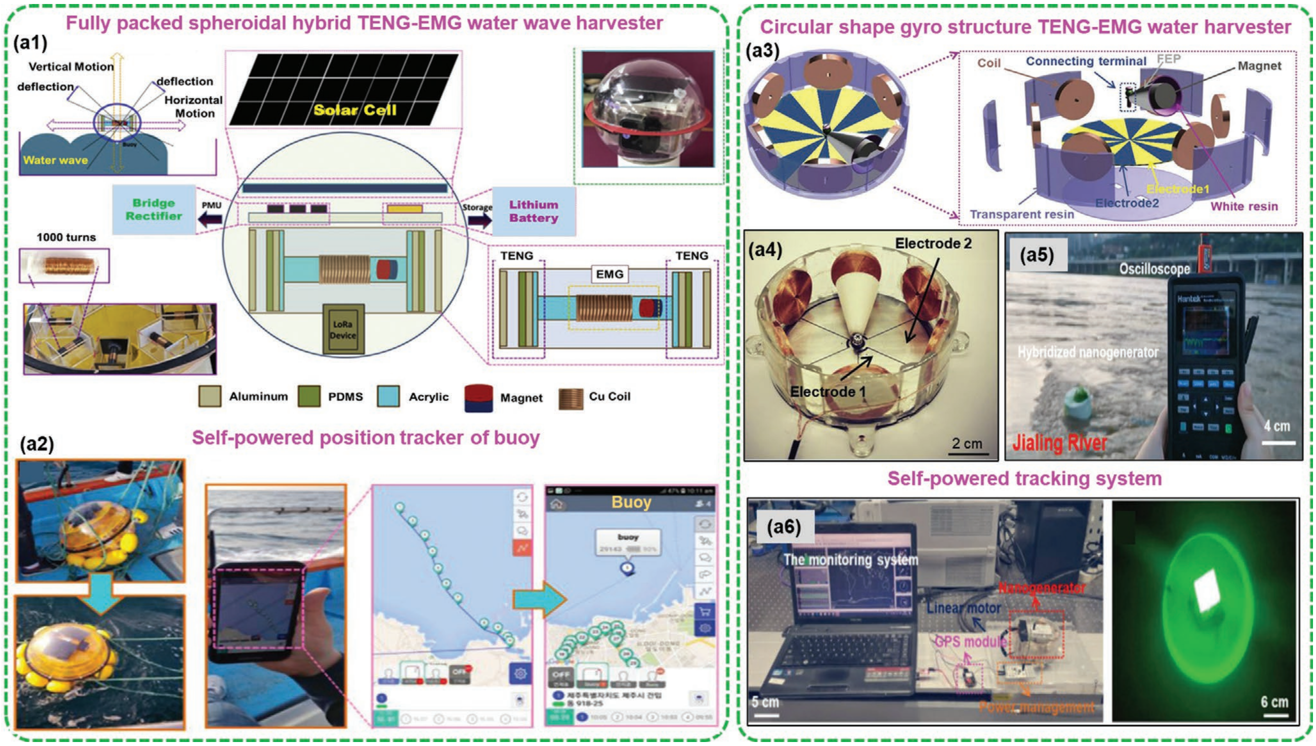


**Figure 4.** a1) Structure of the SB-HG housed with various energy harvesters and electronic components, various motions of the spheroidal buoy on water wave, digital photographic image of smart buoy hybrid generator, multiunit assembly of hybrid components in the middle portion of the spheroidal buoy, a layer-by-layer schematic of TENG and EMG components used in the SB-HG device. a2) Digital photograph of buoy placement in the sea, position tracking using mobile phone tracker application. Reproduced with permission.[86] Copyright 2020, Elsevier. a3) Structure of the hybridized nanogenerator. a4) Digital photograph of the hybridized nanogenerator. a5) The floating buoy hybridized nanogenerator for water wave energy harvesting in the river. a6) Photograph of the self-powered GPS. Repoduced with permission.[87] Copyright 2020, Elsvier.

photograph of the hybrid NG is shown in Figure 4(a4). The arrangement of eight pairs of triboelectric electrodes enabled the recording of an input signal and the monitoring of gyro movement. The outstanding TENG rolling mode technology, which might be TENG's second-generation technology, had demonstrated sturdiness. The autonomous underwater vehicle and the buoy showed how well the device could harness ocean power after attaching the hybrid device for testing, as shown in Figure 4(a5). The self-powered and automated tracking system was then properly connected to an EMG-enabled GPS, as shown in Figure 4(a6). This research aimed not only to solve the energy problem of the tracking system but also to harness the energy of the oceans on a massive scale.

### 3.2. Cylindrical/ Rectangular Structures

To capture extremely low-frequency waves, Feng et al. developed a swing-like cylindrical structure-based hybrid device consisting of light contact TENG and EMG.[88] Flexible brushes of flexible rabbit hair were used to separate the hybrid TENG's stator-rotor pair. UV-cured resin or polylactic acid plastic was used to print the outer shell of the device, as shown in **Figure 5**(a1). Two sets of 12 connected Cu electrodes were used as terminals for the energy outputs of the device. The rotor was a stack of blades that had already been evenly classified as solid and hollow blades. In addition, thin FEP films were adhered to the outer surface of the rotor for electrostatic induction. The stacking blade was supported by a support member suspended from a stainless-steel shaft to allow it to swing. While the FEP films and Cu electrodes in the intended SCC-TENG were separated functionally and structurally, the tribo-pairs of most reported TENGs should be well connected during the operation to ensure surface charges. When rabbit hairs were encased in fluorinated ethylene propylene (FEP) sheets, high-density charges (>20.3 C $m^{-2}$) were generated on the dielectric surfaces. Each water wave triggered in a properly constructed TENG might generate over 60 current pulses in less than 15 s. While the average power density was 0.16 W $m^{-3}$ below a wavelength of 0.1 Hz, the maximum power density at the same resistance was 2.71 W $m^{-3}$. Once EMG was added, the result was even better. Figure 5(a2) shows an image of a six-unit array inside an acrylic box and a short grouping procedure. In Figure 5(a3), parallel SCC-TENGs show an increasing peak ISC value with a roughly linear relationship to the increasing number of units. Figure 5(a4) shows that the thermometer array and the HNG array were combined to form a self-powered hydrological data mapping system. Figure 5(a5) shows a wireless transmitter (EV1527) that can communicate with a receiver and activate an alarm. The applications of the proposed HNG using water wave energy harvesting were successfully demonstrated in Figure 5(a6) by self-powered temperature mapping and wireless transmission.

Wang et al. constructed a fully packed HNG that combined the ineffectual output of an EMG in the same frequency band

 

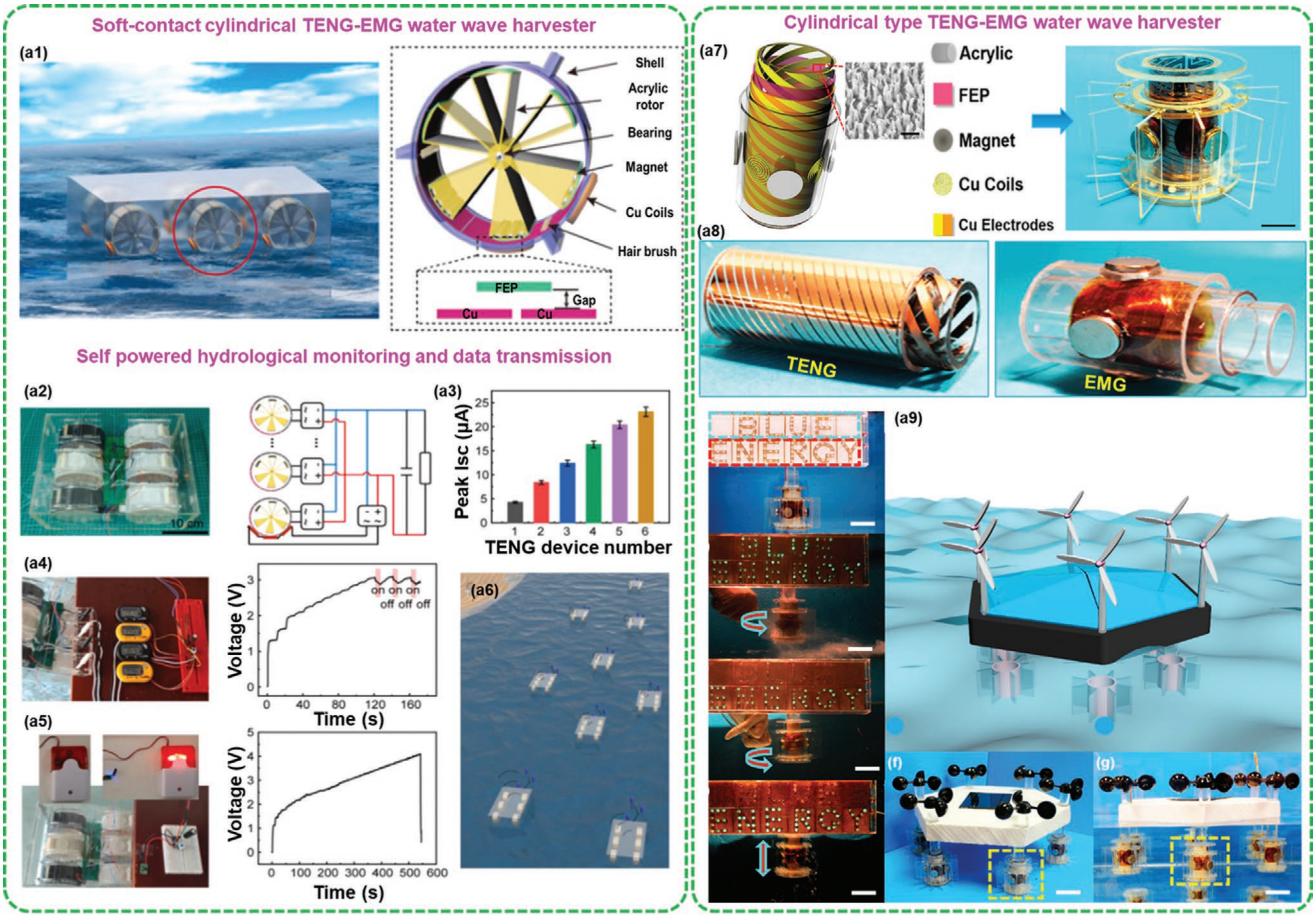


**Figure 5.** a1) Schematic illustrations of the hybrid nanogenerators and their application in ocean wave energy harvesting, the zoom-in illustration shows a gap between the FEP films and Cu electrodes. a2) Photograph of the array device with 6 units, schematic circuit diagram of the arrayed nanogenerators, five of them are SCC-TENGs, and the other is a hybrid unit. a3) Extracted peak ISC of the SCC-TENG array as a function of the parallel unit number. a4) Powering a thermometer array by charging a 330 μF capacitor. a5) Powering a wireless transmitter by charging a 1000 μF capacitor. a6) A blueprint exhibiting the self-powered applications of proposed hybrid nanogenerators in hydrological monitoring and data transmission by large-scale blue energy harvesting. Reproduced with permission.[88] Copyright 2021, Elsvier. a7,a8) Schematic illustration of the functional components of the hybrid nanogenerator, which consists of a spiral-interdigitated-electrode triboelectric nanogenerator (S-TENG) and a wrap-around electromagnetic generator (W-EMG). The light blue rectangle frame displays 40 green LEDs in parallel composed of " BLUE " words connected to the W-EMG. The red rectangle frame inside displays 58 green LEDs in a series composed of " ENERGY " words connected to the S-TENG. A hybrid nanogenerator was used for lighting up the "BLUE" and "ENERGY" LEDs at simulated ocean conditions under rotation mode above the water, rotation mode under the water, and fluctuation mode under the water. a9) Schematic illustration of a proposed comprehensive energy harvesting panel floating on the ocean, which mainly consists of wind-driven generators, solar cell panels, and arrays of hybrid nanogenerators, an oblique-angle-view and lateral-view photograph of the configuration of the hybrid nanogenerator model in ocean-simulated conditions, yellow rectangle frame inset is a single unit of the hybrid nanogenerator. Reproduced with permission.[90] Copyright 2016, American Chemical Society.

with the remarkable output performance of TENG in the low-frequency region (1.8 Hz).[89] This HNG could increase the operating frequency while optimizing energy conversion efficiency. A TENG-EMG device was integrated into the HNG proposed by Wen et al. to harvest energy from ocean waves.[90] As schematically shown, the HNG's basic construction comprised two primary components, an S-TENG and a W-EMG, constructed from three cylindrical tubes positioned coaxially. As seen in Figure 5(a7), a freestanding mode S-TENG was constructed by the inner and middle tubes, which could move to one another. Copper electrodes were used to deposit a foam cut into stripes at different tilts and adhered to the exterior surface of the inner tube. Due to its elasticity and quick-recovery super-resilient capability, this foam, which served as a sturdy supporting substrate for S-TENG, considerably improves the robustness and stability and, more crucially, produces a higher-density triboelectric charge. The source of power generation for this work depended on the rotation mode, which relies heavily on a different HNG structure and absorbs ocean energy, currents, and waves. The EMG was a hybrid component in this study because TENG was completely isolated from the outside using packaging and was indirectly driven by an impenetrable magnetic field between magnetic pairs, as shown in Figure 5(a8). A major implication of this study was that TENG could take low power (rotation speed of 100 rpm or motion frequency of 2 Hz), which is close to the sea level, and the EMG could provide additional outputs for high frequency. Integrated HNG output was upgraded to collect a wide range of frequencies in seawater.

 

The authors also suggested that this novel hybrid nanogenerator floating on the ocean could capture wind, sun, and waves at the same time and a single HNG unit could be used to power several LEDs as shown in Figure 5(a9).

Marine buoys are the primary instrument for collecting ocean hydrology data.[91,92] Recently, Yu et al. developed a unique direct-driven TENG-EMG hybridized wave energy converter (DTEWEC) that could be integrated into the buoy since ocean buoys often lack an effective and dependable power source.[93] The layout plan of the hybrid device with TENG and EMG units is illustrated in **Figure 6**(a1). The surface drifting buoy BUOY-41 served as an operational object for the research team. The hybrid device has connecting grooves on the inlet and outlet of the stator base plate, integrating the structural and functional properties of TENG and EMG. The interdigital electrodes of the TENG unit were fixed in the shallow inner groove, while the coils of the EMG unit were fixed in the deeper outer groove. The outside surface of the mover, which was made by stacking magnets and an iron core, was covered with nylon film, which acted as the material's friction unit. The two pairs of interdigital electrodes were covered with a cylindrical Teflon sheet placed near stator, which was twice the mover. The two electricity-generating units operated concurrently because of the relative movement produced by the mover and stator under the impact of waves. The highest output power density of the TENG unit ended up being 0.768 mW $cm^{-2}$. The peak output power of each stage of the three-phase coil group of the EMG unit was discovered to be 59.4 mW, 47.2 mW, and 50.2 mW, respectively, under the finest wave climate with a wave amplitude of 0.12 m and a wave period of 1.6 s. Figure 6(a2) shows the motion responses of BUOY-41 under the above four-wave heights. As can be seen, the power density of the TENG increases with wave height. As the wave height increases, the power value of the EMG unit also increases. It is shown how the motion of BUOY-41 responds to waves with a height of 0.1 m and periods of 1, 6, 8, and 2.2 s. This study demonstrated how the hybrid device might be employed as an ocean buoy's sustainable power supply unit to accomplish the self-powered power supply, which can significantly prolong the buoy's durability and reliability.

Using a single EMG unit, a self-powered vibration amplitude sensor, and four zigzag multi-layered TENG units, Yang et al. built a TENG-EMG hybridized nanogenerator (TEHG).[94] The magnetic field for the EMG, the positive frictional material for the vibrating magnitude sensor, and the trigger for the stacked TENGs were all simultaneously provided by the magnetic ball in this work. Since the magnet ball could reach a wider active area at a low angle and roll in all directions, the three elements were mostly joined by a curved 3D-printed surface in the core. As the device vibrated arbitrarily under an external force, a relative rotation occurred between the magnetic sphere and the circularly curved surface, triggering the three sections' periodic triggering. Photographs of TEHGs and multilayer TENGs with one to three layers are shown in Figure 6(a3). The testing results showed that the TENG's output peak power was 3.65 mW when the vibration amplitude was 0.4 rad and the working frequency was 1 Hz, demonstrating the advantages of capturing low-frequency micro-vibration energy. The constructed self-powered water-splitting system to convert salt water to $H_2$ is

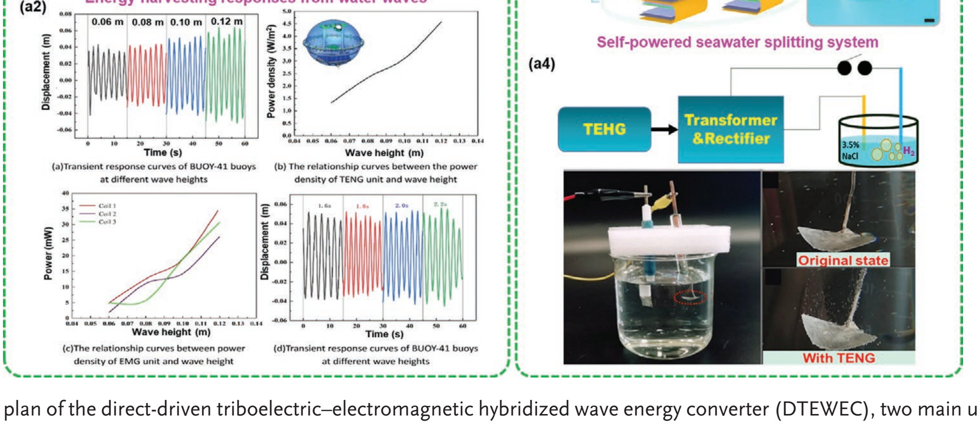


**Figure 6.** a1) Layout plan of the direct-driven triboelectric–electromagnetic hybridized wave energy converter (DTEWEC), two main units of WEC (EMG, TENG). a2) The motion responses of BUOY-41 under the four-wave heights transient response curves of BUOY-41, the relationship curves between power density of EMG unit and wave height and transient response curves of BUOY-41 buoys at different wave heights. Reproduced with permission.[93] Copyright 2022, Springer Nature. a3) Schematic diagram of a hybrid device (TEHG) mainly consists of three parts: a single EMG unit, a self-powered vibration amplitude sensor, and four zigzag multi-layered units of the device, a photograph of the fabricated device. a4) Self-powered seawater splitting system (3.5 wt.% NaCl solution is used in place of seawater), photographs of the TEHG-driven water splitting system, enlarged view of the Pt plate. Reproduced with permission.[94] Copyright 2020, American Chemical Society.

 

shown in Figure 6(a4). After adjustment and fixing, the smaller energy of the water waves can be used to power the water distribution system. In TEHG, the Pt electrode produces a significant amount of hydrogen bubbles after two seconds, and the diagram can be used to determine the dynamic splitting process. Furthermore, the HNG was a promising device for ocean harvesting in calm and stormy waves, particularly in the calm waves, which are more frequent in real-time. It has also been successfully used to power self-powered systems, environmental sensors, and portable electronic devices.

### 3.3. Pendulum/ Swing Structures

Chen et al. powered up wireless sensors by harvesting the low-frequency wave energy employing a chaotic pendulum TENG-EMG hybridized nanogenerator.[95] Hao et al. developed a pendulum-shaped hybrid device to power hydrophones.[96] To reliably harvest water wave energy, Zheng et al. built a TENG unit and an EMG unit-based HNG relying on a swinging magnet design with a permanent magnet as a mass block.[97] The TENG module comprised a bottom friction layer made of polytetrafluoroethylene (PTFE) and Tai Chi-shaped copper electrode, and a swing friction layer made of permanent magnet and polyester fiber (PET). Based on the constructed structure, the swing friction surface would not only move over the bottom frictional layer but would also deliver a changeable magnetic field to the coil that was experiencing wave action. The coil positioned beneath the bottom friction layer was exploited during the permanent magnet's movement to scavenge magnetic energy, as shown in **Figure 7**(a1). However, the output voltage and current of the TENG and EMG could reach up to 90 V and 0.61 μA, 5.3 V, and 6.4 mA, respectively, with the wave at a low frequency of 1.75 Hz in a simulated environment by increasing the size of the swing thread, establishing the electrode of the TENG as Tai Chi shape, and specifying the connection between TENG and EMG in parallel. As shown in Figure 7(a2), the durability test and different states of H-WWEH in ocean waves were performed in a water tank. A self-powered wireless wave height security system for the smart fishery was designed based on amazing results. Incline switches, a wireless transmitter module, and a wireless transceiver module made up the wave height alarm system. The wireless transmission was triggered by the inclination switch. The charging characteristics, including the performances of the device, are shown in Figure 7(a3).

Currently, several cutting-edge technologies (accelerometer buoys, submarines, imaging equipment, integrated smart systems, and positional buoys) are being used to ensure rapid forecasts and quick alerts regarding unusual wave activities in the ocean depths region.[98,99] However, these systems require constant external power to function without interference, which

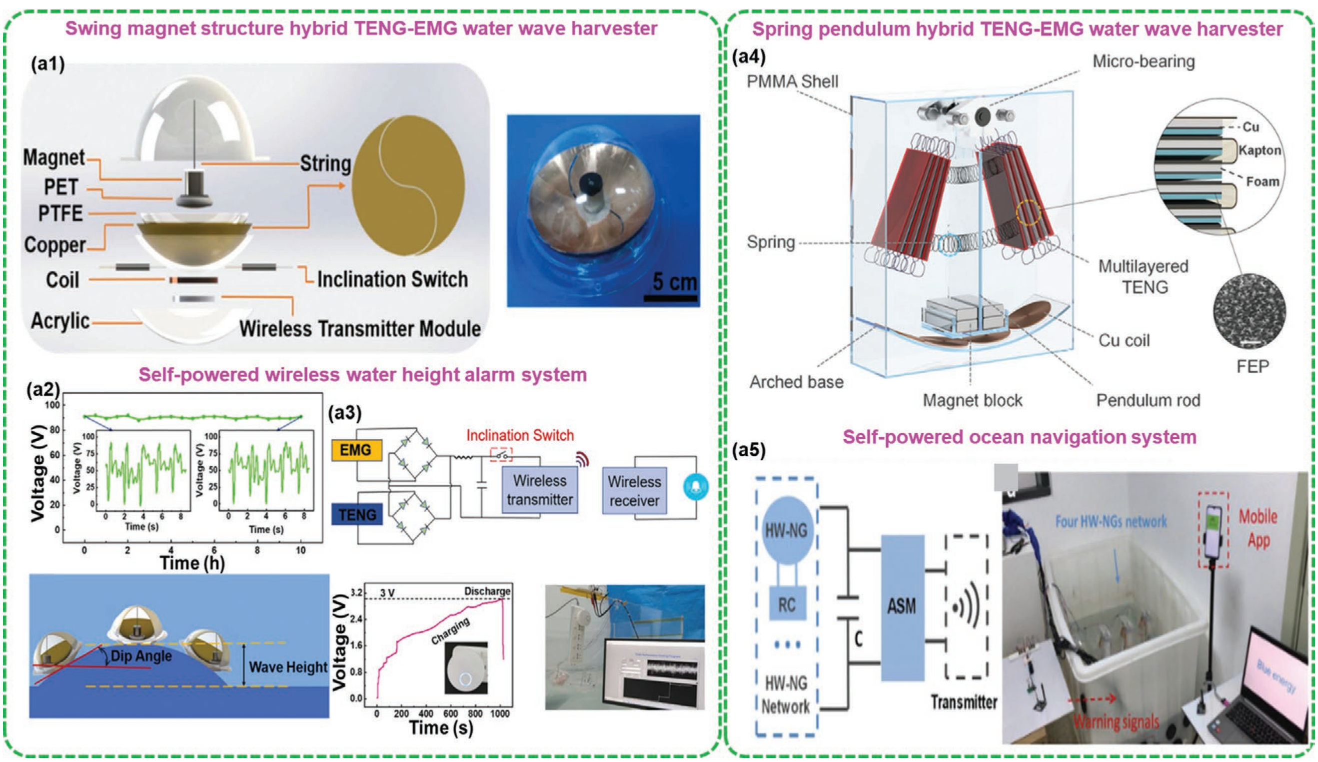


**Figure 7.** a1) Schematic diagram and a digital photograph of the hybridized water wave energy harvester (H-WWEH). a2) Durability of the H-WWEH for 10 h, schematic illustration of different states of H-WWEH on a wave. a3) Schematic diagram of a self-powered wireless water height alarm system, charging characteristics of the wave height alarm system, photograph of the wave height alarm system testing in the water tank. Reproduced with permission.[97] Copyright 2021, Elsevier. a4) Structure and materials design of the HW-NG device, photographs of the multi-layered TENG, the Cu coil used by EMGs, and the HW-NG device, respectively. a5) Circuit schematic of the self-powered RAW system and demonstration of the warning system for ocean navigation. Reproduced with permission.[101] Copyright 2021, Wiley-VCH.

is challenging to manage in remote areas.[100] Therefore, Ren et al. developed an HNG that harvested energy in response to waves and was employed as a source of long wireless transmission power (1.5 km) based on the pendulum structure.[101] The HW-NG device consists of two stacked TENGs and one EMG unit with four Cu coils. There were six TENG pairs in contact separation mode for each multilayer TENG. The attached Cu films serve as both the output electrode of the negative tribo-layer and the positive tribo-layer of the TENG. FEP (dielectric material) was chosen as the negative tribo layer material, as shown in Figure 7(a4). The maritime navigation system (RAW) could be updated appropriately. The combination of TENG and EMG in HW-NG could achieve their corresponding power and enable the hybrid device to obtain satisfactory output across a wide range of operating frequencies. As the frequency approaches 2.0 Hz, maximum output values of 580 V and 28 μA were measured. Using a 433 MHz ultrahigh-frequency (Sub-1G) radio, long-distance cords (1.5 km) could be established in a transmission time of less than one second, depending on the power output in the water waves with a bigger HW-NG network. The output signal is activated automatically with a built-in control circuit and a demonstration of warning system was operated as shown in Figure 7(a5). The navigation and warning systems can be designed using HW-NG network for remote islands or ridges.

A potent real-time hybrid sensor system for wireless marine environment monitoring was developed by Bhatta et al. It simultaneously senses and transmits wireless information without requiring an external power source and produces energy from motion waves.[102] A hybridized ellipsoidal device with six circular coils was intended to cover the fixed direction of the energy-producing waves and was inspired by the elliptical trajectory of devices over shallow sea waves. As integrated self-regulating wave sensors, four pairs of magnetic force actuated TENGs on four sides. The overall device design, a layered view of the component, and a magnified view of the magnetic force-driven pendulum-shaped self-powered triboelectric sensors are shown in **Figure 8**(a1). Electrospun Nylon 6/6 and MXene/PVDF composite nanofiber mats serve as the positive and negative components of each TENG. A PDMS/FeSiCr thin film is utilized as ferromagnetic material for the pair of TENGs induced by the magnetic attraction, which is induced by the freely moving magnet inside the ellipsoid. The surface micrographs of Nylon 6/6 and PVDF/MXene nanofibers are presented in Figure 8(a1). The fully packaged device in a bucket is shown in Figure 8(a2), along with a wave continuously produced by a wave-generating pump connected inside the water bucket.

Additionally, a combination of electricity produced to achieve an autonomous maritime environment monitoring system powered all the circuitry needed for single-channel processing and wireless transmission. The generator could produce 106 mW and 44.8 mW (3 Hz) and primary and minor axis movement directions. Independent sensors have exceptional motion sensitivity, and thus the signals from these sensors collect insightful data about water waves, which is a crucial factor for real-time marine environment monitoring. Photographs of the constructed HSP-AWMSS device labeled with multiple sensor attributes, the software demonstration circuit configuration, and the corresponding custom-developed mobile application for wireless display of wave parameters via Bluetooth communication are shown in Figure 8(a3).

Zhang et al. developed a wave energy collection device by integrating an HNG of an EMG containing a bifilar pendulum, two PENGs, and two TENGs onto a vessel platform.[103] Combining the PENG and heavy EMG with the lightweight TENG increased the device's capacity for power takeoff, enhanced its space efficiency, and made it easier to create floating wave energy collectors. A steady environment inside the shell platform, where the sensor was integrated, could make maintenance and long-term stable activities easier, as shown in Figure 8(a4). Two PENGs were attached to the wedge-shaped pendulum cone of the bifilar copper pendulum after it was wound with coils. A wedge-shaped coil in the middle and a pair of trapezoidal magnets on either side constituted the EMG. PENG consists of two ceramic plates of lead zirconate titanate (PZT) on both sides, a copper electrode in the middle, and two silver electrodes on the outside. A zigzag Kapton substrate, copper electrodes, fine foams, and fluorinated ethylene-propylene films (FEP) were used to construct the TENG. As a result, this design could lead to a simpler wave energy harvester. The HNG concurrently captured gravitational potential and low-frequency ocean wave energy by using the vessel's roller coaster and the bifilar pendulum's swing motion. The developed device attained a higher peak power density of 358.5 $Wm^{-3}$ based on the reasonable utilization space.[103] As shown in Figure 8(a5), a ship with an integrated hybrid module called BCHNG was placed in a water tank, producing water waves that could replicate the motion of ocean waves. As shown in Figure 5(a6), the ship's integrated BCHNG module could control a hygrothermograph in real-time while the vessel operates in wave conditions. Figure 8(a7) shows the corresponding circuit diagram. The energy storage consisted of two 100 μF capacitors connected in series. Figure 8(a8) shows the corresponding peak performance of the ship's integrated BCHNG module in water wave simulation. In addition, two 100 μF capacitors connected in series are used to study the charging curves of three different types of generators and the BCHNG module while driven by a simulated water wave depicted in Figure 8(a9). The development of this technique not only represents a significant advancement in marine renewable energy but also has the potential to facilitate the creation of marine sensing and seawater resource mining systems in the future.

### 3.4. Advanced Structures

Despite significant progress, several problems must be resolved whenever water-wave energy can be harvested.[104] Further research into advanced structural designs and features is required to harvest multidirectional, wide-frequency, and seawater variables successfully. To address these issues, HNGs have been assembled in the tandem disk, spheroidal, and oblate spheroid patterns, which can shield the energy harvester from abrasive environmental factors like humidity and mechanical disruptions.[105–107] Zhao et al. designed a wave energy converter using a heaving point absorber.[108] The design included a transmission mechanism, a heaving buoy, and a TENG-EMG hybrid

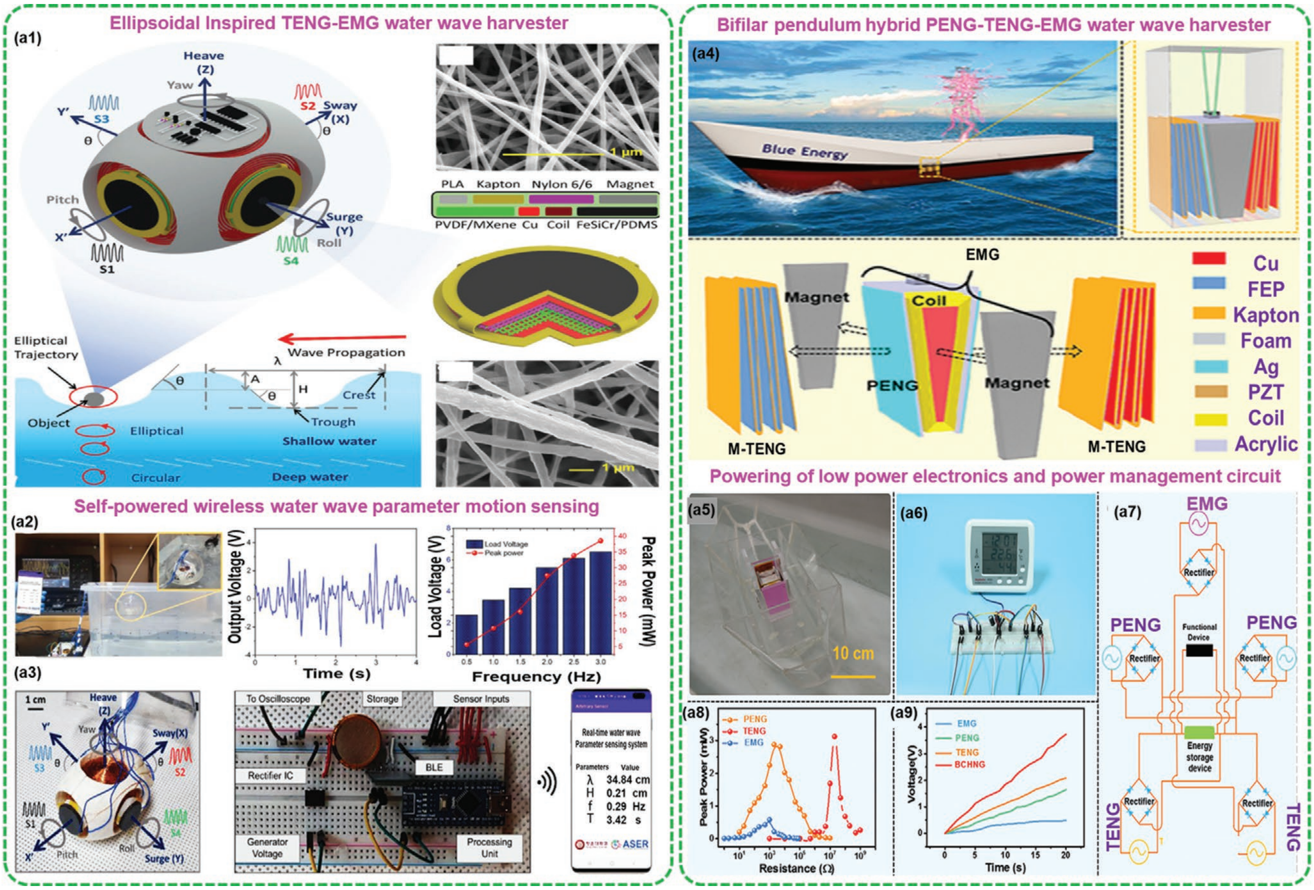


**Figure 8.** a1) Schematic diagram of the arbitrary wave motion sensing system, wave nature, and the zoom view of a single TENG-based self-powered wave motion sensor, the FESEM image of the Nylon 6/6 composite nanofibrous mat, the FESEM image of the PVDF/MXene composite nanofibrous mat. a2) Photograph of the test setup for the water wave application demonstration, the output voltage waveform of the EMG in real water waves, and the VL and Ppeak characterization of the generator in water waves. a3) The labeled photograph of the fabricated HSP-AWMSS before packaging, the photograph of the circuit arrangement, and the developed mobile application displaying the wave parameters wirelessly using Bluetooth communication. Reproduced with permission.[102] Copyright 2021, Wiley-VCH. a4) Device configuration of the vessel with incorporated bifilar-pendulum coupled hybrid nanogenerator (BCHNG) modules, schematic representation of enlarged structure for the BCHNG module, structural components for BCHNG with three kinds of generators. a5) The photo of the boat with incorporated BCHNG modules in the water tank. a6) Demonstration of the boat incorporated with the BCHNG module as a power source to drive a hygrothermograph. a7) The corresponding circuit diagram of the BCHNG module to driving functional device. a8) The corresponding peak-power–resistance profiles of the BCHNG module with three kinds of generators. a9) The charge curve of three kinds of generators and BCHNG modules. Reproduced with permission.[103] Copyright 2022, Wiley-VCH.

generator with encapsulated magnetic coupling. However, the proposed device by Feng et al. could capture kinetic and potential energy from ocean waves. The researchers designed a hybridized ocean wave nanogenerator that combines an EMG and a TENG based on three electrodes resembling a honeycomb.[109]

Since water can readily cause the TENG electrode to short circuit and humidity can diminish the triboelectric effect, especially under harsh conditions, the performance of TENGs with direct liquid-solid contact may be hampered.[110,111] Wang et al. constructed a fully packaged ship-shaped HNG which comprised a TENG and an EMG. The HNG was fabricated using a 3D printing approach, guaranteeing constant output performance and preventing moisture interference.[112] This innovative system features 6 TENGs (contact-separation mode) installed on different ends of the ship and a rolling TENG (free-standing mode) fixed to the ship's bottom. The rolling mode TENG is propelled by a roller having magnets attached in both endings, generating energy as it moves. This innovative design lowers frictional resistance, reduces frictional energy loss, and boosts conversion effectiveness, as shown in **Figure 9**(a1). The contact-separation TENG and EMG could produce a peak power of 800 W at 20 MΩ and ≈9 mW at 1000 Ω, respectively, at 2 Hz. The hybrid generator yielded a better voltage level and a faster charging rate for capacitors than the conventional TENG or EMG. Regarding constructing a self-powered wireless positioning system, it was also demonstrated that the device could power a digital temperature-humidity meter and operate a radio frequency emitter, as shown in Figure 9(a2-a3). A schematic diagram of the seawater desalination unit architecture is shown in Figure 9(a4). A seawater electrodialysis device is shown in the image with an effective capacity of 8 mL in each chamber, and it also shows how the 3D printing method makes the device light and easy to float on water. A related circuit diagram for

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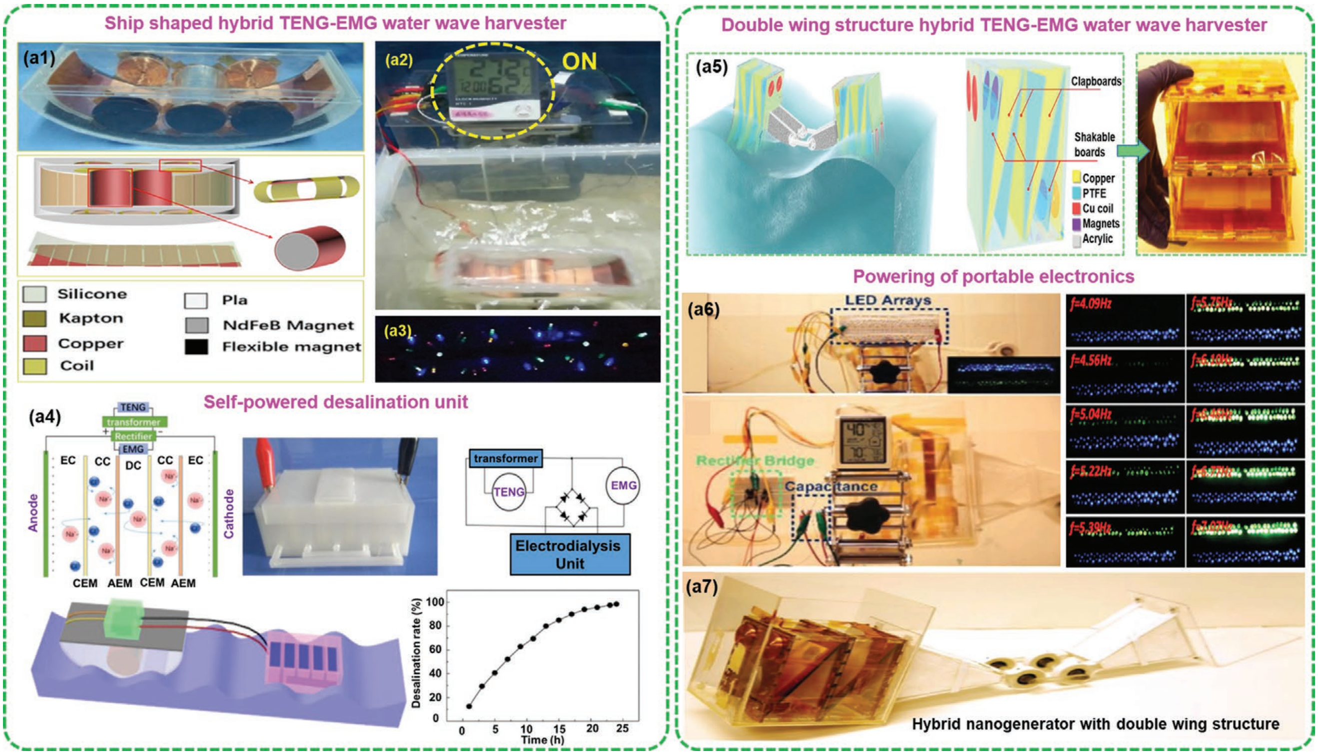


**Figure 9.** a1) Photograph of the ship-shaped hybrid nanogenerator (SHNG), schematic diagram of the designed SHNG, including three parts, contact-separation mode nanogenerator (CS-TENG), freestanding rolling mode nanogenerator (FR-TENG) and electromagnetic nanogenerator (EMG), schematic illustration of the stator of FR-TENG on the bottom, CS-TENG on both sides of the ship, the rolling roller, respectively. a2,a3) The application of SHNG for powering humidity and temperature sensor and 55 color LEDs. a4) The configuration and the photo of the seawater desalination unit (EC: electrode chamber, CC: concentrated chamber, DC: desalination chamber, CEM: cation exchange membrane, AEM: anion exchange membrane), the working circuit diagram of self-desalination system, the photo of a self-desalination system, desalination rate as a function of time with the initial salt concentration of 0.5 M. Reproduced with permission.[112] Copyright 2018, Elsevier. a5) Schematic illustration of the hybrid system with a double-wing structure riding on the water wave, basically constituted by a cubic structured unit hybridizing TENG and EMG, digital photographs of hybrid nanogenerator. a6) Photograph of a hybrid nanogenerator system with a double-wing structure, a hybrid system connected with LED arrays directly, and a thermometer through a rectifier, the average output powers for both TENG and EMG under varied platform working frequencies with LED loads. a7) Illustrates an experimental demonstration using a water wave simulation platform constructed from a homemade water tank and linear motor. Reproduced with permission.[113] Copyright 2019, Wiley-VCH.

seawater desalination in which the output voltage was changed and rectified before being connected via carbon rod electrodes to a seawater electrodialysis machine. The hybrid device successfully desalinated saltwater in three hours with a desalination rate of 29.4%.

Wang et al. designed a hybrid double wing-like structural system with TENG and EMG based on the best cubic structured units for capturing ocean wave energy.[113] The TENG was developed as a cubic structure, and water wave energy was captured by using the contact-freestanding mode. Two cantilever beams attached to the bearing support in the pivot hinge coupled each unit after it was held on a frame by a bracket. To work parallel to the direction of the wave and efficiently ride the wave, the pivot hinge of the nanogenerator was floated on the sea with polyfoam, as shown in Figure 9(a5). The hybrid device produced excellent output over various operational frequencies by merging the TENG and EMG. The device with various inner topological configurations was compared experimentally to improve the TENG output. The effects of oscillation frequency, amplitude, and dielectric materials were also investigated using a separate server. The optimal operating frequency ranges for TENG and EMG were also determined to comprehend this hybrid system fully. Finally, two examples of using an HNG to power thermometers and LED arrays were shown. In the first demo, the EMG and TENG components were connected in parallel to 50 green LEDs. The LEDs lit during the observation showed that both parts had a stable electrical output during the water wave, as shown in Figure 9(a6). The output power of the EMG was larger than that of the TENG when the frequency increased to the EMG-dominant region, and the green LEDs were brighter than the blue ones, as seen in the figure. Besides, Figure 9(a7) illustrates an experimental demonstration using a water wave simulation platform constructed from a homemade water tank and linear motor. The suggested HNG offers a practical method for extensive ocean energy harvesting beyond a wide frequency range.

Wu et al. have created an innovative HNG device resembling a teeterboard, which can capture energy from low-frequency ocean waves widely distributed worldwide.[114] The device features a multi-layered TENG at one end and an EMG at the other. Its lightweight fully loaded TENG unit can be easily moved by the ocean waves, generating an appropriate output without

 

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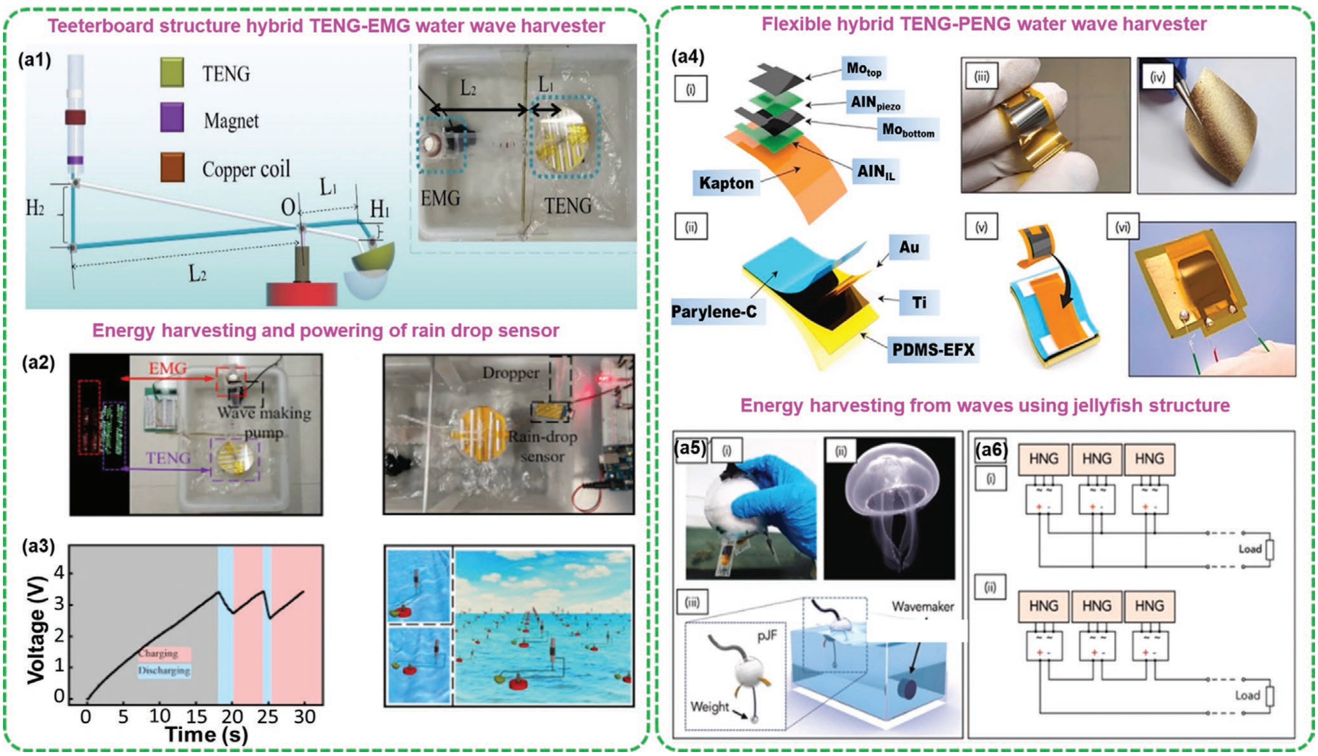


**Figure 10.** a1) A schematic diagram of the motion status of the THNG in the real ocean environment, inset illustrates an as-fabricated device working in a homemade water tank. a2) Photographs of THNG acting as the power source for lighting LEDs and THNG powering a raindrop sensor. a3) Charging voltage profile of a 22 µF capacitor for several consequent working cycles of a raindrop sensor and the proposed network composed of thousands of the THNG for large-scale blue energy harvesting. Reproduced with permission.[114] Copyright 2019, Elsevier. a4) Illustrations of the potential applications of the proposed HNG, (i) 3D expanded views of the PENG (ii) TENG components, with real photos (iii, iv); (v) assembly and (vi) real photo of the full HNG attached on a substrate. a5) (i) Real photo of the piezo-jellyfish (pJF), (ii) resembling the structure of a real jellyfish, (iii) installation of a hanging weight under the pJF during application in the aquarium for wave energy harvesting. a6) Circuits used to connect the HNG devices in the same pJF and to the resistive loads: parallel (i) series (ii) connections. Reproduced with permission.[117] Copyright 2021, Elsevier.

causing harm to the environment. By adjusting the fulcrum point between the TENG and EMG units, the movement intensity of the EMG unit can be easily modified. The fulcrum facilitates the functioning of the teeterboard design of the system. As a result, further research was conducted on the electrical performance of the hybrid device, thus fabricated with different rotation positions. **Figure 10**(a1) shows a schematic diagram demonstrating how the device might move in real ocean waves. The EMG could shift with a suitable amplitude to provide an appropriate electrical output even in a feeble wave condition, which solved the EMG's low-frequency challenge. The hybrid device could also automatically change its orientation to match the direction of the incident wave for the creative construction of the device, allowing it to catch wave energy from every direction. At the optimal working state, the maximum TENG voltage and EMG current were 760 V and 10 mA, respectively. The system could light up more than 200 LEDs. Another practical use of the device was to power a raindrop sensor when the wave frequency was 0.8 Hz by first charging a commercial capacitor (22 µF), as shown in Figure 10(a2). The capacitor could be well charged to 3.5 V in just 18 s, as shown in Fig. 10(a3). When the raindrop sensor is activated, the voltage drops by ≈1 V. By operating within the standard THNG voltage range, the sensor can be powered continuously, making it ideal for hybrid devices that harvest energy from ocean waves. The improved devices could also be incorporated into networks to efficiently capture ocean wave energy on a large scale.

The combination of PENG and TENG is beneficial and performs better for ocean energy harvesting.[16,115] To enhance the ocean wave impact energy harvesting self-powered device, Jurado et al. constructed an HNG by combining TENG and PENG and incorporated the device into a tank used to generate broken waves was made possible through the combination of finite element modeling and experimental electrical characterization.[116] Hence, it was possible to simulate real ocean circumstances at a lower frequency (0.7–3 Hz). Likewise, Mariello et al. constructed a uniquely flexible and multipurpose device for harvesting energy from ocean waves.[117] The biocompatible thin-film piezo-ceramic and soft polymeric materials were combined in an innovative order to establish the HNG, which had a width of under 100 µm. A dual metalized AIN thin film deposited on polyimide served as the substrate for the PENG component. The TENG component comprised a friction film composed of parylene C with a UV/ozone surface-treated layer enclosed by a metalized porous patch made of PDMS and platinum-catalyzed silicone as shown in Figure 10(a4). The obtained power densities under tapping for PENG, TENG, and hybrid were 6.5 mW m$^{-2}$, 65 mW m$^{-2}$, and 230 mW m$^{-2}$, respectively. The hybrid device showed non-algebraically increased performances. Piezo-JellyFish (pJF), a unique buoyant structure, was proposed to take advantage of the device for wave energy harvesting. Figure 10(a5) illustrates the placement of a hanging weight under the pJF during an aquarium application for energy harvesting and a current photograph of the pJF, which accurately depicts the real jellyfish shape. The system generated standing waves of 3 cm amplitude and 3.2 mW $m^{-2}$. Figure 10(a6) shows the parallel and series connections used to connect HNG devices with resistive loads in the same pJF. From the perspective of HNGs, this prototype was an attractive alternative due to its effective uses, ease of manufacturing, shape-adaptability, and broad versatility.

## 4. Pros and Cons of Different Hybrids

By integrating two or more functional mechanisms, hybrid energy harvesters offer a viable strategy for efficiently using ocean energy. They may independently or cooperatively gather energy from one or more sources under various circumstances, increasing energy conversion efficiency and expanding its possible applications. Hybrid systems include several benefits and drawbacks, which are described below.

### 4.1. TENG – EMG Hybrid

The TENG and EMG hybrid can produce high output voltage, current, and power, but a significant impendence mismatch exists. Although the device can work across a wide frequency range, it is quite bulky and heavy due to its complex design. This kind of device also has a highly robust and loosely integrated magnet core causing the device to be weather independent, which means it can function in adverse environmental circumstances or any form of climatic change. The energy conversion efficiency of the TENG-EMG hybrid is excellent as compared to others.

### 4.2. TENG – PENG Hybrid

This hybrid system has low output current and power but a high output voltage and a similar internal impedance to the TENG-EMG hybrid. The impedance of such a device is correspondingly high. However, it has several key benefits; it is extremely lightweight, adaptable, and resilient. The manufacturing procedure is straightforward, but large-scale applications are still an issue since the system is so sensitive to environmental factors. It has a strong integration structure and a wide frequency spectrum for operation.

## 5. Future Improvements of Hybrid Systems

The hybrid system is an excellent choice to harvest ocean energy in exposure to harsh weather such as high temperatures, storms, and the salinity of ocean water. Also, hybrid devices can be incorporated into already established marine systems, such as desalination plants and wave energy converters, thus minimizing the environmental impact of these systems while increasing their efficiency and reliability. However, several issues still need to be resolved to understand the ocean water harvesting capability of hybrid systems fully.

- The development of multipurpose self-charging devices through the implementation of TENG-based hybrid systems is crucial for advancing the field of energy harvesting. To fully realize the potential of these systems, there is a need to enhance their efficiency and performance further. Such improvements can be achieved through continued research and development focused on innovative methods and technologies for maximizing surface charge density, such as the creation of micro-nano structures and the chemical modification of friction surfaces.
- Furthermore, extremely effective power management circuits aim to optimize output power harvesting in TENG-based HNGs. TENGs also have high voltage and pulsed output characteristics, which makes them unsuitable for direct battery charging due to the energy storage device's stable DC input demands. As a result, developing a more effective power-management circuit is crucial to improve hybrid systems' energy transformation and storage performance.
- The device stability and durability, dependability, manufacturing, and production costs are essential factors in developing hybrid systems. The life duration of the hybrid device may be shortened by the polymers employed in different TENGs since they may be photosensitive, heat- and moisture-sensitive, and degradable under specific circumstances. For the triboelectric layers, research into high-performance yet durable materials is important. Better encapsulation materials and technologies to safeguard hybrid systems should be carefully established to be compatible and meet interconnection requirements during installation.
- The structural design must be improved to enhance the unique interaction and shrinking of an all-in-one device. Multimodal wave energy harvesting systems can meet the growing demand of energy needs and can be able to produce grid-scale electricity. The introduction of scalable coating or weaving processes for small, flexible, self-powered electronic systems may arise from all of this. The efficient harvesting of ocean energy may result from further research based on the vital issues in advanced materials, structural engineering, fabrication methods, and system integration.

Although some limitations still exist, there is potential for hybrid devices in ocean water harvesting, and further research and development in this area will likely lead to major technological advances. Overview of ocean energy harvesting, types of energy available in the ocean, components of HNGs, pros and cons of hybrid devices, prospects, and theoretical research applications in the field of HNGs are illustrated in **Figure 11**.

## 6. Conclusions and Perspectives

Hybrid energy harvesting systems hold great potential for efficiently capturing all the dissolved energy from the ocean. Owing to its high-power output, low cost, and scalability, several research studies have explored the use of hybrid systems

 

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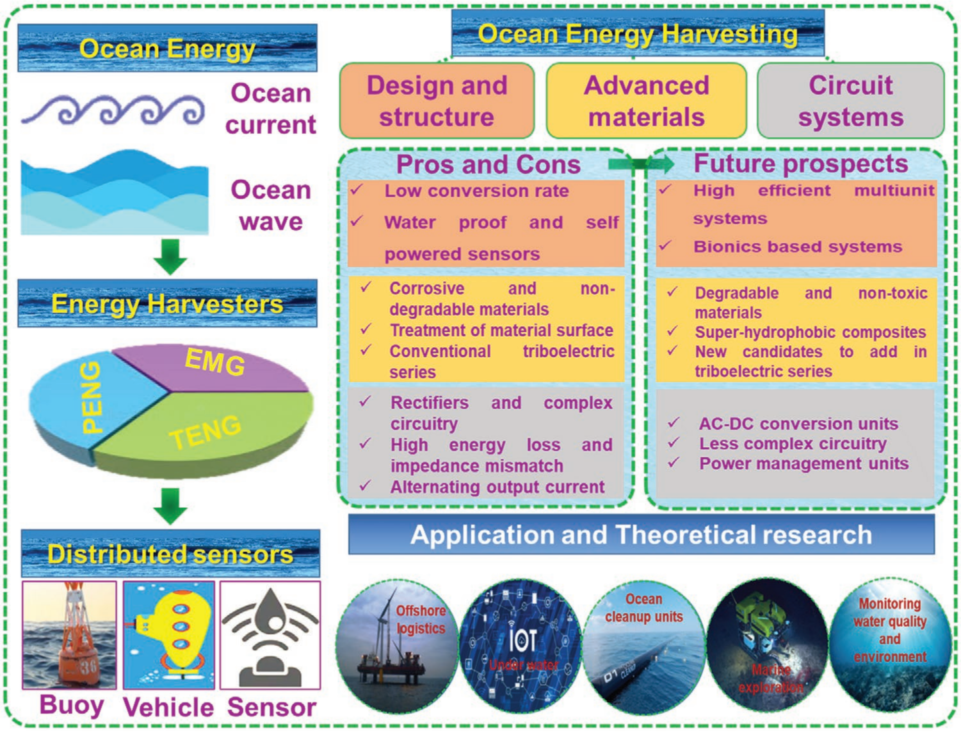


**Figure 11.** Overview of ocean energy harvesting, types of energy available in the ocean, components of hybrid nanogenerators, pros and cons of hybrid devices, prospects, and theoretical research applications in the field of hybrid nanogenerators.

for ocean energy harvesting. This comprehensive review systematically summarizes the latest advancements in enhancing HNGs, emphasizing novel and self-powered devices, designs, and applications. Future improvements for hybrid devices are also briefly outlined, highlighting the ongoing efforts to maximize energy production. In the context of the aforementioned hybrid energy harvesting systems, many inventive and characteristic examples of HNGs have been developed. The researchers have developed and applied different materials, designs, and procedures according to the characteristics of different energy sources and application scenarios. Hybrid harvesters have improved their energy production by integrating two or more energy conversion processes. Efforts are laid to make the most efficient use of the available space and different energy conversion strategies for developing hybrid energy harvesters.

We consider that the future of HNGs will substantially shift as advancements in device designs and integrations for real-world applications will overcome significant barriers. The systematic analysis of these challenges through theoretical and experimental approaches and multidisciplinary research from material science, physics, and electronics will strengthen sustainable HNGs for efficient ocean energy scavenging. Finding standardized measuring parameters is essential to improve energy conversion efficiency, as many influencing elements and operating situations exist. Researchers must realize that developing complicated devices with greater device area to demonstrate hybrid effects is insufficient for improved performance. The research into hybrid energy harvesting technologies will undoubtedly remain at the forefront, and hybrid energy systems will rapidly expand into a wide range of applications over the next ten years. With these advancements, we can create a more sustainable future for our planet while meeting the world's growing energy needs.

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## Conflict of Interest

The authors declare no conflict of interest.

## Keywords

electromagnetic, hybrid systems, ocean wave energy, piezoelectric, triboelectric

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