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Review

Portable Ocean Wave Energy Harvesters: Recent Advances, Challenges, and Future Perspectives

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Abstract

Portable Ocean Wave Energy Harvesters (POWEH) offer a potential approach for supplying autonomous low-power marine sensing systems; however, their long-term reliability, durability, and economic viability remain insufficiently demonstrated. But conventional wave energy converters are often big, expensive, and fixed to seabed structures, which makes it hard to use them in different places and makes it hard to sell them. People have been paying more attention to portable ocean wave energy harvesters in recent years. These are small, light systems that can be set up anywhere and do not need to be moored or anchored. These devices are meant to power autonomous ocean sensors, emergency buoys, and maritime applications that do not need to be connected to the grid. This review looks closely at the development trends, structural designs, and power take-off mechanisms of portable wave energy systems. We compare different types of harvesters, such as mechanical, electromagnetic, piezoelectric, and hybrid ones, based on their design principles, conversion efficiency, and scalability. Focus is directed towards the importance of symmetry in structural design, dynamic response, and energy conversion. The structure, whether symmetric or asymmetric, has a crucial role in determining mass distribution, stiffness traits, vibrational dynamics, hydrodynamic loading, and the capture of multi-directional wave energy, thereby influencing the overall performance, resilience, and stability of portable harvesters. The review goes on to talk about the main problems with dynamic stability, frequency tuning, environmental adaptability, and energy management when things are portable. Finally, new strategies like nonlinear dynamic designs, self-tuning mooring systems, and hybrid energy integration are suggested as ways to improve performance and reliability. The insights from this review are meant to help future innovations that will make it possible to use portable ocean wave energy technologies in a practical and long-lasting way.

Keywords: ocean wave energy harvesting; portable systems; piezoelectric; electromagnetic; triboelectric; power take-off

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1. Introduction

The growing need for energy around the world and the negative effects of fossil fuels on the environment have pushed the switch to renewable energy systems [1–3]. Wave energy is a promising ocean-based renewable because it is very predictable and has a lot of power density [4–7]. Smart ocean technology has changed the way we explore, keep an

eye on, and protect marine environments. There are many different autonomous systems in today's oceans, and each one needs a steady power source. Renewable marine energy harvesting has become necessary for long-term ocean operations as demand has grown. Wave energy has a global power density of 1–10 TW, which is a large part of the world's total energy use right now [8]. It is important to note that some areas, like the Gulf of Mexico, have average wave power densities between 20 kW/m and 65 kW/m, and these numbers can go up during bad weather [9].

The high costs of building and installing WECs are a big problem [10], so people have suggested combining WECs with other structures, like breakwaters, to save money and make the most of available space [11]. These limitations have led to a rising interest in portable and small-scale wave energy harvesters that can be quickly set up and run on their own in a variety of marine settings [12,13].

A POWEH is a small device that can get energy from ocean waves without needing to be permanently anchored or built on the seabed. Portability has a lot of benefits, including:

- Easy to set up: Great for providing temporary or emergency power in coastal or offshore operations [14].
- Operation without maintenance: Built to work on its own with as little mechanical complexity as possible [15].
- Adaptability: Good for powering low-power electronic devices like marine IoT systems, environmental sensors, and autonomous buoys [16].
- Scalability: You can set up systems on their own or in modular arrays [17].

These kinds of systems are very important for building decentralized and resilient marine energy networks, especially for small-scale and off-grid uses where traditional WECs do not work.

Recent research has investigated diverse mechanisms for portable wave energy harvesting, encompassing vibro-impact oscillators [18], piezoelectric beams [19,20], magnet-coil electromagnetic systems [21], and TENGs [17,22]. Additionally, hybrid harvesters that use more than one transduction mechanism have been developed to make broadband response and energy conversion more efficient. Even with these improvements, there are still some problems [23]:

- Keeping dynamic stability even when the sea is rough;
- Getting a broadband frequency response for different wave conditions;
- Increasing power density in a small device volume;
- Making sure the device lasts and does not corrode after long-term use in the ocean.

POWEHs are expected to be very important for powering marine systems that can run on their own and stay alive. Table 1 shows some of the main parts of the most advanced ocean sensors. POWEHs, on the other hand, offer a renewable and eco-friendly energy source that can constantly generate power from ocean waves. This makes them perfect for marine IoT systems, autonomous sensing platforms, buoys, and underwater vehicles. Adding these kinds of devices to future ocean observation networks can greatly cut down on the need for maintenance, make sensors last longer, and help create "smart oceans" that are powered by renewable energy sources spread out across the ocean.

The goal of this review is to give a summary and critical analysis of the current state of research on portable ocean wave energy harvesters. The primary objectives are:

- Classify various types of POWEHs according to structural and functional principles;
- Elucidate their operational mechanisms, design methodologies, and power take-off systems;
- Assess experimental and numerical performance data;
- Pinpoint the principal challenges, constraints, and prospective research avenues.

Table 1. State-of-art of ocean sensors power consumption.

Sensor	Operating Principle	(mW)	Ref.
Wave Logger	Measures wave height and period	6.8	[24]
Sonic Wave	Measures distance or detects objects without touch	24	[24]
Wave Gauge	Measures conductivity, temperature, and depth	90	[25]
Turbidity	Optical scattering/absorption for suspended-particle concentration	120	[24]
Glider payload CTD	Measures conductivity, temperature, and pressure/depth	175	[26]
Nitrate	Optical/UV absorption for nitrate concentration	240	[27]
PH sensor	Electrochemical potential related to hydrogen-ion activity	400	[28]
Tide and Wave recorder	Measure sea level, water depth, and wave characteristics	700	[24]
Pressure	Pressure transducer for hydrostatic/dynamic pressure	700	[28]
Temperature	Measure Temperature	700	[28]
Radiation	Measures radiation	1.2	[29]
Conductive	Measure sea water ability to carry an electrical current	1.4	[28]
Oxygen	Electrochemical or optical dissolved-oxygen sensing	1.4	[28]
Ultrasonic Thickness Gauge	Measures the depth of a sea	4.5	[30]
Current Profile	Acoustic Doppler measurement of water velocity	5	[24]
Underwater Glider	Measure physical, chemical, and biological ocean properties	6.5	[31]
Sonar	Acoustic pulse transmission and echo detection	42	[32]
Autonomous Underwater	Self-propelled robot that operates underwater	2000	[25]

This work aims to guide the next generation of compact, efficient, and reliable ocean wave energy systems that can help make marine energy networks more sustainable by putting together recent advances. It should be noted that in this review, a POWEH is defined operationally as a compact wave-driven energy-harvesting system that can be transported, deployed, retrieved, and relocated without permanent sea-bed or coastal infrastructure. Thus, unmoored devices and systems using temporary or lightweight mooring are included, while permanently installed WECs, breakwater-integrated systems, and tidal current devices are included only as background or comparative technologies when their principles are directly relevant to POWEH development.

From an engineering design standpoint, symmetry is important in many portable ocean wave energy-harvesting systems. The structural symmetry can improve dynamic balance, remove unnecessary rotations, increase the hydrodynamic stability, and ease the manufacturing process [33]. Conversely, intentional asymmetry can be used to increase the operating range, improve the nonlinear effects, or increase the energy capture in stochastic sea conditions [34]. Understanding the relationship among symmetry, structural dynamics, and energy conversion can provide valuable information for the design and improvement of future portable wave energy harvesters [35]. Thus, the present work also investigates design principles associated with symmetry and their influence on system effectiveness.

2. Review Methodology

To improve transparency and reproducibility of the present review, a structured literature search and screening procedure was used. The search strategy was developed to identify studies directly relevant to portable, compact, floating, or lightly moored ocean-wave energy harvesters and the related energy-conversion mechanisms. The literature-selection process involved database searching, duplicate removal, screening of titles and abstracts, assessment of full-text eligibility, and final inclusion of studies. Here, we describe the search strategy, eligibility criteria, screening results, and data-extraction procedure.

2.1. Databases and Search Strategy

The literature search was conducted using Web of Science, Scopus, ScienceDirect, and IEEE Xplore. The final database search was performed on August 2026, and publications available up to this date were considered.

Search terms were selected to cover both the deployment characteristics and energy-conversion mechanisms relevant to POWEHs. The principal keywords included ocean wave energy harvester, portable wave energy harvester, floating wave energy harvester, self-powered ocean sensor, wave-powered sensor, electromagnetic wave energy harvester, piezoelectric wave energy harvester, triboelectric wave energy harvester, dielectric elastomer wave energy generator, and hybrid wave energy harvester.

These terms were combined using Boolean operators according to the requirements of each database. Additional mechanism-specific searches were performed by combining the wave-related terms with electromagnetic, piezoelectric, triboelectric, dielectric elastomer, hybrid, nonlinear, and vibro-impact to reduce the possibility of omitting relevant technologies.

2.2. Eligibility Criteria

A POWEH is operationally defined for the intent of this review as a compact wave-driven energy-harvesting system that is transportable, deployable, retrievable, and relocatable without the need for permanent seabed or coastal infrastructure. Therefore, free-floating/unmoored devices and small systems with light or temporary mooring were considered eligible. This definition is in line with the scope chosen for the present review.

Studies were included if they satisfied one or more of the following criteria:

- Studied a compact or portable device that directly converts the motion induced by ocean waves into useful electrical or mechanical energy;
- Studied electromagnetic, piezoelectric, triboelectric, dielectric-elastomer, or hybrid transduction under wave-induced excitation;
- Reported analytical, numerical, laboratory, or field results relevant to the dynamic or energy-harvesting performance of POWEHs;
- Studied self-powered marine sensing, power management, or energy-storage approaches that were directly relevant to the integration of POWEHs with marine IoT systems.

The main performance comparison excluded studies that dealt with conventional large-scale WECs that required a permanent infrastructure, breakwater-integrated converters, tidal-current or purely current-driven systems, offshore wind energy systems, or energy harvesters for unrelated applications such as human motion, railroad vibration, automotive vibration, or terrestrial structural vibration. Review articles, books, and general WEC studies were retained only as needed to establish the basic principles, terminology, or background information and were not used as direct evidence for POWEH-specific quantitative performance claims.

2.3. Screening and Study Selection

The initial database searches identified 263 records. After removal of 44 duplicate records, 219 publications remained for title and abstract screening. At this stage, studies clearly outside the scope of ocean wave energy harvesting were excluded. The full texts of 171 potentially relevant publications were subsequently assessed according to the eligibility criteria described above following full-text screening.

The main reasons for exclusion during full-text assessment included the absence of wave-induced excitation, exclusive consideration of permanently installed large-scale

WECs, insufficient relevance to portable energy harvesting, absence of accessible performance information, and application to unrelated vibration-energy environments.

2.4. Data Extraction and Study-Quality Assessment

For each eligible POWEH study, the available information was collected according to a common set of parameters. These included device configuration and dimensions, device mass where reported, deployment and mooring condition, energy-conversion mechanism, wave conditions, experimental or numerical test scale, electrical loading, mean and peak electrical power, reported efficiency and definition thereof, field testing status and duration, and indicators of technology readiness. These parameters form the basis for the later comparison at study level presented in this review.

Special attention was paid to the definition and comparability of reported performance measures. Power and efficiency values obtained using significantly different device dimensions, wave conditions, electrical loads or efficiency definitions were not treated as equivalent. Similarly, non-wave energy-harvesting applications were not included in the POWEH-specific quantitative benchmarking for performance values. When a parameter needed for comparison was not explicitly reported in the original study, it was marked as NR (not reported) rather than estimated.

The quality and relevance of the evidence were assessed according to completeness of the reported device characteristics, definition of the excitation conditions, description of the experimental or numerical methodology, availability of electrical output measurements, clarity of the performance metric definition and level of experimental validation. More importance was given to studies providing controlled experimental validation or field testing with well-defined operating conditions. Where relevant to the physical principles or design methodology, numerical or analytical investigations without experimental validation were retained but distinguished from experimental performance evidence.

This was done to minimize selection bias and, more importantly, prevent performance differences due to device scale, excitation conditions, test methodology or metric definition from being interpreted as intrinsic superiority of a particular energy-conversion technology.

3. Design Concepts and Operating Principles

POWEHs can be put into groups based on how they change energy and how they are built. There are four main types: mechanical, electromagnetic, piezoelectric, and hybrid systems. Each method has its own pros and cons when it comes to energy density, size, and how well it works in different marine conditions.

3.1. Mechanical Harvesters

Mechanical systems typically convert the kinetic energy of ocean waves into electrical energy through mechanical motion rectifiers [36,37], pendulum mechanisms [38], or other conversion mechanisms [39–41]. In order to increase their operating bandwidth and make them work better in irregular waves, these devices often use nonlinear dynamics. Some important design factors are:

- A lightweight floating structure for easy transport;
- Nonlinear stiffness or mechanical end stops to boost low-frequency motions;
- Compact mechanical rectifiers for making unidirectional torque;
- Mechanical POWEHs are strong and easy to make, but they often need other systems, like electromagnetic or piezoelectric ones, to work.

3.2. Electromagnetic Harvesters

Faraday's law says that EM systems turn relative motion between a permanent magnet and a coil into electrical power. When they are portable, EM harvesters are usually built as linear generators, rotational generators, or magnetic-coupled rectifiers [42,43]. The benefits of these systems are as follows [44,45]:

- High conversion efficiency at moderate frequencies;
- Easy to control and scale;
- No need for an outside power source.

Some of the problems are low-frequency efficiency [42], physical constraints [46], and difficulty in maintaining alignment [47] when waves hit the system in an irregular way. Recent research concentrates on self-balancing designs, magnetic gears, and adaptable mooring systems to enhance stability and portability.

3.3. Piezoelectric Harvesters

Smart materials like PZT and PVDF are used in piezoelectric harvesters. These materials make electricity when they are put under mechanical strain [48,49]. They are great for small marine applications like sensor nodes and autonomous data loggers because they are small and easy to use [50,51]. There are two main types of architectures:

- Cantilever-beam type piezoelectric harvesters connected to floating structures [52,53];
- Vibro-impact or bistable beams to get nonlinear responses [54–56].

Power output is usually in the milliwatt range, but recent advances in multilayer stacking and dielectric elastomer composites have greatly improved performance. Also, integrating piezoelectric harvesters with mechanical amplifiers or dielectric elastomers can enhance operational bandwidth [57–59].

3.4. Hybrid and Multifunctional Systems

Hybrid POWEHs use two or more transduction mechanisms, usually piezoelectric–electromagnetic or triboelectric–electromagnetic combinations, to take advantage of complementary frequency responses [60]. Hybridization provides:

- A wide range of responses to changing sea states [61];
- A higher power density [62];
- Extra energy pathways for reliability [63].

New hybrid systems use TENGs to take advantage of surface contact electrification, DEAs to make variable capacitance, and mechanical rectifiers to make continuous unidirectional rotation. These kinds of systems are very promising for marine devices that can work on their own and do not need any maintenance.

3.5. Comparison Between Harvesters

Mechanical and electromagnetic systems are better for medium-sized portable devices like self-powered buoys and emergency boats. Piezoelectric and hybrid harvesters are better for small-scale or sensor-level applications. Hybridization and nonlinear dynamics are the best ways to increase efficiency and expand the range of operations right now. Table 2 shows a summary of the different ways that POWER systems work.

Table 2. Different types of energy-harvesting systems applicable for POWEH.

Type	Typical	Advantages	Limitation	Power Range
Motion-conversion	▪ Pendulum ▪ Spring–mass ▪ Vibro-impact	Simple design; Effective at low frequencies	Needs electrical transducer; Nonlinear design complexity	0.1–10 W [64]
Electromagnetic	▪ Magnet–coil ▪ Linear generator ▪ Rotary generator	High power output; Efficient conversion	Heavy magnets; Magnetic damping	0.1–50 W [65,66]
Piezoelectric	▪ Beam ▪ Bimorph ▪ Diaphragm	Compact; Efficient at low frequencies	Low output; Material degradation	μW–mW [14,66,67]
Hybrid	▪ Piezo–EM, ▪ EM–TENG, ▪ DE–impact	Versatile; Maximizes efficiency; Adapts to random condition	Complex design; Synchronization issues	mW–100 W [68,69]

4. Ocean Wave Energy and Floater Hydrodynamic Motion

4.1. Characteristics of Ocean Kinetic Energy (OKE)

The ocean surface gets waves when the wind's kinetic energy moves to it. A promising thing about wave energy is that it can travel long distances with very little energy loss. Wave power is also more stable and predictable than many other renewable sources. This means that smaller and fewer parts can make the same amount of power in the right places [70,71]. Ocean waves have a lot of kinetic energy. For instance, a normal 4-foot, 10-s wave has more than 35,000 horsepower per mile of coastline [24]. The wave power per unit crest width for a regular wave in deep water can be written as:

$$J = \frac{\rho T g^2 H^2}{32\pi} \tag{1}$$

where ρ is the water density, g is the acceleration of gravity, H is the wave height, and T is the period of the wave. Furthermore, the Moon and the Sun's gravity pull on the water to create tidal current energy [24]. These currents are the horizontal movement of ocean water in response to changes in the tide. They are strongest near coastlines, straits, and other narrow passages. An approximate assessment of the power of tidal currents could be [24,72]:

$$P = \frac{1}{2}\rho \int_A U^3 \, dA \tag{2}$$

where ρ is the water density, A is the cross-sectional area of the channel, and U is the flow velocity perpendicular to the channel. The previously mentioned relationship is significant as the potential energy of a tidal current correlates precisely with the cube of its velocity. A minor alteration in the velocity of the tidal current can result in a significant variation in power density.

4.2. Heave Motion of Floater

A standard floating object possesses six degrees of freedom [73], comprising three translational movements and three rotational movements. To talk about the hydrodynamic motion of floater, first look at the schematic and related parameters shown in part (A) of Figure 1. The equation for the heave motion of floater can be written as [37,73]:

$$a_h \frac{d^2 z}{dt^2} + b_h \frac{dz}{dt} + c_h z = F_h sin\omega_e t \tag{3}$$

where a_{h} is the buoy mass plus added mass, b_{h} is the damping coefficient, c_{h} is the elastic coefficient, F_{h} is the encountering force amplitude, and ω_e is the excitation frequency, which can be calculated as follows [18]:

$$\omega_e = \omega - \frac{\omega^2}{g} U_f \cos\phi \tag{4}$$

where ω is the frequency of ocean wave that is equal to $\omega = (2\pi g)^{1/2}(\lambda)^{-1/2}$, U_f is the velocity amplitude of the floater, ϕ is heading angle and λ is the wavelength. Employing linear wave theory, the wavelength can be determined from the period (τ) and the depth of water (h) employing the following relation [18]:

$$\left(\frac{2\pi}{\tau}\right)^2 = \frac{2\pi g}{\lambda} \tanh\left(\frac{2\pi h}{\lambda}\right) \tag{5}$$

The strip theory method can be employed to compute a_h, b_h, and c_h. This approach is implemented with the aim of substituting a 3D hydrodynamic issue with a 2D framework [73]. A floating 3D entity is regarded as 2D slices or bands. Every strip possesses an individual dynamic coefficient, and the aggregate of these coefficients establishes the dynamic coefficients for the entire floater [74]. Employing the strip theory approach, the mass and additional mass of a buoy in vertical oscillation are equivalent to:

$$a_h = m_b + \frac{1}{8}\pi C\rho \int_{-L_f/2}^{+L_f/2} B^2 \, dx \tag{6}$$

where ρ is seawater density, C is the Lewis-form sections coefficient, presented in Figure 1B, B is the floater beam, and L_f is the length of floater. The hydrodynamic added mass represents the additional inertial effect associated with acceleration of the surrounding water as the floater oscillates. Thus, the effective inertia of the floater consists of its physical mass together with the frequency- and geometry-dependent added-mass contribution. The damping moment can be determined for each segment of the floater, and by integrating throughout the floater's length, this coefficient is derived for the whole structure:

$$b_{\mathrm{h}} = \frac{\rho g^2}{\omega_e^3} \int_{-L_f/2}^{+L_f/2} \overline{A}^2 dx \tag{7}$$

In the above relation, $\overline{A}$ is an empirical ratio. The chart shown at part (C) of Figure 1 can be used to measure the empirical ratio $\overline{A}$, and it is based on the floater sectional area coefficient β_n, which is equal to:

$$\beta = \frac{S}{BD_{\mathrm{f}}} \tag{8}$$

where S is sectional area at station, B is the floater beam, and D_{f} is draft of floater at station. The restoring coefficient is defined as follows:

$$c_{\mathrm{h}} = \int_{-L_f/2}^{+L_f/2} \rho g B \, d\xi \tag{9}$$

The force inducing heave motion in a hemispherical buoy can be determined by the Froude–Krylov equation, which is equivalent to [75]:

$$F_h = 2\rho g \zeta_a A_{WP} \tag{10}$$

where A_{WP} is water-plane area and ζ_a is the effective sea wave amplitude.

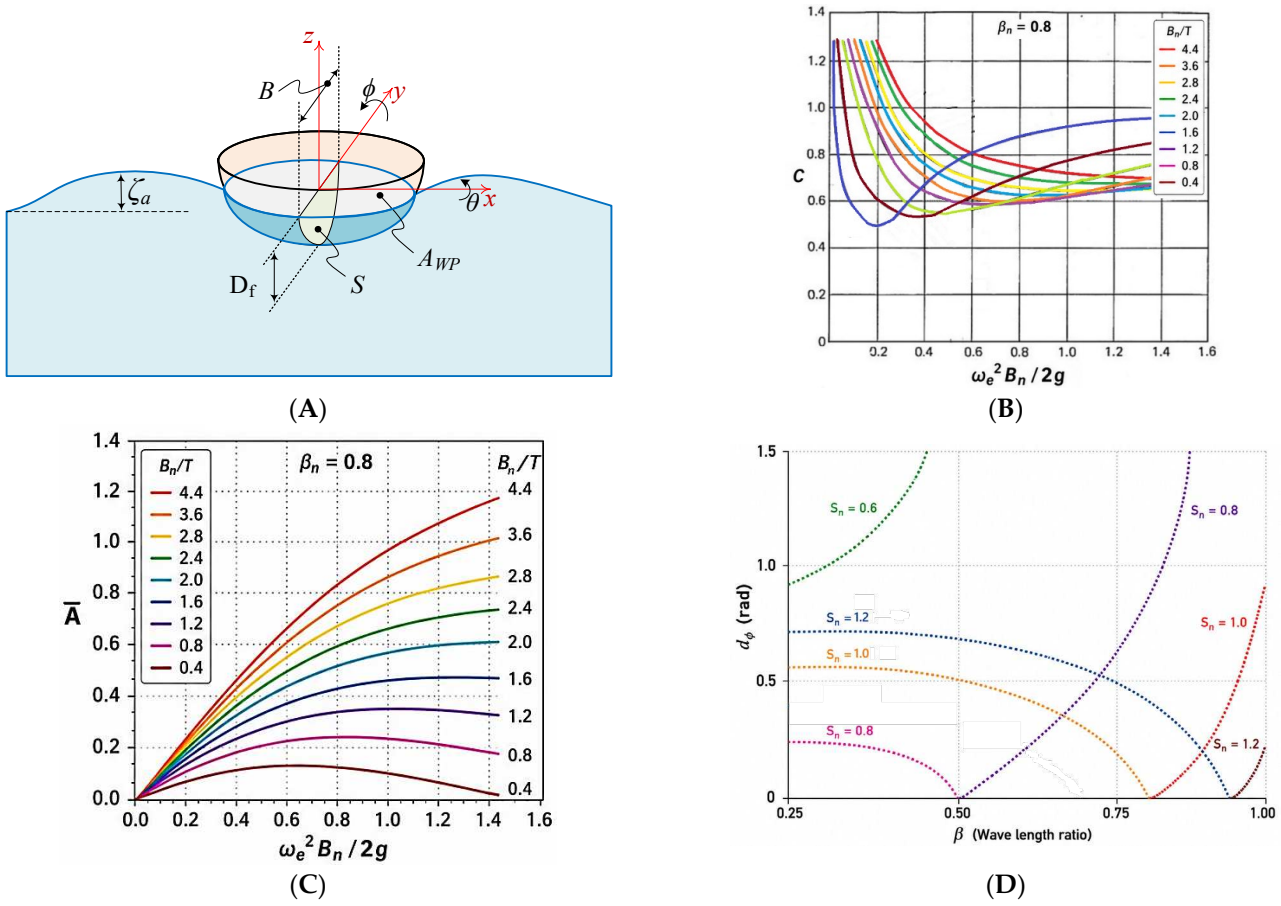


Figure 1. Hydrodynamic representation of the floating body: schematic showing floater beam B, draft D_f, sectional area S, water-plane area A_{WP}, effective wave amplitude ζ_a, roll angle ϕ, pitch angle θ (**A**); Lewis-form sectional coefficient (**B**); empirical amplitude ratio for two-dimensional floaters (**C**); and variation of the empirical roll coefficient $d\phi$ (**D**) based on the concepts discussed in [73].

4.3. Roll Motion of Floater

The governing differential equation of floater rolling can be written as follows [73]:

$$a_r \frac{d^2\phi}{dt^2} + b_r \frac{d\phi}{dt} + c_r\phi = M_r \sin\omega_e t \tag{11}$$

where a_r is effective mass moment of inertia, incorporating both floater mass moment of inertia and hydrodynamic added moment of inertia, b_r is the damping coefficient, c_r is the elastic coefficient, and M_0 is the amplitude of exciting moment. Using the strip theory method, the virtual mass moment of inertia coefficient can be obtained as follows:

$$a_r = I_{xx} + \delta I_{xx} \tag{12}$$

where I_{xx} is the floater mass moment of inertia, and δI_{xx} is the added mass moment of intertia, which is about 20% of the mass moment of inertia ($\delta I_{xx} = 0.2 I_{xx}$) [73]. By employing the strip theory approach, the damping moment for each segment of the floater can be determined, and by integrating over the floater's length, this coefficient is derived for the entire structure.

$$b_r = \frac{1}{16}\rho\omega_e \int_{-L_f/2}^{+L_f/2} B^4 d_\phi^2 \, dx \tag{13}$$

where empirical coefficient d_ϕ is presented in part (D) of Figure 1 where $S_n = 0.5B/T$. In the rolling motion, the corrective torque is exerted on the unbalanced floater at any angle to restore it to equilibrium, and it is equivalent to:

$$c_r = \rho g \int_{-L_f/2}^{+L_f/2} \Delta \overline{GM}_T \, dx \tag{14}$$

where $\overline{GM}_T$ transverse metacentric height. Excitation moment for the entire flouter is equal to:

$$f^* = \frac{4\pi}{3} \frac{\rho g \zeta_a}{L_w} \int_{-L/2}^{L/2} y^3 dx \tag{15}$$

where L_w is the wavelength. It is important to pay attention to that riblets can markedly influence hydrodynamic force variations and reduce cavitation-induced vibrations by around 41% for sawtooth riblets and 43% for scalloped riblets [76].

5. Classification Framework for Portable Ocean Wave Energy Harvesters

When designing a POWEH, it is necessary to find a balance between making it small, strong, and efficient in rough seas. Portable harvesters are often light and self-contained, unlike traditional moored systems [37,77]. How well they can turn multi-directional wave motion into usable electrical energy while keeping dynamic stability and frequency adaptability is what determines how well they work. In this part, this section discusses about the main design categories, dynamic principles, and operating mechanisms used in POWEHs.

5.1. Classification According to Deployment Architecture

Broadly, portable ocean wave energy harvesters can be classified into moored and unmoored (free-floating) systems based on the deployment architecture. This categorization is especially important for portable devices, since the station keeping method directly affects portability, dynamic stability, installation requirements, maintenance, and the relative motion available for energy conversion. POWEHs that are moored use lightweight tethers, elastic lines, or anchor elements to restrict excessive drift, while allowing sufficient wave-induced motion for energy harvesting. The mooring stiffness can also change the natural frequency of the floating system and therefore affect resonance and energy capture. Conversely, free-floating POWEHs do not have a permanent connection to the seabed and generally employ internal oscillating masses, pendulums, or other inertial devices to produce relative motion inside the floating body. They are more portable and easier to deploy, but performance is more sensitive to mass distribution, hydrodynamic damping, drift, and stability in irregular sea conditions [78–80]. Thus, the deployment architecture offers a primary structural classification of the POWEHs, and the energy-conversion mechanism associated with the electromagnetic, piezoelectric, and triboelectric transduction can be considered as a secondary classification within each deployment class.

5.1.1. Light-Moored/Semi-Portable POWEHs

Moored systems are semi-portable devices that use light tethers or elastic mooring lines to stay in place. These designs limit the buoy's movement, but not too much so that energy can still be extracted. The stiffness of the mooring has a direct effect on the system's natural frequency, which in turn affects how well it resonates with waves that hit it [37]. Table 3 shows the differences between moored and unmoored ocean wave energy harvesters.

Table 3. Comparison versus moored and unmoored OWEH.

Metric	Moored	Unmoored	Quantitative Indicator
Station keeping	High	Low	Drift radius/displacement
Stability	Generally higher [81]	Design-dependent [82]	RAO, roll/pitch amplitude
Deployment	More demanding [37]	Simpler [83]	Deployment time/personnel
Added infrastructure	Mooring line/anchor [37]	None	Mooring mass/device mass
Frequency tuning	Mooring dependent [37]	Internal dynamics [84]	Operational bandwidth (Hz)
Maintenance	Mooring + device [81]	Mainly device [17]	Service interval
Portability	Moderate	High	Total mass/volume
Energy performance	Design dependent [85]	Site dependent [77]	W, W/kg or W/m^3

5.1.2. Unmoored/Free-Floating POWEHs

Unmoored systems, on the other hand, work without fixed anchors. These are also called free-floating or self-tuned harvesters. Most of the time, they have internal oscillating bodies or self-contained masses that make the float move relative to itself. Some of the main benefits of unmoored systems are:

- They are truly portable, so they can be quickly set up and taken down;
- They are cheaper to install because they do not need to be anchored to the seabed;
- They can be used on moving platforms, like rescue boats or autonomous floats [86].

But unmoored harvesters need to be carefully designed so they do not become unstable, drift too much, or capsize in rough seas. So, mass distribution, center of gravity, and hydrodynamic damping are all very important design factors [87]. Table 4 shows the most important parts of making a good POWEH system.

Table 4. Key features of effective POWEH designs.

Feature	Description	Example
Compactness	▪ Lightweight, ▪ Self-contained, ▪ Foldable mechanisms	Conical Kresling origami-inspired foldable mechanism [87]
Robustness	○ Dual-mode operation, ○ Flexible materials, ○ Structural integrity	Dual-mode systems for harvesting and protecting modes [87], flexible WECs [88]
Efficiency	• Efficient energy capture, • Optimized dynamic parameters, • Power management	Chaotic pendulum harvesters [89], multi-directional electromagnetic harvesters [90], optimized floater dynamics [77]

5.2. Classification According to Energy-Conversion Mechanism

The PTO system determines when to turn mechanical motion into electrical energy. Table 5 briefly shows different ways that power takeoff systems can change energy. The PTO for portable harvesters needs to be small, dependable, and able to handle low-frequency inputs. Some common PTO mechanisms are:

1. Electromagnetic PTOs: These are common in WECs. They usually have parts that use electromagnetic induction to turn the mechanical motion of waves into electrical energy. For example, ball screw mechanisms change the back-and-forth motion of WEC bodies into one-way rotary motion, which then powers a generator to make electricity [91,92].

2. Piezoelectric PTOs: These turn mechanical stress directly into electrical energy. They are very helpful in places where things shake a lot, like ocean waves. Since the 1970s, people have been looking into using piezoelectric PTOs for ocean energy, and they are still being worked on [93,94].
3. Triboelectric PTOs: These are electromechanical devices that change mechanical energy into electrical energy. They are light, work well, and can handle high voltages [95–97].
4. Hybrid PTOs: These systems, like electro-hydrostatic actuators (EHAs), are very efficient and have a high force-to-weight ratio. They are used in a lot of different fields, such as marine renewable energy [98].

Table 5. Energy conversion and power take-off mechanisms.

Transducer	Mechanism	Application	Examples
Electromagnetic	Mechanical motion to electrical energy	Wave energy converters	[92]
Piezoelectric	mechanical strain to electrical energy	Ocean energy, MEMS, NEMS	[93]
Triboelectric	Generates electricity through contact electrification	Wearable electronics	[95]
Hybrid	Combines multiple mechanisms for optimized performance	Marine renewable energy, automotive	[98]

5.2.1. Electromagnetic

One of the most common ways to power medium-sized portable harvesters is with electromagnetic PTOs. Faraday's law of electromagnetic induction explains how they work. It says that when the magnetic flux through a coil changes, an electromotive force (EMF) is created. When a magnet and coil move relative to each other because of wave excitation, the induced voltage $V(t)$ can be written like this [99–101]:

$$V(t) = -N\frac{d\phi_{(t)}}{dt} \tag{16}$$

where N is the number of coils turns and $\phi_{(t)}$ is the time-varying magnetic flux. The instantaneous power output $P(t)$ and average electrical power P_{ave} are given by [99,100,102,103]:

$$P(t) = \frac{V_{(t)}^2}{R_L} \tag{17}$$

$$P_{\text{ave}} = \frac{1}{T}\int_0^T \frac{V_{(t)}^2}{R_L}dt \tag{18}$$

where R_L is the load resistance and T is the wave period. Recent research has created linear generators, rotational generators, and magnetically-coupled PTOs with mechanical rectifiers that can turn back-and-forth motion into continuous rotation. But at low frequencies, they might lose energy due to magnetic damping and inertia. This can be fixed by using soft magnetic materials and light magnet arrays [104–106]. Furthermore, the power density (power per device volume) is given by [99,100]:

$$PD = \frac{P_{\text{ave}}}{V} \tag{19}$$

where V is the volume of the PWOEH.

5.2.2. Piezoelectric

In application, for piezoelectric converters, losses primarily influence the quantity of energy converted, with the average efficiency of piezoelectric systems being approximately 20% [107]. Piezoelectric PTOs use the direct piezoelectric effect, which happens when mechanical stress on a piezoelectric material creates an electric charge. They are especially appealing for systems that are small and may have relatively low maintenance requirements. The constitutive equations control the electric displacement D [84,108,109]:

$$D = d\sigma + \varepsilon E \tag{20}$$

$$S = s\sigma + dE \tag{21}$$

The piezoelectric strain coefficient is d, the electric displacement is D, the mechanical strain is S, the applied stress is σ, the permittivity is ε, the electric field is E, and the elastic compliance is s. For a cantilever-type piezoelectric beam experiencing dynamic excitation, the output voltage across the electrodes is roughly equivalent to [110,111]:

$$V(t) = \frac{d_{31} Y t_p}{\varepsilon_{33}} \kappa w_{(t)} \tag{22}$$

where d_{31} is the transverse piezoelectric coefficient, Y is the elastic modulus, t_p is the thickness, κ is the curvature, and $w(t)$ is the tip displacement. Piezoelectric harvesters are great for low-power marine sensors and autonomous wireless nodes. They usually provide power in the range of micro-watts to milli-watts. Researchers use the following to improve energy conversion:

- Bistable and multicable configurations for broadband response [112];
- Vibro-impact excitations to increase strain levels [113];
- Dielectric elastomer composites for flexible and corrosion-resistant structures [114].

Table 6 shows different ways to use the piezoelectric transducers in the POWEHs.

Table 6. Different techniques for piezoelectric energy harvesting in POWEHs.

Technique	Description	Example Output
Bistable Configurations	Broadens operational frequency range	Trident-shaped harvester with multiple resonant peaks [115]
Vibro-Impact Excitations	Amplifies strain levels in piezoelectric materials	80 mW using superballs in ocean buoys [113]
Dielectric Elastomer Composites	Provides flexibility and corrosion resistance	10 mW per plate in POWEH device [114]

5.2.3. Triboelectric/Dielectric

TENGs and DEGs are new ways to convert wave energy, especially for small-scale and low-frequency uses [115,116].

Triboelectric Nanogenerators (TENGs)

TENGs make electricity by using contact electrification and electrostatic induction between two materials that have different electron affinities. The ocean waves make contact and separate at regular intervals, which sends charges through an external circuit and creates an alternating current. Some of their benefits are:

- Lightweight and flexible design: TENGs are known for being lightweight and flexible, which makes them useful for a wide range of marine uses. Their design makes it easy to use them in different marine settings, like mounting them on buoys or incorporating them into seabed structures [117,118];
- High voltage output: TENGs can produce high voltage outputs because they are good at turning mechanical energy into electrical energy. Some TENG designs, for example, have reached peak-to-peak voltages of up to 1300 V [119]. This high voltage output is good for powering marine sensors and other electronic devices [120,121];
- TENGs are very durable, which is important for long-term use in harsh marine environments. To make TENGs more durable, new materials and structural designs have been created that can handle mechanical wear and tear as well as environmental factors like humidity and salinity [122,123].

Dielectric Elastomer Generators (DEGs)

DEGs work like variable-capacitance systems, where the capacitance changes when an elastic dielectric membrane is mechanically deformed. When you pull on the membrane, its surface area gets bigger and its thickness gets smaller. This creates a difference in electric potential between the electrodes [124–126]. DEGs have shown that they can store a lot of energy, which makes them good for collecting energy. For instance, equi-biaxial mechanical loading configurations have been used to get energy densities of up to 550 J/kg [127]. The instantaneous energy density of a DEG can be approximated as [128,129]:

$$U = \frac{1}{2} C V_{(t)}^2 = \frac{1}{2} \varepsilon \frac{A_{(t)}}{d_{(t)}} V_{(t)}^2 \tag{23}$$

where C is capacitance, $A_{(t)}$ is the surface area, $d_{(t)}$ is thickness, and ε is the permittivity of the material. DEGs are promising for flexible, bio-inspired wave harvesters that can change shape a lot and work well.

5.2.4. Hybrid

Hybrid POWEHs combine two or more energy-conversion mechanisms in a single device with the aim of exploiting their complementary characteristics and improving energy harvesting under the low-frequency, irregular, and multidirectional excitation of ocean waves. The typical combinations include:

- Triboelectric-electromagnetic (TENG-EMG)
- Piezoelectric-electromagnetic (PZT-EMG)
- Triboelectric-piezoelectric (TENG-PZT)
- Triboelectric-electromagnetic-piezoelectric (TENG-EMG-PZT)

In particular, triboelectric generators can provide relatively high voltage and are responsive to low-frequency motion, whereas electromagnetic generators typically provide higher current and become more effective at higher relative velocity [130,131]. Piezoelectric elements can also be used to induce local deformation or frequency-upconverted structural vibration. Therefore, the combination of these mechanisms may increase the effective operating range and improve the utilization of the irregular wave-induced motion compared to using only one transduction mechanism [132].

This approach has been shown to be feasible by several compact wave-energy harvesters. A hybrid nanogenerator with a teeterboard-like configuration integrating spatially separated TENG and EMG units was developed to harvest low-frequency (<0.8 Hz) and multidirectional ocean wave excitations [133]. This arrangement enabled the two mechanisms to work concurrently and circumvented the low efficiency of conventional EMGs under very low-frequency excitation. A tube-shaped solid–liquid triboelectric–

electromagnetic hybrid generator was then proposed for ultra-low-frequency waves, and the operation was demonstrated down to approximately 0.2 Hz, and the successful application was demonstrated in sea trials [132].

Hybridization is not limited only to TENG-EMG configurations. Wave-impact energy has been harvested by combining the triboelectric and piezoelectric effects simultaneously and three-mode systems integrating triboelectric, electromagnetic, and piezoelectric conversion have been proposed [134]. The latter approach combines the sensitivity of triboelectric conversion to low-frequency motion with electromagnetic generation and frequency-up-converted piezoelectric vibration, extending the range of the exploitable excitation. More recently, hybrid electromagnetic–piezoelectric floating harvesters have also been explored for low-amplitude ocean waves. But the extra transducers, rectification circuits, mechanical parts, and interfaces needed for hybrid systems add to the structural and electrical complexity [135,136]. Thus, their benefits should be evaluated on the basis of the net energy delivered after power conditioning, rather than by adding the peak outputs of the individual transducers. Thus, future hybrid POWEHs for portable marine applications should aim for compact integration, low start-up thresholds, broadband response, environmental robustness, and efficiency of multi-source power management.

5.3. Energy Conversion Efficiency

The efficiency of PTO systems is a critical parameter for assessing system viability. consider the total incident wave power across the characteristic device width is given by:

$$P_{\text{in}} = J_w \, B \tag{24}$$

where J_w is the incident wave-power flux per unit crest width (W/m) and B is the characteristic device width (m). Accordingly, the overall wave-to-electrical efficiency is defined as:

$$\eta = \frac{P_{\text{out}}}{J_w \, B} \tag{25}$$

It should be noted that the incident wave power per unit crest width in KW/m (P_{wave}) is, calculated as [137]:

$$P_{\text{wave}} = 0.49 T H^2 \tag{26}$$

where H is the significant wave height (m) and is taken as the mean of the highest 1/3 of all waves seen in a period of time, and T is the wave period (s).

6. Frequency Tuning and Resonance Matching

Assuming a statistically spatially homogeneous wave field, airborne lidar observations over 10-km swaths have resolved the deep-water directional wave spectrum at frequencies ranging from 0.07 to 0.6 Hz, corresponding to wavelengths between approximately 314 m and 4 m [138]. Ocean waves have a wide range of frequencies, usually between 0.035 and 1.2 Hz. However, the usable bandwidth for ship-borne systems is smaller. Once accelerometer measurements are projected into the ship's center of mass, the ship's response can effectively track the low-frequency wave components in the 0.05–0.2 Hz band [139]. To provide a concise comparison without reproducing the original geographical maps, Table 7 summarizes the representative wind-speed ranges reported by Tokinaga and Xie [140]. Mean wind speeds are usually greatest over the Southern Ocean and the mid-latitude to high-latitude regions of the North Pacific and North Atlantic. Much lower wind speeds occur in the tropical and equatorial regions. Values in Table 7 are approximate ranges based on the reported global distribution and are thus meant to show regional trends rather than precise site-specific conditions.

Table 7. Approximate regional mean wind speed and wave height characteristics [140].

Oceanic Region	Mean Wind Speed (m/s)	Mean Wave Height (m)
North Pacific mid–high latitudes	8–11	1.4–2.0
North Atlantic mid–high latitudes	8–11	1.4–2.0
Equatorial Pacific	4–6	0.6–1.0
Tropical Atlantic	4–7	0.6–1.0
Tropical Indian Ocean	4–7	0.6–1.2
Southern Indian Ocean	7–10	1.4–2.0
Southern Pacific Ocean	8–11	1.4–2.0
Southern Ocean	9–12	1.8–2.2
Maritime Southeast Asia	3–5	0.2–0.8

Besides the wave height, the frequency of the ocean waves is of particular importance in the design of portable ocean wave energy harvesters, since the energy conversion performance is strongly affected by the relationship between the dominant excitation frequency and the dynamic characteristics of the device. Table 8 presents the approximate peak frequencies and associated wave spectral densities for different mean wind speeds, as calculated from the wave spectra in [141]. The dominant spectral peak tends to shift to lower frequencies and is significantly enhanced with the increase in wind speed from 10.3 to 20.6 m/s. For example, the dominant frequency decreases from about 0.13–0.16 Hz at 10.3 m/s to about 0.065–0.070 Hz at 20.6 m/s, and the corresponding peak spectral density increases from a few m^2/Hz to about 104 m^2/Hz. This trend suggests that more energetic waves with longer dominant periods can be generated under stronger wind conditions. From an energy harvesting point of view, these variations underline the need for broadband, tunable or adaptive harvester architectures which can ensure effective energy conversion under different sea states. The tabulated values are approximate values from published spectra and should therefore be regarded as representative and not as exact measurements.

Table 8. Approximate peak frequency and spectral density with mean wind speed [141].

Mean Wind Speed (m/s)	Approx. Peak Frequency (Hz)	Peak Spectral Density (m^2/Hz)
10.3	0.13–0.16	2–4
12.9	0.09–0.10	11–12
15.4	0.085–0.090	34
18.0	0.070–0.075	38
20.6	0.065–0.070	104

For the harvester to get the most power, its natural frequency should match or change to the dominant wave frequencies. There have been reports of different ways to tune:

- Adjusting the stiffness of the system by using adjustable springs or elastic elements [141,142].
- Inertial tuning, which uses movable internal masses or pendulums to change the equivalent mass moment of inertia [143,144].
- Hydrodynamic tuning, which changes the submerged volume or damping characteristics by using adjustable fins or valves [145,146].

Table 9 lists the ways to change the frequency in POWEH and their benefits. All methods have their own problems, but they should be chosen based on their pros, where

they will be used, and the design limitations. Note that the quantitative performance values reported in the tables below should be interpreted in conjunction with the device scale, wave conditions, electrical load, and test method. This review does not consider values obtained under significantly different operating conditions as directly comparable and does not derive a universal performance ranking from the aggregated power or efficiency ranges. It is also important to mention that not all the systems reviewed have been tested under excitation by ocean waves. In cases where specific references on ocean wave energy harvesting were not available, results from excitation sources other than ocean waves have been presented.

Table 9. Frequency tunning methods in different energy harvesters.

Tuning Strategy	Method	Advantages
Mechanical Stiffness Tuning	Adjustable Springs [142]	• Simple implementation • Wide frequency range
	Hyperplastic Membranes [147]	• Effective stiffness adjustment
	Variable Center of Gravity	• Versatile application
Inertial Tuning	Double-Mass Pendulum [144]	• Adaptable • Low-frequency
	Sliding Tuning Mass [143]	• Real-time adjustment
Hydrodynamic Tuning	Adjustable fins/valves [146]	• Enhanced resonance amplitude
	Geometry optimization [145]	• Broad range of oscillation period

7. Performance Evaluation of POWEH and Other Energy Harvesters

7.1. Experimental Evaluation Methods

To judge how well POWEHs work, you need to know how they behave in different situations, how well they convert energy, and how well they adapt to real sea conditions. Because these devices are usually made for small, self-contained, and off-grid use, performance testing looks at more than just the electrical output. It also looks at stability, bandwidth, and durability when the excitations change. This section outlines the primary experimental and numerical methodologies employed to evaluate POWEHs, succeeded by a comparative analysis of documented performance metrics.

7.1.1. Laboratory-Scale Testing

Testing on a small scale in a lab is an important part of making and testing energy conversion systems, such as ocean energy converters and other renewable energy technologies. This kind of testing lets you control the conditions and do the same experiment over and over, which is important for figuring out how the systems being tested work and what their basic behaviors are. When WECs are tested in the lab, wave tanks are often used to make the conditions look like those in the ocean. Small-scale models of WECs are also tested in controlled lab settings to separate dynamic effects and make the analysis easier [148–153].

7.1.2. Field and Ocean Tests

To test ocean energy converters like tidal and wave energy converters in the field, you need to measure tidal, wave, and electric parameters. These tests help us figure out how well the power works and how good the power is. For example, a wave energy conversion system with a permanent magnet tubular linear generator was put through its paces in

the ocean to show how well it worked both dynamically and statically and how well it converted energy [154–161].

7.2. Key Performance Indicators (KPIs)

POWEH performance metrics are different from those for large-scale WECs. They focus on efficiency, compactness, and adaptability instead of total installed capacity. To enable a more rigorous and transparent comparison of POWEH performance, the reviewed studies are evaluated individually, rather than by generalized power or efficiency ranges. The large variations in device size, wave conditions, electrical loading, test procedures, and reported performance measures preclude a universal ranking of the conversion mechanisms reviewed. Thus, the results summarized in Table 9 should be considered as study-level evidence, not as evidence of a general superiority of a certain technology. Hybridization, nonlinear dynamics, and other advanced concepts may provide advantages under specific excitation and design conditions, but the relative benefits of these concepts need to be assessed under normalized and sufficiently similar operating conditions.

7.3. Matching POWEH Output with Marine IoT Loads and Self-Powered Applications

This is important because a harvester producing, for example, 20 mW continuously does not need to directly supply a sensor requiring 100 mW during measurement. It can charge a capacitor/battery and operate the sensor intermittently. The key idea should be:

$$P_{\text{harvest,ave}}\,\eta_{PM} \geq P_{\text{load,ave}} \tag{27}$$

where P_{harvest} and P_{load} are raw electrical output before conditioning. Furthermore, η_{PM} represents combined efficiency of rectification, power management, and storage. For a duty-cycled marine sensor, you can further write:

$$P_{\text{load,ave}} = D\,P_{\text{active}} + (i - D)\,P_{\text{sleep}} \tag{28}$$

where D is the duty cycle, P_{active} is the power during measurement/communication, and P_{sleep} is the power in sleep mode. This is important because, for example, if a sensor requires 100 mW while measuring but only 1 mW in sleep mode and operates actively for 5% of the time, the average load power will be equal to 5.95 mW. To do so, the harvester can charge a capacitor/battery and operate the sensor intermittently. This energy-buffering strategy makes it possible for low-power harvesters to sustain relatively higher instantaneous power by operating intermittently. Based on these considerations, suitable POWEH technologies and energy-management strategies for different marine IoT power requirements are summarized in Table 10.

Table 10. Suitable harvesting strategy based on the power consumption.

$P_{\text{load,ave}}$	Typical Application	Suitable Harvesting Strategy
µW–10 mW	Low-duty-cycle sensor nodes	Piezoelectric/TENG
10–500 mW	Environmental monitoring, data logger	Piezo/TENG/EM/hybrid
0.5–10 W	Communication, advanced sensors, small buoy systems	EM/hybrid
>10 W	High-power communication/sonar/platform loads	EM/hybrid or energy storage essential

The power ranges summarized in Table 11 demonstrate that the practical feasibility of a POWEH cannot be assessed based on the mechanical or electrical power generated by the

harvester alone. Instead, the entire energy path from wave excitation to the final marine IoT load should be taken into account. It can be seen from Figure 2 that the harvester converts the incident wave energy to mechanical motion and then to electrical energy by a transduction mechanism. However, the electrical output generated is normally fluctuating and may not be directly suitable for the voltage and current requirements of the electronic load. Therefore, a rectification and power-management stage are needed to provide a regulated and usable electrical supply. The conditioned energy can then be stored in a rechargeable battery or capacitor which acts as an energy buffer between the variable wave-energy input and the intermittent power demand of the sensor node. The stored energy is then utilized to power the sensing elements, signal-processing electronics, and communication module. This buffering functionality is especially important for wireless marine IoT systems where data acquisition and transmission may require orders of magnitude higher instantaneous power than the long-term average power consumption.

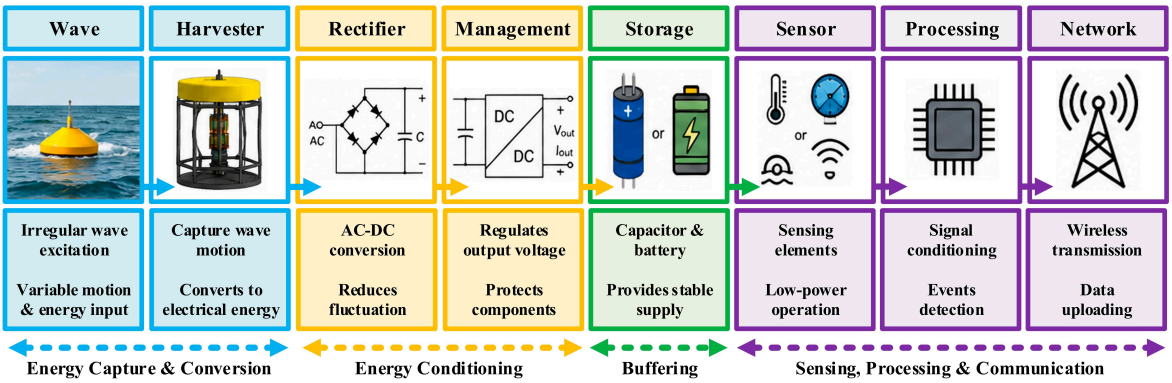


Figure 2. Complete energy-conversion and power-delivery chain of a self-powered marine IoT sensing system based on a POWEH.

8. Symmetry Considerations in Portable Ocean Wave Energy Harvesters

Symmetry is a fundamental idea in engineering design with major implications for how well portable ocean wave energy harvesters perform. The symmetry of a structure generally benefits the same mass distribution, uniform stiffness, less undesired rotation, and better dynamic stability. These features are particularly advantageous for floating and free-floating harvesters under multidirectional wave excitation [162].

But a symmetric system perfectly balanced is not always the best way to extract the maximum energy. Recently, there have been deliberate efforts in several studies to introduce geometric or dynamic asymmetry so as to generate nonlinear responses, to increase relative motion between components, to widen the operational frequency bandwidth, or to improve robustness under stochastic wave conditions. Such asymmetric configurations may be able to allow harvesters to extract energy over a wider range of sea states than conventional linear symmetric designs [163,164].

Moreover, symmetry considerations are also relevant for power take-off mechanisms, multi-degree-of-freedom oscillators, and hybrid harvesting systems. Symmetric layouts are often enabling for modular design and manufacturing, while asymmetric layouts may improve adaptability and energy conversion efficiency depending on the application. Thus, the future portable wave energy harvesters are expected to combine the merits of both the symmetric structural architectures and the controlled symmetry-breaking strategies to maximize the overall system performance [165,166].

From a dynamic point of view, symmetry in POWEHs can be studied at various but related levels: geometric symmetry, symmetry of mass distribution, stiffness symmetry, symmetry of modal characteristics, symmetry in PTO arrangement, and symmetry in wave-

incidence direction. Geometric and mass symmetry usually keep the center of gravity and principal inertia axis near the geometric axes, thereby minimizing unintended coupling between heave, pitch, and roll and improving directional stability. Likewise, symmetric stiffness distributions tend to preserve the paired or predictable natural modes, while deliberate stiffness or mass asymmetry can split modal frequencies and generate extra resonant responses that may extend the effective harvesting bandwidth. At the PTO level, symmetric transducer configurations can provide balanced reaction forces and comparable energy extraction from opposite directions, while asymmetric placement can increase local relative displacement, strain, or velocity and hence improve the electrical output under selected excitation conditions. Directional symmetry is of particular importance for multidirectional waves: axisymmetric or rotationally symmetric floaters may exhibit relatively uniform responses with wave heading, while asymmetric geometries may preferentially enhance selected modes or directions. Therefore, the effects of symmetry or symmetry breaking should be quantitatively evaluated by measurable quantities such as RAO, roll/pitch amplitude, natural-frequency splitting, modal coupling, operational bandwidth, PTO relative displacement or velocity, average electrical power, power density, and conversion efficiency rather than only by geometric description. Table 11 summarizes the principal symmetry-related design mechanisms and their corresponding measurable performance indicators. Note that the symmetry relationships listed in Table 11 are more mechanistic and study-specific than established quantitative trends. The available studies span a broad range of geometry, scale, excitation, PTO configuration, and measured response. Thus, symmetry breaking cannot be assumed to generally improve energy capture; it may improve selected modes or directional response but may also increase undesirable coupling or structural loading depending on the system. Thus, each configuration should be quantitatively assessed according to measured indicators such as RAO, modal frequencies, bandwidth, PTO motion, and electrical power.

Table 11. Reported and potential effects of symmetry and symmetry breaking on POWEH performance.

Symmetry Aspect	Symmetric Design Effect	Symmetry-Breaking Effect	Quantitative Indicator	Representative References
Geometric Symmetry	More balanced hydrodynamic loading	Enhance wave–body interaction and energy capture	RAO, Efficiency, pitch/roll	[167–170]
Mass Symmetry	Balanced inertia distribution; reduced unintended rotation	Shifts CG and can activate or amplify coupled modes	CG position, Inertia, Natural frequency, Motion amplitude	[171]
Stiffness Symmetry	Similar restoring properties in equivalent directions	Splits resonant frequencies, Broaden dynamic response	Natural frequencies, Frequency splitting	[165,166]
Modal Symmetry	More predictable modal response	Promote multimodal response and mode coupling	Modal frequencies, RAO, Bandwidth	[165,166]
PTO Symmetry	Balanced reaction forces and energy extraction	Unequal PTO loading can alter relative motion	PTO force/moment, relative displacement, Average power	[167,171]
Directional Symmetry	Axisymmetric designs reduce wave heading sensitivity	Direction-selective response improve capture for preferred incidence	Directional RAO, Heading angle, Average power	[167]
Overall Symmetry Breaking	Favors stability, repeatability, and balanced operation	Controlled asymmetry increases energy capture, but may increase loads	Average power, Efficiency, RAO, Structural loads	[167–170]

9. Future Research Directions and Prospects

Despite recent progress in POWEHs, several challenges must be addressed before these systems can achieve reliable long-term operation in practical marine environments. Future research should move beyond maximizing instantaneous electrical output under controlled laboratory conditions and focus on broadband energy capture, environmental durability, autonomous operation, standardized performance evaluation, and integration with practical marine loads. The following research directions are considered particularly important for advancing POWEH technology.

9.1. Broadband, Nonlinear, and Self-Tuning POWEHs

One of the principal limitations of compact wave energy harvesters is the mismatch between their relatively narrow dynamic response and the broadband, irregular, and time-varying nature of ocean waves. Conventional resonance-based harvesters can achieve high energy conversion near their natural frequencies, but their performance may decrease substantially when the dominant wave frequency changes. Future POWEHs should therefore incorporate broadband and adaptive dynamic mechanisms capable of maintaining effective relative motion over a wider range of sea states. Nonlinear stiffness, bistable and multicable mechanisms, vibro-impact oscillators, multiple internal masses, and multimodal structures provide potential approaches for broadening the operational frequency range.

9.2. Materials, Corrosion, Biofouling and Durability

Many POWEH concepts are not sufficiently characterized for long-term durability. Laboratory prototypes can show that a harvesting mechanism is feasible, but prolonged exposure to seawater leads to corrosion, fatigue, water ingress, seal degradation, biofouling, and deterioration of functional materials. These effects can alter the structural mass, stiffness, damping, surface properties, and electrical insulation and thus affect the dynamic and energy conversion performance of the device. Therefore, future studies should look at corrosion-resistant alloys, marine-grade polymers, fiber-reinforced composites, protective coatings, encapsulation methods, and flexible materials under extended marine exposure. Special attention should be paid to piezoelectric, triboelectric, dielectric, magnetic, and electrical components, which could be sensitive to moisture and salinity.

9.3. Hybrid Transduction and Integrated Power Management

A hybrid system, using a combination of electromagnetic, piezoelectric, triboelectric, or other conversion mechanisms, offers an opportunity to utilize different components of irregular wave-induced motion. For example, electromagnetic generators can be utilized for relatively large displacement and velocity, and piezoelectric and triboelectric elements can scavenge energy from local deformation, impact, or low-amplitude motion. However, increasing the number of transducers does not necessarily lead to a higher net useful energy, because the additional mechanical components, rectification circuits, electrical interfaces, and control systems introduce losses and complexity. Thus, future hybrid POWEHs should be evaluated based on net energy delivered after rectification and power conditioning, rather than the sum of the peak outputs of individual transducers.

9.4. Long-Term Field Testing and Standardized Performance Assessment

A major limitation in the current literature is the difficulty of comparing POWEH technologies because studies employ different device dimensions, wave conditions, test facilities, electrical loads, and definitions of efficiency. Laboratory wave-tank experiments remain essential for controlled evaluation, but they cannot fully reproduce irregular waves, multidirectional excitation, currents, storms, corrosion, biofouling, and long-term degra-

dation. Future studies should therefore place greater emphasis on extended field testing under documented sea states. At a minimum, experimental reports should provide device dimensions and mass, deployment and mooring conditions, wave height and period or spectrum, test duration, electrical load, mean and peak electrical power, power density, operational bandwidth, and clearly defined conversion efficiencies. Reporting these parameters consistently would enable more reliable study-level comparison and facilitate the establishment of standardized testing procedures specifically for small and portable wave energy harvesters.

9.5. Integration with Autonomous Marine IoT and Sensing Systems

The practical value of POWEHs should ultimately be assessed according to their ability to sustain real marine loads rather than solely according to maximum generator output. Since many marine IoT devices operate intermittently, duty-cycled sensing and communication can enable a relatively low-average-power harvester to support loads with considerably higher instantaneous power requirements. Energy-aware scheduling, adaptive sampling, low-power communication protocols, and intelligent storage management should consequently be investigated together with the harvester itself. Such system-level studies would provide a clearer basis for determining which POWEH technologies are suitable for applications such as wave monitoring, water-quality sensing, environmental observation, autonomous buoys, and other distributed marine sensor networks.

9.6. Scalability, Modularity, and Technology Readiness

Most POWEH concepts remain at laboratory or prototype scale, and increasing their practical energy capacity while retaining portability represents an important challenge. Simply increasing device dimensions can increase mass, structural loads, deployment requirements, and cost, thereby compromising the fundamental advantages of portable systems. Modular architectures may provide an alternative approach in which multiple compact harvesting units are mechanically or electrically combined according to the required power level and operating environment. Future investigations should evaluate modular arrays, mechanical interaction between neighboring harvesters, electrical integration, redundancy, ease of replacement, and deployment logistics.

9.7. Symmetry-Informed Design and Multidirectional Energy Capture

Symmetry and controlled symmetry breaking provide an additional direction for improving POWEH dynamics. Geometric, mass, stiffness, modal, and PTO symmetry can promote balanced motion and reduce undesirable rotational responses, whereas intentional asymmetry may split natural frequencies, activate coupled modes, or increase sensitivity to selected wave directions. Future research should therefore move beyond qualitative descriptions of symmetric and asymmetric configurations and quantify their effects through measurable parameters such as response amplitude operators, natural-frequency splitting, modal participation, pitch and roll amplitudes, PTO relative displacement, operational bandwidth, average electrical power, and conversion efficiency. Optimization of the degree and type of symmetry breaking may be particularly useful for compact devices exposed to multidirectional and stochastic waves, where a single symmetric resonant mode may not provide adequate broadband energy capture.

9.8. Data-Driven Optimization and Intelligent Adaptation

The strongly coupled relationships among wave conditions, floater hydrodynamics, structural dynamics, PTO parameters, and electrical loading make POWEH optimization a multidimensional problem. Data-driven methods may therefore complement conventional analytical, numerical, and experimental approaches. Machine-learning models

trained using wave-tank and field measurements could be employed to identify dominant sea-state characteristics, predict available energy, optimize electrical loading, and select suitable tuning parameters. Digital-twin frameworks could further combine real-time measurements with hydrodynamic and structural models to monitor performance and degradation. Nevertheless, the computational and sensing power required by such approaches should be considered in the overall energy budget, particularly when the POWEH is intended to support an autonomous low-power system.

Overall, future POWEH research should shift from demonstrating energy-generation feasibility toward demonstrating system-level functionality and long-term marine viability. Broadband energy capture, adaptive dynamics, durable materials, efficient power management, standardized testing, symmetry-informed design, and integration with real sensor loads should be investigated concurrently. Most importantly, extended field validation is required to determine whether the performance demonstrated by laboratory prototypes can be maintained under realistic irregular waves, corrosion, biofouling, environmental loading, and long-term operation. Addressing these issues will provide a stronger basis for assessing the technology readiness and practical applicability of portable wave energy-harvesting systems.

10. Conclusions

This review has given a complete picture of POWEHs, a quickly changing type of system that turns ambient wave motion into long-lasting electrical energy for marine applications that do not need to be connected to the grid. The study has summarized their classifications, design principles, PTO mechanisms, and performance characteristics, while also highlighting real-world applications and emerging research directions.

POWEHs have the potential to reduce deployment complexity and support autonomous marine applications; however, their long-term cost, reliability, and maintenance requirements have not yet been systematically demonstrated. These include mechanical, electromagnetic, piezoelectric, triboelectric, and hybrid architectures. Among these, hybrid and nonlinear systems have shown the most promise because they can respond to a wide range of signals, work better, and be more reliable in rough seas.

Successful laboratory demonstrations and a few field tests have been conducted but systematic long-term data on the cost, reliability, maintenance requirements, corrosion and biofouling resistance, survivability, environmental impacts, or commercial readiness of POWEHs is lacking in the literature to date. Such characteristics should therefore be considered as important research and validation needs, not as established advantages. Experimental and numerical studies demonstrate that optimally calibrated portable devices can attain conversion efficiencies ranging from 2% to 40% in moderate wave conditions, producing power from milliwatts (for sensor nodes) to tens of watts (for small buoys or rescue platforms). The successful use of these systems in autonomous ocean-sensing, coastal monitoring, and emergency-rescue systems shows that they are both technically possible and useful to society.

However, there are still a number of problems that need to be solved before widespread commercialization can happen. Some important problems are hydrodynamic instability in systems that are not moored, material degradation in harsh marine environments, a lack of standard testing protocols, and not enough long-term reliability data. To solve these problems, we need to work together on research in advanced materials, smart control, and electronics for managing energy. The next generation of POWEHs is expected to include:

- Self-adaptive systems that use real-time feedback and machine-learning optimization;
- Soft and bio-inspired materials that make them more flexible and durable;

- Hybrid multi-mode arrays that can use heave, pitch, and surge motions at the same time;
- Smart communication modules that let "smart-ocean" ecosystems communicate with each other and stay alive on their own.

Overall, the reviewed literature demonstrates the technical feasibility of portable wave energy harvesting and its potential for supplying low-power marine sensing applications. Electromagnetic, piezoelectric, triboelectric, dielectric, and hybrid approaches each offer distinct characteristics, but the substantial differences in device scale, wave conditions, electrical loading, and testing procedures currently prevent a universal ranking of these technologies. Further progress requires standardized performance assessment, long-duration field testing, improved durability under corrosion and biofouling, and system-level integration with power management, energy storage, and marine sensor loads. Consequently, the practical and commercial viability of POWEHs should be regarded as an important subject for future validation rather than an already established outcome.

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Abbreviations

AUV	Autonomous Underwater Vehicle
B	Frequency Bandwidth
CFD	Computational Fluid Dynamics
DAQ	Data acquisition system
DEAs	Dielectric Elastomers
DEG	Dielectric Elastomer Generator
EM	Electromagnetic
FRF	Frequency Response Functions
FEM	Finite Element Modeling
IoT	Internet of Things
KPI	Key Performance Indicators
MPPT	Maximum Power Point Tracking
PD	Power Density
POWEH	Portable Ocean Wave Energy Harvester
PTO	Power Take-off
R	Reliability

RAO	Response Amplitude Operator
SWL	Still Water Level
TENG	Triboelectric nanogenerator
WEC	Wave Energy Converters

References

1. Hu, X.; Zhang, W.; Zhang, S.; Hao, Y.; Cong, J. The impacts of the global energy transition on China's energy security in the long-term: Heterogeneous evidence from the supply and consumption sides. *Renew. Energy* **2025**, *255*, 123784. [CrossRef]
2. Ozkan, C.; Susanlı, Z.B.; Okay, N. Transitioning Away from Fossil Fuels to Renewables: A Multifaceted Approach and Related Challenges. *Energies* **2025**, *18*, 68. [CrossRef]
3. Dahlan, N.Y.; Ahmad, N.; Ilham, N.I.; Yusoff, S.H. Energy security: Role of renewable and low-carbon technologies. In *Handbook of Energy and Environmental Security*; Elsavier: Amsterdam, The Netherlands, 2022; pp. 39–60. [CrossRef]
4. Zhao, L.; Peng, A. Wave Energy Conversion Technology Based on Liquid Metal Magnetohydrodynamic Generators and Its Research Progress. *Energies* **2025**, *18*, 4615. [CrossRef]
5. Von Jouanne, A.; Brekken, T.K.A.; Lettenmaier, T.; Amon, E.; Moran, S.; Yokochi, A. Advancing the wave energy industry. *IEEE Potentials* **2015**, *34*, 41–47. [CrossRef]
6. Jernlgan, K. Making: Waves. *Offshore Eng.* **2014**, *39*, 26–27.
7. Wang, X.; Liu, X.; Tang, Y.; Zhao, F.; Luo, Y. Numerical analysis of the flow effect of the menger-type artificial reefs with different void space complexity indices. *Symmetry* **2021**, *13*, 1040. [CrossRef]
8. Alamian, R.; Shafaghat, R.; Miri, S.J.; Yazdanshenas, N.; Shakeri, M. Evaluation of technologies for harvesting wave energy in Caspian Sea. *Renew. Sustain. Energy Rev.* **2014**, *32*, 468–476. [CrossRef]
9. Lin, Y.; Bao, J.; Liu, H.; Li, W.; Tu, L.; Zhang, D. Review of hydraulic transmission technologies for wave power generation. *Renew. Sustain. Energy Rev.* **2015**, *50*, 194–203. [CrossRef]
10. Calheiros-Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F.; Lara, J.L. Harnessing wave energy through breakwater integration: A review of technologies, deployment strategies and an open-access database. *Renew. Sustain. Energy Rev.* **2025**, *223*, 115975. [CrossRef]
11. Russo, S. Breakwater and Wave Energy Conversion. In *Encyclopedia of Renewable Energy, Sustainability and the Environment*; Elsavier: Amsterdam, The Netherlands, 2024; Volume 3, pp. 35–48. [CrossRef]
12. Wang, T.; Guo, Z.; Jin, H.; Li, Y.; Liu, B.; Liu, J.; Xu, G.; Xu, P.; Xu, M. A coral-inspired and fully self-powered wave monitoring system based on hybridized triboelectric-electromagnetic nanogenerator. *Sens. Actuators A Phys.* **2025**, *387*, 116451. [CrossRef]
13. Cai, W.; Roussinova, V.; Stoilov, V. Piezoelectric wave energy harvester. *Renew. Energy* **2022**, *196*, 973–982. [CrossRef]
14. Qi, L.; Li, H.; Wu, X.; Zhang, Z.; Duan, W.; Yi, M. A hybrid piezoelectric-electromagnetic wave energy harvester based on capsule structure for self-powered applications in sea-crossing bridges. *Renew. Energy* **2021**, *178*, 1223–1235. [CrossRef]
15. Sharon, A.; Briggs, J.; Wirz, H. Mobile wave energy harvesting system. In Proceedings of the Technical Proceedings of the 2011 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech, Boston, MA, USA, 13–16 June 2011; Volume 3, pp. 683–686. Available online: https://www.scopus.com/inward/record.uri?eid=2-s2.0-81455142738&partnerID=40&md5=d5be52603741fb7c5d94ab82c21af0c4 (accessed on 26 August 2026).
16. Ramoso, V.; Calheiros-Cabral, T.; Giannini, G.; Majidi, A.; Das Neves, L.; Rosa-Santos, P.; Taveira-Pinto, F. Numerical and physical modelling assessment of wave energy converters in the North Breakwater of the Port of Leixões. In Proceedings of the Proceedings of the IAHR World Congress, Lisbon, Portugal, 4–7 June 2022; pp. 5677–5686. [CrossRef]
17. Zhao, X. Renewable energy harvesting with coupled-beam systems. *Ocean Eng.* **2024**, *313*, 119540. [CrossRef]
18. Afsharfard, A.; Shin, H.; Hosseini, S.; Kim, E.S.; Lee, I.; Kim, K.C. Design of vibro-impact electromagnetic ocean-wave energy harvesting system; an experimental study. *Ocean Eng.* **2022**, *263*, 112168. [CrossRef]
19. Liu, R.; Pan, C.; Zhou, H.; Xia, H.; He, L. Enhancement ultra-low-frequency wave energy harvesting through a piezoelectric energy harvester based on C-shaped cantilever beams. *Renew. Energy* **2026**, *256*, 124220. [CrossRef]
20. Jia, S.; Hong, C.; Shi, G.; Han, J.; Xu, R.; Xia, Y.; Xia, H. Scotch yoke structure inspired piezoelectric-electromagnetic hybrid harvester for wave energy harvesting. *J. Intell. Mater. Syst. Struct.* **2024**, *35*, 1540–1557. [CrossRef]
21. Tian, H.; Zhou, B.; Gong, Y. Study of a Multicoil Electromagnetic Wave Power Takeoff System with Pneumatic Velocity Upconversion Mechanism Targeting Low-Frequency Input. *IEEE J. Ocean. Eng.* **2024**, *49*, 416–429. [CrossRef]
22. Li, C.; Pan, G.; Li, H.; Lin, B.; Yang, S.; Fan, W.; Yan, X. Experimental investigation of a hybridized electromagnetic-triboelectric nanogenerator module for wave energy harvesting. *Nano Energy* **2025**, *142*, 111204. [CrossRef]
23. Flocard, F.; Finnigan, T.D. Laboratory experiments on the power capture of pitching vertical cylinders in waves. *Ocean Eng.* **2010**, *37*, 989–997. [CrossRef]

24. Zhao, T.; Xu, M.; Xiao, X.; Ma, Y.; Li, Z.; Wang, Z.L. Recent progress in blue energy harvesting for powering distributed sensors in ocean. *Nano Energy* **2021**, *88*, 106199. [CrossRef]
25. Wang, X.; Shang, J.; Luo, Z.; Tang, L.; Zhang, X.; Li, J. Reviews of power systems and environmental energy conversion for unmanned underwater vehicles. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1958–1970. [CrossRef]
26. Luo, C.; Wang, Y.; Wang, C.; Yang, M.; Yang, S. Analysis of glider motion effects on pumped ctd. In Proceedings of the Oceans 2023-Limerick, Limerick, Ireland, 5–8 June 2023; pp. 1–7.
27. Kramer, A.R.; Puls, K.A. *Documentation of Linear Regression Models for Computing Water-Quality Constituent Concentrations Using Continuous Real-Time Water-Quality Data for the North Fork Ninnescah River and Cheney Reservoir, Kansas*; US Geological Survey: Reston, VA, USA, 2023.
28. Zhou, H.; Jiao, P.; Lin, Y. Emerging deep-sea smart composites: Advent, performance, and future trends. *Materials* **2022**, *15*, 6469. [CrossRef]
29. Delgado, A.; Briciu-Burghina, C.; Regan, F. Antifouling strategies for sensors used in water monitoring: Review and future perspectives. *Sensors* **2021**, *21*, 389. [CrossRef]
30. Waters, T.A.; Instruments. Discovery-DSC-Brochure. 2019. Available online: https://www.researchgate.net/publication/334507398_Discovery-DSC-Brochure (accessed on 26 August 2026).
31. Rudnick, D.L.; Davis, R.E.; Eriksen, C.C.; Fratantoni, D.M.; Perry, M.J. Underwater gliders for ocean research. *Mar. Technol. Soc. J.* **2004**, *38*, 73–84. [CrossRef]
32. Yuh, J.; West, M. Underwater robotics. *Adv. Robot.* **2001**, *15*, 609–639. [CrossRef]
33. Ahamed, R.; Howard, I.; McKee, K. Broadband Wave Energy Harvesting with a Nonlinear 3DOF Magnetic Spring-Based PTO: Design, Testing and Sustainable Design Considerations. *Sustainability* **2025**, *17*, 10870. [CrossRef]
34. Paredes, R.J.; Plaza, D.; Datla, R.; Arias-Hidalgo, M.; Zambrano, P.S.; Marin-Lopez, J.R.; Ahumada, J.M.; Álvarez-Briceño, R.; Soria, R.; Guachamin-Acero, W. Passively-tuned roll-based wave energy converter for enhanced efficiency and frequency adaptability. *Energy Convers. Manag. X* **2026**, *30*, 101575. [CrossRef]
35. Esmaeilzadeh, S.; Alam, M.-R. Shape optimization of wave energy converters for broadband directional incident waves. *Ocean Eng.* **2019**, *174*, 186–200. [CrossRef]
36. Dhangar, P.; Selmokar, P.; Satpute, N.; Korwar, G.; Shinde, N.; Jugulkar, L. Self-Powered MEMS Sensor System for Monitoring of Ocean Parameters. In Proceedings of the 2022 3rd International Conference on Computation, Automation and Knowledge Management (ICCAKM 2022), Dubai, United Arab Emirates, 15–17 November 2022. [CrossRef]
37. Afsharfard, A.; Lee, I.; Kim, K.C. Nonlinear ocean wave energy harvester: A novel mooring-based design for enhanced energy conversion. *Energy Convers. Manag.* **2025**, *346*, 120521. [CrossRef]
38. Zhang, Z.; Sun, X.; Xu, J. A multi-stable pendular triboelectric nanogenerator for ocean wave energy harvesting and level predicting. *Smart Mater. Struct.* **2025**, *34*, 035055. [CrossRef]
39. Ribeiro, J.; Martins, I. Development of a low speed linear generator for use in a wave energy converter. *Renew. Energy Power Qual. J.* **2010**, *1*, 252–257. [CrossRef]
40. Mahmoud, M.; Abdelkareem, M.A.; Wilberforce, T.; Olabi, A.G. Recent progress in wave energy. In *Renewable Energy—Volume 2: Wave, Geothermal, and Bioenergy Definitions, Developments, Applications, Case Studies, and Modelling and Simulation*; Academic Press: Cambridge, MA, USA, 2023; pp. 21–36. [CrossRef]
41. Thiam, A.G.; Pierce, A.D. Electromechanical transduction system design for optimal energy harvesting from ocean waves. *Proc. Mtgs. Acoust.* **2011**, *14*, 030003. [CrossRef]
42. Zhang, X.; Zhang, Z.; Pan, H.; Salman, W.; Yuan, Y.; Liu, Y. A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads. *Energy Convers. Manag.* **2016**, *118*, 287–294. [CrossRef]
43. Faria, C.L.; Martins, M.S.; Matos, T.; Lima, R.; Miranda, J.M.; Gonçalves, L.M. Underwater Energy Harvesting to Extend Operation Time of Submersible Sensors. *Sensors* **2022**, *22*, 1341. [CrossRef]
44. Yin, P.; David, A.K.; Tang, L.; Aw, K. Harnessing Energy from Low-Frequency Vibrations with a Magnetic Gear-Based Electromagnetic Energy Harvester. In Proceedings of the SPIE—The International Society for Optical Engineering, Long Beach, CA, USA, 25–28 March 2024. [CrossRef]
45. Park, J.; Martinez, T.; Jordon, S.; Choi, Y.; Wereley, N.; Flatau, A. Wave-driven electromagnetic energy harvesters: Analysis of different magnetic configurations. *AIP Adv.* **2025**, *15*, 035016. [CrossRef]
46. Moalla, F.; Bradai, S.; Naifar, S.; Kanoun, O. Comparison of monostable and bistable configurations for wideband energy harvesters. In Proceedings of the 5th IMEKO TC19 Symposium on Environmental Instrumentation and Measurements, Chemnitz, Germany, 23–24 September 2014; Volume 2014, pp. 47–50. Available online: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84938807120&partnerID=40&md5=f56e3df940a95f6848bc85963bf4b8a3 (accessed on 26 August 2026).
47. Shi, G.; Liang, X.; Xia, Y.; Jia, S.; Hu, X.; Yuan, M.; Xia, H.; Wang, B. A novel dual piezoelectric-electromagnetic energy harvester employing up-conversion technology for the capture of ultra-low-frequency human motion. *Appl. Energy* **2024**, *368*, 123479. [CrossRef]

48. Panda, P.K.; Sahoo, B.; Chandraiah, M.; Raghavan, S.; Manoj, B.; Ramakrishna, J.; Kiran, P. Piezoelectric Energy Harvesting Using PZT Bimorphs and Multilayered Stacks. *J. Electron. Mater.* **2015**, *44*, 4349–4353. [CrossRef]
49. Dow, A.B.A.; Al-Rubaye, H.A.; Koo, D.; Schneider, M.; Bittner, A.; Schmid, U.; Kherani, N.P. Modeling and analysis of a micromachined piezoelectric energy harvester stimulated by ambient random vibrations. In Proceedings of the SPIE—The International Society for Optical Engineering, Prague, Czech Republic, 18–20 April 2011. [CrossRef]
50. Hwang, W.S.; Ahn, J.H.; Jeong, S.Y.; Jung, H.J.; Hong, S.K.; Choi, J.Y.; Cho, J.Y.; Kim, J.H.; Sung, T.H. Design of piezoelectric ocean-wave energy harvester using sway movement. *Sens. Actuators A Phys.* **2017**, *260*, 191–197. [CrossRef]
51. Kargar, S.M.; Hao, G. A Drifter-Based Self-Powered Piezoelectric Sensor for Ocean Wave Measurements. *Sensors* **2022**, *22*, 5050. [CrossRef]
52. Tang, S.; Ma, C.; Wang, D. A Low-Frequency High-Performance Harvesting System with Combined Cantilever Beam. *IEEE Sens. J.* **2024**, *24*, 18872–18880. [CrossRef]
53. Xie, Z.; Zhou, S.; Xiong, J.; Huang, W. The benefits of a magnetically coupled asymmetric monostable dual-cantilever energy harvester under random excitation. *J. Intell. Mater. Syst. Struct.* **2019**, *30*, 3136–3145. [CrossRef]
54. Shahsavar, M.; Ashory, M.R.; Khatibi, M.M. Utilizing Hertzian contact model for a vibro-impact unimorph bistable energy harvester to increase working frequency bandwidth and harvested power. *J. Intell. Mater. Syst. Struct.* **2025**, *36*, 129–147. [CrossRef]
55. Du, H.; Yang, Z.; Zhou, S. A piezoelectric buckling beam-type bistable energy harvester under rotational excitations. *J. Phys. D. Appl. Phys.* **2023**, *56*, 444002. [CrossRef]
56. Pan, Y.; Yang, F.; Tong, H.; Zuo, X.; Shen, L.; Xue, D.; Liu, C. Experimental and numerical simulation of a symmetrical three-cylinder buoy. *Symmetry* **2022**, *14*, 1057. [CrossRef]
57. Long, S.X.; Khoo, S.Y.; Ong, Z.C.; Soong, M.F. Design, modeling and testing of a new compressive amplifier structure for piezoelectric harvester. *Smart Mater. Struct.* **2021**, *30*, 125010. [CrossRef]
58. Chowdhury, S.; Adhikari, S.; Banerjee, A. Enhancing low-frequency vibration energy harvesting using Negative Stiffness Inertial Amplifiers. *Renew. Energy* **2025**, *247*, 123036. [CrossRef]
59. Mao, H.; He, Y.; Wu, G.; Lin, J.; Ji, R. Study of liquid viscosity effects on hydrodynamic forces on an oscillating circular cylinder underwater using OpenFOAM®. *Symmetry* **2021**, *13*, 1806. [CrossRef]
60. Li, P.; Xu, N.; Gao, C. A Multi-Mechanisms Composite Frequency Up-Conversion Energy Harvester. *Int. J. Precis. Eng. Manuf.* **2020**, *21*, 1781–1788. [CrossRef]
61. Rajarathinam, M.; Ali, S.F. Energy generation in a hybrid harvester under harmonic excitation. *Energy Convers. Manag.* **2018**, *155*, 10–19. [CrossRef]
62. Zhang, G.; Gao, S.; Liu, H.; Zhang, W. Design and performance of hybrid piezoelectric-electromagnetic energy harvester with trapezoidal beam and magnet sleeve. *J. Appl. Phys.* **2019**, *125*, 084101. [CrossRef]
63. Muthalif, A.G.; Hafizh, M.; Renno, J.; Paurobally, M. A hybrid piezoelectric-electromagnetic energy harvester from vortex-induced vibrations in fluid-flow; the influence of boundary condition in tuning the harvester. *Energy Convers. Manag.* **2022**, *256*, 115371. [CrossRef]
64. Tang, T.; Li, Y.; Zhao, H.; Sun, L.; Liu, H. A Wave Energy Harvester with Vertical Pendulum and Mag-Boost Mechanism. In Proceedings of the IEEE 23rd International Conference on Micro and Miniature Power Systems, Self-Powered Sensors and Energy Autonomous Devices PowerMEMS, Tønsberg, Norway, 18–21 November 2024; pp. 151–154. [CrossRef]
65. Viet, N.V.; Carpinteri, A.; Wang, Q. A Novel Heaving Ocean Wave Energy Harvester with a Frequency Tuning Capability. *Arab. J. Sci. Eng.* **2019**, *44*, 5711–5722. [CrossRef]
66. Viet, N.V.; Wang, Q. Ocean wave energy pitching harvester with a frequency tuning capability. *Energy* **2018**, *162*, 603–617. [CrossRef]
67. Mirab, H.; Fathi, R.; Jahangiri, V.; Ettefagh, M.M.; Hassannejad, R. Energy harvesting from sea waves with consideration of airy and JONSWAP theory and optimization of energy harvester parameters. *J. Mar. Sci. Appl.* **2015**, *14*, 440–449. [CrossRef]
68. Panda, S.; Hajra, S.; Oh, Y.; Oh, W.; Lee, J.; Shin, H.; Vivekananthan, V.; Yang, Y.; Mishra, Y.K.; Kim, H.J. Hybrid Nanogenerators for Ocean Energy Harvesting: Mechanisms, Designs, and Applications. *Small* **2023**, *19*, e2300847. [CrossRef]
69. Chen, L.; Li, C.; Fang, J. Design of a multi-direction piezoelectric and electromagnetic hybrid energy harvester used for ocean wave energy harvesting. *Rev. Sci. Instrum.* **2023**, *94*, 125005. [CrossRef]
70. Langhamer, O.; Haikonen, K.; Sundberg, J. Wave power—Sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1329–1335. [CrossRef]
71. Scruggs, J.; Jacob, P. Harvesting ocean wave energy. *Science* **2009**, *323*, 1176–1178. [CrossRef]
72. Bryden, I.G.; Couch, S.J. ME1—Marine energy extraction: Tidal resource analysis. *Renew. Energy* **2006**, *31*, 133–139. [CrossRef]
73. Bhattacharyya, R. *Dynamics of Marine Vehicles*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1978.

74. Lloyd, A.R.J.M. *Seakeeping: Ship Behaviour in Rough Weather*; Ellis Horwood Ltd.: Chichester, UK, 1989. Available online: https://www.scribd.com/doc/250917078/SEAKEEPING-Ship-Behaviour-in-Rough-Weather-A-R-J-M-LLOYD (accessed on 26 August 2026).
75. Kim, S.-J.; Koo, W.; Kim, M.-H. The effects of geometrical buoy shape with nonlinear Froude-Krylov force on a heaving buoy point absorber. *Int. J. Nav. Archit. Ocean Eng.* **2021**, *13*, 86–101. [CrossRef]
76. Kadivar, E.; Kumar, P. A Review of Hydrodynamic Cavitation Passive and Active Control Methods in Marine Engineering Applications. *Symmetry* **2025**, *17*, 1782. [CrossRef]
77. Afsharfard, A.; Lee, I.; Kim, K.C. Study application of an unmoored ocean wave energy harvester with harmonic and random excitation. *Energy Convers. Manag.* **2023**, *293*, 117535. [CrossRef]
78. Pozzi, N.; Bracco, G.; Passione, B.; Sirigu, S.A.; Mattiazzo, G. PeWEC: Experimental validation of wave to PTO numerical model. *Ocean Eng.* **2018**, *167*, 114–129. [CrossRef]
79. Fitzgerald, J.; Bergdahl, L. Including moorings in the assessment of a generic offshore wave energy converter: A frequency domain approach. *Mar. Struct.* **2008**, *21*, 23–46. [CrossRef]
80. Bergdahl, L.; Palm, J.; Eskilsson, C.; Lindahl, J. Dynamically scaled model experiment of a mooring cable. *J. Mar. Sci. Eng.* **2016**, *4*, 5. [CrossRef]
81. Smith, G.H.; Johanning, L. Mooring research to support marine energy development. *Sea Technol.* **2006**, *47*, 23–26.
82. Afsharfard, A.; Bazyar, N.; Kim, K.C. Study Effects of the Floater Geometry on the Output Power of Ocean Wave Energy Harvesters. *Int. J. Aeronaut. Space Sci.* **2023**, *24*, 1102–1110. [CrossRef]
83. Yang, Y.; Reyes, R.; Gonzalez, C.; Echevarria, S. Development of an angularly oscillating wave energy converter. In Proceedings of the ASME 2011 International Mechanical Engineering Congress and Exposition, IMECE 2011, Denver, CO, USA, 10–16 November 2011; pp. 1135–1142. [CrossRef]
84. Nabavi, S.F.; Farshidianfar, A.; Afsharfard, A. Novel piezoelectric-based ocean wave energy harvesting from offshore buoys. *Appl. Ocean Res.* **2018**, *76*, 174–183. [CrossRef]
85. Vicente, P.C.; Falcão, A.F.D.O.; Gato, L.M.C.; Justino, P.A.P. Hydrodynamics of multiple floating point-absorber wave energy systems with inter-body and bottom slack-mooring connections. In Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE, Honolulu, HI, USA, 31 May–5 June 2009; pp. 1217–1227. [CrossRef]
86. Aubrey, D.G.; Wehof, J.; O'malley, S.; Aghabi, R. Elastomeric risers in the offshore wind industry. *Mar. Technol. Soc. J.* **2020**, *54*, 77–83. [CrossRef]
87. Zeng, F.; Wang, T.; Li, J. Origami-inspired dual-mode wave energy harvesting for ocean buoys. *Energy* **2025**, *320*, 135131. [CrossRef]
88. Attili, T.; Heller, V.; Triantafyllou, S. Wave impact on rigid and flexible plates. *Coast. Eng.* **2023**, *182*, 104302. [CrossRef]
89. Li, Y.; Geng, J.; Tang, T.; Fang, Y.; Ma, X.; Chen, Z.; Chen, T.; Liu, H.; Sun, L. Study on Water Wave Energy Harvester for Clean Energy Buoys. *Jixie Gongcheng Xuebao/J. Mech. Eng.* **2021**, *57*, 275–284. [CrossRef]
90. Li, Y.; Qiu, J.; Lan, T.; Song, H. Multi-directional extremely-low-frequency electromagnetic ocean wave energy harvester based on improved double pendulum structure. *AIP Adv.* **2023**, *13*, 015033. [CrossRef]
91. Rezaei, S.; Rahimi, A.; Parvizian, J.; Mansoorzadeh, S. Experimental and numerical study of a novel unidirectional mechanical power take-off system for two-body wave energy converters. *Energy Convers. Manag. X* **2023**, *19*, 100385. [CrossRef]
92. Rezaei, S.; Rahimi, A.; Parvizian, J.; Mansoorzadeh, S.; Düster, A. A rectified unidirectional rotary PTO for two-body wave energy converters. *Ocean Eng.* **2023**, *279*, 114507. [CrossRef]
93. Park, E.; Bassiri-Gharb, N.; Stern, I. Coupling High Resonant Frequency Piezoelectrics to Human-Scale Frequencies for Energy Harvesting. *Procedia Comput. Sci.* **2017**, *109*, 771–776. [CrossRef]
94. Jbaily, A.; Yeung, R.W. Piezoelectric devices for ocean energy: A brief survey. *J. Ocean Eng. Mar. Energy* **2015**, *1*, 101–118. [CrossRef]
95. Haroun, A.; Lee, C. Dielectric-elastomer-enhanced triboelectric nanogenerator with amplified outputs. *Sens. Actuators A Phys.* **2022**, *333*, 113270. [CrossRef]
96. Nguyen, C.T.; Choi, H.R. Properties and applications of dielectric elastomer actuator. In *Smart Materials Actuators: Recent Advances in Characterization and Applications*; Elsavier: Amsterdam, The Netherlands, 2015; pp. 235–248. Available online: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84958867010&partnerID=40&md5=321bb432b84403dbe983b5e8edc50d24 (accessed on 26 August 2026).
97. Vertechy, R.; Papini Rosati, G.P.; Fontana, M. Reduced model and application of inflating circular diaphragm dielectric elastomer generators for wave energy harvesting. *J. Vib. Acoust.* **2015**, *137*, 011004. [CrossRef]
98. Wang, Y.; Huang, S.; Xue, G.; Liu, Y. Influence of Hydraulic PTO Parameters on Power Capture and Motion Response of a Floating Wind-Wave Hybrid System. *J. Mar. Sci. Eng.* **2022**, *10*, 1660. [CrossRef]
99. Fontes, D.T.M.; Rodrigues, A.M. Faraday's Law Low-Cost Experiment without Permanent Magnets. *Phys. Teach.* **2021**, *59*, 345–347. [CrossRef]

100. Kinsler, P. Faraday's Law and Magnetic Induction: Cause and Effect, Experiment and Theory. *Physics* **2020**, *2*, 150–163. [CrossRef]
101. Carapellese, F.; Faedo, N. Mechanical interactions modeling of inertial wave energy converters. *Int. J. Mech. Sci.* **2024**, *284*, 109731. [CrossRef]
102. Afsharfard, A. Application of nonlinear magnetic vibro-impact vibration suppressor and energy harvester. *Mech. Syst. Signal Process.* **2018**, *98*, 371–381. [CrossRef]
103. Afsharfard, A.; Farshidianfar, A. Free vibration analysis of nonlinear resilient impact dampers. *Nonlinear Dyn.* **2013**, *73*, 155–166. [CrossRef]
104. Yakin, A.; Simsek, T.; Avar, B.; Simsek, T.; Chattopadhyay, A.K. A review of soft magnetic properties of mechanically alloyed amorphous and nanocrystalline powders. *Emergent Mater.* **2023**, *6*, 453–481. [CrossRef]
105. Silveyra, J.M.; Ferrara, E.; Huber, D.L.; Monson, T.C. Soft magnetic materials for a sustainable and electrified world. *Science* **2018**, *362*, eaao0195. [CrossRef]
106. Jin, X.; Li, T.; Yao, Y.; Wang, C.; Shi, H.; Chai, G.; Gao, D.; Jia, C.; Xi, L.; Xue, D. MHz High Performance of Soft Magnetic Composite with Ordered Domain Structure for Efficient Conversion of Electrical Energy. *Adv. Funct. Mater.* **2025**, *35*, 2418245. [CrossRef]
107. Parinov, I.A.; Cherpakov, A.V. Overview: State-of-the-art in the energy harvesting based on piezoelectric devices for last decade. *Symmetry* **2022**, *14*, 765. [CrossRef]
108. Nabavi, S.F.; Farshidianfar, A.; Afsharfard, A.; Khodaparast, H.H. An ocean wave-based piezoelectric energy harvesting system using breaking wave force. *Int. J. Mech. Sci.* **2019**, *151*, 498–507. [CrossRef]
109. Erturk, A.; Inman, D.J. *Piezoelectric Energy Harvesting*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
110. Saadatinasab, A.; Afsharfard, A. Novel modeling of circular piezoelectric devices as vibration suppresser and energy harvester. *J. Mech. Sci. Technol.* **2019**, *33*, 2029–2035. [CrossRef]
111. Abbasi, M.; Afsharfard, A. Modeling and experimental study of a hand tremor suppression system. *Mech. Mach. Theory* **2018**, *126*, 189–200. [CrossRef]
112. Upadrashta, D.; Yang, Y. Trident-Shaped Multimodal Piezoelectric Energy Harvester. *J. Aerosp. Eng.* **2018**, *31*, 04018070. [CrossRef]
113. Hann, J.M.; Mudgal, B.V.; Jinoj, T.P.S. Microenergy harvester for remote ocean buoys using piezoelectric sensors coupled with superballs. *Indian J. Geo-Mar. Sci.* **2022**, *51*, 801–810. [CrossRef]
114. Feng, W.; Chen, H.; Zou, Q.; Wang, D.; Luo, X.; Cummins, C.; Zhang, C.; Yang, S.; Su, Y. A Contactless Coupled Pendulum and Piezoelectric Wave Energy Harvester: Model and Experiment. *Energies* **2024**, *17*, 876. [CrossRef]
115. Du, X.; Liu, X.; Feng, Q.; Chen, L.; Song, X.; Fan, C.; Zhang, M.; Yu, H.; Wang, J.; Tao, K. A self-biasing dielectric elastomer generator via integrated triboelectric nanogenerator with four-bar linkage for wave energy harvesting. *Energy* **2025**, *339*, 139107. [CrossRef]
116. Di, K.; Bao, K.; Chen, H.; Xie, X.; Tan, J.; Shao, Y.; Li, Y.; Xia, W.; Xu, Z.; Shiju, E. Dielectric elastomer generator for electromechanical energy conversion: A mini review. *Sustainability* **2021**, *13*, 9881. [CrossRef]
117. Radhakrishnan, S.; Joseph, S.; Jelmy, E.J.; Saji, K.J.; Sanathanakrishnan, T.; John, H. Triboelectric nanogenerators for marine energy harvesting and sensing applications. *Results Eng.* **2022**, *15*, 100487. [CrossRef]
118. Chen, P.; Zhu, X.; Tian, G.; Feng, X. Recent advances of TENGs for marine applications: Opportunities and challenges coexist. *Nano Energy* **2025**, *142*, 111212. [CrossRef]
119. Zhai, C.; Chou, X.; He, J.; Song, L.; Zhang, Z.; Wen, T.; Tian, Z.; Chen, X.; Zhang, W.; Niu, Z.; et al. An electrostatic discharge based needle-to-needle booster for dramatic performance enhancement of triboelectric nanogenerators. *Appl. Energy* **2018**, *231*, 1346–1353. [CrossRef]
120. Li, J.; Dang, T.; Lou, Y.; Cui, W.; Hu, J.; Li, M.; Wang, Q.; Wan, L.; Yu, A.; Zhai, J. Durable Multilayered Sleeve-Structured Hybrid Nanogenerator for Efficient Water Wave Energy Harvesting. *ACS Appl. Mater. Interfaces* **2024**, *16*, 44780–44790. [CrossRef]
121. Rodrigues, C.; Nunes, D.; Clemente, D.; Mathias, N.; Correia, J.M.; Rosa-Santos, P.; Taveira-Pinto, F.; Morais, T.; Pereira, A.; Ventura, J. Emerging triboelectric nanogenerators for ocean wave energy harvesting: State of the art and future perspectives. *Energy Environ. Sci.* **2020**, *13*, 2657–2683. [CrossRef]
122. Shen, F.; Li, Z.; Guo, H.; Yang, Z.; Wu, H.; Wang, M.; Luo, J.; Xie, S.; Peng, Y.; Pu, H. Recent Advances towards Ocean Energy Harvesting and Self-Powered Applications Based on Triboelectric Nanogenerators. *Adv. Electron. Mater.* **2021**, *7*, 2100277. [CrossRef]
123. Zhao, J.; Shi, Y. Boosting the Durability of Triboelectric Nanogenerators: A Critical Review and Prospect. *Adv. Funct. Mater.* **2023**, *33*, 2213407. [CrossRef]
124. Illenberger, P.; Takagi, K.; Kojima, H.; Madawala, U.K.; Anderson, I.A. A Mathematical Model for Self-Priming Circuits: Getting the Most from a Dielectric Elastomer Generator. *IEEE Trans. Power Electron.* **2017**, *32*, 6904–6912. [CrossRef]
125. Sadangi, A.S.; Kumar, A.; Patra, K. Analysis of Stretch-Dependent Capacitance and Its Effects on Energy Conversion of a Donut-Shaped Dielectric Elastomer Generator. *IEEE Trans. Instrum. Meas.* **2022**, *71*, 1–10. [CrossRef]

126. Moretti, G.; Papini, G.P.R.; Righi, M.; Forehand, D.; Ingram, D.; Vertechy, R.; Fontana, M. Resonant wave energy harvester based on dielectric elastomer generator. *Smart Mater. Struct.* **2018**, *27*, 035015. [CrossRef]
127. Kornbluh, R.D.; Pelrine, R.; Prahlad, H.; Wong-Foy, A.; McCoy, B.; Kim, S.; Eckerle, J.; Low, T. Stretching the capabilities of energy harvesting: Electroactive polymers based on dielectric elastomers. In *Advances in Energy Harvesting Methods*; Springer: New York, NY, USA, 2013; pp. 399–415. [CrossRef]
128. Huang, J.; Shian, S.; Suo, Z.; Clarke, D.R. Maximizing the energy density of dielectric elastomer generators using equi-biaxial loading. *Adv. Funct. Mater.* **2013**, *23*, 5056–5061. [CrossRef]
129. Vu-Cong, T.; Jean-Mistral, C.; Sylvestre, A. New operating limits for applications with electroactive elastomer: Effect of the drift of the dielectric permittivity and the electrical breakdown. In Proceedings of the SPIE—The International Society for Optical Engineering, San Diego, CA, USA, 10–14 March 2013. [CrossRef]
130. Sun, X.; Shang, C.; Ma, H.; Li, C.; Xue, L.; Xu, Q.; Wei, Z.; Li, W.; Yalikun, Y.; Lai, Y.-C.; et al. A tube-shaped solid–liquid-interfaced triboelectric–electromagnetic hybrid nanogenerator for efficient ocean wave energy harvesting. *Nano Energy* **2022**, *100*, 107540. [CrossRef]
131. Oy, S.A.; Çavuş, B. A Hybrid Electromagnetic–Piezoelectric Wave Energy Harvester: Design, Optimisation, and Laboratory Validation. *IET Renew. Power Gener.* **2026**, *20*, e70192. [CrossRef]
132. Jurado, U.T.; Pu, S.H.; White, N.M. Grid of hybrid nanogenerators for improving ocean wave impact energy harvesting self-powered applications. *Nano Energy* **2020**, *72*, 104701. [CrossRef]
133. Zhang, C.; Yang, S.; Dai, X.; Tu, Y.; Du, Z.; Wu, X.; Huang, Y.; Fan, J.; Hong, Z.; Jiang, T.; et al. Hybridized triboelectric-electromagnetic nanogenerators for efficient harvesting of wave energy for self-powered ocean buoy. *Nano Energy* **2024**, *128*, 109929. [CrossRef]
134. Tian, S.; Wei, X.; Lai, L.; Li, B.; Wu, Z.; Dai, Y. Frequency modulated hybrid nanogenerator for efficient water wave energy harvesting. *Nano Energy* **2022**, *102*, 107669. [CrossRef]
135. He, L.; Liu, R.; Liu, X.; Zheng, X.; Zhang, L.; Lin, J. A piezoelectric-electromagnetic hybrid energy harvester for low-frequency wave motion and self-sensing wave environment monitoring. *Energy Convers. Manag.* **2024**, *300*, 117920. [CrossRef]
136. Shi, G.; Zeng, W.; Xia, Y.; Xu, J.; Jia, S.; Li, Q.; Wang, X.; Xia, H.; Ye, Y. A floating piezoelectric electromagnetic hybrid wave vibration energy harvester actuated by a rotating wobble ball. *Energy* **2023**, *270*, 126808. [CrossRef]
137. Altunkaynak, A. Extended wave power formulation by perturbation theory and its applications. *Ocean Eng.* **2014**, *88*, 46–54. [CrossRef]
138. Melville, W.K.; Lenain, L.; Cayan, D.R.; Kahru, M.; Kleissl, J.P.; Linden, P.F.; Statom, N.M. The modular aerial sensing system. *J. Atmos. Ocean. Technol.* **2016**, *33*, 1169–1184. [CrossRef]
139. Cifuentes-Lorenzen, A.; Edson, J.B.; Zappa, C.J.; Bariteau, L. A multisensor comparison of ocean wave frequency spectra from a research vessel during the Southern Ocean Gas Exchange Experiment. *J. Atmos. Ocean. Technol.* **2013**, *30*, 2907–2925. [CrossRef]
140. Tokinaga, H.; Xie, S.-P. Wave-and anemometer-based sea surface wind (WASWind) for climate change analysis. *J. Clim.* **2011**, *24*, 267–285. [CrossRef]
141. Stewart, R.H. Introduction to Physical Oceanography. 2008. Available online: https://www.pelagicos.net/MARS4080_6080/readings/IPO_Ch1.pdf (accessed on 26 August 2026).
142. Lee, B.-C.; Chung, G.-S. Frequency tuning design for vibration-driven electromagnetic energy harvester. *IET Renew. Power Gener.* **2015**, *9*, 801–808. [CrossRef]
143. Abdelazim, E.M.; Anis, Y.H.; Shaltout, M.L. Extremum seeking control of a self-tunable variable-inertia vibration energy harvester: Modeling and experimental validation. *Energy Convers. Manag.* **2024**, *302*, 118123. [CrossRef]
144. Cai, Q.; Dai, K.; Zhu, S. Double-mass pendulum energy harvester with tunable ultra-low frequency: An experimental study. *Energy* **2025**, *329*, 136738. [CrossRef]
145. Rodríguez, C.A.; Rosa-Santos, P.; Taveira-Pinto, F. Hydrodynamic optimization of the geometry of a sloped-motion wave energy converter. *Ocean Eng.* **2020**, *199*, 107046. [CrossRef]
146. Azam, A.; Ahmed, A.; Qammar, A.; Shah, A.N.; Zhang, Z.; Zhang, Z.; Aslam, T.; Mugheri, S.A.; Yi, M.; Tan, X. From model-scale to full-scale: Optimizing buoy geometry for enhanced energy conversion in PA-WECs. *Ocean Eng.* **2025**, *332*, 121458. [CrossRef]
147. Dong, L.; Grissom, M.D.; Prasad, M.G.; Fisher, F.T. Application of mechanical stretch to tune the resonance frequency of hyperelastic membrane-based energy harvesters. *Sens. Actuators A Phys.* **2016**, *252*, 165–173. [CrossRef]
148. Sproul, A.; Weise, N. Analysis of a Wave Front Parallel WEC Prototype. *IEEE Trans. Sustain. Energy* **2015**, *6*, 1183–1189. [CrossRef]
149. Sheng, W.; Alcorn, R.; Lewis, T. Physical modelling of wave energy converters. *Ocean Eng.* **2014**, *84*, 29–36. [CrossRef]
150. Wendt, F.; Nielsen, K.; Yu, Y.-H.; Bingham, H.; Eskilsson, C.; Kramer, M.; Babarit, A.; Bunnik, T.; Costello, R.; Crowley, S.; et al. Ocean energy systemswave energy modelling task: Modelling, verification and validation ofwave energy converters. *J. Mar. Sci. Eng.* **2019**, *7*, 379. [CrossRef]
151. Cheng, P.; Guo, H.; Wen, Z.; Zhang, C.; Yin, X.; Li, X.; Liu, D.; Song, W.; Sun, X.; Wang, J.; et al. Largely enhanced triboelectric nanogenerator for efficient harvesting of water wave energy by soft contacted structure. *Nano Energy* **2019**, *57*, 432–439. [CrossRef]

152. Liang, X.; Jiang, T.; Liu, G.; Feng, Y.; Zhang, C.; Wang, Z.L. Spherical triboelectric nanogenerator integrated with power management module for harvesting multidirectional water wave energy. *Energy Environ. Sci.* **2020**, *13*, 277–285. [CrossRef]
153. Lu, Z.-Q.; Zhao, L.; Fu, H.-L.; Yeatman, E.; Ding, H.; Chen, L.-Q. Ocean wave energy harvesting with high energy density and self-powered monitoring system. *Nat. Commun.* **2024**, *15*, 6513. [CrossRef]
154. Wang, X.; Xia, H.; Guo, Y.; Duan, Y.; Wang, M.; Liu, Y.; Si, H. Research on field testing and assessment technology of ocean energy converters. *Ocean Eng.* **2023**, *285*, 115539. [CrossRef]
155. Chen, Z.; Yu, H.; Liu, C.; Hong, L. Design, construction and ocean testing of wave energy conversion system with permanent magnet tubular linear generator. *Trans. Tianjin Univ.* **2016**, *22*, 72–76. [CrossRef]
156. Deng, Z.D.; Jung, H.; Ouro-Koura, H.; Salalila, A.; Friedman, B.; Liu, J.; Copping, A. Efficient Hydraulic-to-electric Energy Conversion for PCM-based Ocean Thermal Gradient Energy System to Power Uncrewed Underwater Vehicles. In Proceedings of the Oceans 2023-Limerick, Limerick, Ireland, 5–8 June 2023. [CrossRef]
157. de Thieulloy, M.J.; Dorward, M.; Old, C.; Gabl, R.; Davey, T.; Ingram, D.M.; Sellar, B.G. On the use of a single beam acoustic current profiler for multi-point velocity measurement in a wave and current basin. *Sensors* **2020**, *20*, 3881. [CrossRef]
158. Li, Y.; Guo, Q.; Huang, M.; Ma, X.; Chen, Z.; Liu, H.; Sun, L. Study of an electromagnetic ocean wave energy harvester driven by an efficient swing body toward the self-powered ocean buoy application. *IEEE Access* **2019**, *7*, 129758–129769. [CrossRef]
159. Chen, X.; Gao, L.; Chen, J.; Lu, S.; Zhou, H.; Wang, T.; Wang, A.; Zhang, Z.; Guo, S.; Mu, X.; et al. A chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for wave energy scavenging and self-powered wireless sensing system. *Nano Energy* **2020**, *69*, 104440. [CrossRef]
160. Wen, Z.; Guo, H.; Zi, Y.; Yeh, M.-H.; Wang, X.; Deng, J.; Wang, J.; Li, S.; Hu, C.; Zhu, L. Harvesting broad frequency band blue energy by a triboelectric–electromagnetic hybrid nanogenerator. *ACS Nano* **2016**, *10*, 6526–6534. [CrossRef]
161. Zhao, T.; Li, Z.; Niu, B.; Xie, G.; Shangguan, L.; Zhang, M.; Zhu, Y.; Ma, Y.; Hu, C.; Li, Y. A pendulum-based nanogenerator for high-entropy wave energy harvesting. *Nat. Commun.* **2025**, *16*, 5480. [CrossRef]
162. Jin, S.; Meng, A.; Li, M.; Xu, Z.; Wu, S.; Chen, Y. Modeling and Analysis of Wave Energy Harvester with Symmetrically Distributed Galfenol Cantilever Beams. *Materials* **2023**, *16*, 5585. [CrossRef]
163. Neira, B.; Pierart, F.G.; Villegas, C.; Cifuentes, C.; Barrientos, V.; Tampier, G.; Knobloch, T.; Corves, B.; Hüsing, M. Broadband Response Enhancement of a Pitching Wave Energy Converter Using a Nonlinear Stiffness Mechanism Under Dry Friction Effects. *Energies* **2025**, *18*, 6022. [CrossRef]
164. Iida, T. Linear analysis of a gyroscopic wave energy converter: Absorbing half of the wave energy over broadband frequencies. *J. Fluid Mech.* **2026**, *1029*, A20. [CrossRef]
165. Al Shami, E.; Zhang, R.; Wang, X. Point absorber wave energy harvesters: A review of recent developments. *Energies* **2018**, *12*, 47. [CrossRef]
166. Zhang, C.; He, L.; Zhou, L.; Yang, O.; Yuan, W.; Wei, X.; Liu, Y.; Lu, L.; Wang, J.; Wang, Z.L. Active resonance triboelectric nanogenerator for harvesting omnidirectional water-wave energy. *Joule* **2021**, *5*, 1613–1623. [CrossRef]
167. Edwards, E.C.; Whitlam, C.; Chapman, J.; Hughes, J.; Redfearn, B.; Brown, S.; Draper, S.; Borthwick, A.G.L.; Foster, G.; Yue, D.K.-P. The effect of device geometry on the performance of a wave energy converter. *Commun. Eng.* **2025**, *4*, 107. [CrossRef]
168. Elhanafi, A.; Fleming, A.; Macfarlane, G.; Leong, Z. Underwater geometrical impact on the hydrodynamic performance of an offshore oscillating water column–wave energy converter. *Renew. Energy* **2017**, *105*, 209–231. [CrossRef]
169. Zhang, Q.; Li, X.; Lin, C.; Jin, P.; He, Q.; Hu, N.; Zhou, B. Experimental study on the combined effects of geometric asymmetry and partial reflection wall on the power performance of a wave energy converter. *Energy* **2025**, *329*, 136772. [CrossRef]
170. López, I.; Carballo, R.; Fouz, D.M.; Iglesias, G. Design selection and geometry in OWC wave energy converters for performance. *Energies* **2021**, *14*, 1707. [CrossRef]
171. Poguluri, S.K.; Kim, D.; Lee, Y.; Shin, J.-H.; Bae, Y.H. Design optimization of asymmetric wave energy converter using artificial neural network model. *Int. J. Nav. Archit. Ocean Eng.* **2023**, *15*, 100529. [CrossRef]

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