

Review

Recent Progress on Wave Energy Marine Buoys

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Abstract: This study aims to introduce and discuss the recent research, development and application of wave energy marine buoys. The topic becomes increasingly appealing after the observation that wave energy technologies have been evolving in the recent decades, yet have not reached convergence. The power supply is usually the bottleneck for marine distributed systems such as buoys. Wave energy technologies are especially useful in this sense, as they can capture and convert the promising “native” renewable energy in the ocean (i.e., wave energy) into electricity. The paper enumerates the recent developments in wave energy capture (e.g., oscillating bodies) and power take-off (e.g., nanogenerators). The study also introduces the typical marine buoys and discusses the applicability of wave energy technologies on them. It is concluded that the wave energy technologies could be implemented as a critical addition to the comprehensive power solution of marine distributed systems. Wave energy buoys are likely to differentiate into “wave energy converter buoys” and “wave-energy-powered buoys”, which is indicated by the ratio of the generated power to the load power.

Keywords: marine buoy; wave energy; energy capture; power take-off; triboelectric nanogenerator; renewable energy



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1. Introduction

A buoy refers to a float on the sea surface, traditionally used to show a navigable channel or to indicate reefs, submerged wrecks, etc. Ever since the 1920s, it has become an important platform, carrying a variety of monitoring devices [1]. Their in-situ measurement data are getting more and more critical in disaster prevention, resource exploitation, scientific research and national security [2,3]. Modern technologies have gradually made the buoy multifunctional, or “smarter” [4]. Smart buoys can be embedded into a full-coverage marine information-monitoring network consisting of radars, vessels, satellites and land-based monitoring nodes [5,6]. With extensive application scenarios, the marine (monitoring) buoys are developing rapidly [7,8]. The U.S. National Data Buoy Center owns 1324 buoy stations that collect and transmit ocean observation data [9]. The World Meteorological Organization and the UN Educational, Scientific and Cultural Organization jointly initialized a data buoy cooperation, namely, the Drifting Buoy Cooperation Panel, which deploys over 400 anchored buoys and 1250 drifting buoys [10].

The extensive application/deployment of marine buoys requires an essentially economically feasible and physically feasible power solution. In fact, powering the distributed devices off the grid has always been a bottleneck problem [11]. Due to limited accessibility to power supply, the traditional buoys have to work in certain ways to reduce power consumption. One option is to adopt devices with only a low voltage and low power. Otherwise, the devices need to operate under intermittent working mode, in which, they work and hibernate periodically [12,13]. The battery limits the independence of the distributed systems; that is, until the emergence of renewable energy technologies. In current practices, many buoys work with a combination of solar panels and rechargeable batteries [14]. This

reduces the hibernating interval, making most small-scale devices functional all of the time, which is critical for real-time monitoring/data acquisition.

As a very “native” and almost exclusive energy in oceans, wave energy would become the “target fuel” of marine buoys for many reasons [15]. Wave energy harvesting is a carbon-free process used to achieve power conveniently in oceans (71% of Earth’s surface), making it a very promising renewable energy [16,17]. Wave energy comes to marine buoys more naturally due to its “surface” distribution. Wave energy highly concentrates within a small portion of the water depth (i.e., near the surface). The dispersion relationship indicates that the water particle velocity decays to 5% of the maximum particle velocity (at the surface) as the depth increases to half of the wavelength [18]. The application domain of marine buoys is exactly the “prime zone” of wave energy.

Solar energy and wind energy are the major competitors of wave energy [19], especially in the aspect of powering marine buoys. Some marine buoys have already adopted solar/wind as their power resources (e.g., WindSentinel buoy [20]). However, that does not mean that they are the ultimate solutions for marine buoys. Ocean waves transmit in water, a medium that has a much higher density than air, meaning that they could yield a higher energy density than wind. In fact, the power density of a wind farm is typically in the order of 0.4–0.6 kW/m², whereas wave energy is typically in the order of several 2–3 kW/m² (solar photovoltaics typically generate power in the order of 0.1–0.2 kW/m²) [21]. Furthermore, wave energy is more consistent than solar/wind energy. In the U.K., wave energy can be harvested up to 90% of the time, whereas solar/wind can be harvested for only 20–30% of the time [22].

In terms of engineering, the wind turbines’ requirement for clearance height is quite incompatible with marine buoys. The clearance height means that the buoy needs to include an additional structure with a considerable (relative to the height of the buoys) freeboard [23,24]. This would significantly increase the capsizing vulnerability, as well as the structural materials, and harm the concealment of marine buoys. Similarly, solar panels’ requirement for surface area forms a challenge for marine buoys [19]. Considering the relatively lower power density of the solar energy, it would create a contradiction between the buoy’s horizontal dimension and its load capacity. In addition, solar panels need to stay away from run-up waves, making a solar power system less stable in marine environments [10,13]. Figure 1 is a concise diagram showing the primary engineering challenges corresponding to various power systems on buoys.

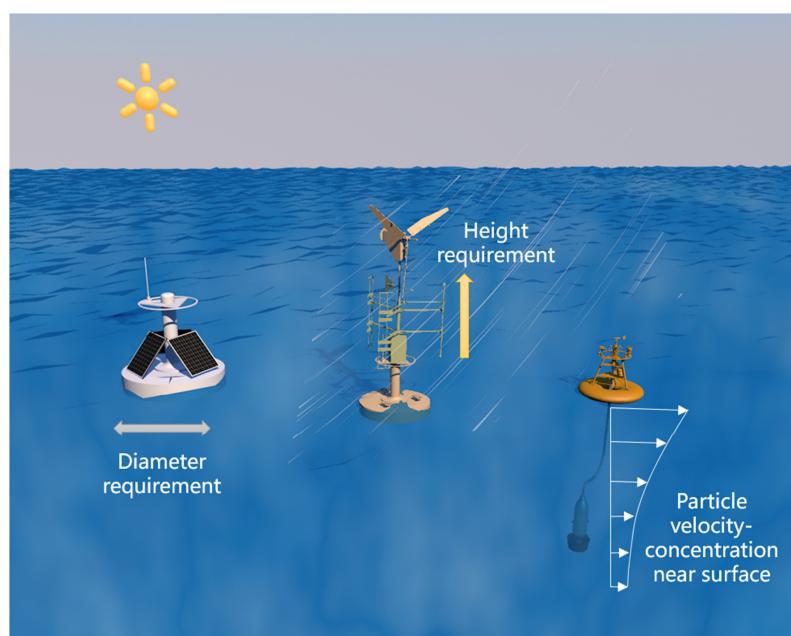


Figure 1. Engineering challenges for various power systems on buoys.

In addition, placing solar panels within the buoys may require bending the panels around the surface (e.g., a spherical shape) to protect them from the marine environment within the hull. This is difficult enough as is, yet can be aggravated by the filter of water overtopping the buoy. Reports mentioned that guano from birds usually accumulate on the surface of buoys in practice, which may greatly impair the efficiency of solar panels over time [10]. There are also considerable ecological concerns with the offshore wind turbines (e.g., noise, collision, electromagnetic field). For example, floating wind turbines could increase the risk of seabird–turbine collision, as the motions of the turbines make collision risk more dynamic [25].

The primary motivation for this review study is the importance of wave energy marine buoys from multiple perspectives. Marine buoys have become the most common, small-to-medium-scale (relative to offshore platforms etc.) floating structure that needs to work off the grid. Therefore, they are very representative in that they reflect the development of the distributed system in this scale (roughly 10^{-1} m~10 m) [15,26]. On the other hand, wave energy utilization on marine buoys primarily aims to provide *in situ* power supply, which is less demanding than power stations (aiming to supply power to the grid or other systems) [27,28]. In this sense, reviewing wave energy marine buoys also renders a benchmark of wave energy technologies. The study will help to understand how well the wave energy technologies could power a distributed system.

The present paper focuses on the application of wave energy technologies on marine buoys. Therefore, common issues of marine buoys, such as batteries, equipment and mooring, are not covered [14,29,30]. The following content is organized as follows: Section 2 reviews the energy capture from wave to structure. Section 3 reviews power take-off (PTO) from structure to wire, with an emphasis on the generators. Section 4 reviews the applications of marine buoys. Section 5 presents the discussions and concludes the review.

2. Energy Capture from Wave to Structure

The wave energy utilization can be decomposed into two critical processes: (wave) energy capture and PTO. Figure 2 depicts the generic working mechanism of a wave energy marine buoy. Energy capture is upstream of wave energy utilization, which refers to the critical process of harvesting the wave (fluid) energy with the main structures (solid) and achieving the mechanical energy for PTO. Therefore, energy capture is governed by the fluid–structure interactions (i.e., hydrodynamics), which are subject to the inputs (e.g., wave height, period, water depth, etc.) and the main structure design (such as floating structure dimension, geometry, mass, moment of inertia, center of gravity, mooring configuration and stiffness, etc.). Though they have not converged, mainstream designs of energy capture include three categories: oscillating water columns (OWC), oscillating bodies (OB) and overtopping devices [31].

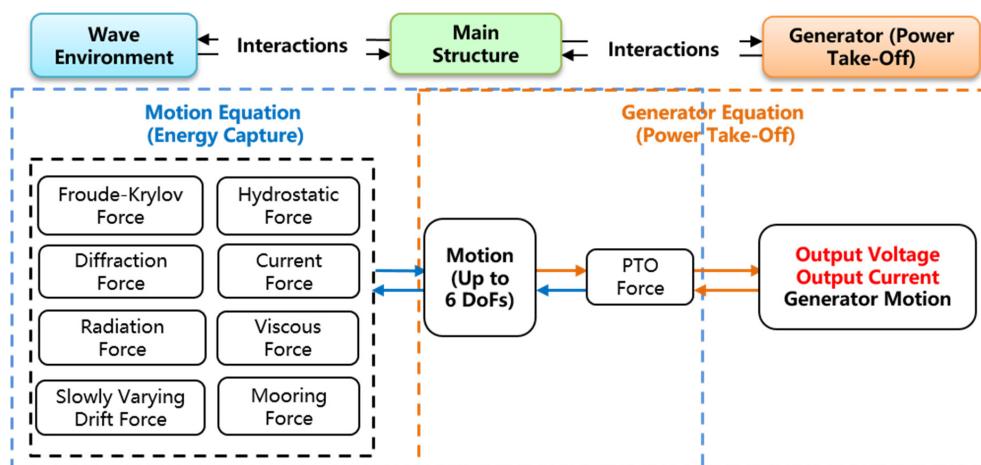


Figure 2. A mechanism diagram of a wave energy marine buoy.

Overtopping devices are structures that “trap” the water from the run-up waves [32]. The trapped water provides a water head higher than the mean sea surface that turns into water flow out through a duct, which drives an axial flow turbine and, in turn, the generator in order to produce electricity [33]. Wave Dragon is the world’s first grid-connected floating overtopping device [34]. Overtopping devices are advantageous in that they largely stabilize the unstable input waves to the PTO and they usually work with low-head hydro turbines (standard for hydroelectric stations) [33,35]. Overtopping devices usually involve larger dimensions (e.g., Wave Dragon [34]) or fixed infrastructures (e.g., OBREC [35]), as they work in a similar way to a reservoir/hydroelectric station. Therefore, an overtopping device is not considered for marine buoys and the following discussions concern the other two types: OWC and OB.

2.1. OWC Prototype for Marine Buoys

The OWC is one of the most common types of wave energy capture [36]. In brief, the OWC involves a hollow structure in order to form an air chamber. The chamber interacts with both the seawater (e.g., at the bottom of the chamber) and the air turbine (e.g., at the top of the chamber). The wave motions compress and depress the air in the chamber so that the air flows in and out the chamber through the turbine (e.g., Wells turbine) to drive the generator [37]. The most significant characteristic of the OWC is the pneumatic PTO. Early studies on wave energy capture focused on the OWC, making it relatively more established. Obviously, the OWC needs a bidirectional turbine instead of a unidirectional turbine (more conventional). The common air turbines for the OWC’s pneumatic PTO are the Wells turbine, Dennis–Auld turbine and impulse turbine. The Wells turbine, a self-rectifying axial flow turbine, is most common for OWC. This turbine consists of symmetrical blades on the rotor so that the fluctuating airflow induces a unidirectional rotation of the rotor [38]. The impulse turbine is also self-rectifying, with its rotation axis aligned with the airflow. Therefore, the airflow is directed to its blades through a guide duct. The Dennis–Auld turbine is a modification to the variable pitch Wells turbine (but has a much larger pitching range) [39].

Ever since the 1970s, industrialized nations (such as the U.K., Australia and Japan) have constructed OWC systems [40]. These OWCs were (test) deployed either at a fixed position onshore/nearshore or floating with a moored position. The Islay OWC, a representative full-size OWC plant with a rated power of 500 kW, was constructed on a rocky cliff in 2000. [41]. Some OWCs have been integrated with breakwaters (e.g., the breakwater OWC in Spain has a rate power of 18.5 kW for each unit) [42]. Compared to these fixed OWCs, floating OWCs could cover offshore wave energy and have a greater flexibility in deployment. For example, the Oceanlinx tested in 2010 is a grid-connected 1:3 scale prototype of a floating OWC (the full-scale prototype is rated at 2.5 MW). More floating OWCs (at a smaller scale) have been analyzed numerically and tested in wave basins [43]. Observations regarding the current OWCs indicate that their whole systems are generally larger than OBs. OWCs could yield a desirable capture width, yet their overall performances are usually limited by the conversion efficiency of the air turbine [38,44]. This should be largely attributed to the working medium (i.e., air). The air turbine is superior in that the turbine and the generator are prevented from making contact with seawater, reducing their corrosion risk [36,38]. However, some OWCs do possess desirable characteristics for integration with marine buoys: floating, axisymmetry and acceptable (small to medium) dimensions.

Powering a marine buoy with wave energy can be dated back to the late 1940s, when Yoshio Masuda, a pioneer of modern wave energy technologies, developed a wave energy navigation buoy. Masuda’s buoys implemented rectifying valves along with their unidirectional air turbine [45]. To improve the capture width of the floating buoy, the backward bent duct buoy (BBDB) was designed later [46]. The BBDB replaces the (previous) central tube with an L-shaped OWC so that the BBDB can also accommodate shallow water. A 1:4 scale model of the BBDB has gone through successful sea trials [47]. On top of the early developments, the later integration of OWC to the floating structure has given rise to

the OWC spar-buoy. The OWC spar-buoy is an axisymmetric floating structure attached with a vertical tube of two open ends. The natural frequency of the OWC is determined by the tube draft and the tube diameter. This prototype has not only been tested for wave energy navigation buoys [48] but also for wave energy power stations [49]. Studies are optimizing the OWC spar buoy to further release its potential [50,51].

2.2. OB Prototype for Marine Buoys

OB is the type with the largest share in various wave energy converter (WEC) designs. Essentially, the category consists of all WECs using the motions (e.g., heave, pitch) of their (or parts of their) bodies to extract wave energy. Roughly, the OB designs take approximately two thirds of the total WEC designs [21]. Point absorbers (mainly utilizing the heave motion) and flap-type designs (mainly utilizing the pitch motion) are the most common OB-type WEC [52]. Currently, much progress in OB-type WEC has taken place.

A common practice to utilize the heave motion is through adopting a two-body system, with one as a stator and one as a motor. The earlier practice of the two-body point absorber, the IPS buoy, consists of a buoy rigidly connected to a submerged tube with a piston to convert the relative motion to drive the generator [53]. The AquaBuOY has adopted a 3 m diameter float attached to a 21.3 m shaft so that the heave motion drives the piston in the shaft [54]. The Wavebob is another two-body point absorber consisting of two co-axial buoys. The relative axial motions are converted into electricity. A fully submerged body is rigidly connected to the lower body to tune to the wave frequency [55]. The PowerBuoy3 developed by the Ocean Power Technologies consists of a base spar and a motor float. Their different hydrodynamic characteristics will induce significant relative heave motion between the two parts to drive its PTO effectively [56].

The Pelamis is a snake-like OB-type WEC that is composed of four cylindrical sections hinged together. The relative pitching of the two adjacent sections drives the hydraulic motor and, in turn, the generator. After full-scale sea trials of a prototype (750 kW rated power), the Pelamis was deployed as the first grid-connected WEC worldwide [57]. Other “pitching”-type WEC designs tend to be more on the “fixed” side. Oyster is such a WEC fixed onto the seabed, and its buoyancy pendulum swings with the waves to drive the hydroelectric generator [58]. The BioWAVE works similarly, but it can accommodate the variable wave directions by rotating around its axis [59].

Pitch and heave can be utilized comprehensively on a floating platform. In 2015, a 100 kW wave energy station, “Xiandao 1”, was launched, in which, large floating bodies are connected to the platform with a hydraulic generator. Sea trials reveal that the configuration has the potential to achieve greater power, so Wanshan was followed by Xiandao 1 (260 kW) and Zhoushan (500 kW) [60]. The Wavestar developed by Demark works with multiple floats, where each float is a single-body point absorber. The floats are attached by arms to the platform so that their heave motions can be transferred via hydraulics into the rotation of a generator [61]. Wavestar has gone through tests from 1:40 scale (in wave basin) to 1:2 scale (in sea trials), and is capable of outputting a power of 600 kW.

The single-body point absorber is also a promising mechanism to extract wave energy [62]. In 2016, AquaHarmonics won the Wave Energy Prize (a U.S. Department of Energy sponsored, nationwide design-built-test) out of the 92 candidates. AquaHarmonics is a very typical OB-type wave energy buoy that rises and falls on the waves passing by, and spins the generator inside through a tether [63]. A floating self-powered buoy developed in 2021 (moored, 40 cm height and 35 cm diameter) could utilize surge, sway, roll and pitch comprehensively through the relative motions of many rolling pellets inside the buoys [64].

This above context has enumerated the representative progresses in wave energy capture and their characteristics. As far as a marine buoy is concerned, essentially, it prefers a smaller size, structure simplicity and axisymmetry, which is fundamentally different from large floating platforms [65]. Therefore, wave energy capture on marine buoys is preferably in the form of an OWC spar buoy (e.g., Figure 3a), two-body point absorber

(e.g., Figure 3b) or single-body point absorber (e.g., AquaHarmonics). Compared with the two-body point absorber, the water column of the OWC spar buoy acts as the motor. Similarly, the internal component of the single-body point absorber serves the purpose of the generator. The appropriate wave energy capture should create the proper motions toward the corresponding PTO.

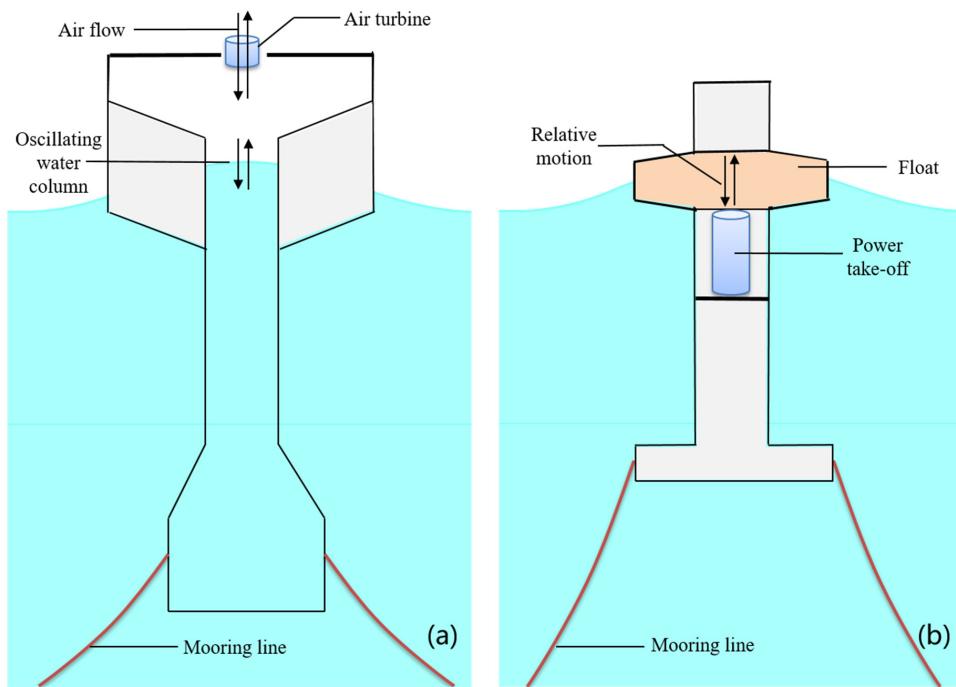


Figure 3. Types of wave energy capture applicable for marine buoys: (a) OWC spar type; (b) two-body point absorber.

3. PTO from Structure to Wire

The PTO is the other critical process that essentially “converts” the mechanical energy into electrical energy, which is governed by structure–generator interactions (i.e., electrodynamics). The performance of the system is highly dependent on the interactions between the wave environment, main structure and the generators. Wave-to-wire modelling (W2W) is being developed to address these interactions with high fidelity [66,67]. The PTO determines not only the output power, but also the dimension, cost and operational life of the system. Based on the generator mechanism, this study classifies wave energy PTOs for marine buoys according to the generator type: electromagnetic generator (EMG) and triboelectric nanogenerator (TENG).

3.1. EMG-Based PTO

EMG is the dominating mechanoelectrical converter, the core of the conventional wave energy PTO [28]. Unlike in thermal or hydraulic power plants, the input wave does not provide a stable medium flow (e.g., water flow). Therefore, the direct wave-induced motions should go through a secondary transmission system before they become the regular mechanical motion (e.g., shaft rotation) preferable to the EMG [68]. The overtopping devices demonstrate the concept of converting the random wave input to relatively stable water flow (through reservoir). However, their dimensions do not conform to the preference of marine buoys [32]. A similar preference applies to the secondary transmission associated with the generator for either OWC-type or OB-type wave energy marine buoys.

The EMGs for wave energy marine buoys mainly consist of conventional rotating generators (mainly utilizing the pitch motion) and linear generators (mainly utilizing the heave motion). The conventional rotating generator directly converts the gear/turbine

rotation into electricity, whereas the linear generator directly converts the linear (e.g., relative heave) motion into electricity [69]. Wave-induced motions of floating structures are usually very significant in heave. Therefore, the linear generator inputs the (wave-induced) reciprocating vertical motion to the permanent magnet vibrator so that it follows the undulating motion characteristics of waves. This simplifies the wave energy PTO process and yields a desirable power density and power factor. Generally speaking, linear generators are innovative and convenient, particularly for wave energy PTO [28].

The University of Beira Interior has designed a linear switched reluctance generator for wave energy conversion. The analysis showed that the linear switched reluctance generator could yield a high power density, robustness, and installation easiness [70]. A novel direct drive permanent magnet linear generator developed by Rhinefrank et al. has been tested on a buoy, and provided 50 W power under 1.5 m waves. The translator shaft is anchored to the sea floor, and the buoy moves armature coils relative to the permanent magnet translator in order to induce the current [71]. Yu et al. have developed a permanent magnet linear generator with a Halbach array for direct wave energy conversion. The current of the windings is 5.4 A when the linear generator is at a rated load. Under this situation, the generator yields an output power of 1 kW, while the copper loss is 80.5 W [72]. SeaBeav is a taut-moored dual-body WEC jointly developed by Oregon State University that consists of a cylindrical spar (in the center) and an outer Taurus-shaped buoy. Inside the float are rings of radially magnetized arc segment magnets surrounding the spar. The relative motion between the spar and the buoy is directly converted to electricity (output of 200 V and 2 A per division) [73]. The linear direct generator greatly reduces the PTO's complexity (by saving secondary transmission) and the transmission loss, which would be particularly suitable for heaving buoys if they could be accommodated with single-body carriers.

The secondary transmission system for the EMG could use air/oil/gear as a medium to achieve rotations accessible to common generators. For OWC, the wave motions are converted to turbine rotations driving the generator. Henriques et al. came up with a systematic design methodology in their study, and the output power of the analyzed EMG in the spar-type OWC can reach 343 kWh/m³ [74]. The two-body PowerBuoy3 designed by Ocean Power Technologies was installed with a load capacity of 40 kW. Its PTO involves a mechanical transmission from the relative linear motion to the EMG rotation [75]. Ding et al. designed an electromagnetic wave energy collector that uses an inertial pendulum to convert the wave-induced pitch motion into rotary motion to drive the rotating EMG. The eccentric pendulum is fixed with the generator rotor so that they can rotate together relative to the generator stator. In order to tune the natural frequency of the device with the wave frequency, the pitch angle of the pendulum can be adjusted. The maximum power density of the device reaches approximately 200 W/m³ [76]. Nicola et al. developed a WEC based on a permanent magnet motor directly coupled with a vertical inertial pendulum. The relative rotation of the pendulum with respect to the hull is used to drive the generator shaft [77]. Yerrapragada et al. developed an electromagnetic PTO based on a horizontal pendulum connected to a vertical rod. Both the roll motion and pitch motion can be converted into the yaw motion of the horizontal pendulum driving the shaft rotation of the EMG. When the working frequency is 1 Hz and the load resistance is 110 Ω, the maximum power is 4.79 mW [78]. Liang et al. designed a wave energy PTO based on a mechanical motion rectifier that uses gears and one-way shafts to convert the wave excitation into rotary motion and feed it to the EMG [79]. A PTO for mooring-less sensor buoys developed by Joe et al. adopts a submerged body as a self-rectifying turbine so that the wave-induced heave motion can be turned into the rotation of the motor. The converter could generate a maximum power of 37.68 W with a mean rotational speed of 11.20 rpm [80]. Figure 4 and Table 1 list some representative wave energy PTOs applicable for marine buoys.

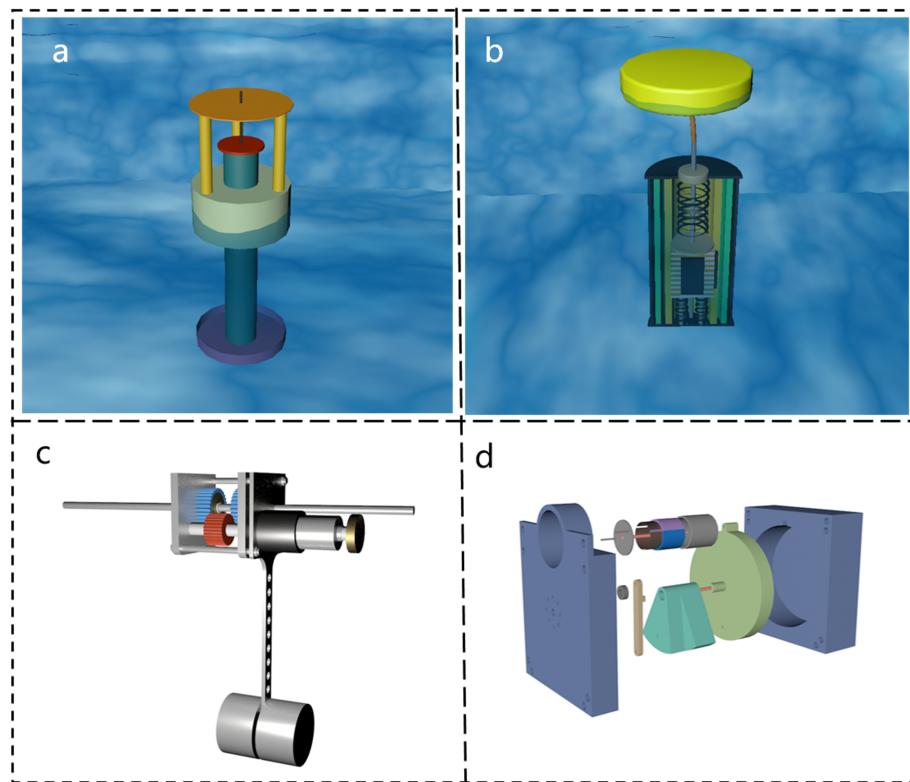


Figure 4. Electromagnetic generator (EMG)-based power take-off (PTO); (a) mechanical transmission PTO [81], reproduced with permission from the authors; (b) permanent-magnet PTO [82], reproduced with permission from the authors; (c) hydraulic flywheel PTO [83], reproduced with permission from CC BY 4.0; (d) pendulum-based PTO [84], reproduced with permission from CC BY 4.0.

Table 1. Typical electromagnetic generator (EMG)-based power take-off (PTO).

Name	Type	Prototype Main Shape	Maximum Power	References
An electromagnetic wave energy collector	Pendulum	Conventional rotating generator	200 W/m ³	[76]
A vertical inertial pendulum wave energy collector	Pendulum	Conventional rotating generator	235 W	[77]
A horizontal pendulum wave energy collector	Pendulum	Conventional rotating generator	4.79 mW	[78]
An electromagnetic ocean-wave-energy-harvesting device	Pendulum	Conventional rotating generator	122 mW	[85]
A low-cost micro-linear generator to harvest energy	Cylinder	Linear generator	20 mW	[86]
A wave power plant	Cylinder	Linear generator	12 kW	[82]
L-10 wave energy conversion	Cylinder	Linear generator	5 kW	[87]
Permanent magnet linear generator wave energy buoy.	Cylinder	Linear generator	10 kW	[88]

Land and sea trials of EMG-based wave energy PTO reveal that they have good (single unit) power and output stability. However, the volume of EMG also brings disadvantages such as a complex structure and high operation and maintenance costs. In sea conditions with a mild wave input, its efficiency is not satisfactory [30,80].

3.2. TENG-Based PTO

The triboelectric effect is usually a negative effect considering that the induced electrostatic charges could cause dust explosions, ignition and dielectric breakdown. Based on the coupling between contact electrification and electrostatic induction, TENG was first invented in 2012 to effectively harvest miscellaneous mechanical energy that is extensively

distributed but difficult to utilize [89]. The working cycle of TENG starts with no initial charge. When two different materials (usually attached to two electrodes) undergo surface contact, triboelectric charges on the two contacted surfaces are created due to their electronegativity difference. Consequently, a potential difference is built and varies as the two contacted surfaces get separated, resulting in an electron flow from one electrode to the other through the external circuit. As the two surfaces get closer again, the charges flow back through the external circuit to compensate for the electric potential variation [90].

Wave energy is a high-density renewable energy easily accessible to marine buoys. However, wave accompanies considerable randomness, as it is a vibration in physical essence. Wave-induced motions should usually go through secondary transmission (and sometimes control) before they can be fed to the conventional generator, making the whole system incompatible or uneconomic to marine buoys (especially small-scale ones) [91]. In this sense, TENG becomes a promising candidate for PTO onboarding small-scale marine buoys, as it could directly convert the miscellaneous motions into an alternating current within a smaller space and simpler structures [92].

Considering varying incident wave directions over time, TENG-based PTOs for wave energy has also evolved into different configurations. At present, most of them work in either vertical contact separation mode or lateral sliding mode. Some lateral sliding mode TENGs are designed to have fixed moving tracks, which is beneficial for improving the efficiency. On the other hand, the array design increases the degree of freedom (and directions) from which the device collects wave energy. Zhang et al. designed a TENG of a snake-like structure (a single layer of $6.4 \times 5.1 \times 2.54$ cm) that could amplify the wave excitation through springs. Under the forced motion of a linear motor at an amplitude of 0.08 m and an acceleration of 2 m/s^2 , the maximum power density reaches 3 W/m^3 [92]. A published torus TENG unit is made up of a torus shell and a ball inside, and the small ball moves circularly inside under the excitation of the simulated waves. At a frequency of 2 Hz and an inclination angle of 5° , its maximum peak power density is 0.21 W/m^2 [93]. Kim et al. designed a tubular floating buoy-based TENG with a fixed track to harvest wave energy. Under mild wave conditions (wave frequency ~ 1.7 Hz, wave amplitude ~ 15 cm), the output of a single unit is 30 V and $1.2 \mu\text{A}$ [94].

Other designs of the lateral sliding mode adopt flexible orbits for the motor of the TENG, corresponding to a high-entropy wave input. Usually, the fixed orbit TENG could only harvest wave energy from various directions by being arranged in adequate multi-directional arrays. Therefore, TENGs with flexible tracks appear to be more appealing. Ahmed et al. developed a duck-shaped TENG as a wave energy PTO. The wave drives the small ball in the duck-shaped PTO to generate an irregular reciprocating motion, yielding a maximum output power of 0.7 mw [95]. Cheng et al. developed a soft-contact spherical TENG as a wave energy power source working in water, lighting multiple LEDs at a rated power of 45 mW [96]. Xu et al. designed a tower-like TENG as a wave energy PTO that consists of multiple layers of 3D-printed arc structures with PTFE balls in each layer. A single unit yields an open circuit voltage of 105 V and short circuit current of $1.3 \mu\text{A}$ [97].

On the other hand, a TENG of the vertical contact separation mode could also be an effective wave energy PTO. An early study on this was conducted by Jurado et al., in which, a vertical contact separation mode TENG was tested under various frequencies. The study found that the TENG could produce a current of 1.22 mA and an energy conversion efficiency of 22.4% [98]. Another TENG-based PTO array device adopts air-driven membrane structures to form a spring-levitated oscillator. The oscillator utilized air as the medium to transmit the wave-induced motions, yielding a maximum power density of 13.23 W/m^3 [99]. An et al. developed a whirling-folded TENG consisting of a multilayered TENG structure with an elastic 3D-printed PLA substrate. The whole unit is sealed in a spherical shell, and can produce a peak power of 6.5 mW (12.4 W/m^3). The air gap between the TENG and the spherical shell could reduce the dielectric shielding effect from the water [100].

In general, TENG is in the phase of small-scale prototype design and laboratory examination. Table 1 has listed the important characteristics of some typical TENG-based PTOs as a development benchmark. The TENG yields a high voltage and better adaptability to low frequency, making it a promising alternative for small-scale appliances (e.g., sensors, illumination). The desirable sizing, structure simplicity and lower costs are the obvious advantages for TENG-based PTOs, yet engineering problems should be taken care of before their practical use. These problems include load matching, system integration and output stability. Figure 5 and Table 2 list some representative TENG-based PTOs applicable for marine buoys.

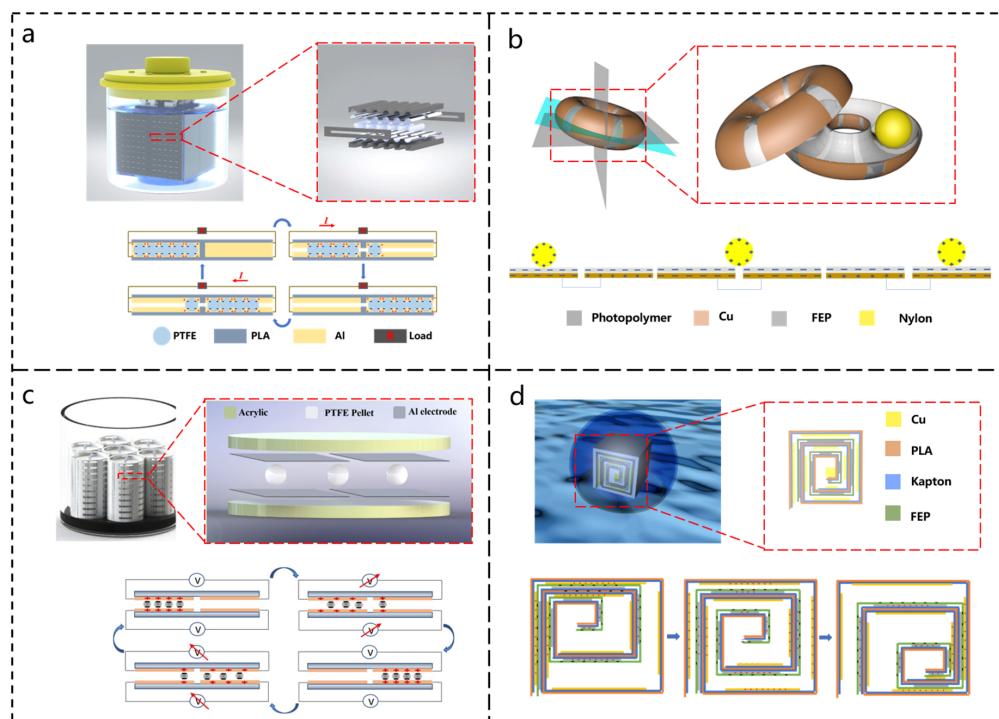


Figure 5. Triboelectric nanogenerator (TENG)-based PTO: (a) stackable fixed track TENG [101], reproduced with permission from MPDI; (b) torus track TENG [93], reproduced with permission from Elsevier; (c) stackable flexible track TENG [64], reproduced with permission from Elsevier; (d) whirling-folded TENG [100], reproduced with permission from the author.

Table 2. Typical triboelectric nanogenerator (TENG)-based PTO.

Name	Prototype Main Shape	Category	Major Material	Power Density	References
Torus-structured TENG	Rings	Fixed trajectory	Cuba, FEP, Nylon, Photopolymer	0.21 W/m ²	[93]
Tower-like TENG	Tower	Unfixed trajectory	PTFE, Nylon, Metal electrode	1.03 W/m ³	[97]
Open-book-like TENG	Book	Vertical contact separation	Al, PTFE	7.45 W/m ³	[102]
Whirling-Folded TENG	Cube	Vertical contact separation	FEP, PLA, Kapton, Cu	12.4 W/m ³	[100]
Stackable TENG	Stackable	Fixed trajectory	PTFE, Al, PLA	49 W/m ³	[101]
Hybridized EMG/TENG	Rectangle	Vertical contact separation	FEP, Cu, Kapton, Acrylic, Magnet	39.5 W/m ³ + 58.1 W/m ³	[103]

The concept of a “hybrid” PTO for wave energy aims to obtain higher power and increase the robustness to the inputs. Current research on hybrid PTOs involves electro-

magnetic, triboelectric and piezoelectric generators (PEG). In particular, the EMG/TENG hybrid generator could combine the high voltage of TENGs with the high current of EMGs. In an early study on the hybridized generator, the TENG part can deliver a peak power of approximately 1.7 mW, whereas the EMG can deliver a peak power of approximately 2.5 mW [103]. Another study on a wave-driven multifunctional power module reveals that, at 2 Hz, the voltage and current of the EMG reach 0.66 V and 2.14 mA, whereas the voltage and current of the TENG module reach 142 V and 23.3 μ A [104]. A heaving-mode hybrid PTO combines a TENG (outputting 2600 V peak voltage and 78 μ A peak current) with an EMG (producing 2.5 V voltage and 30 mA peak current). The hybrid PTO could power a commercial Bluetooth sensing system in wave basin tests [105].

4. Applications of Wave Energy Marine Buoy

The functional loads onboarding the marine buoys include navigation beacons, sensors, data acquisitors and communication devices, etc. With the expansion of buoy functions, the number of electronic equipment carried is gradually increasing, and the power consumption of the buoy is also increasing. In order to ensure the normal operation of marine buoys, solar battery systems need to mix other energy sources, such as wave energy, microbial fuel and wind energy, in order to prolong the service span of the buoy system and improve the charge/discharge efficiency [106]. According to the specific application requirements, a variety of buoy systems have been developed. The representative ones include power supply buoys, data buoys, navigational buoys, drifter buoys and aquaculture buoys [107]. Some of them are listed in Table 3.

Table 3. Typical applications of marine buoys.

Applications	Name	Prototype Main Shape	Year	References
Power supply buoys	OCEANTEC WEC	AUV-shaped	2009	[108]
	Wavebob	Cylinder	2009	[109]
	PB3 power buoy	Cylinder	2016	[110]
	OEbuoy	Elliptical	2019	[111]
Ocean data buoys	POSEIDON buoy	Cylinder	2005	[112]
	BOUSSOLE	Tower-type	2013	[113]
	A canoe-box GPS buoy	Hemisphere	2015	[114]
Aquaculture buoys	Indigenized Indian drifting buoy	Sphere	2017	[115]
	Finfish aquaculture feeding buoy	Cylinder	2006	[116]
	Echo-sounder buoys	NA	2018	[117]
	A low-cost compact autonomous buoy	Cylinder	2018	[118]
	Self-Powered Smart Fishing Net Tracker	Cone	2022	[119]

With the progress of wave energy technologies, some attempts have evolved into large, non-cylindrical platforms, while many still fall into the buoy scale. Large buoys can output the electricity to the grid or to other marine structures instead of serving themselves only. Wavebob is a two-body heaving buoys system developed for the sheltered waters of Ireland. The rated power of Wavebob reaches 1000 kW and is considered highly adaptive to Mediterranean environments [109]. Ocean Power Technologies developed the first commercial WEC in the U.S., PowerBuoy, which acts as an uninterrupted power supply (UPS) that constantly recharges itself by harvesting wave energy. Deployed to supply devices on-board or underwater, the PowerBuoy3 incorporates a redesigned PTO, a battery pack, a higher voltage power management and distribution system and a novel auto-ballasting system [110]. Other power supply buoys include the OEbuoy [111], AquaBuOY [120] and AWS [121]. Generally speaking, power supply buoys yield quite good performances, yet their survivability and financial feasibility are subject to examination and improvements [109]. This is why the power supply buoys are more inclined to step into the segment market (e.g., PowerBuoy in the offshore applications) instead of the general power grid, for now.

In terms of offshore applications, wave energy buoys are very promising. In fact, the earliest successful application of wave energy technologies is realized on a navigation buoy (probably the most straightforward mission for marine buoys). Masuda's navigation buoy captures wave energy with an OWC and converts it to electricity through a turbine-drive rotational generator. The buoys were commercialized in large numbers in Japan and the U.S. as navigation equipment, and proved to be the first successful wave-powered devices in real applications [44]. The first commercially manufactured wave energy device in China also turned out to be the navigation buoy developed by Guangzhou Energy Research Institute. Since the late 1980s, around 800 wave energy navigational buoy products have been purchased by clients in China, Singapore and the U.K [122]. The Chinese wave energy navigation buoys also adopt the combination of an OWC and turbine-drive rotational generator, while the PTOs are becoming more powerful and more mature. On top of this, the buoy-based PTOs developed by the Chinese Academy of Science have evolved into multiple models (10 W, 100 W and kW). In 2020, a comprehensive wave energy data buoy, "Hailing", operated without any failure for one year in South China Sea. "Hailing" implemented two 60 W wave energy pneumatic generators, one 30 W solar panel and a complementary power management system [123]. This means that wave energy could become the major renewable energy source for the mid-scale buoy.

As nerve nodes to the ocean, marine sensors perceive all sorts of valuable physical quantities, such as conductivity (salinity), temperature, depth (pressure), wave, wind, current (tide), radiation, turbidity, potential of hydrogen, dissolved oxygen and nitrogen concentration [124]. In many occasions, the signals from the sensors need to be delivered to data acquisitors, in which, they are turned into time series in certain steps to be stored, transmitted or processed [125–127]. The data are used to predict the weather [128], hurricanes and cyclones [129] and monitor the environment [130]. The earlier representative of the data buoy is the McLane moored profiler designed by Woods Hole Institute (with an auto-lifting function) [131] and that designed by Norway SAIV AS with an electrical winch [132]. The international Argo project has deployed over 3200 oceanographic data buoys to increase sampling quantities and coverage in time and area [133]. Other data buoys could be the buoys carrying GNSS receivers for geological monitoring [134] and the drifting buoys with INSAT communication for the sea surface observations [115].

Compared to power supply buoys or navigation buoys, data/sensor buoys do not require much volume. In fact, data/sensor buoys can be relatively small-scale. The Seahorse buoy is an autonomous profiler designed by Bedford Institute of Canada that consists of a buoy, jacketed wire, suspended weight and buoyant instrument package. The Seahorse buoy utilizes wave energy to deliver the buoyant instrument downward along the mooring line [135]. The successor of Seahorse, Wirewalker, follows a similar wave-powered mechanism, but makes the device even simpler and cheaper [136]. The U.S. Navy's sonobuoy AN/SSQ-101 is an air-deployable active receiver. It is said that AN/SSQ-101 is powered by converting wave energy through an integrated linear magnetic generator [137]. Wave energy greatly increased the mission endurance. In turn, the unit cost of AN/SSQ-101 is significantly reduced so that it can be extended to civilian purposes, such as monitoring marine mammals, port security and seismic activity [138].

Due to the limitations with the battery of the buoy, the service availability of the functional device on-boarding a buoy is largely determined by its standby time and its temporal resolution [139]. The power requirement of the functional devices involved with buoys ranges from 10^{-3} W to 10^2 W. Approximately a quarter of them (mostly small-scale, single-function sensors) have a power consumption of less than 1 W. Over half of them have a power consumption within 1–10 W (e.g., camera). Approximately 20% of the functional devices require a power of 10–100 W (e.g., beacon light), whereas the rest (requiring more than 100 W) are some larger-scale, comprehensive systems [140].

The wave energy technologies could be extended to other marine buoys. In fact, as the world population and economy grow, the demand for marine protein has increased rapidly in the past few decades. Aquaculture buoys are effective equipment used to

increase aquaculture production and, at the same time, protect the environment. Echosounder buoys could reduce the number and impact of fish-aggregating devices [117]. Low-cost aquaculture buoys could collect physical, chemical and biological data from marine farms, which help to determine whether the area is suitable for activities such as lobster breeding [13]. The finfish-breeding buoy could store different types of feed for a long time [116], whereas the feed buoy could feed fish autonomously [141]. Generally speaking, small-scale buoys such as aquaculture buoys follow a design philosophy of being low-cost and robust. Therefore, sensor buoys and aquaculture buoys have become an appropriate application scenario for the TENG-based PTO. A combination of single-body OB and flexible track nanogenerator could power these buoys in a robust way [142,143].

Dynamic environments are usually the negative factors for solar panels, but, to a certain extent, they can supply more energy to wave power systems [144]. Many studies on self-powered buoys are attempting to shift the buoys' power source from solar energy to wave energy in order to reduce weight and to increase the power capacity [145]. For instance, a position-tracking buoy powered by a wave-drive EMG-TENG hybrid generator has been developed by Chandrasekhar et al. Sea trials revealed that the wave-powered buoy realized GPS position tracking for itself a few kilometers away from shore [146]. Li et al. developed an EMG-based wave energy powered buoy that could automatically charge a lithium battery and discharge external loads. In sea trials in the Yellow Sea, it yielded a power density of 210 W/m^3 , which is adequate for supporting many low-power sensors [84]. A modular wave-energy-powered buoy (developed by Vella et al.) went through a series of model tests under both regular and random waves. The buoy generated an average power output value of around 0.9 W under a mild sea state of a 0.2 m wave height, meaning that it could become an observational buoy with a longer lifespan [147]. Chen et al. developed a wave-energy-powered buoy by integrating an EMG/TENG hybrid generator. The buoy served as a self-powered sensing node and transmitted the sensing data over a distance of 300 m in real sea trials [148].

It is found that the above wave energy marine buoys can be categorized into "wave energy converter buoys" (such as Ocean Power Technologies' PB3, AWS' Archimedes Wave) and "wave energy powered buoys" (such as Masuda's navigation buoy, AN/SSQ-101 sonobuoy) depending on whether they can output electrical power to exterior payloads not on-boarding the buoy. There is not a solid boundary for the two buoy types. In fact, PB3 can be scaled down (at a reduced cost) to supply power only to on-board payloads [56]. AWS' Archimedes Wave can be scaled up to over 500 kW per unit, making it closer to a power station [121].

5. Conclusions and Prospects

The study has reviewed the status of wave energy marine buoys, and provides an insight into the development of both wave energy utilization and marine distributed systems. The review is expanded to wave energy capturing, PTOs (generators) and applications of marine buoys. It can be summarized from the study that:

- Concurrent marine buoys usually adopt solar photovoltaic systems as the in situ supplemental power, followed by wind turbines. However, the power density, access easiness and engineering factors make wave energy a more promising alternative (if not a replacement) for marine buoys.
- Wave energy capturing has evolved into three major categories. Though the design has not converged, some prototypes have entered full-scale sea trial stage, demonstrating partial readiness for commercialization. As far as a marine buoy is concerned, essentially, it prefers a smaller size, structure simplicity and axisymmetry for main geometry. Therefore, the two-body point absorber, OWC spar type buoy and single body point absorber appear to be more appropriate for marine buoys.
- Conventional rotational EMGs are the common PTOs for wave energy, and adopt turbine/gears to transmit the wave-induced motion to motor rotations. Linear direct generators are a developing technique used to directly utilize the significant relative

heave motion. TENGs are a novel technique that directly converts miscellaneous mechanical energy to electricity. Their adaptability to a high-entropy input makes them a promising alternative for small-scale buoys.

- The application of marine buoys has mainly extended to power supply buoys, navigation buoys, data/sensor buoys and aquaculture buoys. Power supply buoys and navigation buoys have partially implemented wave energy technologies with EMGs. Sensor buoys and aquaculture buoys require a relatively smaller scale. Therefore, wave energy technologies could become very effective in achieving self-power for these buoys.
- It is determined by the functions of many small-scale buoys that they are largely disposable. Wave energy technologies could extend such buoys' service time so that the unit cost of such buoys can be greatly reduced. In this sense, wave energy PTO should be low-cost, simple and robust. A combination of a single OB and flexible track TENG seems to be a promising technique.
- Wave energy buoys tend to differentiate into "wave energy converter buoys" and "wave-energy-powered buoys", which is indicated by the ratio of the PTO power to the load power. The former specialize in outputting the converted electricity to the clients, whereas the latter emphasize self-powering the applications on the buoy. Both of them need to improve the power density and reduce the costs. The philosophy of converter buoys is concerned more with hydrodynamic responses, whereas the philosophy of wave-powered buoys is concerned more with the integration level.

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