

A Review of Pendulum Systems and Structures for Wave Energy Conversion

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Abstract

Wave energy has emerged as a promising renewable energy source due to its high energy density and consistency compared to solar and wind. This literature review explores the technological components and design considerations of wave energy converters (WECs), focusing on primary systems, power take-off (PTO) mechanisms, and innovative concepts utilizing enclosed-hull converters based on pendulum systems and structures. Various WEC designs are analyzed with respect to their operational principles, advantages and limitations. Special attention is given to recent advances in enclosed WEC systems utilizing pendulum-based inertial converters. These devices offer a flexible means for establishing resonant response of a PTO enclosed within the WEC buoy or hull, and as such, pendulum-based WECs have attracted significant interest within academia and relevant industry stakeholders. Through comprehensive comparison and evaluation, this review identifies key trends and challenges in the development, optimization and commercialization of pendulum-based wave energy technology.

Keywords: pendulum; wave energy; wave power; review; offshore; renewable energy; wave energy converter; energy harvesting

1. Introduction

Wave energy harvesting has garnered increasing attention as societies worldwide strive to diversify their renewable energy portfolios and reduce dependence on fossil fuels. The pressing need to mitigate climate change, ensure energy security, and support sustainable development has driven the exploration of marine energy resources, particularly wave energy. Ocean waves are a dense and predictable source of renewable energy, with global theoretical wave energy potential estimated at approximately 32,000 TWh/year—more than the total global electricity demand [1]. The first Global Ocean Energy Resource report compiled by the International Renewable Energy Agency (IRENA) states the key finding that ocean energy can realistically meet 13% of global power demand [2,3]. This highlights that ocean energy will have a major share of renewable power going forward, and it will be part of decarbonizing energy systems alongside wind and solar. Moreover, unlike solar and wind, wave energy provides more consistent power output due to the inertia of ocean waves and their continuous generation even after storms or wind events have ceased.

From a societal perspective, harnessing wave energy contributes not only to environmental sustainability but also to economic resilience and job creation, particularly in

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coastal and island communities [3,4]. These regions often face high energy costs due to reliance on imported fuels. Wave energy can provide a local, decentralized energy source that enhances grid stability and supports local economies [5]. Moreover, wave energy infrastructure can be co-developed with other marine infrastructure, such as offshore wind turbines, fostering a multi-use approach to ocean space [6]. In addition, the growing urgency to meet international climate goals, such as those outlined in the Paris Agreement, reinforces the societal demand for clean energy innovations [7]. The deployment of wave energy converters (WECs) is aligned with this global effort, offering a promising path to reduce greenhouse gas emissions while leveraging one of the most underutilized natural resources [8]. Governments and research institutions have recognized this potential, leading to increased investments in wave energy technologies, pilot projects, and supportive regulatory frameworks. The societal need for wave energy harvesting stems from its potential to provide sustainable, reliable, and clean electricity, contributing to climate change mitigation, economic growth, and energy independence.

As technological advancements continue to improve the efficiency and viability of wave energy systems, their integration into future energy systems becomes not only feasible but imperative. A major challenge identified by the wave energy community is the device survivability. As a response to this problem, enclosed-hull WECs have emerged as a promising solution in recent years, with pendulum-based systems progressively dominating this technical domain [9,10]. Coupled with the novel opportunities offered by the expanding blue economy, pendulum WECs are identified as an emerging enabling technology. By offering a comprehensive overview of state-of-the-art pendulum WEC technologies, milestones, and open problems in the field, we aim to benefit the research community, offering a gateway for those addressing these challenges. Initially the review objective was identified as the need to report recent developments in enclosed WECs, due to their comparative advantages in terms of survivability and adaptability to harsh and low sea states. Pendulum-based systems also offer design simplicity and a unique possibility of undergoing continuous rotational motion, which altogether led to the current review topic of pendulum-based WECs. Searches were executed across Scopus, IEEE Xplore and Web of Science covering the literature up to September 2026. The complete search string utilized was: ("pendulum" OR "eccentric rot*") AND "wave energy conver*" within article metadata including the article title, abstract, keywords and indexing. The search returned 402 results, of which 112 were used for this review. The original articles were screened for relevance and main-topic suitability. Only research works presenting a novel enclosed-hull pendulum concept, a process strictly related to pendulum systems, or an application improved by pendulum-based WEC integration survived this screening stage. Various papers used the term pendulum for flaps used in Oscillating-Surge WECs (OSWECs) and therefore failed the screening test. Furthermore, various papers reported concepts on Triboelectric Nanogenerators (TENGs). While specific studies on the transduction properties of TENGs for general IoT applications lie outside the main focus of this review, hybrid electromagnetic–TENG mechanisms that utilize internal pendulum dynamics or swinging masses as their primary mechanical driver have been included. Last, some authors used pendula as a power take-off (PTO) case study without a clear scope in the development of pendulum-based PTOs. As such, they were also excluded from this review.

In recent years, valuable review articles have examined built-in and rigid-hull encapsulated wave energy converters (WECs) [9,10]. For example, Hasan Maheen and Yang provided a broad overview of rigid-hull encapsulation concepts [10], while Wang et al. summarized built-in WECs from a high-level structural and application perspective [9]. However, existing reviews treat internal reaction and pendulum mechanisms as secondary sub-components within a generalized structural summary, lacking a dedicated focus on the underlying nonlinear dynamics that dictate energy conversion in pendulum-based WECs.

To fill this critical gap, the present review provides a specialized focus on pendulum-based WECs. Unlike previous works, this review establishes a formal kinematic taxonomy (horizontal, vertical, inverted, and parametric) for pendulum WECs, details recent advances in utilizing parametric resonance and continuous rotational response for extracting wave power, evaluates specialized rotation-initiation control strategies, and explores multi-pendulum internal phase synchronization alongside farm-level array effects. In this way, the present review highlights the potential of fully leveraging the pendulum nonlinear response for rotational energy harvesting.

The review is organized as follows. Section 2 presents an overview of the background of wave energy conversion, focusing on hydrodynamics basics and the main WEC subsystems. Section 3 presents an overview of the main point-absorber-type WECs, the family in which enclosed pendulum-based converters belong, in order to provide a relative technical context. Then, pendulum-based WECs are reviewed in Sections 4 and 5. The concepts are divided into four main categories, namely, horizontal-axis, vertical-axis, inverted and parametrically excited systems, elucidating the various concepts and their associated attributes for efficient wave energy conversion. Lastly, Section 6 presents the main conclusions of this review.

2. Wave Energy Conversion Fundamentals

A WEC is composed of several fundamental components that together enable it to harness energy from ocean waves and convert it into usable electrical power.

2.1. WEC Subsystems

At the core of every WEC is the primary structure, which interacts directly with the water surface and absorbs the wave energy. Depending on the type of device, this structure might be a buoy, a floating body, an oscillating flap, a partially submerged chamber, or even a ramp and reservoir system, as in overtopping devices. This part must be carefully engineered to maximize energy capture while maintaining stability in harsh marine environments. The absorbed wave motion is then transferred to the PTO system, which is the mechanism responsible for converting mechanical motion into electrical energy. PTO systems vary significantly and can include linear or rotational electric generators, hydraulic circuits, pneumatic turbines, or even advanced control systems. The choice of PTO heavily influences the efficiency, control strategy, and maintenance requirements of the WEC.

The harvested mechanical energy must then be processed and transmitted via the electrical subsystem, which includes power electronics (converters, inverters), transformers, and subsea electrical cables. To remain in place, WECs utilize a mooring and anchoring system (chains, synthetic ropes, drag-embedment anchors) which secures the device and often contributes to the dynamic response by adding tension or damping [11]. Modern WECs rely on sophisticated control systems (latching, declutching, reactive control) to adapt to changing sea states, supported by mechanical frameworks like spars or semi-submersibles [12–14]. Performance is monitored via an array of sensors (accelerometers, load cells, gyroscopes), with experimental setups sometimes including onboard energy storage and environmental telemetry [15].

2.2. Mooring

Mooring systems are essential in WECs as they maintain the device's position relative to the seabed while allowing sufficient freedom of motion to capture wave energy efficiently. A well-designed mooring system balances station-keeping stability, hydrodynamic response, and structural reliability while minimizing costs. The dynamic interaction between mooring forces, hydrodynamic loads, and WEC motions strongly influences overall energy capture and survivability.

Catenary moorings [16] utilize heavy chains that rest on the seabed, providing restoring force primarily through line weight. The horizontal restoring force can be derived from the catenary equations. For catenary moorings, nonlinear cable dynamics are often captured using finite-element or lumped-mass models. Taut moorings [16] use lighter synthetic ropes (e.g., polyester) with significant elasticity, modeled as nonlinear springs.

Hybrid moorings combine the capabilities of both the taut moorings and the catenary moorings, offering flexibility and stability for deep-water WECs. Mooring forces not only restrain the WEC but also modify its natural frequencies. Overly stiff moorings can detune resonance, reducing power capture, while compliant moorings may enhance heave or surge resonance, improving performance. Advanced studies couple Computational Fluid Dynamics (CFD) with finite-element mooring models to optimize the balance between station keeping and energy efficiency [17].

Finally, in practical hydrodynamic modeling, the nonlinear catenary restoring forces of the mooring system are often approximated by equivalent linear stiffness (K_m) and damping (C_m) coefficients about the mean equilibrium position [11,18]:

$$F_{moor}(t) = K_m z(t) + C_m \dot{z}(t), \quad (1)$$

2.3. Hydrodynamic Modeling

The dynamics of a WEC are governed by the interaction between the incident wave field and the device's subsystems. A widely adopted approach for modeling these interactions is based on linear potential flow theory, assuming inviscid, incompressible, and irrotational flow [19]. Under these assumptions, the motion of a floating WEC is typically expressed through a Cummins-type integro-differential equation of motion [20]:

$$(M + A(\infty))\ddot{x}(t) + \int_0^t K_r(t - \tau)\dot{x}(\tau)d\tau + Cx(t) = F_{ext}(t) - F_{PTO}(t) - F_{moor}(t), \quad (2)$$

where $x(t)$ represents the displacement vector, $x(t) = [x, y, z, roll, yaw, pitch]^T = x_{hull}(t)$, M is the device's inertia matrix, $A(\infty)$ is the added mass at infinite frequency, K_r is the radiation impulse-response function accounting for wave radiation damping, C is the hydrostatic stiffness matrix, F_{ext} is the wave excitation force due to incident waves, F_{PTO} is the force applied by the PTO system and F_{moor} is the mooring restoring force.

Unlike ordinary equations of motion, the radiation force depends not only on the instantaneous velocity but on the entire past history of motion, reflecting a non-Markovian nature. In the time domain, this radiation effect is equivalently described by the added mass term and the convolution (memory) integral involving the radiation impulse-response function [21–24].

In the frequency domain, the excitation force for a deterministic wave component, the complex excitation force amplitude $\hat{F}_{exc}(\omega)$ is related to the complex wave elevation amplitude $\hat{\eta}(\omega)$ via the linear excitation transfer function $X(\omega)$ (calculated using Boundary Element Method solvers such as WAMIT and ANSYS AQWA) as depicted in Equation (3). For a random sea state characterized by a one-sided wave elevation power spectral density $S_\eta(\omega)$ (such as Pierson–Moskowitz or JONSWAP), the excitation force power spectral density $S_{F,exc}(\omega)$ takes the form shown in Equation (4).

$$\hat{F}_{exc}(\omega) = X(\omega)\hat{\eta}(\omega) \quad (3)$$

$$S_{F,exc}(\omega) = |X(\omega)|^2 S_\eta(\omega) \quad (4)$$

This method is acceptable since the wave height is small compared to the wavelength and the water depth and the fluid velocity is low [25].

When a WEC oscillates in waves, it radiates outgoing waves, resulting in energy losses and reactive forces. Together, the excitation and radiation parameters shape the dynamic Response Amplitude Operator (RAO) of the device.

2.4. Wave Resource

A critical aspect of the design and successful deployment of a WEC lies with understanding the ocean wave resource and applying pertinent models of wave excitation to reveal the dynamic interactions with the wave device.

2.4.1. Spectral Models

A fundamental aspect of wave energy research is the accurate characterization of the sea state, which is essential for predicting both the power performance and survivability of WECs. Before analyzing the mechanical extraction of energy, it is critical to understand the distribution of that energy within the ocean itself.

Ocean waves are typically described using spectral models, which represent the distribution of wave energy across different frequencies. The most widely used formulations are the Pierson–Moskowitz (PM) spectrum and the JONSWAP (Joint North Sea Wave Project) spectrum [26].

The PM spectrum assumes that wind has acted long enough and over a sufficient distance to generate equilibrium conditions, making it ideal for representing fully developed, open-ocean environments. However, real-world offshore conditions are frequently limited by finite fetch and duration. The JONSWAP spectrum refines the PM model to account for these fetch-limited, developing seas by introducing a peak enhancement parameter, γ . This captures the spectral narrowing often observed in realistic sea states.

$$S(\omega) = \alpha g^2 \omega^{-5} \exp \left[-\frac{5}{4} \left(\frac{\omega_p}{\omega} \right)^4 \right] \gamma^{\exp \left[-\frac{(\omega - \omega_p)^2}{2\sigma^2 \omega_p^2} \right]}, \quad (5)$$

where $S(\omega)$ is the one-sided wave elevation power density at angular frequency ω , g is gravitational acceleration, ω_p is the peak frequency, and γ (typically between 1 and 7) controls the spectral enhancement at the peak [27]; σ is the spectral width with values 0.07 for $\omega \leq \omega_p$ and 0.09 $\omega > \omega_p$; α is the non-dimensional Phillips scaling constant. Compared to the PM spectrum, JONSWAP produces higher and sharper peaks, which better represent realistic offshore conditions where wave growth is limited by finite fetch and duration.

2.4.2. Wave Power Flux and Yield Estimation

In wave energy modeling, these spectral descriptions provide the foundation for estimating wave power flux. The average energy transport per unit crest length, assuming deep-water conditions, is given by:

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e, \quad (6)$$

where ρ is seawater density, H_s is the significant wave height, and T_e is the energy period. By combining spectral models such as JONSWAP with site-specific wave climate data, researchers generate wave scatter diagrams, which classify sea states into bins of H_s and T_e . These distributions are then coupled with a device's power matrix to estimate its annual energy production [28].

2.4.3. Integration with Control and Simulation

Beyond simple energy yield estimation, wave spectral models are deeply integrated into the numerical simulations and control strategies required for advanced WEC design. Time-domain models often rely on irregular sea state realizations generated through inverse Fourier transforms of spectra like JONSWAP, ensuring that hydrodynamic models capture realistic environmental variability. Furthermore, advanced control algorithms—such as latching and reactive control—require highly accurate spectral inputs to predict excitation forces and dynamically optimize energy capture.

In summary, the modeling of ocean waves through formulations like PM and JONSWAP underpins the entire techno-economic assessment of WECs. As wave energy progresses toward commercialization, the continuous refinement of these wave spectra and their integration into coupled hydro-servo-elastic models remains critical to bridging the gap between theoretical potential and reliable offshore operation.

2.5. Control Strategies

Since ocean waves are stochastic and irregular, WECs require sophisticated, dynamic control strategies to synchronize the PTO force, $F_{PTO}(t)$, with the incident wave excitation. To translate raw hydrodynamic power into viable electricity, a highly integrated network of mechanical, electrical, and structural subsystems is required.

2.5.1. Passive Damping

The simplest approach is passive damping, modeled linearly as $F_{PTO}(t) = B_{PTO}(t)\dot{x}(t)$, while more advanced reactive control matches the WEC impedance to the wave excitation force, expressed as $F_{PTO}(t) = B_{OPT}\dot{x}(t) + K_{OPT}(t)x(t)$, which satisfies the complex conjugate matching condition for resonance but necessitates complex, bidirectional power flow, where B_{OPT} and K_{OPT} are frequency-dependent coefficients chosen to satisfy the complex conjugate matching condition. This allows resonance with incoming waves but requires bidirectional power flow, which increases control complexity [29].

2.5.2. Rotary Generator Control

Rotary generators in WECs are often based on permanent-magnet synchronous machines (PMSGs). The challenge in marine conditions is the stochastic, irregular nature of incoming waves, which leads to continuously varying input torque. Field-Oriented Control (FOC) [12] is the most common method, as it decouples flux and torque components in the dq -reference frame, allowing independent control of active and reactive power. This is crucial for marine applications, where grid compliance and efficient energy extraction are required under rapidly fluctuating conditions.

To optimize efficiency, Maximum Torque per Ampere (MTPA) strategies are often embedded within FOC to minimize copper losses for a given torque demand [30]. Meanwhile, Maximum Power Point Tracking (MPPT) algorithms adapt generator torque to match the hydrodynamic optimum of the WEC device, thereby improving conversion efficiency across varying sea states [31]. An additional strategy is direct torque control (DTC), which allows faster dynamic response compared to FOC, although at the cost of higher current ripple [32]. In practice, advanced control blends FOC and predictive torque control with wave forecasting, creating a synergy between generator dynamics and the ocean environment.

2.5.3. Latching Control

Latching control is a discrete phase-control strategy designed to maximize the energy extraction of WECs by artificially aligning the velocity of the oscillating body with the

incident wave excitation force [13]. In practice, the mechanism locks the moving component of the WEC in place the moment its velocity reaches zero, typically at the extremes of its oscillation, and holds it until a calculated optimal release time. By deliberately delaying the motion, latching control lengthens the effective natural period of the device to resonate with the frequency of the incoming waves, leading to significantly amplified motion amplitudes and, consequently, enhanced power capture. This approach is particularly advantageous for point absorbers operating in sea states with wave periods longer than the device's own resonant period, allowing for substantial efficiency gains without requiring reactive power flow from the grid.

The physical implementation of latching control introduces severe nonlinearities into the system dynamics, presenting complex challenges for the design of the PTO system. If the control acts as a discontinuous switching function, then the PTO must be equipped with robust mechanical, hydraulic, or magnetic braking mechanisms capable of instantly locking against significant structural loads and releasing with minimal frictional losses. Furthermore, in irregular ocean waves, achieving optimal efficiency requires advanced wave forecasting and noncausal control algorithms to accurately predict the future excitation force and determine the exact release threshold [33]. The interplay between these sudden dynamic shifts and the inherently nonlinear behavior of advanced PTO systems necessitates rigorous transient analysis to prevent mechanical fatigue and ensure the survivability of the converter under harsh marine conditions.

2.5.4. Model Predictive Control

Model Predictive Control (MPC) is an advanced control strategy that uses a mathematical model of a system to anticipate its future behavior and optimize its performance over a defined time window [34]. Unlike traditional reactive controllers, such as standard PID controllers that adjust based strictly on past and present errors, MPC is inherently proactive. It actively computes a trajectory of future system states based on a sequence of proposed control inputs. By mathematically simulating how the system will react, the controller can select the optimal sequence of actions that minimizes a specific objective.

The core mechanism driving MPC is known as Receding Horizon Control. At every single sampling interval, the controller logs the current state of the system and solves a complex, real-time optimization problem to forecast a finite number of steps into the future (the “prediction horizon”). Although it calculates a full sequence of optimized future inputs, the system only physically executes the very first control action of that sequence [35]. In the next time step, the controller takes an updated measurement of the system's state, shifts the horizon forward by one step, and recalculates the optimization problem. This continuous feedback loop allows the controller to instantly correct for unmeasured disturbances, model inaccuracies, or changing dynamics.

2.6. WEC Classification and Topologies

Typical classification of WEC devices is based on location and on the operating principle determining the device type.

2.6.1. WEC Topology

Wave climates and hydrodynamic loads vary drastically with water depth and proximity to land. Based on this, WECs are primarily classified by their deployment location.

Onshore systems are installed directly on or adjacent to the coast, typically integrated into fixed structures such as breakwaters. These devices benefit significantly from simplified installation and maintenance, as their proximity to land eliminates the need for complex, deep-water mooring systems and long subsea transmission cables. A pioneering example is the Islay LIMPET (Land Installed Marine Power Energy Transmitter) in Scotland,

a shoreline Oscillating Water Column (OWC) embedded into a coastal structure and connected directly to the grid. Furthermore, nearshore or coastal-structure-integrated WECs (CSI-WECs), such as breakwater-embedded OWCs or wall-mounted heave devices, serve a dual utility by simultaneously protecting coastlines while generating energy [36].

Nearshore WECs are situated in shallow waters, typically at depths of less than 50 m and within a few kilometers of the shore. These systems capture a more meaningful wave resource than onshore devices, while avoiding the logistical and structural demands of deep-water deployments. Nearshore technologies encompass a variety of energy capture principles, including point absorbers and attenuators, and can either be anchored to the seabed or mounted on existing coastal infrastructure [37]. A classic example of this category is the Oyster.

Offshore WECs are deployed in deeper waters, exceeding 50 m in depth, and are often located several kilometers from the coast. These devices are designed to harness the highest possible wave energy densities, as deep-water waves have not yet lost energy to seabed friction. However, tapping into the offshore energy reservoir introduces substantial engineering challenges. The severe marine environment significantly increases both Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Furthermore, offshore systems require highly resilient, complex mooring arrays and long, dynamic cabling systems, which can pose environmental or navigational concerns.

2.6.2. Classification by Technology Type

While WECs can be classified based on geometry, operation mode, and installation location, the vast majority of developmental and commercial systems fall into three fundamental technological categories: Oscillating Water Columns (OWCs), overtopping devices, and oscillating bodies as seen in Figure 1.

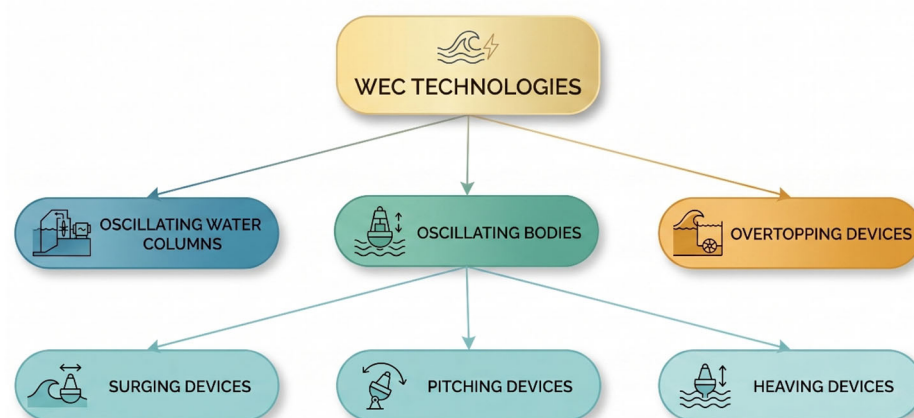


Figure 1. Fundamental WEC categories.

OWCs [38] are characterized by a partially submerged, hollow structure that opens to the sea below the waterline. These systems utilize the periodic, wave-induced rise and fall of the water's free surface within the chamber to compress and depressurize a trapped air column. This pneumatic pressure forces the air through pipes and into a bidirectional air turbine (such as a Wells turbine), which drives an electrical generator. Recent studies indicate that optimizing the chamber's shape and draft can significantly enhance the pneumatic power capture of OWC systems.

Overtopping devices [39] operate on principles similar to traditional hydroelectric dams. They are designed with a ramp structure that captures water from incident waves and directs it into elevated storage reservoirs situated above the mean sea level. The

potential energy of this stored water is then converted into electrical energy as the water falls back to the sea through low-head hydraulic turbines connected to generators.

Oscillating-body devices [40] are the primary focus of this review. Unlike OWCs and overtopping systems that rely on fluids (air or water) as intermediate mediums, oscillating bodies interact mechanically with the wave field. These devices are constructed from one or several components that permit continuous oscillation and displacement around a designated reference point. As incident sea waves excite the primary structure, the mechanical motion is directly transferred to the PTO system.

Oscillating-body WECs can be engineered to match the frequency of incoming waves (resonance tuning) and operate across multiple degrees of freedom (heave, pitch, roll), and as such they generally allow the PTO system to absorb greater portions of the wave's energy compared to other WEC types. This category encompasses traditional heaving point absorbers, multi-body attenuators, and pendulum-based configurations, among others.

2.7. Performance Metrics

A key aspect of WEC development is a commonly understood framework for performance evaluation and concept benchmarking.

2.7.1. Power Evaluation

To evaluate whether a WEC design is viable for commercialization, its theoretical hydrodynamic efficiency must be translated into realistic electrical output metrics.

WECs utilize a power matrix coupled with site-specific wave climate data (scatter diagrams) to calculate the expected power generation. The power matrix consists of the two variables H_s and T_e/T_p (energy bins), which are the significant height and the period of the waves [41], and the value inside the cells is given by $P(H_s, T_p) = \frac{\eta_{PTO}}{T_{sim}} \int_0^{T_{sim}} P(t) dt$, where η_{pto} is the efficiency or the percentage of power converted to electricity, and T_{sim} is the time duration of the tests. As observed in Figure 2, when height H_s exceeds structural design limits, the PTO could go into lock-down/survival mode, setting output power to 0.

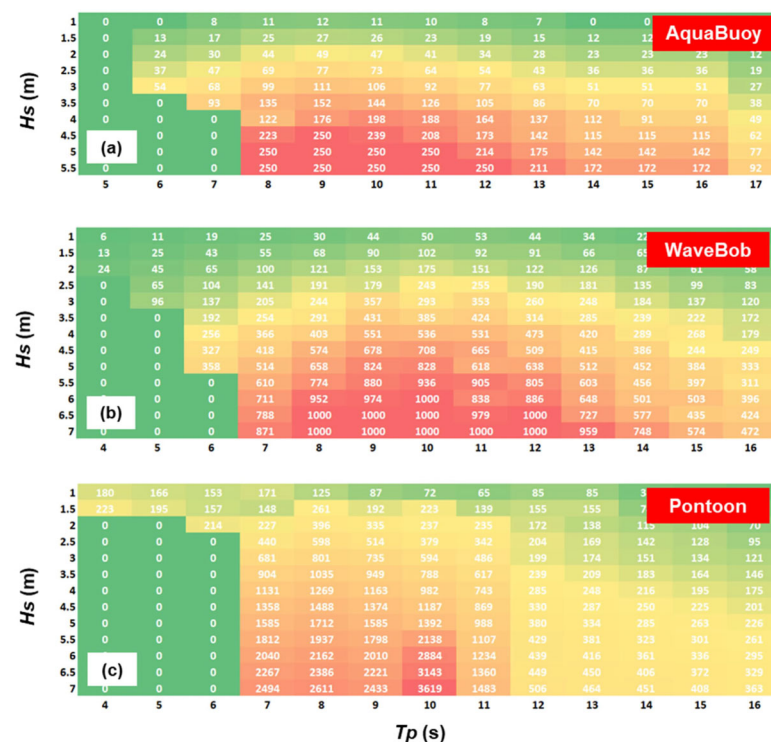


Figure 2. The power matrices of (a) AquaBuoy, (b) WaveBob and (c) Pontoon from [42].

2.7.2. Capacity Factor and Capture Width

The Capacity Factor (C_f) is a fundamental indicator of a WEC's operational utilization and economic viability. It is defined as the ratio of the mean actual net electrical power generated over a given operational period (P_{avg}) to the device's continuous rated maximum generator capacity (N_p). Alternatively, over an annual timeframe ($T_{annual} = 8766$ h), C_f represents total net electrical energy produced divided by the theoretical maximum energy output if the device operated continuously at rated capacity. Another fundamental metric for evaluating primary hydrodynamic efficiency is the Capture Width C_w . It is defined as the ratio of the mean absorbed mechanical or electrical power, P_e , to the incident wave energy flux per meter of wave crest, P_w . Conceptually, to enable horizontal efficiency comparisons across floaters of different physical scales, C_w is normalized by the characteristic physical breadth of the floater (B), yielding the dimensionless capture width ratio (CWR). These metrics are given by:

$$C_f = \frac{P_e}{N_p} 100\%, \quad (7)$$

$$C_w = \frac{P_e}{P_w}, \quad (8)$$

$$CWR = \frac{C_w}{B} = \frac{P_e}{P_w B}. \quad (9)$$

While WECs offer theoretical energy production proportional to $H_s^2 T_e$, their real-world capacity factors typically span from 5% to 35%, with the majority of early-stage projects operating under 15%. For context, the Mutriku Wave Plant in Spain (an onshore OWC array) achieved an average capacity factor of 11% between 2014 and 2016 [43]. The Pelamis and AquaBuoy systems achieved 9–11% in the Mediterranean, though they exceeded 20% in more energetic Canadian waters [44]. Conversely, the nearshore Eco Wave Power installation in Valencia, Spain, achieved a capacity factor of ~29%, rivaling local solar efficacy [45].

2.8. Economic Feasibility

Economic feasibility is a primary driver in WEC design and commercialization [46,47]. The Levelized Cost of Energy ($LCOE$) is a major evaluation metric for a WEC to reach commercialization and consists of the cost per unit MWh. According to Vanegas-Cantarero et al. [48] the $LCOE$ can be formulated as

$$LCOE = \frac{CapEx + \sum_{t=1}^n \frac{OpEx_t}{(1+r)^t} + \frac{DecEx_n}{(1+r)^n}}{\sum_{t=1}^n \frac{AEP_t}{(1+r)^t}}, \quad (10)$$

where n is the life expectancy of the device in years, t is the year from the beginning of the installation, r is the discount rate (%) which accounts for the value of the money as a function of time, $CapEx$ is the total initial cost of the device which takes into consideration the fixed assets and $OpEx$ includes the ongoing costs for running the project throughout its lifetime. $DecEx$ is the expenditure incurred during end-of-life platform decommissioning, retrieval and disposal. Finally, AEP_t is the annual net electrical energy production delivered to the grid in year t .

$$AEP_0 = PC C_f AF 8766, \quad (11)$$

$$AEP_t = AEP_0(1 - d)^t \quad (12)$$

where PC is the project capacity, C_f is the capacity factor, AF is the availability factor ($0 \leq AF \leq 1$), and 8766 is the number of hours in a year, including leap years. The project capacity is defined as the number of devices multiplied by the devices' rated powers, d is the annual performance degradation rate resulting from biofouling or structural mechanical wear, and AEP_0 is the baseline first-year net electrical production.

To reduce overall LCOE and enhance WEC robustness, engineers can apply probabilistic structural optimization. This optimization incorporates both energy performance and reliability objectives. For example, Garcia-Teruel et al. optimized the hull geometry of a point-absorber WEC to minimize damage equivalent load at welds while maximizing mean power output under diverse sea states [49].

Understanding and prioritizing failure modes is critical. Techniques like FMECA (Failure Modes, Effects and Criticality Analysis) [50] inform maintenance and design decisions by quantifying relative component criticality. Recent experience has revealed that in hydraulic PTO subsystems, valves and pumps are the most failure-prone components (~87% of annual failures). In mechanical PTOs, fatigue in bearings is dominant (~74%) and in mooring systems, while the probability of failure is lower, they still pose a high economic risk if they do so.

To evaluate system survivability, bottom-up Reliability, Availability, and Maintainability (RAM) modeling calculates the component-level failure rate λ_C (expressed in failures/10⁶ operating hours) based on standard reliability handbooks (e.g., MIL-HDBK-217F and OREDA databases):

$$\lambda_C = \lambda_B \pi_E \pi_{FM} \pi_{DS}, \quad (13)$$

where λ_B is the base failure rate from the component's databases (failures/10⁶ h), π_E is the environmental adjustment factor (accounting for ocean temperature variations, salinity, and wave-induced cyclic fatigue loads), π_{FM} is the failure mode adjustment factor and π_{DS} is the data-source adjustment factor. System-level availability (AF) is subsequently derived by coupling component failure rates λ_C with Mean Time to Repair ($MTTR$) and site-specific weather accessibility windows [51].

Enhancing the reliability and survivability of WECs requires a comprehensive probabilistic framework encompassing fatigue failure modeling, structural optimization, component-level reliability and failure mode prioritization. By integrating these advanced reliability approaches into design, control and maintenance strategies, developers reduce downtime, extend operational lifetimes and increase economic viability.

3. Point-Absorber WECs

The following chapter gives an insight into point-absorber (PA) WECs and the current state-of-the-art systems for harvesting wave power. A PA comprises a floating body interacting with surface waves and a PTO unit referenced or anchored to the seabed. The floating body oscillates under the excitation of waves, and its motion drives the PTO mechanism to generate electricity.

3.1. Design of PA WEC

A key objective in primary system design is to maximize wave energy absorption through effective coupling with the incident wave field. This interaction is governed by the relative motion between the device and the water surface, often described by hydrodynamic theories such as potential flow theory. In PAs, for instance, the vertical heave motion is dominant, and resonance tuning is often applied so that the natural frequency of the floater matches the dominant wave frequency, thereby maximizing energy capture. For an SDOF heaving point absorber in regular waves, the complex displacement response is

$$\hat{z}(\omega) = \frac{\hat{F}_{exc}(\omega)}{[K - \omega^2(m + A(\omega))] + j\omega [B_{rad}(\omega) + B_{PTO}(\omega)]} \quad (14)$$

where $A(\omega)$ is the added mass, B_{PTO} is the power take-off damping coefficient, B_{rad} is the radiation damping, K is the hydrostatic stiffness, m is the effective mass and ω is the wave angular frequency.

Linear resonance theory shows that energy absorption is maximized when the system is in resonance, i.e., $K = \omega^2 (m + A(\omega))$, and the PTO damping matches the radiation damping $B = B_{rad}$. Designing the primary structure to fulfill these conditions requires careful consideration of geometry, added mass, and damping properties, all of which are affected by the shape and size of the WEC [29].

Primary systems must also be structurally robust, capable of surviving harsh marine environments while maintaining performance. They are subject to complex loading, including wave slamming, fatigue, and corrosion. Hence, the materials used are typically marine-grade composites, stainless steels, or concrete, and may be coated for additional protection. Designers must also consider biofouling and maintenance access, particularly for submerged components. In summary, the PA WEC design involves a delicate trade-off between hydrodynamic efficiency, mechanical durability, and economic feasibility.

The heave motion of a floating body is one of the most efficient modes for wave energy extraction due to its strong coupling with the predominant energy content of ocean spectra. In PA WECs, the buoy responds in heave to incoming wave excitation forces, which are maximized when the natural frequency of the system is tuned close to the spectral peak of the wave climate [29]. The governing equation of motion in the heave direction can be written as Equation (2), taking into consideration only the heave displacement $z(t)$. In the frequency domain, assuming harmonic motion $z(t) = Ze^{j\omega t}$, the mean absorbed power is given by

$$\bar{P}_{PTO}(\omega) = \frac{1}{2} B_{PTO}(\omega) \omega^2 |\hat{z}(\omega)|^2 \quad (15)$$

It should be noted that, as stated in the previous paragraphs, the maximum power absorption is still achieved when the PTO damping matches the radiation damping of the system. The average absorber power over a sea state is then calculated by integrating the spectral density of the waves with the capture width of the WEC:

$$P_{avg} = \int_0^\infty \frac{B_{PTO}(\omega) \omega^2 |X(\omega)|^2 S_\eta(\omega)}{[K - (m + A(\infty))\omega^2]^2 + \omega^2 [B_{PTO}(\omega) + B_{rad}(\omega)]^2} d\omega, \quad (16)$$

Heaving WECs often employ hydraulic PTOs (converting buoy motion into pressurized fluid), mechanical linkages (such as ball-screw or rack-and-pinion systems), or direct-drive linear generators where the translator moves vertically within a stator [52]. Linear generators are particularly attractive as they eliminate intermediate conversion stages, yielding higher efficiency and reduced maintenance. However, they require strong permanent magnets and large dimensions to handle the low-frequency, high-force nature of wave-induced motion. It should be noted that the capture width presented in Section 2.7.2 plays a significant role in choosing the optimal PTO system.

3.2. Power Take-Off Mechanisms

The PTO is one of the most critical components of any WEC, serving as the interface between the moving hull and the electrical grid. It must accommodate bidirectional, low-frequency wave motions while providing power smoothing and conversion [53,54]. Across all configurations, the PTO ultimately behaves as an energy-extraction damper within the system's equation of motion.

3.2.1. Hydraulic PTO

Hydraulic systems are frequently used in high-force, low-velocity applications. Hydraulic PTOs drive a pump that pressurizes fluid to power a motor coupled to a rotary generator. The flow Q is related to piston area and velocity by $Q = Av$, while force is $F = Ap$. While accumulators allow for output smoothing, these systems incur losses due to fluid friction and present environmental risks regarding oil leakage [55–57].

3.2.2. Mechanical PTO

Mechanical transmissions are mechanisms, such as rack-and-pinion and ball-screw mechanisms, that directly convert translational hull motion into rotational generator motion. These drives can achieve enhanced mechanical efficiency (up to ~97%) and frequency up-conversion that greatly improves generator efficiency. In a rack–pinion system, a sliding rack on the buoy engages a gear (pinion) on a generator shaft, as seen in Figure 3. The PTO force F in mechanical drives can be modeled as $F = kx + c\dot{x}$, where k and c represent stiffness and damping introduced by the mechanism and generator loading. However, purely mechanical PTOs suffer from continuous cyclic loading leading to fatigue and introduce nonlinearities like gear backlash and friction [58].

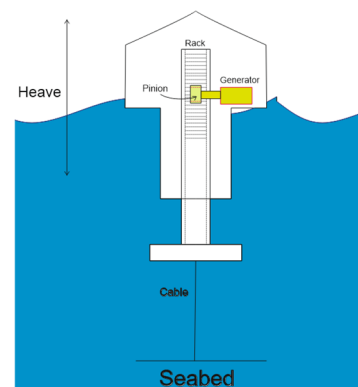


Figure 3. Sketch of a WEC that utilizes a rack-and-pinion rectification mechanism (adapted from [59]).

3.2.3. Direct-Drive Linear Generators

Direct-drive linear generators consist of a translator that moves directly within a stator, eliminating intermediate mechanical conversion stages. Driven by Faraday’s law, the moving magnets induce voltage, producing an opposing force and a back-emf ($V = k_e \dot{x}$) proportional to velocity. In an idealized linear generator model, the PTO force is $F_{pto} = -k_e x - c_e \dot{x}$ where c_e is a controllable (through electrical load) damping coefficient. The electrical power extracted is $P = F_{pto} \dot{x}$. Direct-drive linear generators eliminate intermediate conversion stages: the heaving motion is converted directly to electricity. This can yield high overall efficiency and reliability due to fewer mechanical components. For instance, full-scale prototypes such as the Archimedes Wave Swing (AWS) have used permanent-magnet linear generators to great effect. A schematic of a direct-drive generator can be observed in Figure 4a, along with inerter-based and hydraulic PTO systems in Figure 4b,c.

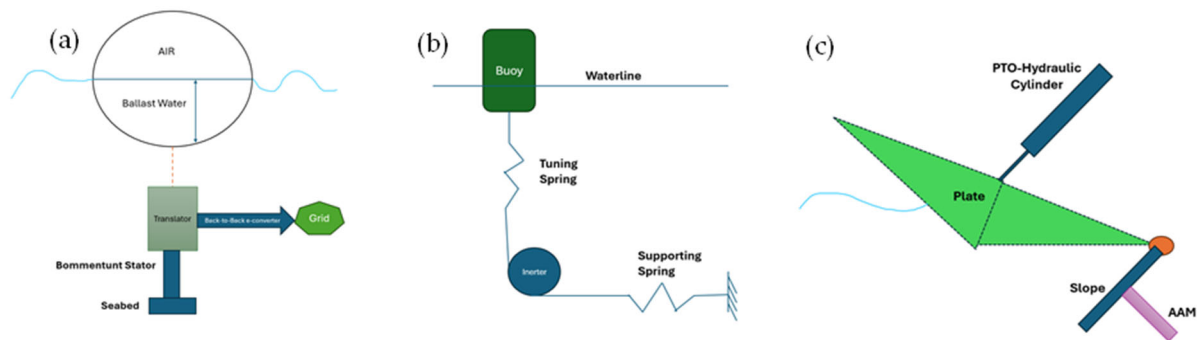


Figure 4. (a) Adjustable draft point-absorber WEC from [60]; (b) PA with inerter from [61] and (c) S-PWEC from [62].

The main limitation is force density, since, to achieve high power at low speed, a large machine with strong magnets is needed, increasing mass and cost. From a control point of view, a linear PTO often implements viscous damping. Under harmonic waves and linear dynamics, the optimal PTO impedance (damping) for maximum capture is the complex conjugate of the WEC's intrinsic impedance, which means in simple heaving systems, choosing $c_{PTO} = B_{rad}$ maximizes power. Thus, PA PTO models often incorporate a term $B_{pto}\dot{x}$ or equivalent electrical damping whose magnitude can be tuned for resonance or force feedback. Representative PAs can be observed in Figure 5.

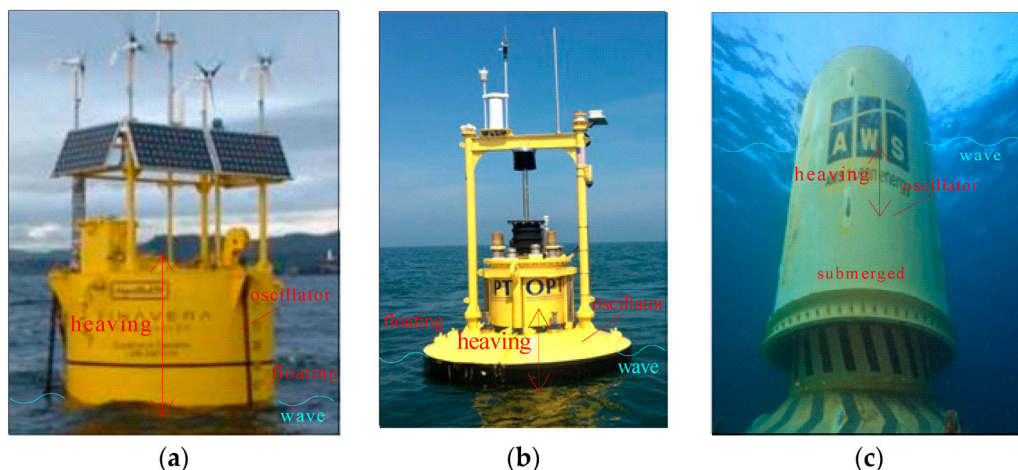


Figure 5. (a) The AquaBuoy WEC; (b) the PowerBuoy WEC and (c) the AWS WEC from [63].

3.2.4. PEGs and TENGs

For low-frequency environments, experimental designs incorporate piezoelectric generators (PEGs) and TENGs. PEGs generate charge via mechanical stress, while TENGs produce high-voltage, low-current outputs through contact separation of materials [64]. They are particularly effective at ultra-low frequencies and offer advantages such as portability, low cost, simple design, and environmental friendliness. Zhang et al. [65–67] and Zhao et al. [68] reported that their self-adaptive TENG achieved a mass power density of 502 mW/kg, $\sim 80\times$ higher than a comparable electromagnetic generator in low-frequency conditions. This indicates that this PTO technology is promising but it is still considerably immature for meso- and large-scale WECs, currently suitable only for low-power, smart monitoring.

3.3. Overview of PA WECs

Table 1 illustrates the extensive diversity in contemporary PA WEC designs, highlighting a broader industry trend toward maximizing capture width through active resonance tuning and adaptive geometry.

Table 1. Strengths and weaknesses of representative PA WECs.

Name	Ref.	PTO System	Strengths	Weaknesses
Adjustable Draft Point Absorber	[60]	Bottom-mounted linear PM generator	Increased energy capture; adaptive resonance tuning; scalable	Complex control; asymmetrical stroke; higher buoy cost
Point Absorber with Inerter	[61]	Mechanical inerter with PTO damping control	High adaptability; 250% more power; built-in damping optimization	Complex system; time delay in control; energy cost of control not included
Seabased Unit	[69]	Linear PM generator via rope drive	Simple dynamics; proven array deployment; minimal environmental impact	Rope damping; float vulnerable to extreme waves; limited generator stroke
LifeSaver Device	[70]	Winch-driven generators	High instantaneous power; integrated mooring winches; scalable	Extreme peak loads; high smoothing cost; structural failures
CorPower C4 Device	[23]	Geared PTO with negative-spring resonance tuning	Resonance-enhancing; compact PTO; scalable to MW level	Gearbox complexity; mooring loads in storms; novel mechanics need validation
Slope-Pendulum WEC (S-PWEC)	[62]	Adjustable angle mechanism (AAM)	High efficiency (up to 95%); adaptive slope design; scalable	Complex design; heavy structure; still experimental
Bulbous-Bottom Resonant Buoy	[71]	Ball-screw PTO	Up to 28% higher efficiency; good for low-energy coasts; simple PTO	Complex mooring; sensitive to parameters
AWS	[72]	Linear generator	Large stroke; high rating (1 MW); submerged design	Expensive installation; maintenance challenges; depth limitations
CETO 5/6	[73,74]	Hydraulic PTO/onboard PTOs	Multi-DOF capture; submerged reduces loads; flexible PTO location	Complex mooring; costly hydraulic piping; large device footprint
OPT PowerBuoy	[75]	Ball-screw PTO + rotary generator	Self-reacting; high PTO efficiency (~90%); deep-water-capable	Heavy spar deployment issues; fatigue concerns; heave only
Wavebob	[76]	Hydraulic or direct-drive PTO	High heave gain; proven sea trials; scalable	Parametric resonance issues; very deep draft; hydraulic PTO leakage
SEAREV	[77]	Hydraulic or direct-drive PTO	Compact; protected components; multi-axis capture	Nonlinear dynamics; pendulum fatigue; space constraints
Wello Penguin	[78]	Pendulum-driven rotary generator	Simple pendulum; multi-mode capture; low noise	High LCOE; bearing maintenance; pitch comfort issues
WaveStar	[79]	Hydraulic or linear generator PTOs	Modular scalability; retractable floats; high efficiency per arm	High CAPEX; complex maintenance; fixed structure
FO3 Device	[80]	PTO units below splash zone	Deep-water-capable; high capacity; protected PTOs	Very high LCOE; complex control; expensive platform

Devices such as the CorPower C4 utilize negative-spring technology to artificially broaden the resonance bandwidth, while others, like the adjustable draft point absorber and the PA with an inerter, physically alter their dynamic properties to match shifting sea states. While these innovations significantly enhance energy capture efficiency, they inherently introduce mechanical complexity and necessitate sophisticated control algorithms, which can negatively impact long-term reliability and increase maintenance costs.

Another fundamental distinction among the surveyed technologies is their deployment strategy and reaction frame. Fully submerged architectures, exemplified by the AWS and the CETO systems, operate below the waterline to mitigate the extreme loads of severe storms. Though beneficial for survivability, this approach introduces substantial sub-sea maintenance and sealing challenges. Conversely, surface-piercing buoys often rely on deep-draft spars to provide a stable reaction mass. Devices like the OPT PowerBuoy and Wavebob achieve high PTO efficiency by leveraging the relative heave motion against

these stable spars, but they frequently encounter parasitic parametric resonance and demanding logistical requirements during offshore installation.

Finally, the evaluation underscores a sharp contrast between highly simplified kinematics and complex, multi-modal platforms. The Seabased Unit represents a minimalist approach, employing a direct-drive linear generator on the seabed to eliminate intermediate mechanical losses, albeit at the expense of a limited stroke length and vulnerability to extreme wave impacts. In contrast, large-scale modular platforms such as WaveStar and the FO3 device integrate multiple absorbers onto a single massive semi-submersible or jack-up structure. While these multi-absorber configurations offer high capacity and keep sensitive PTO components safely above the waterline, their commercial viability is currently hindered by the substantial CAPEX required. To bridge the gap between survivability and structural cost, enclosed-hull designs like SEAREV and the Wello Penguin utilize internal oscillating masses, providing increased protection for the PTO.

3.4. Comparison of PAs and Pendulum-Based WECs

While both PA and pendulum-based WECs fall under the broader category of oscillating-body devices, their fundamental operating principles, mechanical architectures, and energy conversion pathways differ substantially. A PA WEC extracts energy primarily through heave motion—the vertical rise and fall of a buoy relative to a fixed or reacting reference—and its performance is tightly coupled to linear resonance: maximum power absorption is achieved when the device’s natural frequency matches the dominant wave frequency, a condition that must be met across the full spectrum of realistic sea states. This narrow bandwidth is a structural limitation, and scaling the device to capture lower-frequency waves requires proportionally larger masses and dimensions, directly inflating CAPEX. Pendulum-based WECs, by contrast, exploit the multi-directional motion of a wave-excited hull to drive an internal pendulum or reaction mass. Rather than depending on a single-degree-of-freedom resonance condition, these systems can harness pitch, roll, and surge simultaneously and, crucially, are capable of exploiting parametric excitation to achieve continuous rotation. This rotational regime is inherently more favorable for power generation, delivering a quasi-continuous mechanical output to the generator. The practical trade-off is mathematical complexity; pendulum WECs involve nonlinear dynamics that are far harder to model and control accurately, and their sealed-hull architectures, while protective, introduce challenges around bearing fatigue, internal component access, and heat dissipation. A structured comparison of the two device families across key design parameters is provided in Table 2.

Table 2. Differences between PA WECs and pendulum-based WECs.

Feature	Pendulum WEC	Point-Absorber WEC
Motion	Enclosed	Exposed
Energy Source	Heave, surge, pitch, roll	Vertical (heave, sometimes surge/pitch)
Structure	Prominent eccentricity	Compact buoy, simple float
Location	Can be nearshore or offshore	Mostly offshore
Complexity	Mechanical transmission needed for PTO	Simpler PTO (linear generator or hydraulic)
Wave compatibility	Broader wave-spectrum adaptability	Resonance-based, efficient in specific conditions

4. Overview of Pendulum-Based WECs

While the above technologies are mostly well established and some have been tried on open seas, they often face challenges related to efficiency losses, mechanical

complexity, maintenance demands, and performance degradation under irregular wave excitation. In particular, the low-frequency nature of ocean waves, typically in the range of 0.05–0.3 Hz, poses fundamental difficulties for efficient energy conversion, as most electrical generators operate optimally at much higher rotational speeds [81]. Frequency up-conversion mechanisms are therefore required, adding complexity and potential reliability concerns. These limitations have motivated the exploration of alternative PTO concepts capable of exploiting nonlinear dynamics to enhance energy harvesting performance under realistic, stochastic wave conditions [82,83].

Pendulum-based WECs present a highly promising evolution in this domain. Unlike standard PAs that rely on direct relative vertical motion, pendulum WECs frequently operate as internal reaction mass devices, isolating the sensitive PTO components within a sealed hull. They harness the multi-directional, wave-induced motion of the floater (such as pitch, roll, and surge) to excite an internal pendulum, translating chaotic sea states into continuous rotational or oscillatory dynamics [84–86]. In such systems, wave-induced motions excite the oscillation or rotation of a pendulum, which is mechanically coupled to an electrical generator. Early pendulum WEC concepts primarily relied on classic SDOF pendula subjected to direct forcing from wave motion, typically exploiting surge or pitch excitation [82]. Variants include vertical-axis pendula, tilting pendula, spherical pendula, and gimbaled configurations, each offering different dynamic characteristics and energy capture potential [14,87–97]. However, purely forced pendulum systems often exhibit narrow resonance bandwidths and limited efficiency when subjected to broadband or stochastic wave excitation [95,98,99].

A major advancement in pendulum-based energy harvesting has emerged through the exploitation of parametric excitation, whereby system parameters, rather than external forces, are modulated in time. In the context of wave energy, this naturally arises when the pendulum's pivot undergoes periodic motion due to wave-induced buoy displacement [100]. The fundamental advantage of parametrically excited pendula lies in their ability to achieve and sustain continuous rotation, which significantly outperforms simple oscillatory motion in terms of energy extraction. Foundational analytical models have established the primary resonance boundaries required to transition from small oscillations to highly energetic rotations [101–103].

4.1. Description and Mathematical Modeling of Pendulum WECs

A major advantage of pendulum-based WEC lies in their ability to leverage parametric excitation. Rather than relying solely on direct forcing, the motion of the floater dynamically modulates the pendulum's parameters, enabling the system to achieve highly energetic, continuous period-one rotations. This nonlinear behavior acts as a native frequency up-conversion mechanism, allowing the PTO to operate efficiently even under irregular wave inputs. However, relying on standard linear models to describe these parametrically excited systems is highly inaccurate, as linear approximations fail to capture the rich multi-stability and enhanced motion characteristic of full-scale operation.

To fully optimize and control these advanced nonlinear dynamics, an accurate and comprehensive mathematical representation of the pendulum's interaction with the wave field is essential. To model these kinematics, Reid et al. [104] collated all the pendulum types (vertical, horizontal, etc.) and compared these orientations with WEC motions. They assumed a mass m at a distance l from the beginning of the axis. This pendulum could be excited in the heave and surge direction and tilted by an angle of φ by the incident waves. The effects of heave and surge are added to the pendulum's equation of motion using the displacement parameters H and S , where the latter is split into S_1 and S_2 due to surge and sway acting horizontally in both the X and Y axis. Then, with reference to Figure 6a, the following equation occurs for the pendulum's relative angle θ which is

universal for all the pendulum WEC's motions, though not taking into consideration external factors such as mooring and floater hydrodynamics.

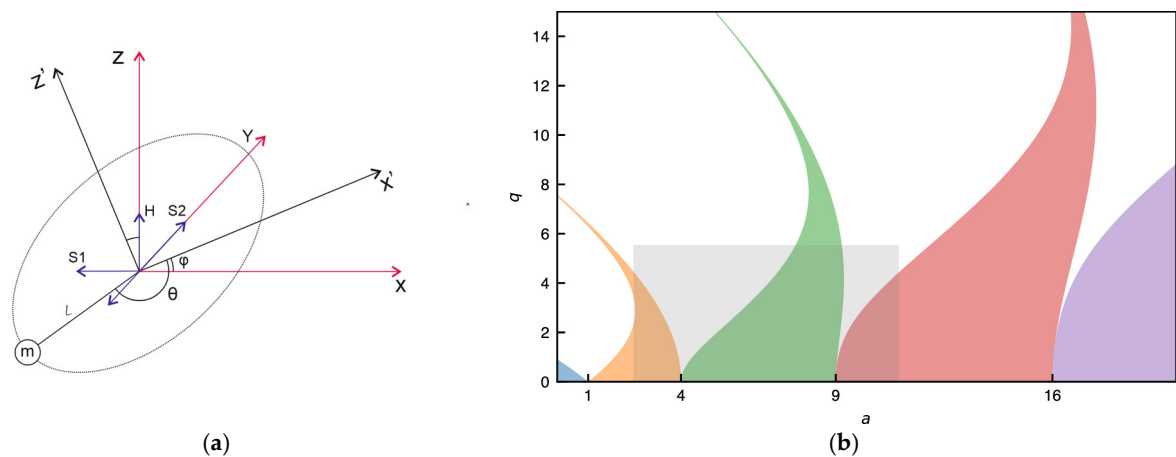


Figure 6. (a) Adapted schematic of the pendulum considered in [104]; (b) typical stability diagram of the Mathieu equation (reproduced by [105]).

$$\ddot{\theta} = -\frac{\dot{s}_1}{l} \sin\theta \cos\varphi - \frac{\dot{s}_2}{l} \cos\theta + \frac{\dot{H}}{l} \sin\theta \sin\varphi - \dot{\phi}^2 \sin\theta \cos\theta - \frac{g}{l} \sin\theta \sin\varphi - \frac{c\dot{\theta}}{ml'} \quad (17)$$

Linearizing Equation (17) by using small-angle approximations, the authors derived the amplitude–frequency regions corresponding to the well-known parametric resonance tongues [106]. A typical example of the stability diagram is shown in Figure 6b, where $a = 1$ corresponds to the primary parametric resonance. The white tongues describe the instability regions of the linearized pendulum fixed point. These regions drive a non-trivial response of the pendulum with the possibility of surpassing the global bifurcation threshold and entering a rotational response regime. Further numerical and dry experimental analysis using a long-stroke shaker showed the typical softening response of the pendulum around the primary parametric resonance due to heave, surge and tilt excitations independently. However, in all reported observations, the pendulum underwent swinging motion.

The above should be extended with the fully coupled floater–pendulum equations of motion in order to hold representative modeling value for a pendulum-based WEC. Detailed derivation of the coupled floater–pendulum equations is given by Pozzi et al. [107]. Moreover, an interesting approach of incorporating multiple synchronized pendula in a common hull could enhance the robustness of the WEC harvesting operation. Terrero-Gonzalez et al. [108] provide the coupled equations along with relevant experimental results under non-ideal vertical forcing. In Section 5 of this review, pendulum-based WECs will be analyzed based on their main axis of oscillation or rotation.

4.2. Categorization of Pendulum-Based WECs

As the literature demonstrates, pendulum-based WECs have diversified significantly to address the inherent low-frequency challenge of ocean waves. To fully understand the current state of the art, it is useful to categorize these systems across four primary dimensions: kinematic orientation, excitation mechanics, kinematic complexity, and the restoring force paradigm. The most fundamental classification relates to the kinematic axis and degrees-of-freedom (DOF). Traditional vertical-axis pendula oscillate around a horizontal pivot, making them highly directional and primarily responsive to discrete surge or pitch motions. To mitigate this directional sensitivity, recent designs have introduced horizontal-axis flywheels and omnidirectional spherical pendula. For example, the SWINGO WEC leverages a gimballed gyro pendulum to capture multi-directional wave fields,

exploiting the mechanical coupling between pitch and roll to activate the internal mechanism [109]. Similarly, enclosed horizontal-axis flywheels provide rotation that is inherently insensitive to the incident wave angle, offering a robust solution for highly chaotic sea states [93].

Beyond physical orientation, pendulum WECs are distinguished by their fundamental excitation mechanics. Directly forced pendula rely on the immediate pushing or pulling of the wave motion, which often results in narrow resonance bands and suboptimal performance in irregular seas. Conversely, parametrically excited pendula utilize the wave-induced heave or surge of the hull to modulate the pendulum's pivot point. This parametric modulation, governed by the Mathieu equation [104], acts as a native frequency up-conversion mechanism, allowing the system to transition from localized oscillations into highly energetic, continuous period-one rotations.

The third categorization dimension involves kinematic complexity and mass distribution. Standard single-mass pendula require impractically long arms to achieve natural frequencies below 1 Hz. To circumvent this geometric constraint, multi-mass and tunable configurations have emerged. Tunable devices, such as adjustable scissor-like pendula, actively modify their length to adapt to real-time sea states [110] as shown in Figure 7a. More advanced architectures, like the Double-Mass Pendulum Energy Harvester (DMPEH), shown in Figure 7b, distribute mass across a vertical shaft, allowing the system's structural inertia and natural frequency to be tuned independently of its overall physical footprint [85].

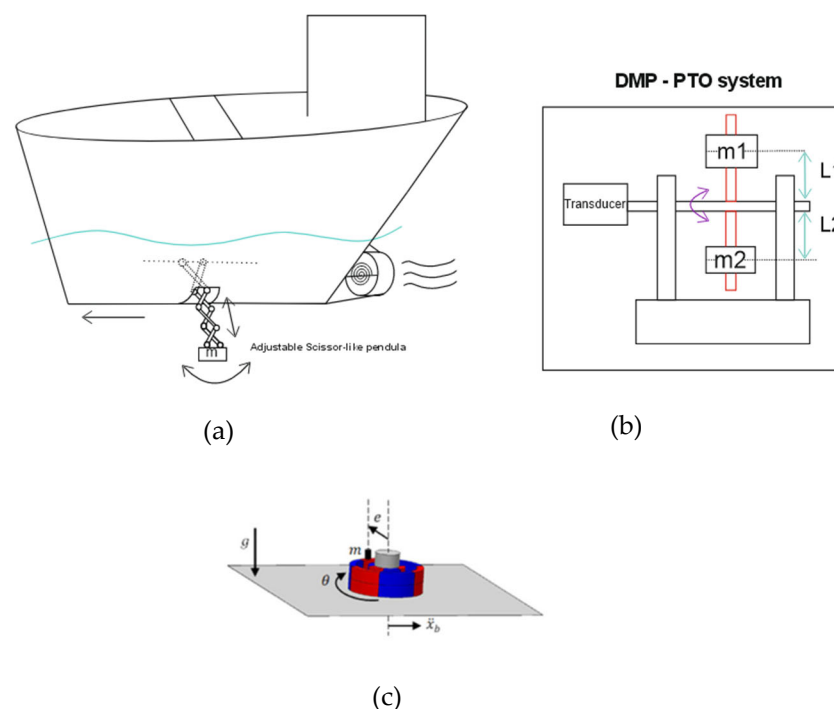


Figure 7. (a) Adjustable scissor-like pendula concept (adapted from [110]) and (b) Double-Mass Pendulum Energy Harvester (adapted from [85]); (c) magnetic-induced restoring torque concept [86].

Finally, the last identified classification lies in the restoring force paradigm. Traditional pendula rely purely on gravity to return to equilibrium, creating a high potential energy barrier that weak ocean waves struggle to overcome. “Reduced gravity” concepts address this geometric limitation by physically tilting the rotational plane to artificially lower this gravitational barrier [88]. Recent variants of this approach integrate highly customized nonlinear restoring forces. By employing magnetic coupling to reshape the

potential energy, these systems drastically lower the rotational threshold [86]. A concept of this is shown in Figure 7c.

All the above approaches effectively enable advanced energy transfer to the PTO, enabling continuous energy extraction even under ultra-low-frequency and weak forcing conditions.

4.3. PTO Architectures

Translating the non-uniform mechanical oscillations or rotations of an internal pendulum into stable, grid-compliant electrical power requires specific power take-off configurations, as seen in Figure 8. The mechanical energy harvested by rotating or swinging masses is processed through four primary power take-off architectures, each exhibiting unique electromechanical extraction properties.

4.3.1. Mechanical Transmissions with Up-Conversion

Due to the slow angular velocities of wave-driven pendula, mechanical gear trains, rack–pinion devices, or one-way bearings are frequently utilized to convert bidirectional reciprocating swings into high-speed, unidirectional rotation. For instance, He et al. [111] utilize a horizontal hollow shaft coupled with a three-bevel gear array and one-way bearings to rectify chaotic swings into a single direction. This mechanical up-conversion increases the duty cycle of the generator and minimizes kinetic losses associated with continuous motion reversal.

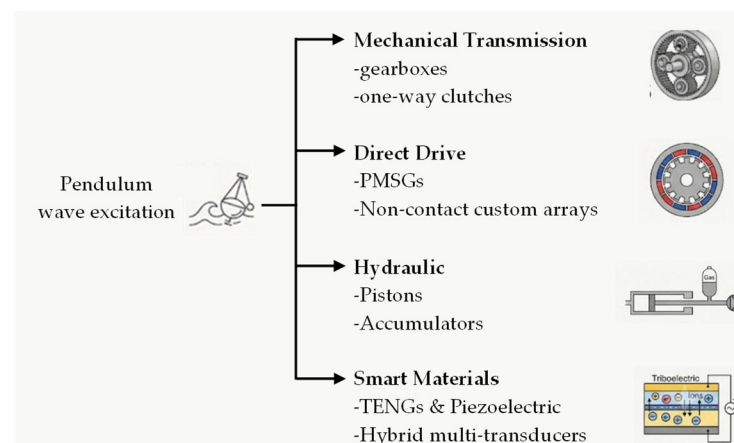


Figure 8. Common PTO systems for pendulum-based WECs.

4.3.2. Direct-Drive Rotational Generators

Direct-drive architectures eliminate intermediate mechanical interfaces by coupling the pendulum or flywheel shaft directly to a permanent-magnet synchronous generator [12]. Field-Oriented Control is applied within the $d - q$ reference frame to decouple the flux and torque currents, allowing independent active and reactive power smoothing under stochastic inputs. Under large-amplitude dynamics, traditional linear impedance matching fails, requiring amplitude-dependent load tuning (dynamic electrical resistance adjustment) to stabilize single-period rotations and prevent abrupt transitions into chaotic regimes.

4.3.3. Hydraulic PTO Circuits

Commonly applied in heavy, low-frequency configurations such as the SEAREV [77] and inverted pendulum devices, hydraulic PTOs use the pendulum's angular displacement to drive a double-acting hydraulic ram or piston. The piston forces fluid through high-pressure accumulators to smooth the intermittent power spikes before driving a

variable-displacement hydraulic motor coupled to a conventional rotary generator. While capable of handling extreme structural forces, these systems require careful management of fluid friction losses and sealings.

4.3.4. Smart Material Transducers

For micro-scale or decentralized marine applications, recent pendulum configurations integrate triboelectric (TENG) and piezoelectric (PEG) nanogenerators to optimize ultra-low-frequency extraction. Devices like the MIP-TENG utilize contact separation or sliding modes between distinct polymer membranes (e.g., PTFE and nylon) fixed to the swinging mass. These systems generate high open-circuit voltages at low frequencies but exhibit high internal impedance.

5. Pendulum-Based WEC Devices and Concepts

To systematically address the low-frequency nature and directional sensitivities characteristic of real ocean environments, pendulum-based WECs have expanded into several design architectures. Following the feature analysis in Sections 4.2 and 4.3, the concepts sourced from the literature are categorized below according to their kinematic orientation, axis layout, and structural behavior into four areas; namely, horizontal-axis and vertical-axis devices and tilted, inverted pendulum and parametrically excited systems. Note that although parametric coupling is unavoidable in all enclosed pendulum WEC concepts, Section 5.4 discusses persistent efforts in the development of pendulum WECs that specifically utilize parametric resonance as the dominant conversion mechanism, in order to establish continuous rotational motion under wave excitation.

5.1. Horizontal-Axis Pendulum Systems

Horizontal-axis systems feature internal masses or mechanisms rotating or oscillating around a horizontal pivot, aligning their primary inertial response with discrete wave-induced motions such as surge, pitch, or heave.

The SEAREV WEC (Système Electrique Autonome de Récupération de l'Energie des Vagues) [77] can be considered a pioneer in horizontal-axis pendulum-based WECs as it is one of the first designs that has been studied and contains an enclosed-hull internal reaction mass system. Before this, the vast majority of devices exposed their sensitive pistons, joints or moving components directly to harsh, corrosive marine environments. SEAREV provided a system that could safely seal all its mechanical, hydraulic, and electrical components inside a completely waterproof hull. It relied strictly on wave action to roll the outer hull around an off-center internal pendular mass to extract clean electricity. The first SEAREV variant, the SEAREV G1 which can be observed in Figure 9a, was designed to maximize survivability by eliminating tall emerging structures and avoiding mechanical end-stops for the internal moving components. The hull shape was derived via numerical optimization using genetic algorithms and gradient methods to minimize total device mass while maximizing power absorption. Even though latching control was chosen numerically and was proven to fit best the SEAREV device providing a 35% power advantage over other control strategies, the implementation necessitated real-time control. For optimization convenience, the power take-off was modeled as a linear damper, with secondary investigations focusing on a hydraulic circuit using high-pressure accumulators for power smoothing. In 2006, a 1/12-scale model of the G1 was physically tested in the ECN large wave tank. The trials exposed major hydrodynamic and mechanical deficiencies, such as severe hull slamming due to large-amplitude pitch oscillations that caused impacts between the flat lower section of the bow and the water surface, inducing significant structural risks. Another significant operational limitation that the lab-tested device showed was that the latching control yielded an energy increase of only 10% due

to the braking force being applied strictly to the internal pendulum's relative motion rather than the hull itself. Most critically, the device suffered from parametric roll at specific wave frequencies due to the dynamic hull instabilities.

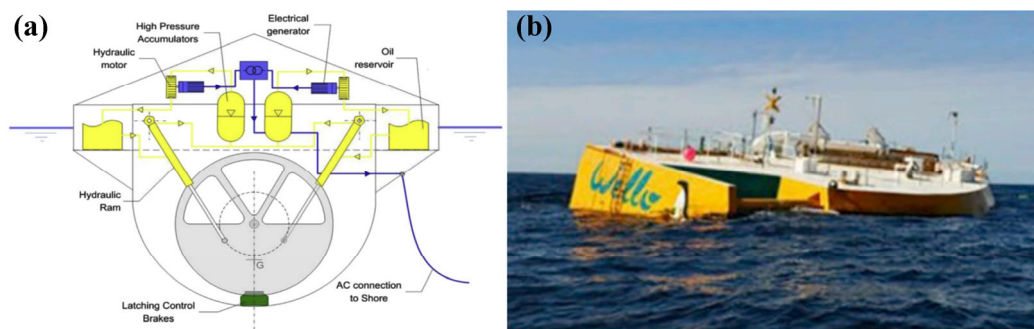


Figure 9. (a) The SEAREV G1 and (b) the Wello Penguin device [112].

With an economic payback time exceeding 50 years, the ECN team concluded that a major architectural restructuring was necessary. Developed between 2006 and 2007, the SEAREV G21 was explicitly redesigned to eradicate the slamming and parametric roll instabilities encountered during the G1 tank tests. To eliminate the parametric roll, the ECN team shifted the hull from a weight-driven stability framework to a width-driven stability geometry. To prevent slamming, the flat bottom panels under the bow were replaced with rounded profiles lacking re-entrant angles. This change also diminished manufacturing complexity by eliminating expensive structural stiffener requirements. The internal pendulum wheel mass was reduced in size, and the overall geometry of the hull was modified to be asymmetric along the fore and aft plane to leverage pitch–heave coupling. This new model introduced declutching control to gate power extraction by decoupling the PTO, with a 30% improvement over the prior design. In addition, by combining latching and declutching mechanisms, the 1/12-scale test successfully demonstrated a 19% measured power increase when coupled with an increased PTO damping coefficient.

Despite the successes of the G21, economic assessments completed in 2008 indicated that high *CapEx* still prevented the device from competing on the utility-scale electricity market. This led to a final optimization cycle from 2007 to 2009, resulting in the SEAREV G3. The G3 model revised the fundamental mechanical operating principle of the previous iterations since the off-centered pendular wheel was replaced by a massive, centered inertia cylinder. By aligning the internal cylinder's center of gravity with its rotational axis, the physical mechanical stress limits on the pendulum shaft were eliminated, allowing a significant expansion of internal mass. Also, to achieve drastic manufacturing cost reductions, the solid cast-iron internal mass was replaced entirely with low-cost water ballast. As a result, the G3's optimized geometry achieved a mean annual wave energy absorption of 1620 MWh, delivering a net 1140 MWh/year directly to the grid. Throughout its successive design adjustments, the SEAREV technology successfully increased annual energy production by 90% from G1 to G3. Concurrently, by substituting structural steel mass for internal fluid ballast and optimizing the hydrodynamic width, the required commercial feed-in tariff needed to achieve economic profitability was reduced by a factor of 2.5. This established SEAREV as an influential case study for navigating early-stage Technology Performance Level (TPL) transitions before full-scale open-sea industrialization.

The inertial sea wave energy converter (ISWEC) [113], developed by the MOREnergy Lab at the Politecnico di Torino, serves as a prominent architectural baseline for enclosed-hull, self-reacting wave energy converters designed to operate without any fixed structural reaction point on the seabed. Although not using a pendulum system per se, it has served as a predecessor of the pendulum wave energy converter (PeWEC) developed by

the same research group and a successful paradigm for enclosed-hull WECs as seen in Figure 10.

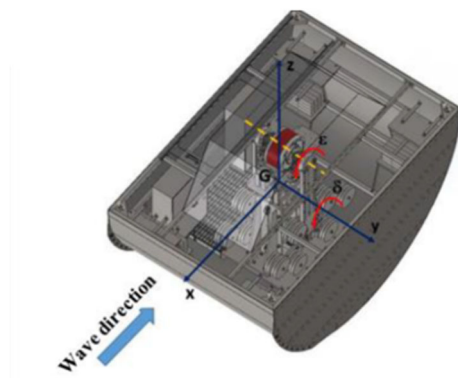


Figure 10. The PeWEC device from [9].

Following SEAREV, early work on oscillating pendulum WECs with much more streamlined power flows was reported by Serena et al. [114]. The proposed concept featured a hull enclosing a horizontal shaft, one end of which was connected to a conventional rotary generator and the other to a coaxially hinged pendulum. IRWEC1 was also reported in a 2016 article [115]. The concept utilized the pitch reaction of a similar structure with a horizontal-axis eccentric flywheel and a belt-assisted transmission to generate power. Despite rigorous wave tank testing and promising initial results, recent advances of this work could not be found in the literature. This concept can be considered as a predecessor of the much more advanced PeWEC [107,116–125], developed through a collaborative framework between the Politecnico di Torino and ENEA, which represents a modern advancement in enclosed passive-reaction marine technology. The PeWEC architecture evolved directly from the active gyroscopic principles of the ISWEC device, which had been under iterative development since 2006. While the active gyroscopic approach allows real-time frequency tuning by modulating the flywheel's spin speed, it imposes an ongoing parasitic electrical load on the system. To eliminate this efficiency penalty while preserving a fully enclosed-hull profile, the PeWEC uses a passive internal pendulum configuration that responds to wave-induced hull pitch oscillations without requiring external electrical power to trigger its inertial response. The device was specifically optimized for the high-frequency, short-wavelength, and low-amplitude sea states characteristic of the Mediterranean Sea [117,121]. Using long-term meteorological-oceanographic tracking data from Pantelleria Island, Italy, the design point was mapped to the site's most energetic sea state, establishing a 1:12 Froude scale model framework for experimental basin validation [125].

The physical prototype is built around three tightly coupled subsystems: an optimized cylindrical hull, a tunable dual-pendulum assembly, and a nonlinear mooring circuit. The hull features a cylindrical lower section with a length of 3 m, a width of 2 m, and a cross-sectional radius of 1.5 m, yielding an undamped natural pitch frequency that matches the 2.2 s scaled design wave period [107,116].

The internal reaction mechanism houses a central permanent-magnet synchronous motor acting as a direct-drive rotary PTO damper, with a pair of pendular structures positioned symmetrically to maintain longitudinal mass symmetry. Each pendulum arm is equipped with adjustable radial bars and an array of placement holes, allowing researchers to physically shift cast steel disks to alter the pendulum mass, length and COG distance, for precise structural resonance tuning. Mooring is obtained via a high-compliance, multi-segmented mooring line integrating a submerged jumper buoy and low-stiffness nylon ropes. This setup acts mechanically as a hardening spring, ensuring low restoring

forces during nominal generation while scaling stiffness exponentially to prevent severe loads during extreme wave impacts. The numerical modeling framework of the PeWEC underwent a major refinement during its experimental validation campaign at the IN-SEAN towing tank in Rome [124].

Initially, the time-domain simulator coupled multi-body mechanical equations with a linear potential flow formulation via the Cummins equation. Experimental parameter variations in the PeWEC's PTO damping coefficient revealed two distinct operational regimes for maximizing electricity extraction. Under conditions where the wave excitation matches the system's coupled resonance periods (2.0 s and 2.5 s), which manifest due to the strong multi-body mass coupling between the hull and the pendulum, the device operates highly efficiently at low control thresholds, achieving optimal power capture at a localized damping coefficient of $c = 120$ to 180 Nms/rad, while maintaining a stable *CWR* of approximately 50%. Conversely, when the system is excited at the uncoupled natural hydrostatic resonance period of the bare hull (2.2 s), an inverse behavioral trend occurs: the hull pitch amplitude and net torque absorption scale proportionally with increasing control loads. At this frequency, the absolute maximization of mean absorbed power and overall capture efficiency is achieved by driving the controller to its maximum operational parameter boundary of $c = 600$ Nms/rad. This bifurcated control behavior demonstrates that adaptive real-time impedance matching is critical for optimizing internal reaction pendular WECs under fluctuating, stochastic sea states.

Recent work in PeWEC has shifted towards data-driven control strategies [119,120], acknowledging the importance of the strong coupling of mooring–floater–PTO dynamics. Improvements of up to 20% in the mechanical power transferred to the PTO have been reported [119]. PeWEC is currently amongst the most meticulously and consistently developed pendulum-based WECs, moving steadily towards commercial power grid connection [123]. Nevertheless, the main operating principle regards swinging motion of the encapsulated pendulum. As it then stands, the main drawback of the device is the low power-to-weight ratio, which lags far behind the most advanced PA-type WECs.

The Swinging Omnidirectional (SWINGO) WEC is a recently proposed variant of both the ISWEC and the PeWEC aiming to deliver power from various DOFs [109,126]. To accurately capture its complex dynamic behavior, Carapellese et al. [109] derived the full nonlinear mathematical model of the device. The presented simplified mathematical model results suggest that, despite the increasing complexity, power output is nearly doubled with respect to the individual gyroscope and pendulum configurations. The study highlights that relying solely on linear models, which assume infinitesimally small rotations, becomes highly inaccurate for full-scale implementations. To overcome these limitations and effectively maximize energy conversion, Carapellese et al. [126] apply a Harmonic Balance (HB) procedure to analyze the steady-state nonlinear dynamics and tune the passive, proportional PTO controller. Through both forward and backwards frequency sweeps, their findings indicate that the optimal damping parameter calculated from the comprehensive nonlinear model is approximately 30% larger than the parameter derived from the benchmark linear model. Furthermore, the authors assessed the stability properties of the nonlinear solutions. This stability analysis reveals that under low damping conditions, the SWINGO system exhibits multi-stability behavior, where multiple stable solutions co-exist depending on the initial conditions, which is a dynamic characteristic completely neglected by linear modeling. Despite this bistability at lower control values, the study successfully demonstrates that when the controller is tuned to the optimal condition for maximum power transfer, the nonlinear system reliably converges to a single stable attractor.

While rotational mechanisms and horizontal-axis flywheels offer distinct advantages for multi-directional waves, extracting energy from the ultra-low-frequency bands typical

of ocean waves (<1 Hz) remains a fundamental geometric challenge for traditional pendulum WECs. In a standard pendulum, achieving a natural frequency below 1 Hz necessitates impractically long pendulum arms, demanding massive installation spaces. To circumvent this geometric constraint, recent research has pivoted toward multi-mass configurations. Notably, Cai et al. [85] introduced and experimentally validated a Double-Mass Pendulum Energy Harvester (DMPEH) designed specifically to provide tunable, ultra-low-frequency operation without extending the device's physical footprint. The DMPEH, which can be observed in Figure 7b, consists of an upper and lower mass mounted on a single rotating vertical shaft connected to an electromagnetic transducer. By simply adjusting the vertical position of the upper mass, the structural inertia is modified, allowing the system's natural frequency to be tuned independently of its overall length. Through shake-table testing, the authors demonstrated that this frequency tuning strategy is highly effective; dynamically tuning the upper mass to match excitation frequencies improved power output by up to 560% compared to a detuned state, effectively transforming the DMPEH into a broadband energy harvester capable of operating between 0.2 and 1.4 Hz. Furthermore, the DMPEH studies provide critical insights into managing the chaotic dynamics inherent in nonlinear PTOs. Similarly to gyroscopic systems, the DMPEH transitions alternatively through rotational and chaotic behaviors as wave excitation amplitudes increase. However, the authors established a direct correlation between the external electrical load circuit (PTO damping) and the mitigation of these nonlinearities. They found that applying smaller load resistance—which corresponds to higher electromagnetic damping—effectively limits the rotational angle and suppresses chaotic vibrations, maintaining the system in a more predictable state. Ultimately, numerical assessments of a medium-scale DMPEH integrated into a floating navigation buoy indicate that this technology can reliably output power in the order of tens of W. Flume tests were performed at a downscaled prototype corresponding to wave periods of 0.7 to 1.35 s, validating the numerical models. Projecting to a larger scale of up to 0.17 Hz wave frequency, the authors reported an expectation of reaching 1 kW of recovered power. However, despite being close to the typical ocean conditions, the size and weight of device required and the implications for operability and survivability of the device were not reported.

Wang et al. [110] designed an adjustable pendulum mechanism addressed for energy harvesting directed to Unmanned Marine Vehicles (UMVs). This pendulum has adjustable length, which enables it to have a dynamic natural frequency in order to maximize the wave energy harvesting capabilities. When the pendulum is folded, it is stored inside the UMV, diminishing drag forces applied to the device. When it unfolds, it is capable of progressively adjusting its length based on a control strategy in order to adapt to the wave excitation. The control strategy that was implemented linearly unfolded the scissor-like structure of the pendulum until it achieved a maximum voltage output. The authors experimented with a six-DOF motion platform with a control interface to simulate the periodic rolling motion of a UMV. Under rolling excitation with amplitude of about 2.41° and frequency of 0.8 Hz, the device provided 1.078 W along with an energy efficiency of 19.84%. Then the authors, in another study [127], experimented with the heave and roll motion of the pendulum, where, at 0.8 Hz, they managed to achieve an average power output of 5.47 W, which corresponds to a normalized power density of $26.25 \text{ W/g}^2\text{kg}$.

Huang et al. [128] designed a novel spring pendulum buoy in order to address the narrow power capture bandwidth typical of traditional oscillating buoys. By leveraging two degrees of freedom—radial and rotational—the device aims for efficient, broadband energy harvesting, particularly in bimodal wave spectra, containing both wind waves and swells. The WEC consists of a buoy, a rotation shaft, and two spring-loaded telescopic swing arms that allow the buoy to slide radially and rotate around the shaft. Analysis of the concept showed an energy redistribution from one DOF to the other, which implies a

linkage of the two DOFs. The total capture width ratio curve exhibits a significant bimodal characteristic, demonstrating dual-frequency capture. This is attributed to the combination of the two DOFs and the nonlinear spring capture affecting the rotational DOF. The experimental procedure shows a total average power increased by ~60%.

He et al. [111] designed a “sundae cup-shaped” intelligent buoy designed for self-powered and self-sensing hydrological monitoring, specifically targeting the waters near cross-sea bridge piers. The system leverages wave energy to simultaneously power its sensors and perform real-time environmental anomaly detection. The buoy integrates a single-axis inertial pendulum within a sundae cup-shaped lower shell. This structure maintains a low center of gravity to prevent the buoy from overturning while amplifying the reciprocating swing amplitude under wave excitation. A motion conversion mechanism utilizes a horizontal hollow shaft, three bevel gears and a one-way bearing. This gear set accurately converts the chaotic, bidirectional reciprocating swing of the internal pendulum into a stable, unidirectional rotational output for the upper sensing module. The unidirectional rotation from the gear mechanism drives a TENG module consisting of a turntable with PTFE balls rolling against copper foil tracks. The periodic contact and separation generate clear, distinct voltage signals. The experimental validation of this concept was tested on a six-DOF vibration platform, with average power generation of 12.11 mW at an optimal input excitation of 0.5 Hz and a 50 mm amplitude.

In recent years, various authors have considered blending vibration energy harvester concepts with wave excitation, mostly for the purpose of powering floating wireless sensor nodes or monitoring equipment (e.g., [129–131]). The ultra-low frequency of ocean waves renders pendulum systems extremely beneficial for coupling wave motion to a custom harvesting circuit.

5.2. Vertical-Axis Pendulum Systems

Vertical-axis configurations feature flywheels or pendular masses rotating parallel to the horizontal plane, reducing directional sensitivity to incoming waves and capturing multi-axis angular motions like roll and pitch.

The vertical-axis pendulum wave energy converter (VAPWEC) [14], extensively researched and experimentally validated by Boren et al. [90] at Oregon State University, represents a distinct example within the category of enclosed-hull internal reaction mass WECs. In terms of mechanical layout, VAPWEC consists of a shallow cylindrical wave-following hull that houses an internal shaft–pendulum–bearing assembly coupled directly to a rotary generator, whereby the pendulum swings in a horizontal plane relative to the hull. Comprehensive experimental testing of a small-scale generic VAPWEC prototype at the O.H. Hinsdale Wave Research Laboratory (HWRL) [90] revealed unexpected hydrodynamic behavior regarding station keeping and inertial mass allocation. While early design assumptions predicted that a highly flexible catenary mooring line would offer the hull enough freedom to pitch and roll, the shallow draft hull simply rode directly over the incident wave crests without experiencing significant angular displacements, resulting in negligible internal pendulum motion and zero power generation. Conversely, a highly taut mooring framework—similar to a tension-leg platform layout—was found to be more favorable for establishing a meaningful internal reaction. When restrained by taut lines, the watch circle of the hull is significantly restricted, forcing the bow to pitch aggressively upward as a wave crest approaches and snap downward into the trough immediately after. This highly dynamic hull oscillation mechanically amplifies the swinging amplitude of the internal horizontal pendulum, maximizing power extraction. Crucially, physical tank testing demonstrated that scaling up the internal reaction mass does not guarantee a linear increase in power capture efficiency. Experimental comparisons between a regular and a heavy pendulum configuration showed that the more massive

internal components increased the operating draft and induced a steep hull tilt. This altered buoyancy caused incident waves to break prematurely and slam violently against the bow, dissipating primary hydrodynamic energy and failing to yield higher net electrical output.

To overcome the performance limits of static passive damping, Boren et al. [14] introduced an active control framework based on Model Predictive Control (MPC) combined with integral error tracking to continuously synchronize the horizontal pendulum's trajectory with incoming wave profiles. While early monochromatic studies [132] concluded that vertical-axis pendula maximize energy conversion exclusively when forced into continuous, unidirectional rotation, high-fidelity simulations in multi-frequency irregular wave environments revealed that allowing bidirectional rotations resulted in higher predicted power output (increasing from 23 kW to 52 kW projected power). However, the rapid angular accelerations and sudden direction reversals dictated by bidirectional tracking generate significantly large, instantaneous peak power spikes that can overwhelm standard electrical circuits. Managing these sudden spikes requires a substantially oversized generator and complex power-smoothing architectures, which can inflate *CapEx*. Furthermore, repeated reversals impose intense mechanical fatigue on the internal gearboxes and bearings, while the rigid, taut mooring setup transfers significant structural loads directly onto the anchoring foundation, presenting a long-term challenge for utility-scale deployment.

Building upon work from the Oregon group, Chen and BelBlazo developed a numerical model of a device with similar working principle and reported that the Eccentric Rotor Wave Energy Converter (ERWEC) required a significantly high mass ratio to maintain increased power yield [91] when the pendulum mass over the buoy mass is considered. Research conducted in Shangdong University has led to the gradual development of an ERWEC variant utilizing a hydraulic PTO for energy scavenging [55]. Genetic algorithms were used to optimize the hydraulic PTO control, reporting significant performance gains. The same group also conducted extensive research on the attributes of favorable mooring modes [89,133]. Ten different mooring configurations were analyzed in [89] using wave tank test data with regular and irregular waves. The analysis involved the development of a custom index to evaluate the mooring performance based on anchor line tension. It was concluded that the mooring mode shown in Figure 11b is the most advantageous for the low-energy seas that this class of WECs typically targets. Chen et al. [134] and Duan et al. [135] focused on the hydrodynamics performance of these WEC devices, which the authors entitled the Sealed Buoy Wave Energy Converter (SBWEC), considering a PTO with mechanical transmission driving a rotary generator. They computed the pitch RAOs for cylindrical and hemispherical buoys and found that cylindrical buoys slightly outperformed their hemispherical counterparts in terms of hydrodynamic conversion efficiency, but at the expense of multiple times stronger peak force. Furthermore, they found that the converted power per unit of underwater device area in high- and low-energy sea states was of similar magnitude, building promising evidence for the utilization of such WECs even in low-energetic seas. The SBWEC results for low-energy sea states were further elaborated in [135] with the Shandong peninsula as a test site. A buoy diameter of 4 m was found to be optimal for 14 m wavelengths exciting the converter. However, the predicted power output of 150 W was disappointingly low for the projected massive 4.2 t device [135], showing that the significant potential of the vertical-axis pendulum WEC concept requires further improvements in power density.

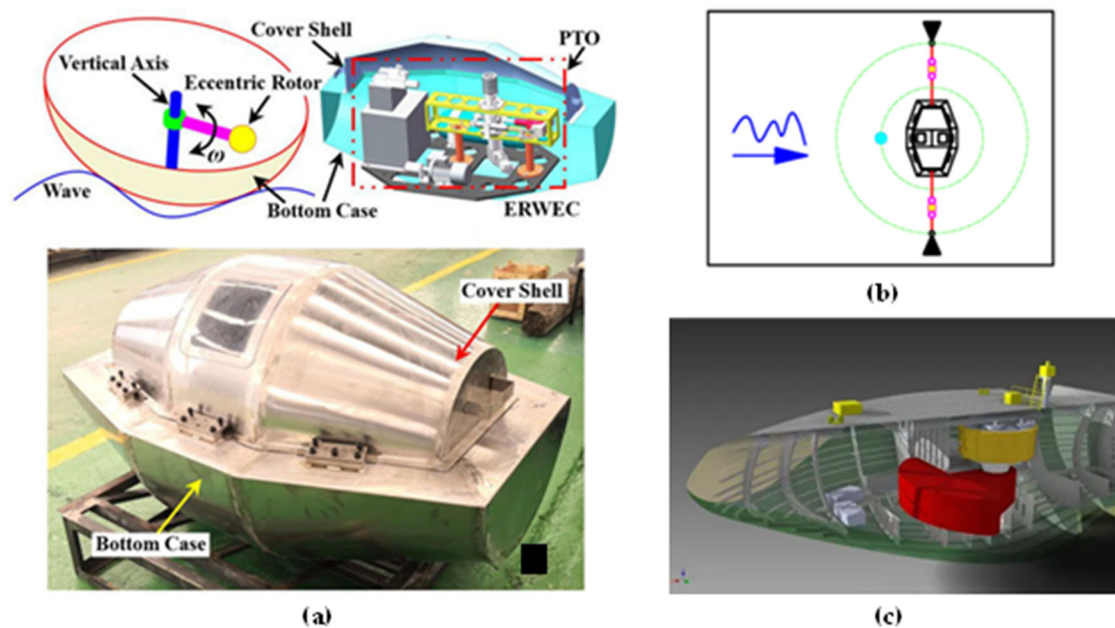


Figure 11. (a) ERWEC with hydraulic PTO [55]; (b) mooring mode F, best for low-energy seas [89]; (c) rendering of the Penguin inner components.

A device that had attracted significant interest within the wave energy community is the Penguin developed by Wello Oy. The Penguin featured a boat-shaped hull enclosing a massive eccentric rotor with its main rotation axis aligned vertically. The promise around this device was very high around the late 2010s, when the 500 kW, 1600 t device of 30 m in length underwent testing in Orkney where it unfortunately sunk (news reported at the industry-renowned media outlet Offshore Energy, found at <https://www.offshore-energy.biz/penguin-sinks-off-orkney/> (accessed 14 June 2026)), despite a 2-year long operation in the harsh Scottish waters. A second deployment attempt in the Biscay Marine Energy Center of a revised 0.6 MW, 44 m long device was again unsuccessful, as the device was unexpectedly towed off sea due to leakage (similarly to above, <https://www.offshore-energy.biz/wello-retrieves-penguin-device-due-to-damage-by-floating-object-hit/> (accessed 14 June 2026)). There is surprisingly very little reporting of the device details in the literature, mostly limited references within review papers. However, the Penguin has been discontinued, and thus this review shall not further discuss the device, although a root-cause analysis would indeed be beneficial for the community.

The vertical-axis parametric pendulum wave energy converter (VAPPWEC) [136], as depicted in Figure 12, was proposed by researchers at the Ocean University of China. Mechanically, the system relies on wave-induced multi-axis hull displacements (specifically surge, sway, roll, and pitch) to induce time-varying gravitational components and linear accelerations within the pendulum's localized coordinate frame. These multi-DOF excitations break the pendulum out of static equilibrium and force it into highly energetic parametric resonance states. Notably, the layout establishes an uncoupled operational profile relative to heave motions.

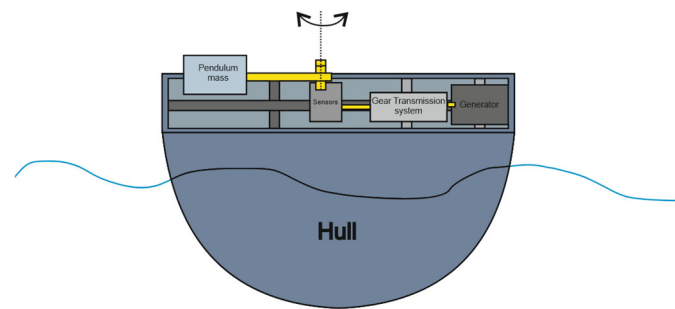


Figure 12. A sketch of the VAPPWEC (adapted from [136]).

Experimental basin characterization reveals that the vertical layout demonstrates a distinct parametric resonance zone characterized by three co-existing orbital motions: period-one pure-rotation, period-one oscillation–rotation, and highly stochastic chaotic regimes. From a power generation perspective, the pure-rotation orbit serves as the ideal generation regime because it maintains continuous, unidirectional motion that supplies a steady kinetic velocity profile to the direct-drive generator, optimizing electromechanical conversion efficiency. Comprehensive optimization mapping shows that the device achieves vastly superior capture efficiency under linear damping control rather than constant damping constraints, yielding a maximum capture width ratio of 39.05%. However, the physical device demonstrates strict operational trade-offs. While proper loading control can successfully transition a suboptimal oscillation–rotation profile into a highly efficient pure-rotation attractor, implementing an excessive damping load that surpasses the system’s critical threshold will completely eliminate its rotational potential. Under such overly damped states, the pendulum abruptly drops out of resonance and locks into a low-velocity, small-amplitude localized oscillation, causing a severe drop in net electrical output. Furthermore, a significant operational challenge occurs near the boundary separating the parametric resonance zone. In this boundary (experimentally occurring near the 1.7 s to 1.9 s wave period band), the system dynamics exhibit low robustness, resulting in protracted transients and chaotic regimes, complicating real-time control.

Antoniadis et al. [137] designed a multi-link mechanism, in which the internal bodies can move in a prescribed path relative to the external bodies. Another advantage that maximizes conversion and storage of wave energy is the optimization and distribution of mass and inertia for each individual body in the system. Due to the abovementioned considerations, the PTO system can remain simple and generate predictable power. This WEC design consists of a closed hull around the internal mechanism, with a plate at the bottom for maximizing reaction, increasing the added mass and lowering the CoM of the WEC. The resulting device can provide a reliable and simple mechanism to meet the severe conditions for survivability under extreme weather conditions.

Pan et al. [138] proposed a multi-directional, hybrid triboelectric-assisted electromagnetic energy harvesting system driven by an eccentric rod, essentially functioning as a pendulum. In this design, the chaotic, multi-directional motion of the wave field forces the eccentric rod into a reciprocating rotation, which simultaneously drives both the TENG and generator units. The crucial innovation lies in the system’s phase-synchronized collaborative circuit. Since both generators are driven by the exact same mechanical pendulum motion, their alternating electrical outputs are naturally matched in phase. By capitalizing on this synchronous phase, the high-voltage output of the TENG is used to bias a low-voltage rectifier circuit. This effectively lowers the forward voltage drop and activation threshold required for the generator to harvest energy. As a result, the TENG actively assists the generator, allowing the combined PTO to efficiently capture and rectify

energy even during the slow, low-amplitude swing phases of the pendulum where a standalone generator would otherwise produce minimal usable power. This hybrid approach demonstrates that pendulum-based WECs can be drastically improved not just through mechanical tuning, but by integrating complementary smart materials and collaborative energy harvesting circuits to enhance low-frequency wave harnessing.

Various research works, e.g., [92,139–142], have utilized variants of the above vertical-axis pendulum mechanics to capture energy for powering smart floating buoys and ocean monitoring equipment. Although wave energy is indeed offering a viable alternative for sustainable power complementary to energy storage and solar cells, most of these works focus on custom energy transduction, energy harvesting circuitry and power management.

5.3. Inverted Pendulum Systems

Inverted layouts position the pendulum's mass above its pivot point, establishing an inherently unstable equilibrium that is highly responsive to low-amplitude or low-frequency marine oscillations. Typically, restoring springs are used to stabilize this equilibrium point, and the pendulum swinging motion is converted to usable electricity with a hydraulic PTO or a mechanical transmission. Early inverted pendulum WEC concepts evolved from the Oscillating-Surge WECs such as those in [56,96,143–146].

The inverted pendulum wave energy converter (IPWEC) is an enclosed-hull, reacting inertial WEC with a hollow cylindrical hull operating perpendicular to incoming waves [147], as depicted in Figure 13. Wave-induced surge, heave, and pitch motions generate relative movement between the hull and an internal reaction mass positioned above its pivot point and connected to a torsional spring and direct-drive generator. The main advantage of the IPWEC lies in the elevated Center of Gravity (CoG) of the pendulum, which offers significant structural and control benefits compared with conventional normal pendulum wave energy converters (NPWECs). Optimization showed that the IPWEC can achieve comparable power capture using a pendulum mass 35% smaller and angular motions 50% lower than an equivalent NPWEC. Reduced motion amplitudes decrease the risk of internal collisions and end-stop impacts. In addition, advanced impedance-matching control reduces reactive power requirements by approximately 75%, lowering electrical and mechanical losses and improving overall efficiency. During survival conditions, the holding moment required to lock the pendulum is reduced by 50%, decreasing the size, weight, and cost of the locking system. Design optimization identifies two operational branches. The first uses a highly elevated COG, long arm, and light mass, improving performance in short-period waves but increasing damping and locking demands. The second employs a heavier mass and shorter arm, resulting in behavior closer to conventional pendulum systems. A key limitation of the IPWEC is its inherent instability, requiring sufficient spring stiffness to ensure safe operation under all sea states.

Afsharfard et al. [148] considered a similar working principle with a hull-mounted inverted pendulum able to perform omnidirectional harvesting by means of a string-driven PTO that mechanically rectified and up-converted the harvested power. A unique contribution of this work lies in the arrangement of multiple unmoored harvesting units attached to a shared central storage unit, which improves *CapEx* and *LCOE*. The floater shape was optimized considering various alternative options and numerical estimation of power generation showed about 10 W/kg for a 1 m long pendulum.

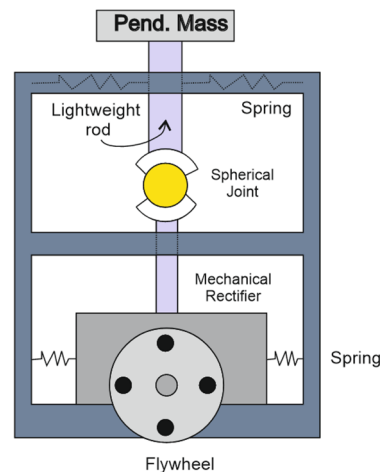


Figure 13. Schematic diagram of the structural configuration of IPWEC (adapted from [147]).

Zhang et al. [67] implemented resonance mechanisms improved by nonlinear dynamics to amplify vibrations in the low-frequency band, designing a multi-stable inverted pendulum TENG (MIP-TENG). Each MIP-TENG comprises a closed and hollow structure, an inverted pendulum element made up of a swing component and magnets, two tension springs, two copper films and a PTFE and nylon membrane. When the MIP-TENG is excited by the base excitation for ocean waves, the inverted pendulum turns around the axis and the membrane. The authors decided upon the inverted pendulum due to easier control implementations, due to both its stiffness and nonlinearity. For low amplitudes (around 6°), the pendulum oscillates around the equilibrium and generates a constant 3 V output. For higher amplitudes (10°), the pendulum oscillates further from equilibrium and manages to generate up to 20 V. In addition, this system classifies wave excitation amplitudes by evaluating the dynamic response in the frequency domain. During higher-amplitude excitations, when the system enters inter-well oscillation mode, a distinct third harmonic amplitude emerges and by comparing these amplitudes against reference values, the system categorizes the wave levels. This suggests that WECs can serve dual purposes, extending beyond primary power generation to include auxiliary functionalities. Then, the authors arranged six MIP-TENG units in a circle which enabled omnidirectional wave energy harvesting and, also, wind direction detection.

In the same line of work for self-powered monitoring equipment, Xie et al. [149] had previously proposed a hybrid harvester utilizing both TENG and a custom electromagnetic transducer, as depicted in Figure 14. The enclosed inverted pendulum was designed to perform vibro-impact omnidirectional motion under wave excitation of the floater; however, TENG produced 3 orders of magnitude less power than the conventional electromagnetic transduction of the magnetic tip mass.

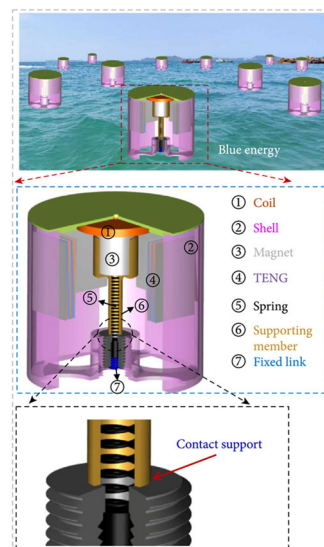


Figure 14. Vibro-impact hybrid inverted pendulum WEC [149].

5.4. Parametric Pendulum Systems

Parametric systems rely on wave-induced displacements (such as heave or surge) to dynamically modulate the pendulum's parameters, specifically its pivot point, over time. This behavior, governed by the Mathieu equation in the linearized small-angle regime, triggers parametric resonance and enables the pendulum to break out of localized oscillations and enter highly energetic, continuous rotation. This subsection reviews recent efforts and concepts with the specific aim to utilize parametric resonance for continuous rotational operation of a pendulum-based PTO.

The concept of using a rotating horizontal-axis pendulum to harvest energy from ocean waves was first proposed in the mid-2000s by researchers in the Centre of Applied Dynamics Research in the University of Aberdeen, UK. The basic principle involves using the heaving motion of a floating buoy as the driving motion of a pendulum's pivot. This is a celebrated mathematical system with rich nonlinear dynamics that includes asymptotic stability of the hanging-down equilibrium for weak (or detuned) pivot motions, among others. Parametric resonances occur since the pivot motion effectively modulates the pendulum's potential energy, thereby injecting energy via the primary stiffness term. The motivation comes from established works, such as [150,151], which have shown that the pendulum may jump to alternative response regimes under proper forcing conditions, including swinging oscillations, chaotic motion and continuous unidirectional rotation. In fact, the primary parametric resonance that unfolds for a 2:1 frequency ratio of the driving frequency to the pendulum's natural frequency leads to a notably broad region of forcing conditions that may push the pendulum into unidirectional rotations. The unidirectional rotation of the pendulum yields multiple times higher harvested power compared to its oscillatory counterpart (see for example [152]), building a strong incentive for pursuing this concept for wave energy conversion.

Xu et al. [153] conducted extensive numerical bifurcation analyses to map the resonance zones leading to rotating orbits of the parametrically excited pendulum, with zero initial velocity and small initial displacement. Horton et al. [154] considered the tilted pivot motion to account for heave–surge coupled motion, reaching similar findings. Further work from the Aberdeen group [108,155] and by Alevras et al. [99] considered the natural extension of placing multiple pendula in the floater for stabilization of the floater and showed interesting synchronization effects that could counteract the destabilizing inertial reaction forces. Notably, when multiple parametric pendula are mounted on a

shared structure, such as a common elastic support within a floating WEC hull, their individual nonlinear dynamics become mechanically coupled. Najdecka et al. [155] investigated this synchronization phenomenon both theoretically and experimentally using two rotating parametric pendula subjected to harmonic excitation. Their study identified two primary synchronous states dictated by the system's coupling: complete synchronization and phase synchronization. A critical finding for the design of multi-oscillator WECs is the direct correlation between these specific synchronization modes and the overall efficiency of power extraction. The researchers conclusively demonstrated that when the pendula synchronize in anti-phase, the configuration is significantly more beneficial from an energy harvesting perspective compared to in-phase synchronization. This anti-phase behavior proves advantageous because it interacts more favorably with the flexible support, enhancing the overall stability of the continuous rotational motion.

Following the initial numerical investigations, Xu and Wiercigroch [156] and Lenci et al. [157] derived approximate analytical solutions of the rotating response using perturbation techniques, extending to the tilted case as well [158]. Critically, the boundaries of the parameter space that includes the rotary response were approximated, revealing a second necessary condition that must be satisfied for rotations to initiate. Specifically, Lenci et al. [157] showed that the saddle-node bifurcation that gives birth to the rotating solutions occurs at a minimum frequency-dependent ratio, γ in their notation, of the modulation amplitude over the pendulum's damping ratio that approaches 2 as the frequency ratio increases. This condition is present alongside the frequency ratio that should be about 2:1 in order to reach the primary parametric resonance. Lenci and Rega [159] and Lenci et al. [94] also provided experimental evidence of rotating orbits of a heaving pendulum, deploying wave tank tests in the Hydraulic Laboratory of the Polytechnic University of Marche, Ancona, Italy. Nevertheless, and despite the concrete importance of acquiring proof-of-concept data, significant deviations from the previous numerical and approximate results were observed. Lenci and Rega [159] attributed these to the strongly nonlinear regime that is central to this concept, elucidating the difficulty of this exercise.

The above results triggered exhaustive analyses of the effect of stochastic excitation on the potential for rotational response of the parametric pendulum, due to the inherent randomness of ocean waves. Indeed, Yurchenko et al. [160] used a rigorous method based on path integrals to compute the probability for rotational response under simply filtered Gaussian noise. By analyzing the joint Probability Density Function of the pendulum response, they showed that increasing noise intensity contaminates the rotational region with intermittent random oscillations; however, rotations were shown to be robust enough to dominate most of the stochastic response. Similar findings were reported considering the pendulum energy instead of the mechanical response [161]. Moreover, Najdecka et al. [95] used spectral sampling to study the effect of stochastic vertical and horizontal excitation. They fitted a PM spectrum to real wave data obtained off the Aberdeen shore and generated pseudo-random time histories. They also found that rotational response is attainable, although at the expense of higher required forcing. Furthermore, Alevras et al. [82] extended the stochastic analysis to the auto-parametric pendulum, i.e., accounting for elastic restoration of the pendulum pivot. This approach captures the concept's dynamics more realistically since it includes the elastic effects of the floater. Following the same methodology, the authors found that the elastic support filters the incoming ocean stochasticity, allowing for a more robust rotational response. These works build confidence that the deterministic conclusions can be extended to real ocean environments. Nevertheless, more detailed modeling up to the wave-to-wire level is required to comprehend the realistic effects of ocean randomness on the sustained rotational response of the parametric pendulum WEC, let alone that the deterministically obtained conditions for

the frequency ratio and the non-dimensional amplitude can only partially be fulfilled from the above developments.

In fact, returning to the previous deterministic analyses, the nondimensional amplitude is derived as the ratio of the pivot's acceleration amplitude over the acceleration of gravity. Furthermore, damping in WECs primarily—and indeed favorably—stems from the PTO capturing power. Consequently, the resource-given buoy heaving acceleration should be significant with respect to gravity in order for the WEC to carry a substantial capacity in terms of the rated generator power whilst maintaining rotational response. Both necessary conditions stumble upon the inherently low frequencies observed in ocean environments. To address the low-frequency constraints characteristic of real ocean environments, Yurchenko and Alevras [84] introduced the concept of the N-pendulum, specifically focusing on a tri-pendulum configuration, as a structural solution to the physical scaling limitations of parametric PTO systems, as seen in Figure 15a,b. For a standard mathematical pendulum to achieve primary parametric resonance with typical ocean wave periods (which average approximately 10 s, or 0.1 Hz), very fine adjustment of the pendulum eccentricity is required. The N-pendulum architecture overcomes this issue by arranging N rigidly connected arms equally spaced around a central hub. Extending the length of a single arm or increasing its lumped mass relative to the remaining balanced arms, the system exhibits dynamics that completely decouple the equivalent natural frequency from the device's physical length.

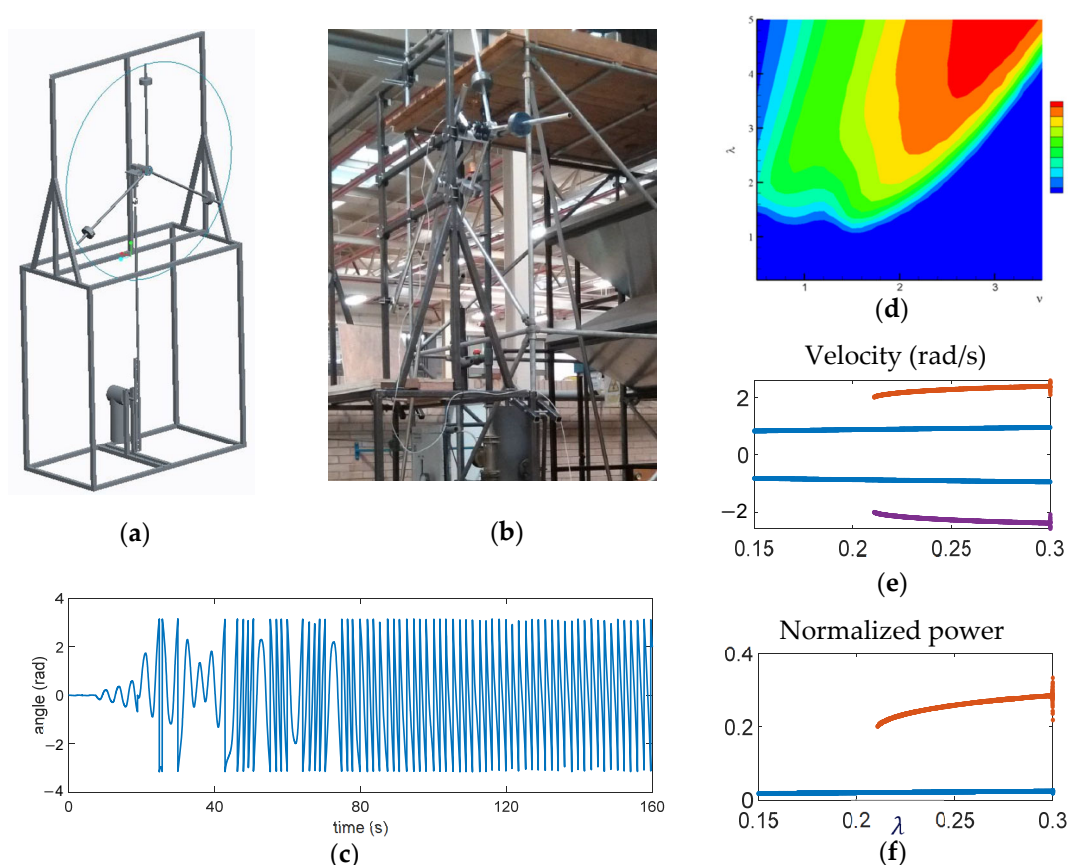


Figure 15. (a) Sketch of an experimental rig with tri-pendulum; (b) physical rig in tilted configuration; (c) angle of rotational response sustained for excitation <1 Hz; (d) parameter space plot denoting rotations in red for random planar pivot motion; (e,f) bifurcation diagram of velocity and normalized harvested power for the parametric pendulum showing rotations in red/magenta and oscillations in blue (adapted from [162]).

The primary advantage of this design is its ability to achieve ultra-low natural frequencies within a compact, structurally realistic envelope (typically between 2 and 5 m), rendering it highly practical for integration inside floating platforms or heaving buoys. Furthermore, because the equivalent frequency is dictated by the relative difference between the asymmetrical arm lengths rather than the absolute distance from the pivot, the natural frequency and the structural moment of inertia can be selected independently. Alevras et al. [163] developed a dry lab experimental rig to test these expectations using a slider-crank excitation source. The authors reported various test cases, being able to present sustained rotary response of the proof-of-concept model for an excitation lower than 1 Hz, as shown in Figure 15c. Dotti and Virila [162] extended this work to thoroughly consider an arbitrary number of eccentric masses, closing the energy harvesting loop with a simple resistive power capturing circuit. Indeed, their numerical modeling reported that the very same pendulum system would harvest about 7 times more power when the pendulum rotated compared to the oscillating counterpart under the same forcing conditions (see Figure 15e,f), establishing a promising piece of evidence for the further development of this concept.

Although satisfying the frequency condition has been shown to be flexibly achievable, reaching the highly efficient period-one rotational state remains a primary design objective. However, ocean waves often lack the amplitude required to drive a standard vertical pendulum over the homoclinic orbit. In fact, the experimental campaigns above have shown a particular difficulty in doing so. To overcome this without resorting to complex up-conversion mechanisms, Yurchenko and Alevras [88] investigated a novel WEC design predicated entirely on a parametrically excited pendulum operating under a “reduced gravity” framework. By purposely orienting or modifying the pendulum’s rotational plane, as seen in Figure 16, the effective gravitational restoring torque acting on the mass is significantly reduced. Their numerical models and deterministic analyses demonstrated that this reduction allows the pendulum to easily break out of localized, small-angle oscillations and enter sustained, continuous rotational motion even at low-amplitude regular waves. Experimental proof of the concept was also provided in the same work. Dostal and Pick [164] moved a step further and considered a JONSWAP spectral excitation of the tilted tri-pendulum. They showed that prominent rotational response can be sustained in the long term even under stochastic excitation and despite minor detuned intervals.

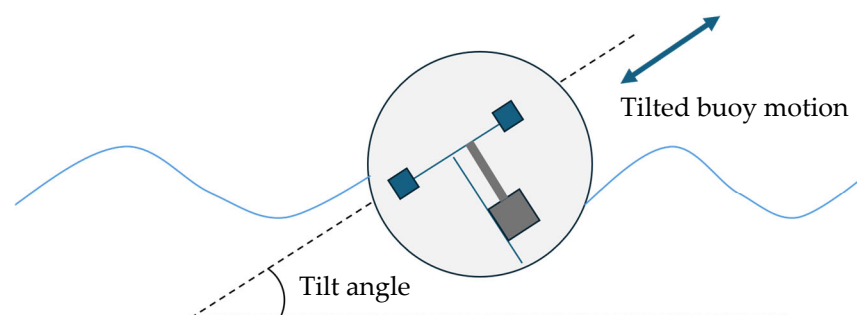


Figure 16. The schematic of the low-gravity parametric pendulum WEC (adapted from [88]).

This “reduced gravity” approach demonstrates that carefully tailored nonlinear physical geometries can inherently solve both conditions of the low-frequency conversion problem, paving the way for simpler, more robust offshore energy harvesters. Dotti and Virila [162] reported that a tilt angle greater than $\pi/3$ reduces the amplitude threshold for rotations to emerge, stating a preliminary estimation of harvested power of up to 5 kW/t. Recently, Liu et al. [152] considered a similar tilted configuration for a submerged WEC.

Their numerical results revealed rotational and chaotic motion, with the rotary configuration yielding 18.5 W/kg as opposed to oscillations reaching only 6 W/kg. Although experimental confirmation is highly required, these numbers outperform most of the advanced PA WECs, providing considerable promise concerning the parametrically excited pendulum WEC. Building upon the framework of “reduced gravity” systems to overcome the energy barriers of parametric resonance, recent works have proposed utilizing magnetic interactions to actively reshape the pendulum’s potential energy. Trandafir and Alevras [86] recently introduced a novel design employing a nonlinear magnetic pendulum specifically designed for ultra-low-frequency and weak vibration energy harvesting.

Giorgi et al. [93] proposed an inertial energy harvester utilizing a horizontal-axis fly-wheel enclosed within a floating hull, a configuration specifically designed to be insensitive to the incoming wave direction. Addressing the complex optimization challenges inherent in nonlinear PTO systems, their analysis reveals multiple response regimes depending on the prescribed motion and the applied PTO damping parameter. The study demonstrates that continuous, periodic rotational solutions are the most effective for maximizing energy extraction. In this rotational regime, the instantaneous power never drops to zero, contrasting sharply with oscillatory regimes where power extraction ceases at every velocity reversal. However, the research also exposes a critical hurdle for practical application: the boundary between optimal periodic rotation and suboptimal chaotic motion is highly sensitive to the PTO damping coefficient. Small variations in damping can trigger abrupt transitions into chaos, causing reduced average power conversion and underscoring the absolute necessity for robust, optimal control strategies in the design of next-generation nonlinear PTOs.

5.4.1. Advanced Control for Rotation Initiation

In nonlinear pendulum-based WECs, managing the basin of attraction is a critical operational challenge because these systems exhibit multi-stability, where multiple stable steady-state regimes (such as continuous period-one rotation or localized small-amplitude oscillation) co-exist within the exact same wave parameter space. The boundary separating the periodic rotational attractor from a suboptimal chaotic or oscillatory attractor is sensitive to both wave stochasticity and PTO damping variations. In real-world, irregular sea states governed by JONSWAP or PM spectra, random wave fluctuations can abruptly push the internal pendulum out of its high-energy rotating basin into a low-yield localized oscillation zone. Consequently, advanced control methods are required to actively expand the rotational attractor basin, suppress chaotic transitions, and robustly re-initiate continuous rotation after detuning perturbations.

De Paula et al. [101] applied chaos control methods to extend the region of occurrence of period-1 rotations. Specifically, they applied a continuous perturbation approach to stabilize the unstable orbits of a parametric pendulum–shaker system that exist within the chaotic attractor. Time-delayed feedback was used to negate the Lyapunov exponents of such orbits thereby avoiding chaos. Moreover, they suppressed period-doubling bifurcations that destabilize the desired rotational solution, thus extending the stability region of this response. In fact, they reported that minimal control effort is required once the rotational orbit is realized. This points to the possibility of utilizing small amounts of energy for control in order to initiate and preserve the rotational response, which is highly favorable for energy harvesting purposes.

Vaziri et al. [103] experimentally investigated methods for initiating and maintaining period-1 rotation in a harmonically excited parametric pendulum. Three distinct start-up control strategies were evaluated: a bang-bang method, a velocity comparison method, and a time-delayed feedback (TDF) approach with multi-switching. The bang-bang strategy applies a constant-magnitude torque whose sign tracks the instantaneous pendulum

velocity, progressively amplifying oscillation amplitude until rotation is achieved; however, the method proved sensitive to the excitation parameters, succeeding at higher forcing amplitudes but failing at lower ones. The velocity comparison method overcomes this limitation by referencing the pendulum's velocity at two key angular positions against the known velocities on the target period-one orbit, yielding robust start-up across a wide frequency range at the cost of requiring prior knowledge of the reference orbit.

The TDF controller was found to be the most versatile, generating a feedback signal proportional to the difference between the current and time-delayed angular displacement, with the delay set equal to the excitation period; once the system locks onto the periodic orbit the control effort vanishes automatically. Critically, the authors demonstrated that TDF can simultaneously maintain rotation under continuously varying forcing frequency and amplitude, as well as in the presence of additive noise up to 10% of the maximum control signal magnitude, confirming the robustness necessary for stochastic sea states. Finally, the study was extended to a two-pendulum configuration in which two independent TDF controllers successfully initiated both in-phase and anti-phase synchronized rotation and restored synchrony after an external mechanical perturbation, with the control effort decaying to zero once steady rotation was re-established. From a WEC design standpoint, these findings establish TDF as a low-power control architecture capable of bridging the gap between arbitrary initial conditions and the sustained period-one rotation required for maximum energy yield, while remaining compatible with the multi-pendulum anti-phase synchronization identified as optimal by Najdecka et al. [155]. De Paula et al. [165] also extended their previous work on chaos control to experimental investigations showing successful managing of the rotational orbit and good agreement with model predictions.

Reguera et al. [166] used the intuitive control approach to modulate the pendulum length in order to preserve rotational motion of a parametric pendulum. They imposed a telescopic adjustment of the pendulum length based on a logistic function reading the pendulum state. Interestingly, they reported that the pendulum would enter the rotational regime under a typical PM spectrum wave excitation regardless of the initial conditions. Despite the promising utility of this straightforward approach, the energy expended for the control effort was not investigated therein.

Dotti et al. [167] introduced and experimentally validated a velocity-based control law designed to be both theoretically and constructively simpler than TDF, while delivering comparable performance. An external control torque is applied to the pendulum, defined as inversely proportional to its instantaneous angular velocity above a velocity threshold and zero otherwise. This threshold aims to model a limit for the engagement of rotational motion, meaning that the controller automatically switches off once rotation is established, consuming energy only during the brief start-up phase. The threshold itself is expressed entirely in terms of the damping parameters and the natural frequency, with no reference to the external excitation period—a deliberate design choice that decouples the control law from knowledge of the forcing waveform. Experiments on a pendulum wheel mounted on a crank-rod shaker confirmed that rotations can be initiated from rest or from oscillation under multiple harmonic forcing conditions and recovered under an irregular forcing protocol in which the excitation was interrupted and resumed at random intervals. The authors benchmarked their approach directly against the conclusions of Vaziri et al. [103], concurring that TDF is the most capable of the methods assessed to date but arguing that the velocity law is the most practical for real ocean deployments since its period independence makes it naturally suited to stochastic sea states.

The most recent contribution from this group, Virla et al. [168], addressed the practical construction challenges inherent in prior torque-based methods by replacing mechanical couplings with a non-contact electromagnetic actuator. A permanent magnet

mounted on the outer rim of a pendulum wheel interacts with a fixed, externally powered air-core coil to produce a repulsive tangential force acting as the control source. The threshold velocity condition that gates activation is identical in form to the one established in the earlier velocity-based study. Validated through both simulation and experiment, the electromagnetic controller successfully drives the pendulum from oscillatory initial conditions into stable rotations across the transition region of the forcing parameter space. Basin-of-attraction analyses showed improvements from roughly 20% to nearly 80% in the rotating initial conditions in this intermediate regime. Robustness tests demonstrated that the control remains effective under angular velocity measurement noise up to $\pm 48\%$ of the true value, while pseudo-random PM forcing simulations confirmed that intermittent rotational losses are reliably recovered by repeated control pulses. The elimination of mechanical contact and the physical grounding of the control law represent meaningful progress toward a maintainable, sea-deployable actuator for pendulum WECs, and the authors identify optimal pulse scheduling and control gain adaptation as the primary open problems for future work.

Moving beyond passive damping or non-invasive gating techniques, researchers have investigated the implementation of predictive, closed-loop tracking architectures capable of proactively adapting to time-varying wave profiles. These established control techniques have been applied to pendulum WEC systems designed to operate away from the primary parametric resonance. Therefore, exploring MPC methods for initiating, maintaining and recovering the pendulum rotational response in real stochastic ocean environments is an interesting avenue to explore in future developments.

For clarity and concise comparison, Table 3 collects the technical parameters of the representative pendulum-based WECs reviewed in the preceding sections. To evaluate the validation maturity of each concept, the experimental testing stage is categorized into four distinct levels: numerical (purely computational or time-domain simulation frameworks), which is equivalent to Technology Readiness Level (TRL) 1–3; dry lab (benchtop testing using electrodynamic shakers or motion platforms) equivalent to TRL 3–4; wave tank (scaled hydrodynamic testing in wave flumes or towing basins) equivalent to TRL 4–5; and sea-tested (full-scale or large-scale open-ocean trials) equivalent to TRL > 6. It should be noted that the performance metrics reported in Table 3 (such as mean/peak power and power density) reflect the specific metrics, operational sea states, and internal damping conditions declared by the respective authors in their original studies. Because these values were obtained across disparate prototype scales, wave spectra (regular vs. irregular JONSWAP/PM), and PTO load setups, direct horizontal benchmark comparisons across all concepts cannot be strictly standardized; rather, they serve to illustrate the maximum output potential demonstrated within each device’s intended operational envelope.

Table 3. List of pendulum-based WECs.

Name	Ref.	Type ¹	PTO	Control	Performance	Testing
VAPWEC	[14,90]	V	Rotary generator	MPC	Mean <52 kW	Wave Tank
VAPPWEC	[136]	V	Rotary generator/transmission gears	Linear damping control	Optimal Conditions: ~10 kW	Wave Tank
Spring Pendulum Buoy	[128]	V	Nonlinear spring cap-ture	Passive control (nonlinear stiffness)	Peak: 250 W	Wave Tank
Hybrid TENG-EMG	[138]	V	Hybrid TENG and EMG	Phase-synchronization circuit	60 mW	Dry Lab
Vertical-Axis Uni-directional Rotor	[97]	V	Rotational mechanical	N/A	N/A	Wave Tank
Sundae Cup-Shaped Buoy	[111]	H	TENG + mechanical PTO	N/A	Peak: 12.11 mW	Dry Lab
Multi-Link WEC	[137]	H	Mechanical PTO	Nonlinear reactive	750 kW	Numerical

DMPEH	[85]	H	Electromagnetic transducer	N/A	3.5 kW	Dry Lab
SEAREV (G1, G21, G3)	[77]	H	Direct-drive	LOD control and de-clutching	1620 MWh/year (G3)	Sea-Tested
PeWEC	[107,116,117]	H	Rot. generator	Generator current	110 kW rated (~400 MWh/year Mediterranean site yield)	Wave Tank
Adjustable Pendulum UMV	[110]	H	Electromagnetic	Adjusting length	5.47 W mean	Dry Lab
Horizontal-Axis Flywheel	[93]	H	Rotational generator	PTO damping control	<30 kW	Numerical
SWINGO	[109,126]	H	Proportional PTO controller	Passive control	N/A	Numerical
IPWEC	[147]	I	Rotary generator/mech. rectifier	Complex conjugate control, impedance matching	2 W/kg	Dry Lab
MIP-TENG	[67]	I	TENG	Stiffness/nonlinear control	0.05–0.1 mW	Dry Lab
TDF Multi-Pendulum	[95,103,169]	P	Rotary generator	Time-delayed feedback	N/A	Dry Lab
Tri-Pendulum WEC	[84,88,163]	P	Rotary generator	N/A	2.5–7.8 kW	Dry Lab
EM Actuator Pendulum	[168,170]	P	Rotary generator	Velocity control	~5 W	Dry Lab

¹ Type is denoted by letter as H: horizontal axis; V: vertical; I: inverted; P: parametric.

5.4.2. Multi-Pendulum Synchronization and WEC Array Effects

Mounting multiple parametric pendula within a single floating hull introduces non-negligible mechanical coupling via the shared elastic structure. Theoretical and experimental studies [171] demonstrate that multi-oscillator systems exhibit two primary phase-locking states: in-phase and anti-phase synchronization. Najdecka et al. [155] investigated the potential for synchronous motion of parametrically excited pendula mounted on a common platform. Recently, the same group experimentally investigated the sensitivity of the synchronization conditions to system parameter discrepancies [108]. From an energy-extraction perspective, anti-phase synchronization is significantly more advantageous. Under anti-phase rotation, the opposing transverse reaction forces generated by the rotating masses cancel each other out [172], drastically reducing parasitic high-frequency reactive loads on the primary hull, while enhancing the overall dynamic stability of the continuous period-one rotational regime [173].

When deploying pendulum WEC buoys in offshore farm arrays, hydrodynamic interactions (wave scattering and radiation interferences among adjacent floaters) modify the local wave climate. Constructive interference increases the local excitation amplitude, widening the parametric resonance bandwidth and lowering the threshold required for rotation initiation. Conversely, destructive interference reduces the pitch/roll excitation, potentially causing internal pendula in downstream buoys to drop out of stable rotation into suboptimal chaotic or small-amplitude oscillatory regimes [174,175].

5.5. Applications

WECs offer a highly dense and consistent renewable energy source capable of enhancing grid stability and supporting local economies, particularly in coastal and island communities that often face high energy costs and insecurity due to a reliance on imported fuels. At a broader scale, wave energy infrastructure has the potential to be co-developed alongside other marine industries, such as offshore wind turbines. This multi-use cost-sharing approach to ocean space not only maximizes resource extraction but also contributes significantly to international climate change mitigation efforts, economic resilience,

and energy independence. Beyond large-scale utility generation, WECs are proving increasingly viable for independently powering remote offshore marine infrastructure. Practical applications in this domain include providing reliable electricity for meteorological sensors, navigation lights, and ocean buoys [130]. WEC technology is also expanding into dual-purpose applications that go beyond primary power generation to include auxiliary functionalities like environmental sensing. For instance, specialized intelligent buoys can leverage wave energy to simultaneously power their systems and perform real-time hydrological monitoring or anomaly detection, which is highly useful for safeguarding structures like cross-sea bridge piers [111]. Additionally, some advanced designs can analyze their own dynamic mechanical responses to classify wave excitation amplitudes or detect wind direction, effectively transforming the power generator into a self-sustained marine diagnostic tool [67]. Apart from grid power, pendulum-based WECs can be central for powering small devices like ocean IoT sensor nodes, unmanned surface vehicles, and submerged monitoring devices, or even fish farms, building strong promise for leveraging ocean power to sustainably power the blue economy. In order to support offshore aquaculture, ocean platform power, and coastal facilities, WECs must have high availability and minimal maintenance intervention. For oceanographic IoT, sensing and autonomous marine vehicles, pendulum-based WECs must prioritize compact volumetric footprints, low start-up activation thresholds under weak ocean excitations, and omnidirectional sensitivity. Table 4 includes a non-exhaustive list of the applications that pendulum-based WECs are or could be involved in, according to the literature articles and reports. Please note that only pendulum-based WECs with an intended application clearly embedded in the device's engineering are included. This table is intended as an initial pathway guide for applications that could potentially be supported by pendulum-based WECs.

Table 4. List of applications considered for pendulum-based WECs.

Application	Pendulum Type	References
Ocean Monitoring	Horizontal	[176–178]
	Vertical	[130,139,141,142,179,180]
	Inverted	[67]
Power Generation	Horizontal	[77,123,181–183]
	Vertical	[184]
IoT	Horizontal	[130,176,179,185,186]
	Vertical	[187]
	Inverted	[188]
Offshore infrastructure	Horizontal	[185,189–192]
	Vertical	[142,193]
Unmanned Marine Devices	Horizontal	[127,176,194–196]
	Vertical	[92]

Overall, the integration of pendulum-based WECs in marine equipment and infrastructure as a sustainable power source seems to be the most mature area of application, including various examples of horizontal, vertical and inverted pendulum-based systems. Utility-scale power generation is a much tougher path to follow, with some downturns in the recent past, such as the Penguin, yet the horizontal-type technology is steadily maturing as the progress with PeWEC is showing. Pendulum WECs, enabled by their fully enclosed PTO designs, are gaining traction as a niche renewable energy technology for remote-island applications. Lastly, there is significant room for performance improvements and stronger industry penetration by advancing sophisticated conversion principles, such as rotary parametric pendula, that could yield significantly higher power from ocean waves.

6. Conclusions

This review has presented a comprehensive survey of technologies for harvesting ocean wave power, with a particular focus on pendulum-based systems and their evolution toward sophisticated nonlinear energy harvesting devices. Interest in these devices and concepts is driven by climate change and the pressing need for energy portfolio diversification and energy security in remote communities, as well as the demand for sustainable power for emerging blue economy sectors. Spanning the fundamental physics of ocean waves, hydrodynamic modeling, energy harvesting principles, necessary subsystems, advanced control strategies, and economic feasibility, this review establishes a cohesive framework within which the state of the art can be evaluated and the future research directions identified.

The analysis of PA WECs demonstrates that, while these devices represent the most commercially mature class of oscillating-body converters, their performance is fundamentally constrained by the narrow bandwidth of linear resonance. Pendulum-based WECs emerge from this review as a compelling and fundamentally distinct paradigm. By operating as internal reaction masses, they decouple the sensitive PTO components from direct wave impact within a sealed hull, while exploiting multi-directional wave-induced motions—such as pitch, roll, heave and surge—to excite an internal pendulum. The most promising advantage of this architecture lies in its capacity to harness parametric resonance. Through the wave-induced modulation of the pivot point, the pendulum can transition from bounded small-angle oscillations into continuous rotation. This rotational regime constitutes an inherent motion rectification, enabling the PTO to deliver continuous mechanical output leading to multi-fold improvements in the harvested power.

The theoretical and experimental works reviewed herein—spanning vertical-axis pendula, gimbaled gyro pendula, horizontal-axis systems, multi-mass configurations, and eccentric rotors, collectively confirm that exploiting these nonlinear rotational dynamics significantly outperforms direct-force oscillatory designs in terms of average power extraction and bandwidth. Although swinging horizontal-axis pendulum systems have hitherto enjoyed successful progression to sea trials, their parametric counterpart holds significant promise for further improvements in real-world performance.

Despite the technological advances to date, several challenges must be addressed before pendulum WECs can achieve widespread commercial viability. The sensitivity of the rotational regime to PTO damping demands robust and adaptive control strategies that can operate reliably under stochastic wave inputs. The integration of multi-pendulum synchronization arrays, combined with active nonlinear control strategies such as MPC-based methods, represents the most critical frontier for the field. From an economic perspective, reducing *CapEx* and *OpEx* requires probabilistic structural optimization, rigorous failure mode analysis and component-level reliability modeling to extend operational lifetimes in harsh offshore environments. Looking ahead, advancing the still-limited penetration of machine learning and artificial intelligence in this WEC branch will assist in delivering structural innovations and online robust control strategies to enable highly energetic rotational modes in real ocean waters. Ultimately, realizing the full potential of pendulum-based WECs will require a sustained, interdisciplinary research effort spanning nonlinear dynamics, advanced control theory, novel smart materials, and rigorous economic modeling—a challenge that, given the immense scale of the global wave energy resource, is essential to pursue.

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