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A comparative state-of-the-art review of wave energy converters: point absorbers, linear absorbers, and hybrid systems

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HIGHLIGHTS

- Comparative framework for point absorbers, linear absorbers, and hybrid absorbers.
- Integrated wave-to-wire modeling enables realistic performance and design optimization.
- Artificial intelligence control methods improve power capture and system survivability.
- Techno-economic analysis links costs, scalability, readiness levels, and integration trends.
- Strengths–weaknesses analysis and roadmap outline barriers, investment needs, and future research.

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ABSTRACT

Harnessing energy from ocean waves has gained increasing attention as a viable component of sustainable energy strategies due to its high power potential and predictable availability. This review provides a comprehensive assessment of three primary categories of wave energy conversion systems: point absorbers, linear absorbers, and hybrid systems. Drawing upon more than 200 scientific publications, the study examines the operational principles, structural characteristics, performance indicators, and control methodologies associated with each class. Special emphasis is given to recent technological advances, including adaptive power take-off architectures, and multifunctional offshore platforms that integrate wave, wind, and aquaculture. A comparative evaluation highlights performance trade-offs, techno-economic considerations, and environmental implications, while a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is employed to identify both barriers and growth prospects. The review concludes by outlining future research directions, particularly the need for real-time control, large-scale demonstration, and integrated multi-use concepts. This study aims to serve as a reference for academics, engineers, and policymakers in shaping the next generation of marine renewable energy technologies.

Abbreviations

WEC	Wave Energy Converter
PA-WEC	Point Absorber Wave Energy Converter
LA-WEC	Linear Absorber Wave Energy Converter
HS-WEC	Hybrid System Wave Energy Converter
PTO	Power Take-Off
LCOE	Levelized Cost of Energy
TRL	Technology Readiness Level
DoF	Degree of Freedom
PFT	Potential Flow Theory
BEM	Boundary Element Method
CFD	Computational Fluid Dynamics
SPH	Smoothed Particle Hydrodynamics
DEGs	Dielectric Elastomer Generators
AI	Artificial Intelligence
RL	Reinforcement Learning
MPC	Model Predictive Control
O&M	Operational and Maintenance
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
EMEC	European Marine Energy Centre

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FOWT	Floating Offshore Wind Turbine
GA	Genetic Algorithm
SWOT	Strengths, Weaknesses, Opportunities, Threats
ESO	Enhanced Snake Optimizer
MUP	Multi-Use Platform
DC	Direct Current
SEA	Strategic Environmental Assessment
EIA	Environmental Impact Assessment
SCADA	Supervisory Control and Data Acquisition
ADCPs	Acoustic Doppler Current Profilers
MSP	Marine Spatial Planning
EEZ	Exclusive Economic Zone
IEA	International Energy Agency
PPA	Power Purchase Agreement
OEE	Ocean Energy Europe
IRENA	International Renewable Energy Agency
PV	photovoltaic
EMS	Energy Management System
DAQ	Data Acquisition
RMSE	Root Mean Square Error
NRMSE	Normalized Root Mean Square Error
SHM	Structural Health Monitoring
IEC	International Electrotechnical Commission
Nomenclatures	
I_t	Investment cost at time t
M_t	Operation and maintenance cost
F_t	Fuel or consumables (typically zero for WECs)
E_t	Electricity generated
r	Discount rate
T	Project lifespan (years)

1. Introduction

The urgent necessity to mitigate climate change and shift toward cleaner energy portfolios has heightened global interest in renewable sources. Among these, ocean wave energy stands out as a largely untapped yet potent option, with considerable advantages such as high power density, dependable availability, and widespread distribution across coastlines [1,2]. Ocean waves encapsulate both kinetic and potential energy formed through atmospheric wind interaction and gravitational influences. The persistent nature of wave motion renders it a reliable candidate for large-scale electricity production.

To exploit this resource, wave energy converters (WECs) have been engineered to transform ocean wave motion into usable electrical energy. A variety of WEC designs have been proposed and tested over the past decades, each characterized by distinct operational mechanisms, structural layouts, and site-specific applications [3,4]. Despite technological progress and the successful demonstration of several prototypes, widespread commercialization remains constrained by issues such as economic feasibility, environmental durability, long-term reliability, and integration challenges within existing offshore infrastructure [5]. Recent research has highlighted the role of wave–current interactions in marine renewable energy systems, showing that coupled hydrodynamic conditions can substantially influence unsteady loads, operational stability, and energy yield. Such insights are increasingly relevant for informing deployment strategies, risk mitigation, and system integration in emerging wave energy projects [6,7].

This paper focuses on three principal categories of WECs (Fig. 1), each demonstrating promising development trajectories:

1. Point Absorbers (PA-WECs)**:** These are typically compact, floating devices designed to harvest energy from vertical (heave) motion induced by waves. By tuning to match incoming wave frequencies, these systems can achieve enhanced energy absorption. Foundational contributions by Budal and Falnes [8], along with theoretical advancements by Evans [9,10], have been instrumental in guiding current designs. Modern PA-WECs have seen ongoing evolution in structural forms, mooring techniques, and advanced control systems [11,12].
2. Linear Absorbers (LA-WECs): A broader category of line-type WECs that extract energy along the wave direction. Within this category, attenuators (e.g., Pelamis) represent the most widely recognized subset. In addition, several linear absorber concepts employ linear electric generators aligned with the wave propagation direction, enabling direct conversion of heave motion into electrical power [13]. Attenuator-type LA-WECs typically comprise multiple linked segments aligned with the wave direction, with energy extraction arising from their relative motion. The Pelamis device, for instance, has been extensively explored in terms of hydrodynamic response [14,15], structural design [16,17], and lifecycle cost analysis [18,19].
3. Hybrid Systems (HS-WECs): Hybrid WECs integrate wave energy extraction with offshore infrastructure to form multifunctional platforms. Studies have shown integration with floating wind turbines can improve spatial efficiency and stabilize output [20]. Other

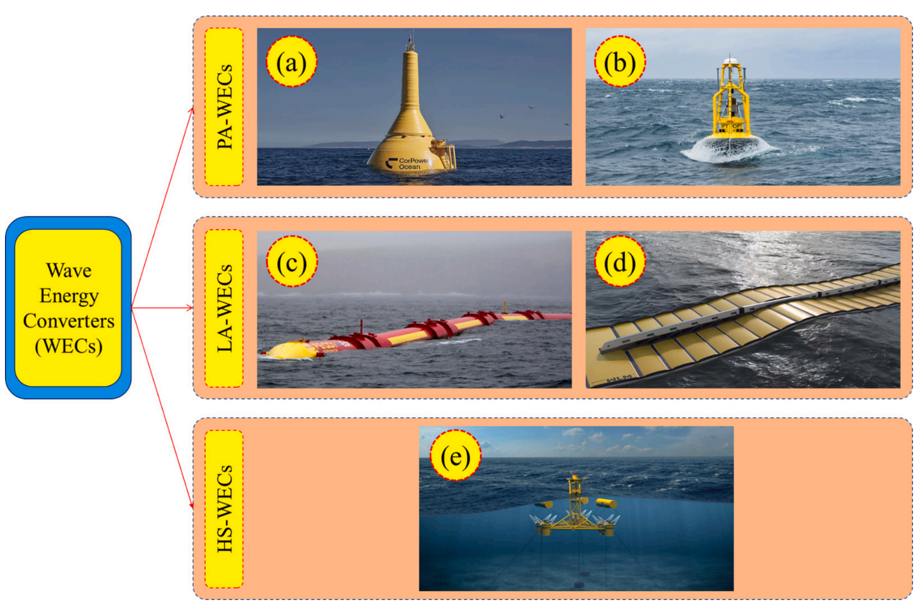


Fig. 1. Principal categories of WECs: point absorbers (a) CorPowerC4 WEC [26], (b) PB3 PowerBuoy [27]; linear absorbers (c) Pelamis WEC [28], (d) Spine-like WEC [29]; and (e) hybrid systems [30], illustrating their conceptual layouts and development trajectories.

works highlight synergies with breakwater systems that reduce installation costs [21,22], while co-location with aquaculture facilities offers diversified economic benefits [23]. Multi-use offshore platforms further extend these concepts by merging energy production with maritime services [24,25]. Collectively, such hybrid approaches aim to overcome the limitations of single-mode WECs through system-level coordination and shared assets.

Although several review papers have addressed different aspects of WECs, most have concentrated on specific device types or isolated technical domains—such as hydrodynamic modeling, control algorithms, or economic assessments—without providing a unified comparative perspective. In particular, literature on point or linear absorbers tends to underrepresent emerging technological trends, while analyses of hybrid platforms rarely explore their synergy with established devices. Furthermore, only a limited number of studies consider broader dimensions such as commercialization progress, system-level synergies, or adaptive control strategies. As a result, the literature still lacks a holistic, technology-inclusive review that spans both technical depth and system-level integration. The present work addresses this gap by adopting a unified analytical lens across four primary WEC categories—point absorbers, linear absorbers, and hybrid systems—while systematically examining their operational principles, performance indicators, control challenges, and deployment trajectories. This foundation sets the stage for a set of clearly defined review objectives that guide the structure and content of this study. Specifically, the main goals of this review are to:

- Categorize leading WEC technologies into four principal classes—point absorbers, linear absorbers, and hybrid systems—based on their operational principles and current development status;
- Compare performance characteristics and trade-offs across these categories, including both conventional and hybrid configurations;
- Examine recent progress in hydrodynamic modeling, experimental investigations, power take-off (PTO) design, and advanced control methodologies;
- Evaluate techno-economic indicators such as levelized cost of energy (LCOE), technology readiness level (TRL), scalability, and environmental impact;

Highlight representative case studies (e.g., large-scale PA and LA prototypes, and multi-use hybrid platforms), together with integration challenges that influence deployment

- Support academia, industry, and policymakers in formulating innovation strategies for next-generation marine energy systems;
- Identify existing limitations in current approaches and outline clear directions for future research, with emphasis on real-time optimization, multi-functional platforms, and large-scale demonstration.

In summary, this review offers a multi-perspective evaluation of wave energy technologies by not only describing their physical mechanisms and control principles, but also critically comparing their maturity, environmental integration, and commercialization pathways. Its novelty lies in synthesizing the three principal WEC categories—point absorbers, linear absorbers, and hybrid systems—within a unified analytical framework that connects operational concepts with control strategies and deployment readiness. In addition to highlighting hybrid system integration trends and multifunctional platform synergies, the review uniquely incorporates three underrepresented yet essential dimensions in a comparative context: (i) techno-economic analysis, including cost metrics and investment implications; (ii) commercial readiness indicators, such as TRLs; and (iii) environmental and system-level integration, covering aspects such as biofouling, mooring, and grid compatibility. These elements, often treated in isolation in prior reviews, are here jointly examined to provide a holistic, technology-inclusive view of WEC development and its future prospects. The structure of this review is summarized in Fig. 2.

2. Wave energy fundamentals

Wave energy is a concentrated, predictable, and largely untapped renewable energy resource that can play a significant role in decarbonizing global power systems. Harnessing ocean waves requires a deep understanding of the physical characteristics of wave motion, energy transport, and site-specific wave dynamics. This section outlines the core physical principles that underpin WECs, examines resource assessment techniques, and presents the mathematical frameworks used in WEC modeling and design.

2.1. Global wave energy potential and site considerations

The theoretical wave energy potential worldwide exceeds 2 TW, with economically exploitable resources concentrated along windward western coasts of continents [1]. A global mapping initiative by Satymov et al. [1] provided high-resolution, hourly assessments of wave power flux, showing that regions such as the North Atlantic, Southern Ocean, and western Pacific consistently offer wave power densities exceeding 40–70 kW/m of wave crest [26,31,32].

Fig. 3 compares the power output performance of three distinct WEC designs—point absorber, attenuator, and two-body heave system—-under standardized deployment conditions. This comparison highlights key differences in operational bandwidth and power capture characteristics. Fig. 3(a) illustrates the wave power matrix for the CorPower PA-WEC, a buoy-type system tuned for resonance in moderate sea states and detuned during storms to enhance survivability. The matrix is based on a 400 kW nominal unit, optimized for depths of 30–100 m and capable of deeper deployment. Fig. 3(a) reflects performance across varying wave heights and periods, showing how energy output scales with resource conditions [26]. Fig. 3(b) presents the power matrix of the Pelamis attenuator-type LA-WEC, a hinged, snake-like device that generates electricity from the relative motion between connected floating segments. The matrix reflects the performance of a 750 kW nominal unit, positioned head-on to wave direction. A conservative installation density of 14.79 MW/km^2 was applied to estimate its technical output across different wave conditions [33]. Fig. 3(c) shows the power matrix for an F-2BH WEC, a two-body system with one floating and one submerged component linked through a spring-damper mechanism. Energy is extracted from the vertical motion difference between the bodies, driven by wave-induced heaving. The matrix corresponds to a 1 MW nominal unit, while the deployment density of 14.79 MW/km^2 follows values adopted in earlier comparative assessments of array-scale performance [34,35] and technology benchmarking studies [36,37].

Accurate evaluation of these power matrices depends not only on device characteristics but also on the quality and resolution of input wave climate data. The energy yield and spatial deployment potential of each WEC design are highly sensitive to regional wave conditions, such as significant wave height and energy period. To ensure consistent and realistic assessments, resource modeling typically relies on long-term, high-resolution datasets. These datasets serve as the foundation for generating technology-specific power matrices across global and regional sites, typically derived from ERA5 reanalysis data [38], WaveWatch III simulations [39], and satellite altimetry combined with in-situ buoy measurements [40].

2.2. Factors influencing wave energy extraction

Understanding the factors that affect wave energy extraction is essential for optimizing converter performance and siting. Even with high theoretical wave power, device efficiency and reliability can vary significantly based on local sea state complexity. Environmental and oceanographic conditions introduce spatial and temporal variability

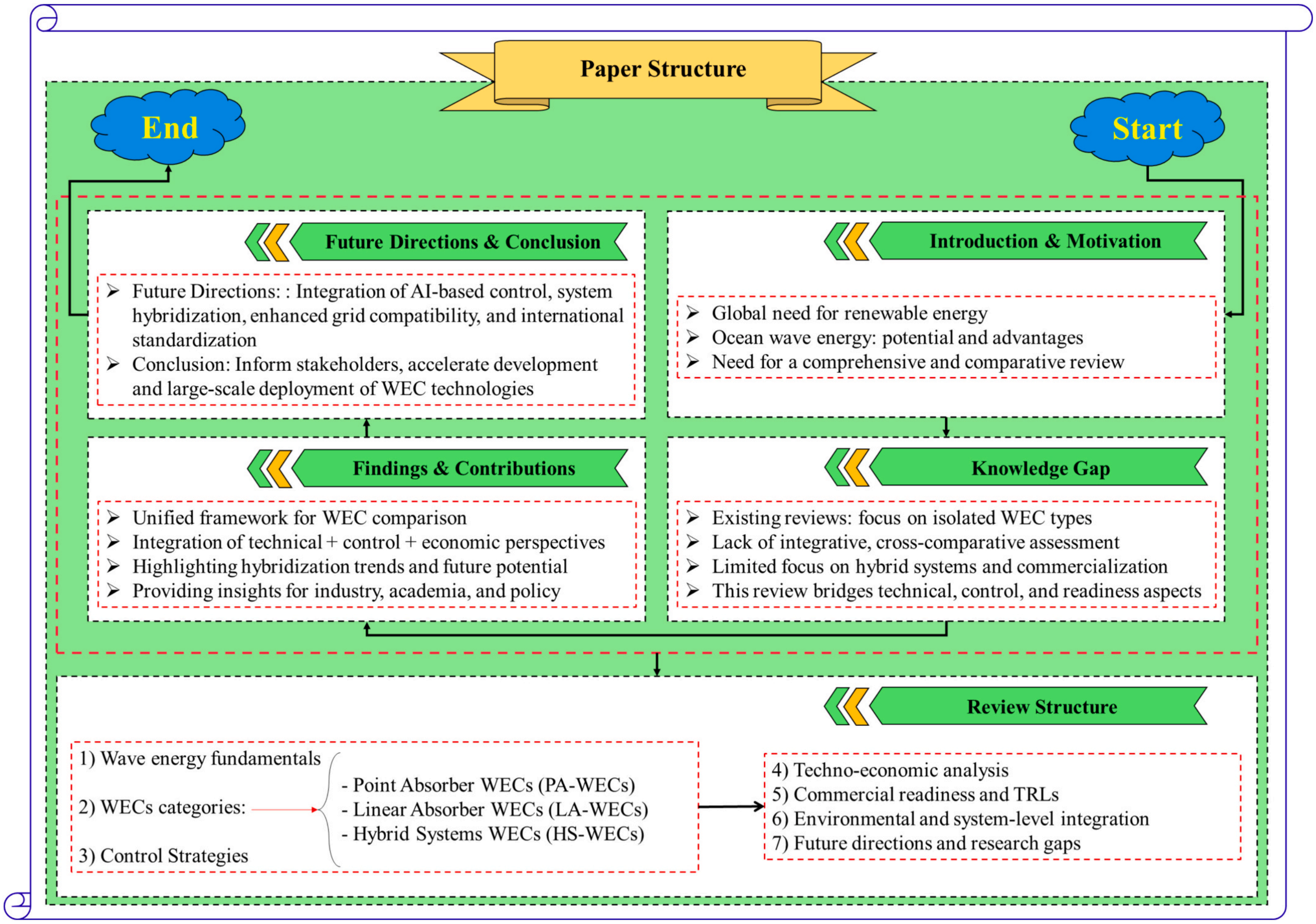


Fig. 2. Flowchart summarizing the structure and key thematic components of this review on WEC technologies.

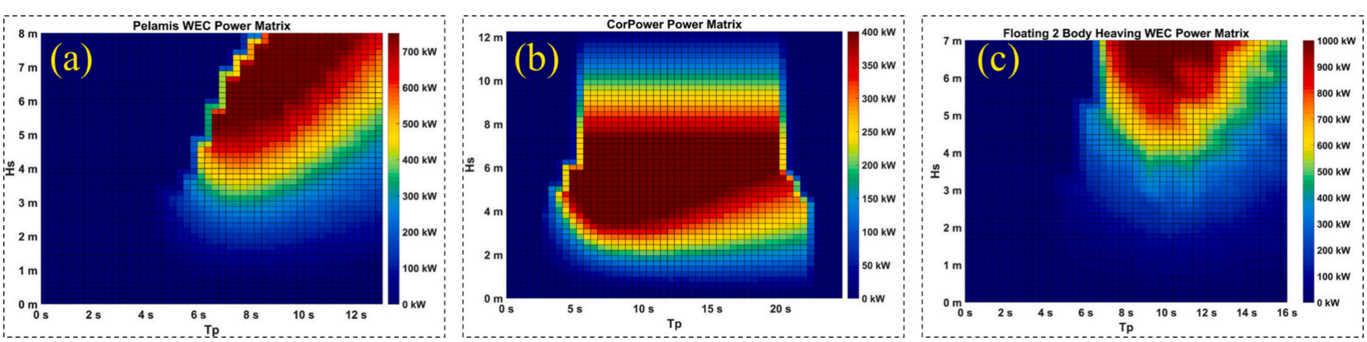


Fig. 3. Power matrices for three WEC designs: (a) CorPower point absorber (400 kW), (b) Pelamis attenuator-type LA-WEC (750 kW), and (c) F-2BH two-body heave device (1 MW). All results assume a uniform deployment density of 14.79 MW/km^2 to enable direct performance comparison across wave conditions [1].

that impacts energy capture. These influences are particularly relevant when deploying in nearshore or highly dynamic coastal environments. Therefore, a range of physical and site-specific factors must be considered beyond just average wave energy levels. Therefore, a range of physical and site-specific factors must be considered beyond just average wave energy levels, as summarized in Table 1.

Recent studies on dual-purpose farms show that nonlinear stiffness mechanisms can both harvest energy and attenuate coastal waves, providing multifunctional benefits for deployment sites [41]. In parallel, other works have addressed the seasonal variability of wave resources, identifying challenges in matching WEC design to dynamic site conditions [42,43].

Table 1
Environmental and wave-related factors influencing the efficiency and feasibility of wave energy extraction.

Factor	Impact on WEC performance
Wave directionality	Affects efficiency for unidirectional vs. omnidirectional devices
Wave steepness and nonlinearity	Influences higher-order hydrodynamic forces
Wave breaking and turbulence	Limits deployment in shallow water and affects structural loading
Bathymetric refraction and shoaling	Alters wave field distribution near coasts, impacting energy concentration and directionality

3. Point absorber wave energy converters (PA-WECs)

3.1. Overview and operating principle

PA-WECs are compact WECs that extract energy from heaving motion induced by waves. These devices typically consist of a buoyant structure oscillating relative to a fixed reference (seabed, submerged body, or another moving element), often around a single degree of freedom (DoF). Due to their small footprint and omnidirectional response, they are ideal for deep-water offshore deployment [10].

3.2. Classification of PA-WECs

PA-WECs are typically small, axisymmetric devices that oscillate primarily in the heave direction due to incoming wave forces. An example of a multi-float PA-WECs is the Wavestar WEC, which features a series of hemispherical floats mounted on arms connected to a common platform. Building on this concept, recent studies have investigated Wavestar-like arrays supported by truss-type octagonal floating platforms, demonstrating enhanced structural stability and deployment feasibility in offshore environments [44]. Each float moves vertically with waves, transmitting energy to a hydraulic PTO unit. The modular layout enables multiple units to operate in tandem, enhancing energy consistency and resilience under variable sea conditions [45]. Recent reviews have systematically examined research approaches for multi-point absorber configurations, highlighting their potential to improve energy capture and reliability through coordinated array dynamics [46]. This modular approach reflects broader trends in PA-WEC design, which can be classified as follows:

- Single-body WECs (heave buoys with seabed reaction) [47–49],
- Two-body WECs (buoy + reference body) [50–53],
- Self-reacting devices (e.g., inertial mass or reaction wheel designs) [54–57].

One of the earliest and most iconic PA-WEC designs is the Salter Duck, a cam-shaped rotor that extracts energy through pitching motion induced by passing waves. Unlike conventional heaving buoys, the Duck converts wave energy via its angular displacement, making it highly efficient in unidirectional swell environments. Recent studies have explored both single-unit and multi-duck configurations, analyzing energy capture under different geometries and wave conditions [58,59].

Numerical models confirm that rotor spacing plays a critical role in hydrodynamic interaction and wake effects, while array layout and inter-device motion coupling have been shown to significantly influence overall performance and power capture [60,61].

Moreover, experimental validations have been conducted to assess the real-world efficiency and dynamic response of Salter Duck systems in wave tanks [62]. These findings have revitalized interest in oscillating-body devices as a viable subset of PA-WECs. Recent innovations include the use of bistable structures [63], multi-DoF oscillators [64], and submerged bodies with advanced damping mechanisms [65].

The primary types of PA-WECs are summarized in Table 2, which categorizes them based on their structural setup and reaction mechanisms. In addition to this structural classification, Table 3 synthesizes development trends across PA-WEC prototypes, highlighting PTO types, achieved power scales, and indicative TRL levels. This complementary perspective shifts from a purely descriptive view toward a comparative and analytical evaluation of technological progress.

The main difference between the Aquabouy and Wavebob WECs (Fig. 4) lies in their PTO unit. Both devices are point absorbers, meaning they capture energy from the vertical motion of waves, but they utilize different mechanisms to convert this motion into usable electricity [51,66,67].

3.3. Hydrodynamic and structural modeling of PA-WECs

The response of PA-WECs is traditionally modeled using linear potential flow theory (PFT); however, nonlinear viscous damping, realistic PTO constraints, and mooring-induced motions necessitate more complex simulations. Heo and Koo [73] developed efficient computational routines to estimate dynamic loads on heaving PA-WECs. Al Shami et al. [74] analyzed different submerged body shapes using numerical wave tanks, quantifying how viscous drag coefficients affect absorbed power. Li et al. [75] confirmed that dish-shaped buoys with perforated damping plates can significantly enhance absorption efficiency in floating two-body converters.

Complementary work has validated numerical wave tank approaches based on overset mesh techniques for Wavestar-like converters, confirming their accuracy in simulating complex wave–structure interactions [76]. Their work supports drag estimation in two-body designs and nonlinear coupling validation. Numerical analyses of paired oscillating buoy converters show that suitable spacing and PTO tuning may induce constructive hydrodynamic interactions, enabling array-level power enhancement compared with isolated units [77].

Hydrodynamic analysis typically begins with linear PFT, where boundary element methods (BEM) are applied to estimate excitation forces, added mass, and radiation damping. However, for more complex and nonlinear scenarios, particularly in shallow waters or near-structure regions, advanced approaches are required. These include nonlinear Morison-based models suited for shallow deployments [11], computational fluid dynamic (CFD) simulations capable of resolving turbulent and viscous effects in wave–structure interaction [78,79], and smoothed particle hydrodynamics (SPH) solvers that offer accurate treatment of free surface dynamics and violent sloshing events [80].

3.4. Power take-off (PTO) technologies

The PTO architectures discussed in this section are not a rigid or mutually exclusive classification. In practice, designers often combine concepts such as multi-stable springs with rack-and-pinion, hydraulic, or direct-drive systems. This integration aims to enhance operational bandwidth, controllability, and overall energy yield. Accordingly, the following categorization is intended as a functional overview of dominant PTO principles rather than a strict taxonomy.

Emerging micro- and nano-scale energy harvesting mechanisms, such as triboelectric or nano-friction generators [81], have been proposed in the broader energy-harvesting literature. However, these

Table 2
Classification of PA-WECs based on body configuration and reaction mechanism, including single-body, two-body, and self-reacting designs.

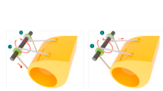
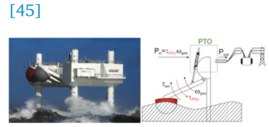
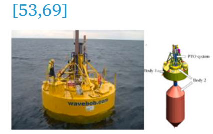
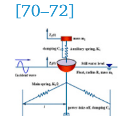
Type	Single-body		Two-body		Self-reacting
Description	Buoy oscillates against seabed mooring		Relative motion between buoy and internal mass/floater		Buoy with internal reference (spring/mass)
Examples	Salter's Duck [58,59]	AquaBuOY [67,68]	Wavestar [45]	Wavebob [53,69]	Adaptive bistable PA [70–72]
Figures					

Table 3
Key development trends of PA-WECs, highlighting PTO diversity, capacity scaling, and indicative TRL evolution.

Prototype / Project	Country	PTO type	Rated capacity	TRL (approx.)	Key notes / trends
Budal point absorber (1970s)	Norway	Hydraulic	<10 kW	3–4	Early conceptual model; introduced resonance-based capture
OPT PowerBuoy (2000s–2020s)	USA	Hydraulic–electric	150–800 kW	6–7	One of the most commercially pursued PA designs
Wavestar	Denmark	Hydraulic	500 kW (per float)	6–7	Scalable multi-float design, grid-tested
CETO	Australia	Submerged hydraulic	240 kW	6–7	Nearshore deployment; connected to desalination
Seabased buoy	Sweden	Linear generator	30–50 kW	6	Compact, array-oriented, direct-drive generator
WaveBob	Ireland	Hydraulic	~250 kW	5–6	Focused on survivability; limited commercialization
Recent lab-scale PA (2020s)	China	Hybrid PTO (hydraulic + linear)	5–50 kW	3–4	Trend toward hybridized PTO for broader bandwidth
CorPower Ocean C4 (2020s)	Portugal	Resonant control + hydraulic	~300 kW	7–8	Flagship European PA-WEC; grid-connected at Aguçadoura, supported under EuropeWave PCP

Note: TRL values are indicative estimates for comparative purposes. A detailed framework and discussion of TRLs is provided in Section 8.5.

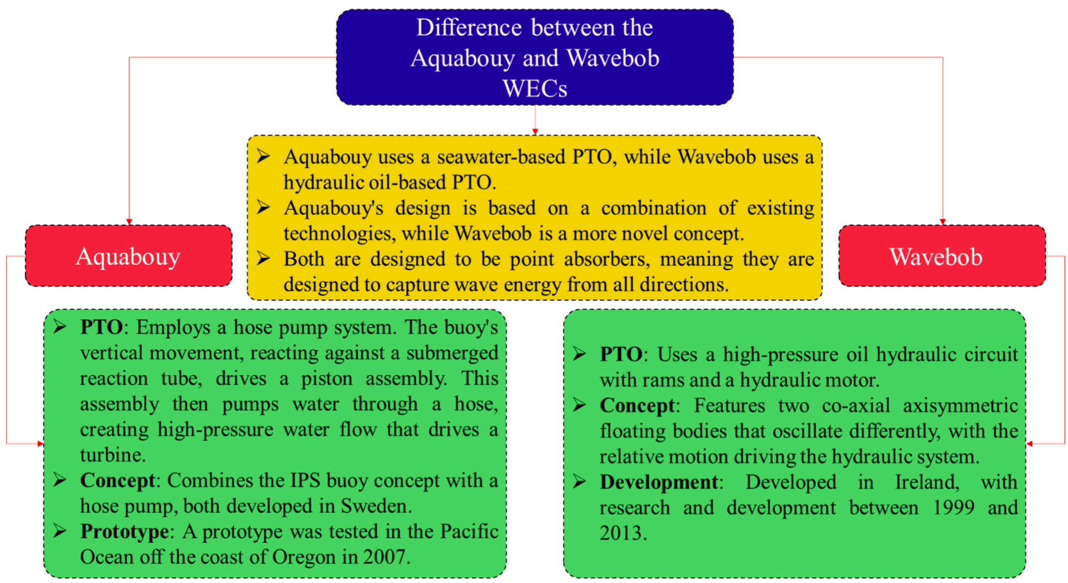


Fig. 4. Comparison of Aquabouy and Wavebob PA-WECs, highlighting the differences in their PTO unit used to convert vertical wave-induced motion into electrical energy.

approaches remain largely decoupled from utility-scale WEC PTO design and are therefore beyond the scope of the present review.

Sun et al. [82] investigated a novel multi-DoF buoy array with optimized structural spacing, showing enhanced capture factor through coordinated oscillations. Control strategies such as latching and declutching improve energy capture under broadband waves. Dai et al. [56] integrated an onboard flywheel for energy smoothing, while Everett et al. [83] combined numerical and wave tank testing for a nearshore PA-WEC. Recent surveys have comprehensively summarized PTO topologies, performance trade-offs, and future research challenges, especially for self-reacting and seabed-referenced PA-WECs [84]. These advancements highlight the growing role of tailored PTO mechanisms in optimizing energy extraction:

- Hydraulic PTOs: Common in early prototypes like Wavestar and AquaBuOY. Offer tunable damping but involve complex maintenance [85,86].
- Bistable or magnetic PTOs: Introduced for broadband capture, especially under irregular waves [70,87].
- Vertical inertia systems: Novel approaches where additional mechanical oscillators store and release energy [88].
- Parallel hydraulic cylinder PTOs: Demonstrated improved broadband capture in 3-DoF absorbers under irregular seas [89].
- Double-wing flywheels: Applied for compact platforms and unmanned WEC systems [56,90].

These systems enhance dynamic response by temporarily storing excess energy in mechanical form and releasing it when wave input decreases, which helps smooth the power output. Their benefits are most pronounced under irregular sea states, where wave frequency variability would otherwise reduce conversion efficiency. In addition, flywheel-based configurations (Fig. 5) can decouple device response from phase mismatches, further improving power consistency. Such designs are increasingly being integrated into hybrid wind–wave platforms, especially in nearshore zones where multi-source stability is essential [31].

Dielectric elastomer generators (DEGs), soft electrostatic transducers operated through stretch–charge–relax cycles, have re-emerged as a promising route for PTO systems owing to their high specific power, silent operation, and simplified mechanics. In line with recent European PTO research agendas, DEGs are increasingly positioned as frontier options complementing conventional hydraulic and linear-generation systems. Current demonstrations suggest a TRL of approximately 3–5, with EU research lines building on earlier PolyWEC outcomes and related technological concepts [91,92].

In summary, PTO development in PA-WECs prioritizes compactness and adaptability, with research strongly oriented toward broadband

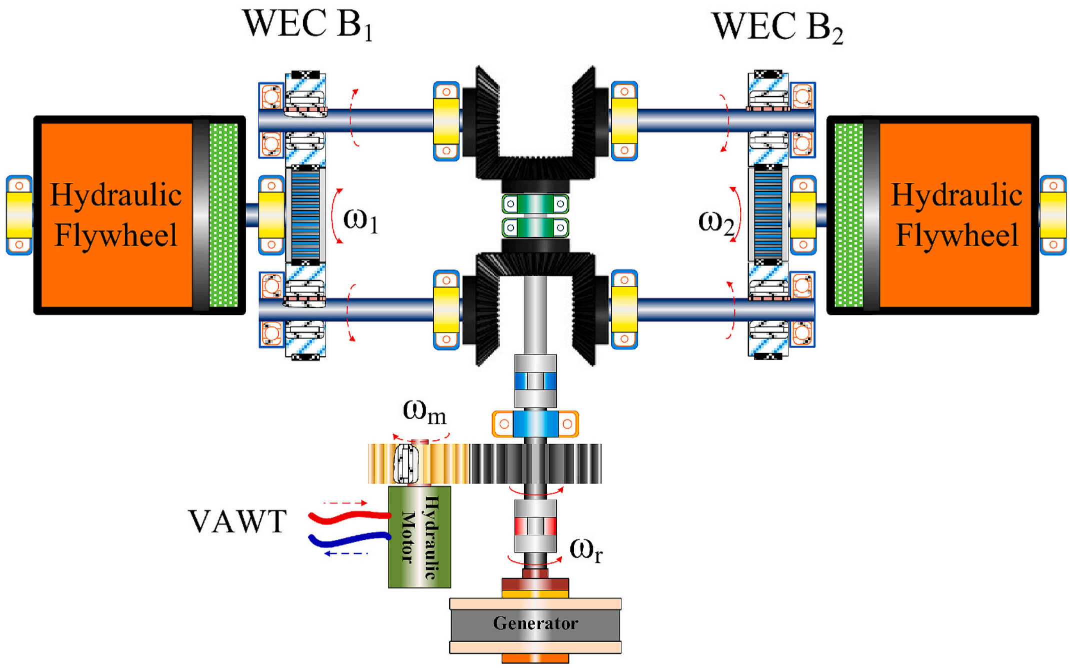


Fig. 5. Schematic of a hybrid wind–wave energy converter system incorporating a flywheel-based PTO [31].

energy capture under variable sea states. The diversity of concepts—ranging from hydraulic and linear electrical generators to innovative magnetostrictive or dielectric elastomer systems—reflects an emphasis on scalable, modular solutions. Compared to other WEC classes, the PTO agenda for PA-WECs is therefore centered on enhancing energy bandwidth while maintaining mechanical simplicity and cost-effectiveness.

3.5. Advanced control strategies

Yang and Wang [93] explored Artificial Intelligence (AI)-driven multistep forecasting for offshore wind speeds, which can be integrated into HS-WEC control to anticipate wave–wind interactions. These data-driven approaches enhance real-time control, maintenance planning, and overall reliability of marine energy farms. Building on these forecasting capabilities, several real-time and predictive control strategies have been developed to enhance energy yield:

- Latching control: Temporarily holds the device at peak position to extract more energy during favorable wave moments. First explored by Mei [9], now adapted with AI [94] and validated experimentally under irregular sea states [95,96].
- Declutching control: Decouples the PTO during inefficient motion intervals [97].
- Impedance matching: Optimizes PTO resistance to match wave loading dynamically [94,98].
- Reinforcement learning (RL) and model predictive control (MPC): Recent applications in HS-WECs [99,100].
- Damping wings: Verified experimentally and numerically to expand bandwidth and increase power in single-buoy absorbers [101].

Recent studies also explore integrating supplementary inertia mechanisms and mechanical PTO (Fig. 6) tuning to improve control response and power smoothing in heave-mode devices [102,103]. These techniques aim to combine mechanical adaptability with active control for enhanced efficiency across a range of sea conditions.

For PA-WECs, the compact geometry and omnidirectional response make them particularly suited to latching and reactive control strategies. Latching can substantially increase capture width by synchronizing oscillations with wave crests, but its implementation is limited by actuator response time and potential fatigue in mooring systems. Reactive control, although theoretically optimal for narrow-band resonance, faces practical challenges due to the broadband nature of ocean waves. Predictive control has gained increasing traction for PA-WECs because their relatively simple hydrodynamic models allow efficient integration with wave forecasting tools, enabling real-time adaptation of PTO damping. Nevertheless, the trade-off between control complexity and device simplicity remains a central issue for scaling PA-WEC farms.

3.6. Environmental durability and biofouling

Recent studies have identified biofouling as a significant source of efficiency loss in WECs, where the buildup of algae, barnacles, and other organisms on submerged surfaces increases hydrodynamic drag and damping forces. Experiments using fouling proxies on scale models—such as comparisons between clean and algae-laden surfaces—demonstrate measurable reductions in heave response and output power. To address these performance losses, various biofouling mitigation techniques have been proposed and implemented:

- Anti-fouling coatings: Including non-toxic, biomimetic, or biocide-free paints that resist organism attachment
- Periodic in-situ cleaning: Regular maintenance using robotic brushes or diver-based cleaning to prevent thick fouling layers
- Bio-inspired surface designs: Surface microstructures (e.g., shark-skin mimics or superhydrophobic patterns) that discourage microbial adhesion and early-stage fouling

These combined interventions aim to preserve device hydrodynamics, reduce maintenance costs, and maintain consistent energy output over operational lifetimes in marine environments [71,104,105].

3.7. Notable case studies and performance

Experimental validation continues to play a critical role in advancing WEC design accuracy, model calibration, and deployment strategies. Aiswaria et al. [63] validated a heaving PA-WEC integrated into a breakwater in irregular waves. Giassi et al. [106] showed that simplified

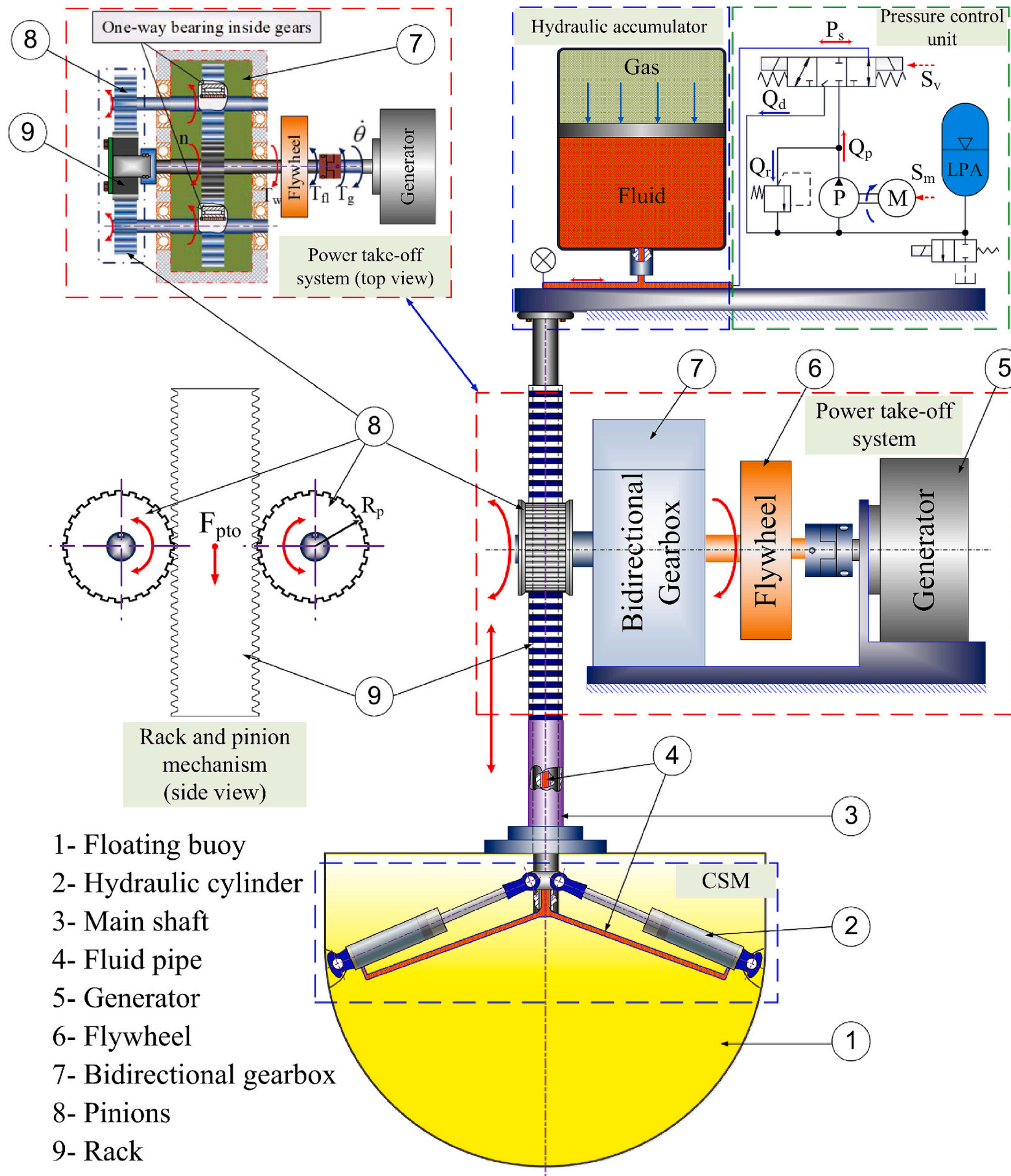


Fig. 6. Schematic of a heaving PA-WEC with optimized mechanical structure and PTO unit for enhanced energy capture [102].

numerical models can replicate full-scale results under tuned parameters. Fàbregas et al. [65] optimized bottom-referenced buoys for large arrays using frequency-domain hydrodynamic modeling, improving spacing strategies to reduce shadowing effects. Key examples of real-world WEC deployments and their performance outcomes are summarized in Table 4.

Table 4
Summary of notable WEC case studies, highlighting device type, deployment location, rated capacity, and reported performance metrics.

Project	Design	Output	Notes
Wavestar	Multi-float arms	Up to 600 kW (scaled)	Stable output; multi-point extraction [107–109]
AquaBuOY	Buoy + hose pump	~250 kW (target)	Failed due to mooring and corrosion
Self-reacting PA	Internal reference	6–12% efficiency in tests	High bandwidth in irregular waves [70]
Chain-Driven Buoy	Top-mounted PTO	8–10% in simulation	Novel design [110]

3.8. Limitations and future enhancements

Despite significant progress in wave energy technology, several technical, economic, and environmental challenges continue to limit large-scale deployment. Variability in wave resources, high capital costs, and mechanical fatigue from harsh marine environments hinder commercial viability. Many prototypes still face durability issues, especially under storm conditions, leading to high maintenance demands and limited operational lifespans. In addition, the lack of standardized testing procedures and grid integration frameworks further delays market entry for promising concepts. Addressing these limitations is essential to unlock the full potential of wave energy as a stable and complementary renewable source. To move from pilot-scale demonstrations to commercially viable deployments, these limitations must be addressed through targeted innovation and system-level optimization. Recent studies have begun to outline both the technical barriers and potential solutions shaping the future of wave energy. These challenges and innovation pathways are visually summarized in Fig. 7.

4. Linear absorber wave energy converters (LA-WECs)

4.1. Overview and concept

LA-WECs are a broader category of line-type devices that extract energy from the relative motion between floating bodies aligned with the direction of wave propagation. Within this category, attenuator-type LA-WECs (e.g., Pelamis) represent the most widely recognized subtype. Unlike PA-WECs, which primarily rely on heave motion, LA-WECs are long, slender structures that deform in multiple modes—pitch, surge, and flexure—in response to passing wave trains [111]. These devices typically consist of two or more floating bodies connected by hinges, joints, or flexible connections, which oscillate due to wave-induced pitch and heave forces. The motion is captured by a PTO mechanism at the joints, typically hydraulic cylinders [45,112,113].

The Pelamis WEC (Fig. 8) is the most well-known example of an attenuator-type LA-WEC, composed of multiple hinged cylindrical segments connected by hydraulic cylinders (rams) [114]. These hinges capture the relative angular motion between segments [115,116] and convert it to hydraulic pressure, driving an electric generator [117,118].

Relative to PA-WECs, LA-WECs exhibit larger instantaneous power capture in long-crested, aligned seas due to distributed DoFs and extended interaction length. This advantage comes at the cost of stronger directional sensitivity and higher structural as well as operation and maintenance (O&M) complexity—particularly hinge fatigue, segmented cabling, and installation logistics (e.g., tow-out and connection of multiple joints). While PA-WECs are omnidirectional and simpler to scale numerically across sites, LA-WECs benefit from broader effective bandwidth once articulation and phase-control are tuned, yet require more sophisticated supervisory control to manage inter-segment loads and survivability. Array interactions also differ: PA-WECs typically demand spacing to mitigate shadowing, whereas LA-WECs impose alignment and heading-keeping requirements for optimal capture. From a techno-economic perspective, LA-WECs can deliver higher power per unit length in target sea states but face CAPEX (capital expenditure) and OPEX (operational expenditure) penalties due to mechanical complexity and maintenance windows; conversely, PA-WECs favor modularity and manufacturing simplicity, albeit with narrower capture bandwidth. In practice, site conditions (wave climate directionality, maintenance access, and allowable installation limits) drive the crossover in performance and cost between the two classes.

While Pelamis exemplified the first-generation attenuator concept, the landscape has evolved substantially in recent years with a new wave of European developments. Mocean Energy has progressed from the Blue X sea trials at the European Marine Energy Centre (EMEC) to the planned Blue Horizon 250, a 250 kW hinged attenuator supported by the EuropeWave PCP programme for grid-connected demonstration, thereby establishing a clear industrial pathway from prototype to pre-commercial scale [119]. In parallel, Wavepiston is demonstrating a modular linear absorber concept at PLOCAN, expanding progressively with extended strings [120], while SWEL's Waveline Magnet represents a spine-like flexible attenuator pursuing ultra-low structural mass [121–123]. Together, these initiatives illustrate how contemporary LA-WECs extend the concept beyond historical devices like Pelamis and address the structural and economic challenges outlined above (see Table 5).

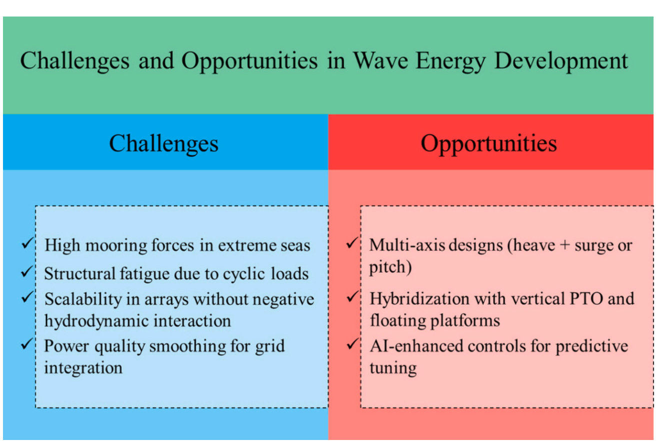


Fig. 7. Key technical challenges and innovation opportunities for advancing wave energy systems from pilot-scale to commercial deployment.

4.2. Structural mechanics

LA-WECs, also referred to as attenuators, operate by converting wave-induced bending motions along hinged segments into usable energy. These systems are typically oriented parallel to wave propagation, allowing them to flex and absorb energy along their length while maintaining structural continuity. A typical LA-WEC consists of:

- Floating modules (rafts),
- Hinges with hydraulic cylinders,
- End moorings or dynamic positioning systems.

Dong et al. [112] numerically optimized such configurations, showing elliptical rafts have reduced drag and improved power efficiency in specific wave periods. Liu et al. [113] analyzed a two-raft system using hydraulic PTO in shallow water, identifying optimal draft and hinge damping for stable energy capture. Zhao et al. [125] demonstrated that multi-DoF raft-type WECs significantly outperform single-mode designs when tuned for surge-pitch coupling, especially in oblique wave fields. Continued advancements in PTO systems—including rotary, linear, and hybrid architectures—have played a key role in improving the viability of LA-WECs under diverse sea conditions [126].

4.3. PTO mechanisms

In LA-WECs, PTO mechanisms are most commonly implemented as hydraulic rams at the hinge joints (Fig. 8), with accumulators used to smooth output [127]. Hybrid systems, such as electro-hydraulic or flywheel-assisted PTOs, have also been explored to improve broadband tuning and response under irregular sea states [128,129]. While rotary and direct-drive options have been tested, their application remains limited due to scaling challenges in long articulated devices [13,17]. Overall, PTO research for LA-WECs emphasizes scaling long-stroke hydraulic systems and ensuring their structural reliability under cyclic loading. Compared with PA-WECs, the focus is less on diversity of PTO concepts and more on durability and efficiency of hydraulic transmission for offshore deployment.

4.4. Experimental prototypes and numerical validation

Skene et al. [132] investigated a raft–FOWT (floating offshore wind turbine) hybrid system, showing that raft motions stabilize turbine pitch and indirectly enhance wind power quality, while simultaneously enabling wave energy harvesting. Zitti and Brocchini [133] emphasized the role of inertial mass distribution and segment length on the hydrodynamic resonance of raft segments. Their work provides criteria for structural tuning in frequency-rich seas. The Pelamis system has also served as a benchmark in experimental and numerical validation studies:

- Pelamis (P1, P2):
- Developed by Ocean Power Delivery, Scotland,

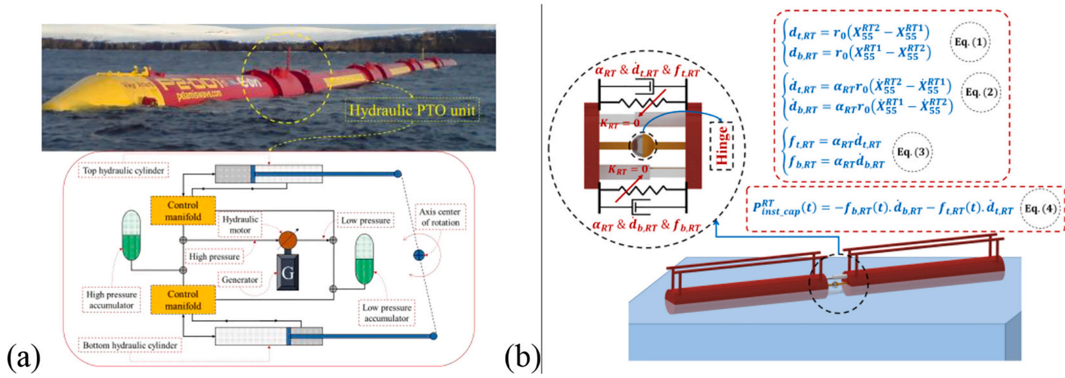


Fig. 8. (a) Schematic of a hydraulic PTO system used in hinged LA-WECs [130] (b) Governing equations [131].

Table 5
Recent developments in LA-WECs highlighting state-of-the-art prototypes and demonstration projects in Europe.

Developer	Device	Type	Scale & Site	Status (Year)	Notable features	Indicative TRL
Mocean Energy [119]	Blue X → Blue Horizon 250	Hinged attenuator (LA)	EMEC, Orkney	Sea trials completed; EuropeWave funding to deploy ~250 kW grid-connected prototype (2025)	Subsea-power use case; Scottish build	6–7
Wavepiston [120]	Modular linear absorber	LA (pumping plates along string)	PLOCAN, Canary Islands	Ongoing multi-module demonstration; long string expansion (2024–2025)	Modular/CAPEX-lean architecture	6–7
SWEL [121,124]	Waveline Magnet	Spine-like flexible attenuator	Cyprus & other sea trials	Multiple at-sea tests; low-mass flexible raft	Morphological compliance, simple build	4–5

Note: Some technical and performance details for the Waveline Magnet prototype are not reported consistently in the open literature. The missing entries reflect limitations in publicly available sources and the early demonstration status of the concept, rather than omissions in data collection.

- 4–5 hinged segments, ~180 m total length,
- Full-scale sea deployment at EMEC,
- Max rated output: ~750 kW,
- Efficiency: 22–25% in optimal sea states [18,114,134].
- Jin et al. (2023):
- Two-body hinged raft,
- Modeled with WEC-Sim for EMEC site,
- Validated with lab experiments [135].
- Shi et al. (2021):
- Introduced torsion bistable mechanism,
- Improved energy capture in broadband seas [136].
- Liu et al. (2021)
- Used hydraulic PTO with latching control,
- Enhanced efficiency under irregular waves [137].

4.5. *Control strategies and optimization*

Control systems play a central role in enhancing the efficiency and survivability of hinged WECs [138]. By regulating motion and PTO timing, these strategies can significantly boost energy yield while protecting mechanical components. Both passive and active control approaches are being explored, ranging from mechanical tuning to AI-driven real-time adaptation. These techniques are implemented through various advanced control methods, including:

- Latching control: holding a hinge at rest until optimal wave phase arrives,
- Declutching: momentarily disengaging PTO to avoid destructive loading,
- Tuned mass dampers: altering joint inertia to broaden resonance bandwidth,
- AI optimization: real-time damping adaptation via neural nets or genetic algorithm (GA) [90].

Control strategies for LA-WECs face fundamentally different challenges compared to PA-WECs, owing to their elongated geometry and articulated segments. Latching and declutching methods have limited effectiveness here, as hinge-connected bodies exhibit delayed phase responses under irregular waves, which reduces the timing accuracy of hold-release cycles. Instead, reactive and impedance-matching controls—implemented through long-stroke hydraulic PTOs—are more relevant, as they can redistribute loads across segments and enhance capture width under directional seas. However, these methods also amplify structural stresses and hinge fatigue, requiring robust monitoring and redundancy. Recent studies suggest that MPC and RL can improve energy routing along multiple joints while simultaneously extending structural life, but their computational demand remains a bottleneck for real-time deployment. Thus, unlike PA-WECs, where broadband tuning dominates, LA-WEC control research must balance hydrodynamic efficiency with mechanical survivability.

4.6. *Design challenges and structural fatigue*

Environmental assessments—such as mooring load profiles, anchor scour, and marine ecosystem interactions—are increasingly incorporated into the structural and operational design of LA-WECs. While these systems offer high power potential due to their extended interaction with wave crests, they also face several critical challenges:

- Joint fatigue from cyclic pitching motion [139],
- Hydraulic leakage and maintenance burden,
- Poor performance in multidirectional seas,
- Complex mooring for long segmented bodies.

To address these limitations, several design innovations have been proposed:

- Flexible raft structures with semi-rigid couplings,
- Joint redesign with dampers and motion limiters,
- Adaptive positioning via dynamic mooring systems.

4.7. Hydrodynamic interactions in arrays

Deploying LA-WECs in arrays introduces additional complexities such as wave shadowing, diffraction, and hydrodynamic interference. To maximize collective energy extraction, optimization of device spacing, phase control, and joint synchronization becomes essential. Studies using BEM and CFD simulations have demonstrated that:

- Closely spaced rafts can suffer up to 25% drop in performance,
- Phase-shifted operation can improve collective absorption [140,141].

These findings underline the importance of array-level control strategies and informed spatial layouts. A comparative overview of key LA-WEC studies is presented in Table 6, highlighting system types, PTO mechanisms, control innovations, and key performance outcomes.

5. Hybrid system wave energy converters (HS-WECs)

5.1. Introduction and motivation

The concept of HS-WECs stems from the need to maximize offshore infrastructure utilization, improve energy consistency, and reduce LCOE through shared platforms and multi-source generation. These systems typically integrate WECs with wind turbines, floating breakwaters, or aquaculture platforms. By combining multiple functionalities within a single offshore asset, hybridization offers several advantages:

- Load sharing and motion damping,
- Complementary energy profiles (wind and wave out-of-phase),
- Reduced installation and maintenance costs,
- Increased platform utilization factor [132,143,144].

Recent research highlights a shift toward modular, reconfigurable hybrid energy farms that accommodate different environmental and economic contexts [20,21,145].

5.2. Classification of hybrid systems

5.2.1. Hybrid WEC–breakwater and multi-DoF systems

Several HS-WECs combine with floating breakwaters. Zheng et al. [146] tested an oscillating buoy integrated with a breakwater under real sea conditions, demonstrating dual benefits: coastal protection and energy harvesting. Zhou et al. [147] tested a multi-DoF hybrid array capable of pitch, heave, and surge motion. Their results confirmed higher capture width ratios and improved motion stability for wave fronts at oblique angles.

Beyond the growing integration of WECs with FOWT, other hybrid configurations—such as multi-use offshore platforms and aquaculture–energy systems—are gaining increased attention. These approaches leverage shared infrastructure to lower capital intensity, enhance spatial efficiency, and diversify revenue streams through combined energy and marine-resource production. However, they also introduce new challenges in system complexity, grid connection, regulatory permitting, and environmental management. A consistent evaluation of such hybrid systems requires assessing not only their technical feasibility but also their cost-effectiveness and integration pathways relative to standalone WECs. These dimensions are revisited in Section 8.4 using comparative matrices and SWOT (strengths, weaknesses, opportunities, threats) analysis, establishing a coherent analytical framework across device categories.

5.2.2. Structural design and optimization

Song et al. [148] developed a semi-opened moon-pool–breakwater–WEC hybrid, evaluating hydrodynamic pressure distribution and capture width ratio using CFD simulations. Their system showed high adaptability to various swell angles and wave heights. Recent optimization strategies further improve the effectiveness of these HS-WECs.

Complementary to breakwater-integrated concepts, a hybrid-absorber architecture that couples a line-type raft system with Wavestar-style point absorbers has been investigated as a route to broaden the effective capture bandwidth while distributing structural loads more evenly. In this configuration, the hinged raft segments provide directional interaction length and hinge-based energy transduction, while the hemispherical floats deliver omnidirectional heave response and reactive damping leverage. Parametric studies on segment length, hinge damping, and float spacing indicate that the combined topology reduces sensitivity to wave directionality and improves capture factor in mixed sea states by coordinating phase across the raft joints and the heaving floats. The mechanics of the coupling—through shared hydraulic manifolds and tuned valve timing—enable power smoothing without penalizing peak absorption, offering an integrated path to survivability and yield in reconfigurable hybrid platforms [131,149].

Yang et al. [88] introduced an enhanced snake optimizer (ESO) to design optimal layouts for hybrid wind–wave WEC arrays, achieving significant gains in both energy capture and layout efficiency. The study demonstrated that intelligent algorithms could dynamically adjust spacing and alignment of WEC units in relation to prevailing wave and wind vectors as outlined in Table 7, which categorizes key hybrid offshore system types and their advantages.

These HS-WEC types, summarized in Table 7, are not just theoretical models—they've been implemented or tested in various configurations worldwide. Their development highlights how combining multiple offshore functions can lead to greater resource utilization, shared infrastructure, and improved economic feasibility. Such integration also enhances resilience against environmental variability, allowing systems to adapt to fluctuating wave and wind conditions. These concepts have been demonstrated in several real-world or pilot-scale examples (Fig. 9), including: Wavestar–Wind hybrid [150], Comb-type flap–breakwater system [151], integrated aquaculture–WEC platforms [21,152–154].

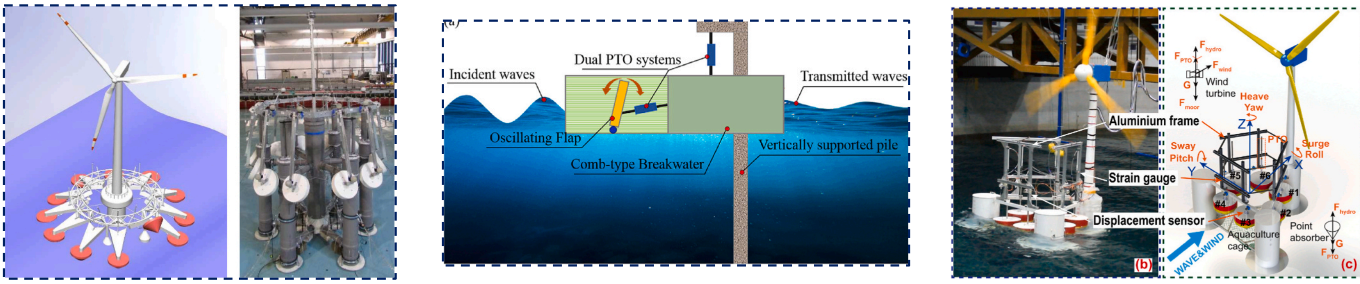
Fig. 10 provides a general schematic of HS-WEC pathways. This schematic (Fig. 10) illustrates a combined wind–wave power plant where both the wind turbine and WEC share a common generation system. Wind drives the turbine–generator, while waves actuate a hydraulic PTO coupled to the same generator via either a direct current (DC) bus or hydraulic linkage [155,156]. Their design highlights the

Table 6
Summary of LA-WEC Studies.

Study	System	PTO type	Unique feature	Output
Pelamis [17,18,134]	5-segment	Hydraulic	Full-scale sea trial	~750 kW
Jin et al. [135]	2-body raft	Hydraulic	EMEC site validation	~65–70% match
Shi et al. [136]	Torsion-bi-stable	Mechanical	Broadband spectrum	+18% energy
Liu et al. [137,142]	Hydraulic	Latching control	Adaptive damping	+12% efficiency

Table 7
Common hybrid offshore energy system types, their integrated components, and primary functional benefits.

Type	Components	Key benefit
Wind–wave	Floating wind turbine + WEC array	Co-generation, motion damping
Wave–breakwater	Flap–breakwater system	Broadband wave-energy capture and enhanced coastal protection
Multi-use platforms (MUPs)	WEC + aquaculture + wind + solar	Infrastructure synergy



(a) Wavestar–Wind hybrid [150] (b) Flap–breakwater system [151] (c) Aquaculture–WEC platforms [21]

Fig. 9. Examples of hybrid offshore renewable energy systems.

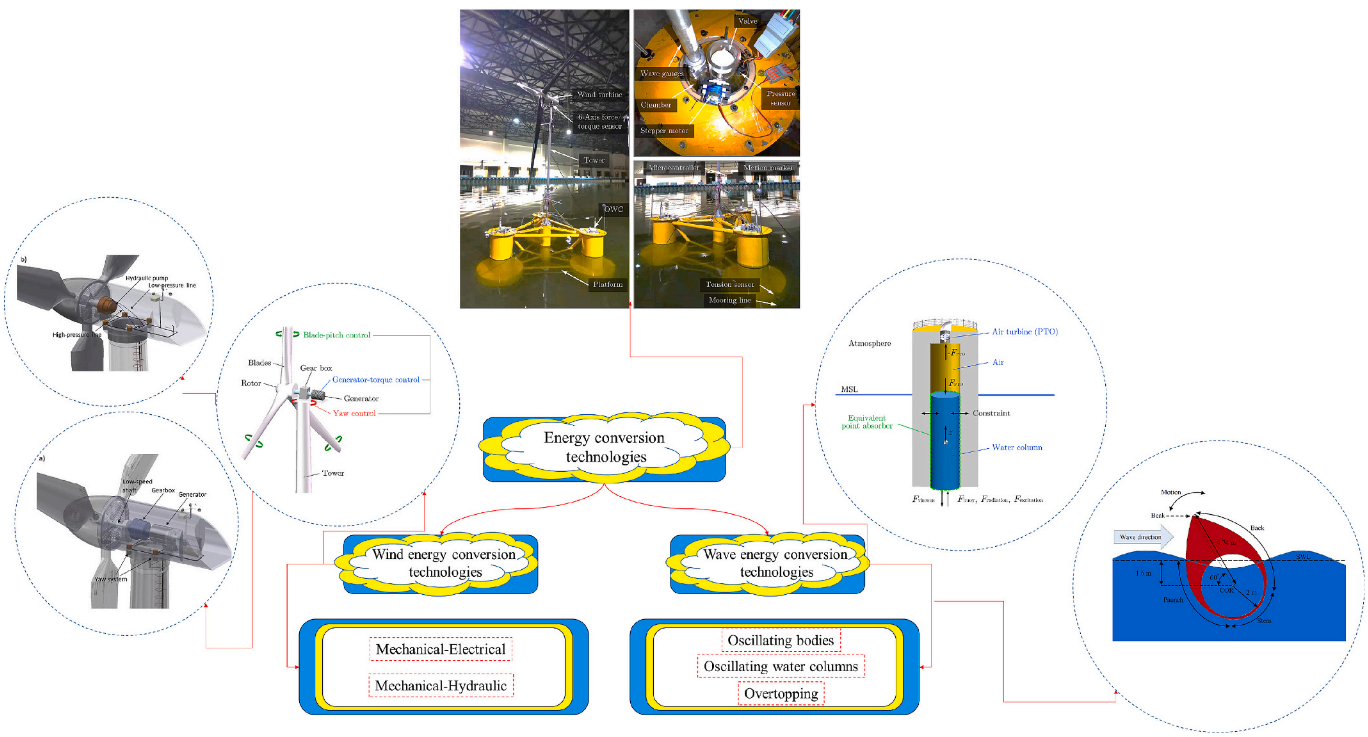


Fig. 10. Combined wind–wave energy conversion schematic using shared generation through hydraulic or DC coupling (adopted from [145,155–157]).

synergy in converting both energy sources into electricity with shared infrastructure [157].

5.3. Control systems and synchronization

HS-WECs require multilayered control systems, coordinating multiple PTOs and dynamic loads. These systems must balance inputs from wave and wind sources, often with differing frequencies, amplitudes, and response times. Synchronization is especially critical when components like floating turbines and point absorbers share structural or electrical interfaces. Effective control not only improves power quality and efficiency but also enhances survivability during extreme events. To address these challenges, several key strategies have been developed:

- Centralized impedance matching for wave–wind interaction [94],
- Wave prediction + dynamic mooring adaptation,
- Artificial intelligence to optimize PTO damping and system power dispatch [90].

Beyond control synchronization, PTO research in HS-WECs must address the complexities of multi-device coupling, energy routing, and storage integration. Unlike PA- and LA-WECs, where PTO focus is typically device-centric, hybrid platforms require system-level coordination across heterogeneous converters. This includes harmonizing multiple hydraulic and electrical PTOs, balancing short-term wave fluctuations with more stable wind inputs, and ensuring compatibility with energy storage units for smoothing and dispatch. Emerging studies emphasize that the PTO in HS-WECs should be viewed not as a single unit but as an integrated network, where reliability, redundancy, and intelligent routing are as critical as conversion efficiency. Consequently, research priorities for hybrid PTOs increasingly converge on advanced supervisory control, modular power electronics, and real-time optimization algorithms. A cross-comparison of PTO research priorities across WEC types is summarized in Table 8.

A critical distinction in HS-WEC control lies in the need to simultaneously coordinate heterogeneous subsystems—wave absorbers, wind turbines, and auxiliary platforms—each with different dynamic response times. Unlike PA- or LA-WECs, where latching and declutching primarily target resonance bandwidth extension, HS-WECs require multi-input supervisory control to manage both electrical and structural

Table 8
PTO research priorities and challenges across different WEC types, from device-level to hybrid system integration.

WEC Type	PTO Research Priorities	Distinctive Challenges
PA-WECs	- Broadband capture via linear/hydraulic PTOs - Compact and modular designs for arrays - AI-based tuning for variable sea states	- Efficiency drops outside resonance - Mooring-induced load fluctuations
LA-WECs	- Long-stroke hydraulic PTO scaling - Structural reliability in hinged joints - Advanced damping strategies for fatigue reduction	- Mechanical wear at joints - High installation and maintenance cost
HS-WECs	- Multi-device PTO synchronization - Hybrid routing with wind/storage - Supervisory control for dispatch optimization - Modular power electronics for reliability	- Coupling complexity - Capital intensity - Grid compliance under fluctuating input

coupling. For example, predictive latching of oscillating buoys can be synchronized with wind turbine pitch control to smooth aggregated power delivery, while impedance matching must account for shared mooring stiffness and structural loads. Furthermore, storage-assisted control strategies—such as coupling wave PTO outputs with battery or hydrogen buffers—are increasingly emphasized in HS-WEC research to mitigate variability and optimize dispatch. These control priorities demonstrate that while conventional strategies (latching, reactive, model predictive) remain applicable, their implementation in HS-WECs must be adapted to system-level constraints, particularly in terms of synchronization, energy routing, and survivability.

5.4. Recent case studies and performance

Recent research and pilot deployments have focused on the operational integration of WECs with offshore wind turbines, breakwaters, and MUPs. These HS-WECs are tested not only for energy output but also for structural interaction, platform stability, and cost-efficiency. Case studies offer valuable insights into design trade-offs, site-specific challenges, and the real-world effectiveness of control strategies [158]. Marchesi et al. [159] developed and analyzed a numerical model for a two-oscillating-body wave energy converter in shallow water, supported by flume-scale experimental comparisons. Their results demonstrated good agreement between linear hydrodynamic predictions and measured time-series responses, particularly under mild wave conditions. Numerical simulations of flap-type WECs integrated on floating wind platforms demonstrate output stabilization while preserving hydrodynamic efficiency [160]. Several notable case studies are visually illustrated and summarized in Table 9, which highlights the system type, location, methodology, and performance outcome for each.

5.5. Design challenges and integration barriers

HS-WECs present unique design challenges due to the combined structural, hydrodynamic, and control requirements of multiple technologies. Integrating wave and wind converters on a shared platform demands careful consideration of load coupling, motion amplification, and mooring stability. Electrical integration also introduces complexity in power management, synchronization, and storage. These barriers must be addressed to ensure reliability, cost-effectiveness, and long-term survivability in harsh marine environments. These technical hurdles span both physical and control domains, often magnified when multiple systems share mechanical and electrical subsystems. These challenges are summarized below, along with emerging solutions aimed at enhancing system integration and resilience:

- Hydrodynamic interference and control conflicts [161],
- Platform design complexity [162],
- Higher initial capital cost,
- Grid synchronization and energy management issues.

Solutions include:

- Machine learning for hybrid optimization [90],
- Soft mooring strategies to isolate vibrational feedback [163],
- Submerged WECs to reduce above-water profile drag [20].

6. System-level integration and environmental considerations

To make cross-category implications explicit, this section synthesizes integration issues across PA-, LA-, and HS-WECs rather than treating them in isolation. Array hydrodynamics, grid-compatibility, environmental risk, and monitoring needs are compared side-by-side and later tied to the comparative matrix (Table 19) and SWOT (Table 20). In brief, PA arrays emphasize spacing and phase control; LA systems add hinge-load management and hydraulic smoothing; and HS platforms introduce additional wind–wave coupling and power-routing constraints. System-level studies on FOWTs show that nonlinear hydrodynamics critically affects survivability, stationkeeping, and environmental loading, underscoring the need for robust nonlinear modeling in hybrid and wave energy system design [164]. These distinctions are noted here and further consolidated in Sections 7. 8. to support techno-economic and TRL synthesis. The success of wave energy technologies—whether standalone or hybrid—relies not only on device-level performance but also on system-level integration, including power transmission, array layout, grid compatibility, and environmental sustainability. This

Table 9
Recent HS-WEC case studies with details on system configuration, experimental method, and observed performance trends.

System	Hybrid type	Key results	Test method	Ref.
Wavestar–wind	Rectilinear PA-WEC array + FOWT	✓ +10% energy, −20% pitch ✓ Enhanced damping and shared mooring benefits	Numerical model (BEM)	[25]
Comb-flap–breakwater	Dual PTO + breakwater	✓ Wave load attenuation up to 60% ✓ Capture width ratio ~ 0.18 across swell conditions ✓ Enhancing coastal protection	Numerical model (CFD)	[151]
MUP	FOWT + WEC + cage	✓ 5.2% more energy ✓ Stable under 3 DoF motion	Physical model	[21]
Shape-optimized platform	FOWT + WEC (elliptical)	✓ +6% improvement with elliptical hulls ✓ Improvement of capture factor	Numerical model (BEM)	[20]
WEC-wind	DC-linked hybrid WEC and wind turbine	✓ Improved power smoothing ✓ Improved PTO efficiency ✓ Yielding up to 8.4% total energy gain ✓ Reduced energy curtailment under fluctuations	Optimization model	[88]

section discusses the broader ecosystem required to deploy WECs reliably at scale.

6.1. Array design and hydrodynamic interaction

When WECs are deployed in arrays, their mutual hydrodynamic interactions can amplify or dampen wave forces. These interactions affect wave shadowing, refraction, diffraction, and resonance coupling, and must be managed through:

- Spacing optimization (e.g., $\geq$2–4 device diameters apart),
- Phase control of oscillators to avoid destructive interference,
- Row-by-row staggering for directional wave conditions [130,141].

Tools used for array modeling:

- BEM-based solvers: For linear interaction analysis,
- CFD and SPH: For nonlinear interactions under extreme sea states,
- WEC-Array: A MATLAB-based open-source code.

6.2. Grid integration and power quality

WEC-generated electricity is intermittent and varies with sea states, making power smoothing and conditioning essential before grid integration. The inherent variability in wave amplitude and period results in fluctuating voltage and frequency at the power output terminals. Without appropriate conditioning, this variability can impair power quality and limit compatibility with utility-scale transmission systems. For hybrid platforms, the challenge increases as multiple energy streams—wave, wind, and solar—must be synchronized into a unified output. Therefore, robust energy conversion, storage, and control systems are required to ensure stable, grid-compliant electricity delivery. The following technologies are increasingly adopted to manage these complexities and improve grid compatibility:

- Hydraulic accumulators: intermediate fluid storage for hydraulic PTOs,
- Flywheel storage or supercapacitors: short-term energy buffering devices,
- Converters and rectifiers: waveform conditioning to grid standard (e.g., 50 Hz),
- DC microgrids: emerging architecture for hybrid offshore farms [151].

Challenges include:

- Voltage and frequency regulation,
- Harmonic distortion due to non-sinusoidal PTO outputs,
- Subsea cable losses and marine fouling.

6.3. Structural mooring and survivability

High survivability in storm events is crucial for long-term success. Heo and Koo [73] simulated reaction forces in moored heaving absorbers under extreme waves. Potapenko et al. [165] compared slack and stiff mooring strategies, highlighting trade-offs in power absorption and tether tension. Hu et al. [166] examined how a central platform affects buoy interaction in multi-buoy systems, finding that spacing and phase synchronization are critical to avoiding destructive coupling. These studies underline the importance of mooring design in balancing energy capture with structural safety. Building on these findings, key factors and mooring layout types that influence WEC survivability are summarized below:

- Mooring system stiffness and configuration,
- Buoyancy control under wave run-up,
- Extreme event resistance (e.g., 100-year wave).

Common mooring layouts:

- Catenary (deep water),
- Taut-leg (reduces footprint),
- Dynamic positioning systems (hybrid/large platforms).

6.4. Environmental impact

Environmental concerns are increasingly central to WEC design. Thomson et al. [167] found in the Pelamis LCA that steel production, mooring lines, and servicing logistics dominated carbon footprint. Jaramillo-Lopez et al. [168] proposed the use of system identification-based modeling to monitor structural health and identify early signs of mechanical degradation, integrating real-time ecological data from onboard sensors. Although wave energy is relatively clean, its deployment can impact local ecosystems. Key environmental concerns associated with WEC deployment are summarized in Table 10.

Tools like strategic environmental assessment (SEA) and environmental impact assessment (EIA) are mandatory in many regions to evaluate the potential ecological footprint of wave energy projects. These frameworks assess impacts on marine biodiversity, sediment transport, underwater acoustics, and coastal dynamics. They are essential for ensuring regulatory compliance, gaining public acceptance, and minimizing conflicts with fisheries or conservation zones. Such assessments are particularly important for HS-WECs, which may have more complex spatial and operational footprints than single-source platforms. To reduce identified risks, several mitigation strategies have been proposed and implemented:

- Use of bio-friendly coatings,
- Deploying in low-sensitivity areas,
- Acoustic shielding of PTO components,
- Modular, removable mooring blocks.

6.5. Monitoring, sensing, and data analytics

Effective WEC deployment requires constant condition monitoring to reduce downtime and optimize performance throughout the system's lifespan. Modern sensing technologies provide real-time insights into structural health, PTO efficiency, mooring loads, and environmental conditions [169]. These data streams support both preventive maintenance and adaptive control, helping extend component life and minimize unexpected failures. In HS-WECs, synchronized monitoring across wind, wave, and auxiliary subsystems is critical for reliable operation and energy management. The following tools and techniques are commonly used to implement such integrated monitoring frameworks:

- Embedded sensors: strain gauges, accelerometers, and PTO torque sensors for structural and mechanical monitoring,
- Wave radar and acoustic Doppler current profilers (ADCPs): instruments for real-time sea-state estimation,
- Digital twins: virtual replicas for predictive maintenance [90],
- AI-based fault diagnostics: data-driven analysis using supervisory control and data acquisition (SCADA) systems.

Table 10
Primary environmental concerns related to WEC deployment, including ecological, acoustic, and visual impacts.

Impact area	Potential effect
Marine life	Collision risk, habitat disruption
Acoustics	PTO and mooring vibrations may affect cetaceans
Seafloor	Anchors and cable routes disturb benthic habitats
Visual	Above-surface visibility in nearshore projects

Recent advancements enable sensor fusion for multi-WEC farms, combining data from wave buoys, turbine nacelles, and PTO units to produce a holistic view of the platform.

6.6. Policy and permitting considerations

Successful WEC deployment depends not only on technical viability but also on compliance with national and regional maritime policies. Navigating these regulatory frameworks is critical for site approval, environmental clearance, and long-term operational licensing. HS-WECs, which often span larger footprints and involve multiple technologies, must address overlapping jurisdictional and usage constraints. Early engagement with regulators and alignment with coastal zone management policies can streamline permitting and de-risk project timelines. WEC deployment must adhere to regulatory frameworks such as:

- Marine Spatial Planning (MSP),
- Exclusive Economic Zone (EEZ) laws,
- Natura 2000 (for EU-based projects),
- Clean Energy for All Europeans Package.

In addition to these frameworks, permitting may involve considerations such as:

- Navigation clearance,
- Compatibility with fisheries,
- Protection of cultural sites,
- Consultations with stakeholders.

To harmonize with international best practices, the European Commission and the IEA (International Energy Agency) recommend that WEC farms comply with Integrated MSP [170], EIAs [171], and specific zoning standards for navigation and aquaculture [172]. WEC integration into multi-use zones is growing [173], but policy alignment across jurisdictions remains a challenge [174,175]. Recent work suggests standardizing a modular permitting framework for multi-use offshore systems [176,177].

6.7. Synthesis—System-level lessons across device classes

The following synthesis highlights the main integration lessons across the four WEC categories, linking hydrodynamic behavior, PTO strategies, and grid/environmental factors in a concise comparative form.

- PA-WECs: array spacing ≈2–4D (D = device characteristic length) and phase control are primary; grid-side smoothing (improving power quality — reducing variability, ramps, and harmonics) via PTO damping or short-term storage is recommended.
- LA-WECs: hinge load limiting and hydraulic smoothing are pivotal; installation/maintenance windows drive availability.
- HS-WECs: co-simulation of aero–hydro–servo is mandatory; energy routing and curtailment logic manage conflicts; shared moorings cut CAPEX but raise coordination needs. (See Table 19 & Table 20).

7. Economic feasibility and levelized cost of energy

The economic viability of wave energy technologies hinges on their ability to generate electricity at a competitive cost over their operational life. The primary metric used to assess this is LCOE, which represents the total lifecycle cost per unit of electricity generated:

$$LCOE = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{1}$$

Where:

- I_t: investment cost at time t,
- M_t: operation and maintenance cost,
- F_t: fuel or consumables (typically zero for WECs),
- E_t: electricity generated,
- r: discount rate,
- T: project lifespan (years).

This section analyzes the cost components, presents case studies, and identifies opportunities to reduce LCOE in both standalone and hybrid configurations.

7.1. Methodological note on techno-economic data

For clarity, TRL and LCOE values reported in this review are treated with explicit methodological transparency. Values directly cited from source studies are preserved in their original form, while comparative ranges presented in harmonized tables were derived under aligned assumptions (discount rate 7%, project lifetime 25 years, inclusive of CAPEX and OPEX). This distinction ensures that project-specific results remain traceable to their original references, while harmonized values provide a consistent basis for cross-category benchmarking.

7.2. Capital and operating cost breakdown

Thomson et al. [167] found that for the Pelamis system, the steel structure, PTO, and cabling accounted for most of the capital emissions and cost burden. Giassi et al. [106] noted that simplified mechanical designs and modular components reduced the economic uncertainty and design-for-disassembly offered savings in the long term. The breakdown of typical cost components for WEC systems is shown in Table 11.

For instance, in the Pelamis P2 project, capital costs were estimated at €4.2 million per device, with ~20% attributed to hydraulic PTO units and ~ 35% to structural fabrication [18].

7.3. Case studies

Al Karim [178] developed a simplified WEC system model for early-stage economic projections, showing that PTO characteristics strongly influence overall costs. These case studies underline how component performance shapes system-level metrics such as LCOE and deployment feasibility. Chen et al. [179] conducted a techno-economic assessment of WECs arranged on an octagonal platform, employing multiple financial parameters to highlight the sensitivity of cost projections to platform configuration. A comparison of LCOE estimates and performance highlights from major WEC and hybrid projects is provided in Table 12.

7.4. Sensitivity analysis

Techno-economic sensitivity analysis is used to identify the parameters that most strongly influence LCOE and investment risk in wave energy systems. Across both standalone and hybrid configurations, the dominant cost drivers are device availability, capacity factor, and learning rate, which directly affect energy yield and OPEX intensity. In

Table 11
Typical cost distribution of WECs, including CAPEX, OPEX, and maintenance costs across system components.

Cost category	Description	Typical share of total cost
CAPEX	Device manufacturing, installation, mooring, cabling	60–75%
OPEX	Maintenance, monitoring, insurance	20–30%
Grid integration	Power electronics, cables, substations	5–10%
Decommissioning	End-of-life removal, site restoration	2–5%

Table 12
Case-study LCOE values for representative PA- and LA-WEC prototypes, highlighting techno-economic performance under different deployment conditions. Assumptions: discount rate 7%, project lifetime 25 years, CAPEX and OPEX included.

System	Rated capacity	LCOE estimate	Key insights	Ref.
Pelamis P2 (UK)	750 kW	300–350 €/MWh (initial) ~150 €/MWh (scaled)	Hydraulic losses, joint fatigue, high installation cost	[180]
Wave dragon (Denmark)	4 MW	190–250 €/MWh	Civil structure cost, turbine efficiency, scalability challenges	[180]
Submerged breakwater–PA hybrid	Site-dependent	Site-specific; optimized ±8% yield	Adaptive geometry improved energy capture; local wave analysis used for LCOE estimation	[181]
Hybrid wavestar + wind platform	–	~12% lower than standalone FOWT	Shared infrastructure reduced CAPEX and enhanced energy yield stability through wave–wind interaction	[25]

hybrid configurations, additional sensitivities arise from shared infrastructure, power-routing strategies, and system-level control coordination. Explicitly isolating these drivers provides a clearer basis for prioritizing design optimization and early-stage risk mitigation. Factors that strongly influence LCOE include:

- Device availability: downtime above 15% sharply increases OPEX per kWh,
- Capacity factor: typically 20–35% for WECs; hybrid systems may reach 45%,
- Learning rate: 10–15% cost reduction per doubling of deployment,
- Array size and shared infrastructure: economies of scale lower cost per kW.

7.5. Funding mechanisms and business models

Securing stable and long-term funding is a major challenge for WEC and hybrid marine energy projects, given their high capital intensity and long payback periods. To reduce investment risk, projects often require a combination of public incentives, private capital, and structured revenue streams. Innovative business models are emerging that bundle wave energy with other maritime services such as aquaculture, desalination, or offshore data centers. These diversified value streams improve bankability and attract broader investor interest in early-stage or demonstration deployments. WECs often rely on:

- Feed-in tariffs (e.g., Portugal, UK),
- Blue Economy grants (e.g., Horizon Europe),
- Public–private partnerships,
- Power purchase agreements (PPAs) for island and coastal communities.

A promising trend is multi-stakeholder leasing of marine zones for combined aquaculture–energy use, where energy sales offset O&M costs for food production.

7.6. Comparative costs with other renewables

Wave energy remains less mature than wind and solar, but its consistency and potential for grid balancing make it a strategic long-term asset. While capital costs are currently higher, site-specific advantages and hybrid configurations can improve economic viability over time. Ghaneei and Mahmoudi [182] created a simulation framework for Pelamis that includes cost, energy output, and environmental data. Their optimization revealed the importance of regional wave resource intensity in achieving LCOE competitiveness. A comparative overview of LCOE and capacity factors for major renewable sources is provided in Table 13, which compiles representative 2023–2025 estimates derived from IRENA, Ocean Energy Europe, and recent techno-economic assessments.

The target LCOE for WECs to become economically competitive is approximately 100 €/MWh, as defined by the International Renewable Energy Agency (IRENA) and Ocean Energy Europe (OEE). This benchmark aligns wave energy with mature renewables such as offshore wind power and solar photovoltaic (PV) systems. Achieving this cost target depends on reducing capital expenditures, increasing energy yield, and scaling up deployments. It serves as a strategic reference for guiding technology development, investment, and policy support in the marine energy sector [91,183].

7.7. By-device cost drivers and priorities (comparative perspective)

Cost structure and LCOE trajectories differ materially by WEC class; below we distill the dominant drivers and near-term levers (linked to Table 13 and the design attributes in Table 19):

- PA-WECs: CAPEX sensitivity to hull count and moorings; control-driven yield uplift (latching/RL/MPC) and modular PTO standardization reduce LCOE.
- LA-WECs: hydraulic PTO scale-up and hinge reliability drive OPEX; improved seal/bearing life and condition-based maintenance reduce downtime.
- HS-WECs: shared infrastructure lowers CAPEX/MWh, but energy-routing and Energy Management System (EMS) complexity add cost; co-optimized wind–wave dispatch increases capacity factors.

Key insight: Table 13 benchmarks LCOE ranges at system level; the levers above indicate how each class can converge toward competitive levels.

7.8. Future cost reduction strategies

Zhang et al. [184] evaluated a WEC repurposing strategy for decommissioned offshore platforms, proposing a cost-effective reuse framework. This model is highly relevant for regions with aging oil infrastructure. Such platform reuse strategies align well with broader efforts to streamline deployment and reduce lifecycle costs. To lower LCOE and boost competitiveness, key directions include:

- Modular device fabrication using composite or recycled materials,

Table 13
Comparative LCOE ranges for WEC configurations (PA, LA, and HS), illustrating indicative techno-economic variability. Assumptions: discount rate 7%, project lifetime 25 years, CAPEX and OPEX included.

Technology	Typical LCOE (€/MWh)	Notes
Solar PV (utility-scale)	30–50	Mature, cheap hardware
Offshore wind	60–80	Higher O&M, stable capacity
PA-WEC (today)	150–350	With advanced PTO: ~120
LA-WEC	180–300	Joint fatigue increases OPEX
Hybrid WEC–wind	90–160	Shared costs, higher CAPEX

- AI-based maintenance prediction to reduce OPEX [90],
- Floating microgrids for islanded communities and offshore aquaculture applications,
- Standardization of PTO modules across device classes.

While many of the proposed strategies—such as modularization, predictive maintenance, and standardization—are indeed shared with other renewable technologies like offshore wind, the competitiveness benchmark of ~100 €/MWh for WECs remains valid. This threshold, set by IEA, IRENA, and OEE, reflects a general market-entry target rather than a strict comparison to the latest wind or solar costs. Even if wind continues to reduce its LCOE, achieving ~100 €/MWh in wave energy signals a level at which private investment and policy support become viable. Moreover, WECs provide system-level benefits such as temporal complementarity with wind, improved grid stability, and alignment with multi-use offshore infrastructure, which justify their pursuit even if absolute LCOE values differ slightly from those of other renewables.

7.9. Experimental validation and testing methods

Experimental testing is critical for validating WEC designs, improving numerical models, and reducing deployment risk. Validation typically progresses through three main stages:

1. Scaled model testing in wave tanks,
2. Sub-scale testing at sea,
3. Full-scale prototype testing and deployment.

Each stage provides data to calibrate hydrodynamic models, assess structural integrity, and evaluate control strategies under real-world conditions.

Table 14
Examples of major hydrodynamic laboratories for wave energy research.

Facility	Location	Specialization	Key facilities	Ref.
COAST Lab	Plymouth, UK	Combined wave, current, wind flumes	Ocean basin, wave–current flume	[185]
LHEEA (Centrale Nantes)	Nantes, France	Ocean engineering, WEC hydrodynamics	50 × 30 × 5 m wave tank, flumes	[186]
IFREMER	France	Offshore engineering, marine environmental studies	Carène basin, wave–current flume	[187]
DHI	Hørsholm, Denmark	Coastal and offshore modeling	3D wave basins, wave flumes	[188]
HR Wallingford	Oxfordshire, UK	Water engineering, sediment transport, WEC testing	Deep Ocean Basin (75 × 32 m), fast-flow flumes	[189]
FloWave Ocean Energy Research Facility	Edinburgh, UK	Combined wave–current energy testing	25 m diameter circular tank with wave & current generation	[190]
MARIN	Wageningen, Netherlands	Maritime hydrodynamics, offshore platforms	Deepwater basins, cavitation tunnels, wave flumes	[191]
Deltares	Delft, Netherlands	Hydraulic and wave energy research	Wave basins, flumes, hybrid energy capability setups	[192]

7.10. Scaled model testing

Physical model tests typically use Froude scaling, ensuring that inertial and gravitational forces are properly represented. Facilities such as HR Wallingford, LHEEA, and IFREMER offer controlled environments to test WEC behavior in regular and irregular wave spectra. Laboratory-scale testing commonly applies Froude scaling to ensure dynamic similarity between model and full-scale systems [63,83]. While this approach preserves dominant wave–structure interactions, it cannot fully capture viscous losses, PTO dynamics, or mooring nonlinearities. Consequently, extrapolation from laboratory to prototype scale introduces uncertainties, particularly for complex PTO or hybrid configurations. Recent studies emphasize combining multi-scale experiments with numerical co-validation to mitigate these effects and improve TRL assessment reliability. Advanced hydrodynamic facilities equipped with multi-DoF tracking and variable bathymetry (Table 14, Fig. 11) support such integrated testing.

7.11. Instrumentation and sensing

Accurate instrumentation is critical in scaled WEC testing to validate numerical models and quantify performance metrics such as motion response, power output, and structural loads. Sensors must be carefully selected and positioned to capture high-resolution data under dynamic wave conditions. Common measurements include heave, surge, pitch, mooring tension, PTO force, and real-time wave elevation. Integration of sensing systems with synchronized Data Acquisition (DAQ) provides a comprehensive understanding of WEC behavior during prototype trials. To capture these parameters effectively during experiments, a combination of advanced measurement tools and synchronized acquisition systems is required. The following tools are typically integrated into experimental setups to achieve this level of measurement precision:

- Wave probes: resistance- or capacitance-type sensors for wave elevation [193],
- Load cells: measurement of PTO force and mooring line tension [194],
- Pressure sensors: monitoring of submerged components [195],
- DAQ systems: platforms such as National Instruments or LabVIEW for synchronized data acquisition [196].

Output data are used to validate models built in WEC-Sim, OpenFOAM, StarCCM+ or AQWA, with post-processing often done in MATLAB or Python.

7.12. Sub-scale and full-scale offshore trials

Zhang et al. [184] performed experimental sea trials on a multi-DoF WEC retrofitted to decommissioned platforms, validating survivability and motion damping effectiveness. Their work also confirmed the economic potential of device reuse. Dell'Edera et al. [197] used high-fidelity modeling and wave basin experiments to validate moored floating body dynamics under irregular sea states. A summary of full-scale WEC prototype testing efforts and deployment locations is presented in Table 15.

7.13. Calibration of numerical models

Calibration of numerical models is a critical step to ensure the accuracy and reliability of simulation results. This process involves adjusting model parameters and input conditions to closely match experimental or field data. Techniques such as sensitivity analysis and optimization algorithms are often employed to systematically refine the model. Proper calibration helps in reducing discrepancies caused by uncertainties in boundary conditions, material properties, or numerical

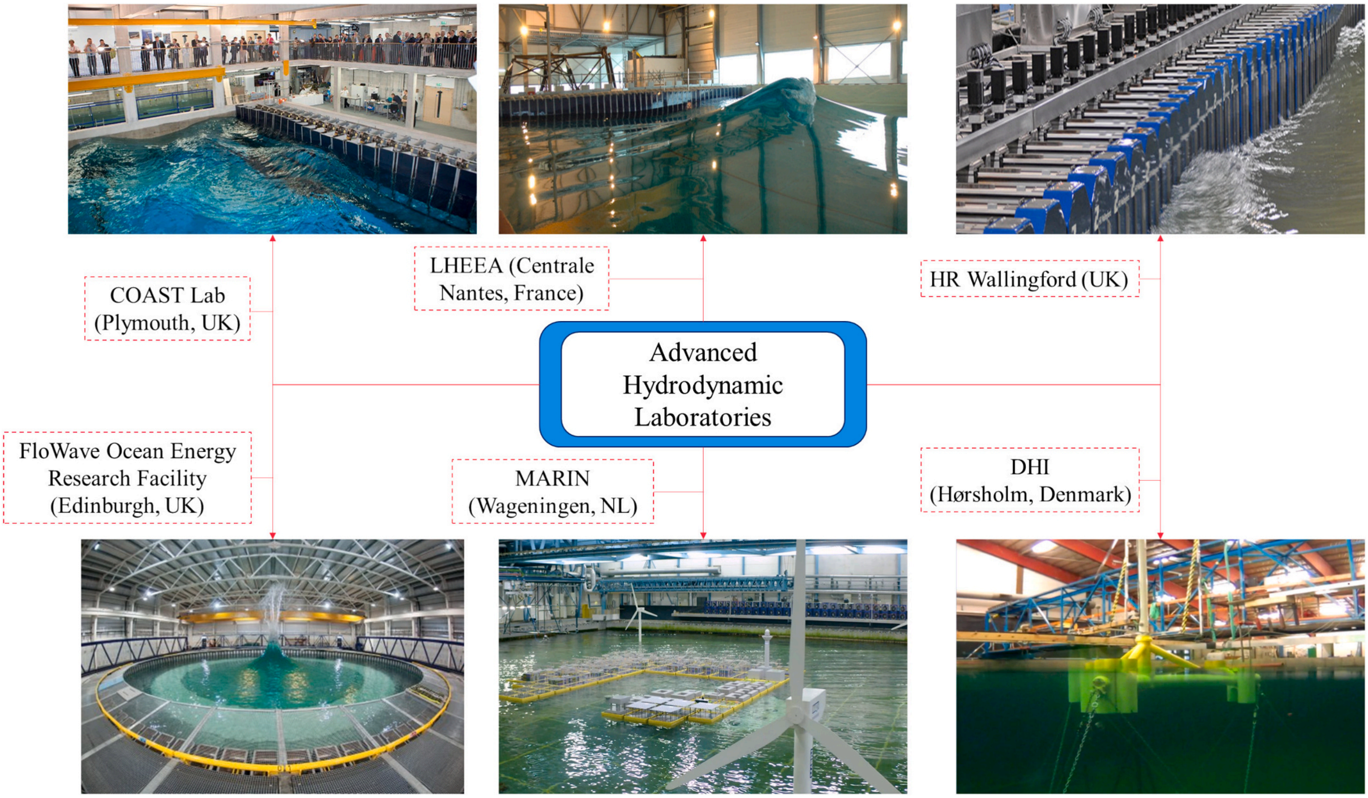


Fig. 11. Selected advanced hydrodynamic laboratories supporting wave energy research and validation, (adopted from [185,186,188–191]).

Table 15
Summary of sea-tested WEC prototypes and test sites, including device types, key performance considerations, and representative facilities.

Category	Details
Key testing objectives	✓ Survivability in extreme conditions ✓ Biofouling and corrosion ✓ Long-term energy output variability
Notable prototypes	✓ Wavestar (Denmark): Multi-float arms; 20 kW prototype tested in North Sea for over 2 years [107] ✓ Pelamis P1/P2 (UK): Grid-connected floating linear absorber at EMEC [17,18,134] ✓ SEAREV and HACE: Oscillating-body and impact-type devices tested on Atlantic coastlines
Test sites	✓ EMEC, Orkney ✓ BIMEP (Spain) ✓ SEM-REV (France)

schemes. Ultimately, a well-calibrated model enhances confidence in its predictive capability for complex engineering problems. Key purposes and comparison methods used for calibrating numerical WEC models are summarized in Table 16.

These validations are essential for gaining regulatory and investor confidence. Accurate calibration builds trust in performance predictions, especially under real sea conditions. This, in turn, strengthens confidence among regulators, developers, and potential investors.

Table 16
Experimental validation purposes and corresponding methods used for comparing measured and simulated data in numerical WEC model calibration.

Purpose of using experimental data	Methods for comparing measured vs. simulated data
Validate radiation and diffraction coefficients	RMSE (root mean square error) and NRMSE (normalized RMSE)
Refine PTO damping values	Time–frequency analysis (e.g., wavelet transform)
Analyze nonlinear behavior under wave–structure interaction	Spectral error metrics

7.14. *Digital twins and remote monitoring*

Experimental validation remains a cornerstone of wave energy research and development. Progressing from wave tanks to offshore prototypes provides essential performance and durability insights. The rise of digital twins and standardized testing protocols promises to streamline the pathway from concept to commercialization, while reducing risk and improving investor confidence. Modern projects increasingly use digital twins—real-time digital replicas of physical systems. Core components, benefits, and tools used in digital twin frameworks for WEC systems are presented in Table 17.

7.15. *Standardization and guidelines*

Standardization plays a vital role in ensuring consistency, comparability, and credibility across WEC development efforts. Organizations such as the IEC (International Electrotechnical Commission), EMEC, and

Table 17
Components, benefits, and tools commonly used in digital twin implementations for WECs.

Category	Details
Integrated components	✓ Live sensor data (wave height, PTO force, joint motion) ✓ Control algorithms (AI, MPC) ✓ Structural health monitoring (SHM) models
Key benefits	✓ Predictive maintenance ✓ Remote diagnostics ✓ Performance forecasting
Tools used	✓ ANSYS Twin Builder ✓ Simulink with IoT integration ✓ Cloud SCADA platforms

DNV have established protocols covering power performance, environmental monitoring, and design load criteria. For example, IEC TS 62600–103 focuses on quantifying power output under defined conditions, while EMEC guidelines outline best practices for survivability and ecological assessment. DNV-RP-C205 provides a framework for modeling site-specific environmental conditions to inform structural and mooring design. Adhering to these standards supports project bankability, facilitates technology certification, and streamlines future deployment at scale [198–200]. A summary of key international testing and validation protocols is provided in Table 18. Adhering to these standards ensures interoperability, bankability, and future scaling.

7.16. Wave-to-wire modeling approaches

Wave-to-wire models form a critical bridge between ocean hydrodynamics and onshore power delivery by integrating wave input, hydrodynamic response, PTO behavior, control strategies, and electrical output within a unified simulation framework. These models provide holistic insights into WEC performance under real-sea conditions and enable advanced control system development, grid compliance testing, and cost–benefit evaluation.

Several recent studies have advanced wave-to-wire methods. Tan et al. [201] developed a spectral-domain wave-to-wire model for PA-WECs that incorporates frequency-dependent response and generator dynamics. Similarly, Tan et al. [202] analyzed the impact of adjustable draft on system response, revealing trade-offs between hydrodynamic excitation and power extraction as illustrated in the modular structure of the wave-to-wire system shown in Fig. 12. Curran et al. [203] offered one of the earliest theoretical frameworks for aerodynamic wave-to-wire conversion, highlighting phase loss during mechanical-to-electrical transformation. Dong et al. [204] extended this by embedding adaptive control into wave-to-wire simulations, offering stability in rapidly changing sea states.

For hybrid concepts, Hu et al. [207] introduced an electromagnetic–triboelectric PTO within a wave-to-wire model to enhance multi-modal harvesting efficiency. Similarly, Wang et al. [208] used wave-to-wire analysis to optimize hull geometry and orientation of ocean monitoring buoys under varying wave conditions. Coupled time-domain models, such as those in Yi et al. [209], incorporate control strategies and electrical interfaces to simulate floating WEC arrays, providing realistic system-level responses (Fig. 13).

Wave-to-wire modeling also supports system-level reliability and control robustness. Nagumo et al. [210] integrated mooring dynamics and wave directionality into a lightweight floating system, assessing how tower stiffness and guy-wire layout influence energy transfer. Rasool et al. [211] used wave-to-wire simulations to evaluate grid integration impacts and power quality in wave farms (Fig. 14), while Wang et al. [212] demonstrated enhanced energy yield for a two-body barge WEC through optimized damping coefficients and control logic.

Yao et al. [213] embedded storage optimization within a wave-to-wire model for real-time power smoothing. Meanwhile, Asiikkis et al. [97] addressed dense array modeling with hydraulic PTOs and showed the importance of inter-device coupling. Other contributions focus on buoy-specific applications, such as the vibro-impact design explored by Chen et al. [214]. By combining hydrodynamic and electromechanical domains, wave-to-wire modeling provides a robust decision-making tool for system optimization, controller validation, and techno-economic analysis. Tan et al. [215] proposed a spectral-domain wave-to-wire method that accelerates array evaluation while retaining accuracy in power metrics. Future work should focus on standardized frameworks for wave-to-wire benchmarking and experimental validation to accelerate technology convergence.

Table 18
Key international standards and guidelines for testing, validation, and environmental assessment of WECs.

Organization/ Standard	Focus area	Ref.
IEC TS 62600-103	Power performance assessment of WECs	[198]
EMEC guidelines	Environmental monitoring, performance, and survivability	[199]
DNV-RP-C205	Site-specific environmental conditions and load definitions	[200]

8. Discussion and technology readiness

8.1. Technology evaluation across WEC types

WECs exhibit a wide range of structural, hydrodynamic, and control characteristics depending on their classification. Each type—whether PA-WEC, LA-WEC, or HS-WEC—offers distinct trade-offs in efficiency, survivability, scalability, and integration potential. Evaluating these differences is crucial for guiding both site-specific deployment and long-term technology roadmapping. While standalone devices optimize specific performance aspects, hybrid configurations increasingly dominate due to their multifunctional potential. Based on our extensive review of PA-WECs, LA-WECs, and HS-WECs, several important technical and strategic insights emerge:

- PA-WECs are structurally simple, scalable, and omnidirectional but suffer from limited power capture bandwidth and mooring complexity in deep water.
- LA-WECs (including attenuator-type devices such as Pelamis) offer higher instantaneous power in aligned wave fields but face issues with hinge fatigue and complex installation.
- HS-WECs (e.g., WEC + FOWT, WEC + breakwater) offer synergy and efficiency gains but require advanced control strategies and capital-intensive platforms.

Taken together, hybrid wave energy systems should be viewed not merely as extensions of standalone WECs, but as integrated energy–infrastructure solutions whose value emerges from system-level coordination, shared assets, and multifunctional deployment contexts. Each class of WEC presents a distinct trade-off between efficiency, complexity, deployment environment, and cost.

8.2. Comparative matrix

As WEC technologies evolve toward commercialization, structured comparisons across device types become increasingly valuable. PA-WECs, LA-WECs, and HS-WECs differ significantly in their response dynamics, integration complexity, and scalability. Understanding these differences helps stakeholders—from developers to policymakers—prioritize investments and deployment strategies. A comparative matrix also provides a quick reference for evaluating technical maturity and suitability for specific operating environments or infrastructure settings. A structured comparison of core performance and design attributes across WEC types is presented in Table 19.

8.3. Challenges hindering commercial deployment

Nielsen and Plum [216] and Kraemer et al. [217] both presented early insights from the McCabe wave pump, a seminal PA-WEC. Their experimental results revealed discrepancies between predicted and actual behavior, highlighting early modeling limitations still relevant today. These foundational studies underscore how many early challenges—such as modeling uncertainty and design inefficiencies—still echo in today's deployment landscape. Building on these foundations, a recent review highlights that articulated multi-body absorbers still face persistent challenges such as hinge wear, cyclic fatigue, and hydraulic efficiency losses, which remain critical barriers to commercialization [218]. These unresolved issues continue to manifest as major barriers in

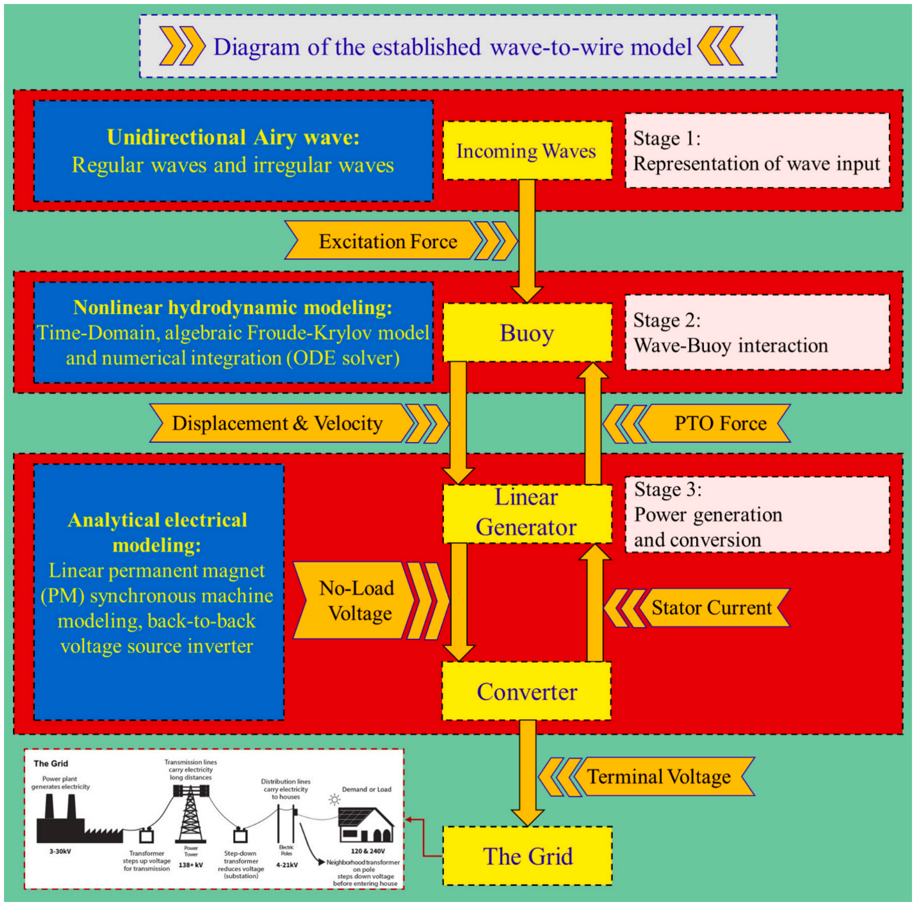


Fig. 12. Schematic of the established wave-to-wire model integrating hydrodynamic, mechanical, and electrical subsystems for a point absorber WEC with linear generator, (adopted from [201,205,206]).

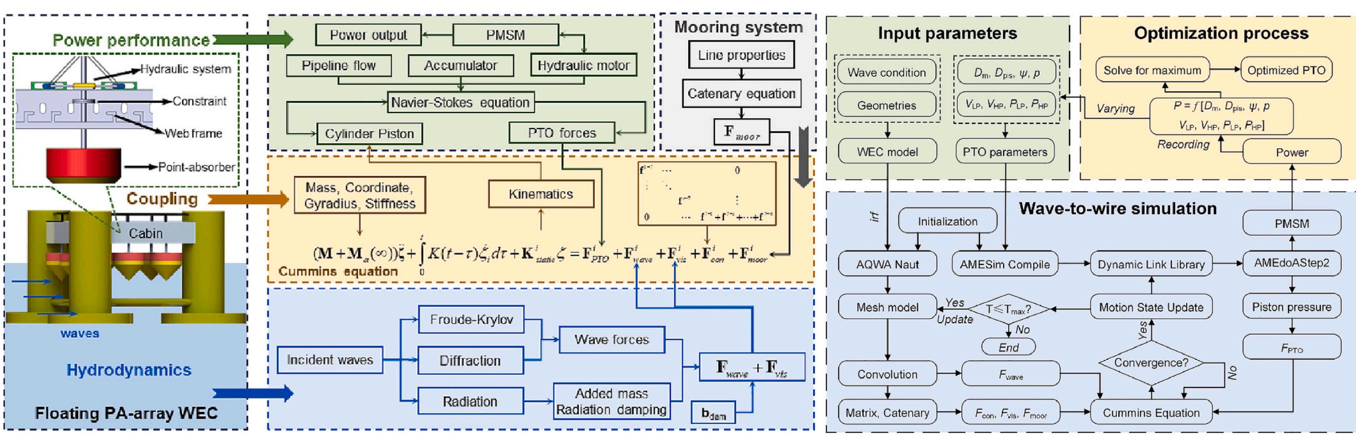


Fig. 13. Coupled wave-to-wire simulation of a floating point absorber array showing system layout and power output smoothing under irregular waves [209].

modern WEC commercialization efforts, such as:

- High LCOE relative to wind and solar,
- Corrosion and fatigue in marine environments,
- Absence of standardized control architectures,
- Lack of regulatory clarity for hybrid platforms.

8.4. SWOT analysis

Strategic evaluation of WEC technologies through SWOT analysis provides a comprehensive lens for understanding their commercial readiness. Each WEC type—PA-WEC, LA-WEC, and HS-WECs—offers unique technical strengths but also faces distinct operational and regulatory constraints. PA-WECs are valued for simplicity and ease of scaling, though mooring challenges and narrow bandwidth affect competitiveness. LA-WECs deliver high power per unit length but face structural fatigue and directionality limitations. HS-WECs benefit from shared infrastructure and multifunctional use but demand higher capital and advanced control integration. Understanding these strengths, weaknesses, opportunities, and threats can help guide research and development investment, policy support, and deployment strategy. The comparative SWOT analysis below highlights these factors across the

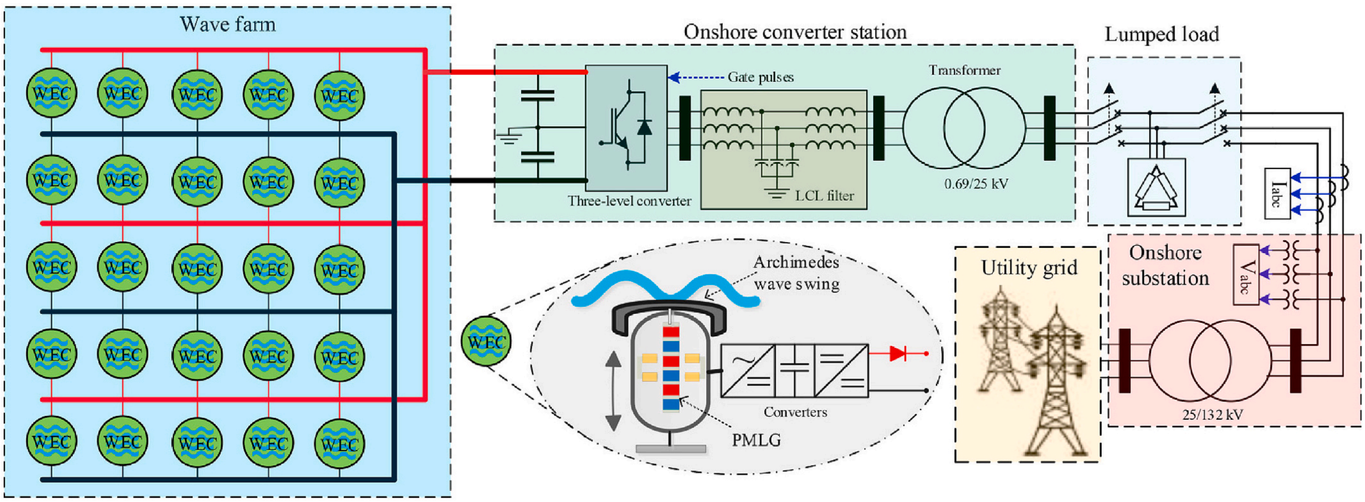


Fig. 14. Simulated power quality at grid interface under different wave conditions [211].

Table 19
Comparative evaluation of PA-WECs, LA-WECs, and HS-WECs based on performance, maturity, and deployment characteristics.

Attribute	PA-WECs	LA-WECs	HS-WECs
Directional sensitivity	Low (omnidirectional)	High (aligned only)	Variable (configuration-dependent)
Mechanical complexity	Low–Medium	High	Very High
Survivability	Moderate	High (flexible)	High (stabilized platforms)
PTO maturity	Mature (hydraulic, linear)	Mature (hydraulic, rotary)	Emerging (multi-PTO integration)
Array compatibility	Moderate	Low (wave shadowing)	High (shared platforms)
Typical capacity factor	20–30%	25–35%	35–45% (predominantly model-based; limited field validation)
TRL	6–8	6–8	4–6

four major WEC categories. A comparative SWOT analysis for each WEC type is presented in Table 20.

8.5. Technology readiness level assessment

The TRL framework is a standardized metric used to assess the maturity of emerging technologies, including WECs, from initial concept to full commercialization [219]. It provides policymakers, investors, and developers with a structured path to evaluate where a given technology stands in its innovation lifecycle and what validation steps are required next. According to the EU H2020 framework, TRLs range from 1 to 9, progressing from basic research (TRL 1) to full commercial deployment (TRL 9). Early stages (TRL 1–3) focus on concept validation and lab-scale feasibility, while mid-levels (TRL 4–6) require component and subsystem testing in laboratory or controlled environments. The final stages (TRL 7–9) demand real-world testing, operational demonstration, and market readiness. The IEA-OES roadmap complements this structure by aligning each TRL stage with ocean-specific engineering outputs, including wave tank testing, environmental integration, power quality verification, and certification processes (e.g., via IEC/IECRE) [220]. These definitions ensure comparability and facilitate international coordination of technology development.

A harmonized TRL and commercialization comparison across PA-, LA-, and HS-WECs is presented in Table 22. In contrast to Table 21, which highlights representative examples at different stages, this synthesis benchmarks device categories against a common set of indicators, including maturity range, operational experience, capacity factor trends, standardization progress, indicative LCOE bands, and

Table 21
TRLs with corresponding definitions and WEC examples, based on EU H2020 and IEA-OES guidelines.

TRL	Definition	Example technologies
1–3	Basic research, proof-of-concept	Novel PTOs, AI controllers
4–5	Component/subsystem validation	Lab-tested self-reacting PA-WECs
6–7	Prototype in relevant environment	Pelamis P2, Wavestar
8–9	Commercial operation/scale-up	hybrid aquaculture-WECs

Table 20
SWOT analysis of PA-WECs, LA-WECs, and HS-WECs across technical, operational, and strategic dimensions.

WEC type	Strengths	Weaknesses	Opportunities	Threats
PA-WECs	- Simple design - Scalable - Omnidirectional - Proven hydraulic PTO reliability	- Fatigue under cyclic loading - Narrow bandwidth - Deep-sea mooring requirements - Limited field data	- Real-time control - AI-based tuning - Growing offshore investment - Supportive renewable energy policies	- Corrosion - Survivability challenges - High cost - Uncertain regulatory frameworks
LA-WECs	- High power per unit - Scalable segments - Modular design flexibility	- Joint fatigue under cyclic loading - Directionality constraints - Hinge wear	- Joint redesign potential - Application of bistable mechanisms - AI-based damping control	- Mechanical failure - Offshore repair cost - Regulatory uncertainty
HS-WECs	- Shared infrastructure - Broader energy capture potential - Strong resonance effects - Potential for large-scale arrays	- Capital intensive - Complex control coordination - Complex mooring systems - Limited prototype validation	- Multi-use offshore farms - Synergy with offshore wind/aquaculture - Advances in control strategies	- Regulatory delay - Ecosystem interaction uncertainty - Competing marine energy technologies - High capital expenditure

commercialization pathways. Reported capacity-factor values for hybrid systems should be interpreted as indicative trends rather than operational benchmarks, as most are derived from numerical simulations or short-duration pilot deployments.

To ensure transparent benchmarking across device categories, a harmonized TRL rubric and a consistent LCOE convention (discount rate 7%, project lifetime 25 years, inclusive of CAPEX and OPEX) are applied in this synthesis. Under these aligned assumptions, PA- and LA-WEC families cluster predominantly within TRL 6–8, with indicative LCOE bands of approximately 200–400 €/MWh. In contrast, HS-WEC configurations map primarily to TRL 4–6 and exhibit a wider LCOE uncertainty range (approximately 350–650 €/MWh) due to limited field validation and integration complexity. Deviations observed in individual case studies (Table 12) reflect original project-specific assumptions and are interpreted accordingly. This harmonized perspective provides a clearer basis for techno-economic benchmarking and emphasizes differentiated development priorities for each device class.

8.6. Industry and investment trends

The global wave energy sector is gradually shifting from isolated prototypes toward integrated commercial solutions, driven by technological convergence and policy incentives [221]. Northern Europe, Australia, and East Asia are emerging as frontrunners in MUP deployment and infrastructure co-funding.

Governments and funding bodies like Horizon Europe and Innovate UK are promoting digital innovation through twin modeling, AI-enhanced PTOs, and remote diagnostics. Startups and scale-ups are also leveraging green finance instruments such as blue bonds, carbon offset credits, and impact investment funds.

Nevertheless, mainstream investors remain cautious due to perceived technology immaturity and uncertain bankability metrics. Stronger public–private partnerships and regulatory harmonization are seen as key enablers for unlocking large-scale funding. Key market directions and remaining investment barriers are summarized in Table 23.

8.7. Remaining research gaps

Despite notable advancements in WEC development, significant research challenges remain across modeling, economics, durability, and integration. Many existing tools lack holistic representation of coupled physical processes, while economic benchmarking suffers from inconsistent methodologies. Furthermore, long-term operational data for WECs remain scarce, limiting insight into real-world degradation, reliability, and cost evolution. Addressing these gaps is essential not only for advancing standalone WECs, but also for accelerating the deployment of hybrid energy platforms within multi-use marine environments.

To close these gaps, several high-priority research areas must be addressed, including:

- System-level co-simulation: Integrated aero-hydro-structural simulations are still fragmented and computationally intensive, lacking real-time feedback for control testing.
- Multiphysics modeling: Advanced numerical frameworks must combine fluid dynamics, mooring behavior, elasticity, and control to improve design reliability and prediction accuracy.
- AI-driven control systems: RL, digital twins, and adaptive control algorithms remain underutilized in both PTO optimization and platform-wide decision-making.
- Long-term durability modeling: Very few prototypes have operated for more than five consecutive years; empirical data on biofouling, fatigue, corrosion, and maintenance downtime is critically needed.
- Standardized cost metrics: Inconsistent LCOE modeling across projects limits comparability and investor confidence; common evaluation frameworks must be adopted.

Table 22
Harmonized TRL and commercialization comparison across major WEC categories, integrating maturity levels, operational evidence, and indicative LCOE ranges.

WEC type	TRL range (2024–2025)	Prototype / Deployment	Operating hours (cumulative)	Capacity factor (reported)	Standardization progress	Indicative LCOE band (€/MWh)	Commercial pathway highlights
PA-WECs	6–8	Multiple full-scale demos (e.g., Wavestar, CorPower C4)	>150,000 h (CorPower, OPT)	20–30%	IEC/IECRE certification in progress	250–400	Modular farms, niche off-grid, EU pilot farms
LA-WECs	6–8	Full-scale prototypes (e.g., Pelamis legacy, Waveline Magnet pilots)	~100,000 h (historic Pelamis, newer LA trials)	25–35%	Limited certification; structural reliability focus	200–350	Segment-scalable arrays, long-stroke PTO innovation
HS-WECs	4–6	Lab-scale & early pilots (wave–wind & MUPs)	5000–25,000 h (mainly pilot-scale)	25–40% (modeled; limited field validation)	Early-stage; no IEC hybrid certification	350–650	Co-deployment with floating wind, EU Blue Economy initiatives

Table 23
Recent industry trends and investment barriers in the wave energy and hybrid marine energy sector.

Category	Details
Emerging Trends	- Hybrid renewable marine parks in Northern Europe - Co-funded floating platforms for multi-use (wind, wave, aquaculture) - Digital twin platforms with predictive analytics - AI-enhanced PTO and control modules
Investment Barriers	- Uncertain returns on capital - Regulatory permitting (especially for hybrid zones) - Risk-averse insurance markets

- Environmental integration: Early-stage models rarely account for sediment transport, marine ecosystem interactions, or regulatory compliance in coastal deployments.
- Cross-sector integration: Synergies with aquaculture, desalination, and offshore hydrogen systems offer high socio-economic value but require multidisciplinary research and policy coordination.

Bridging these research and standardization gaps is essential for advancing WEC technologies from experimental validation toward reliable, bankable, and grid-integrated commercial solutions.

9. Future research directions

As wave energy transitions from pilot-scale testing to commercial viability, aligning research with emerging policy and industrial needs becomes critical. Future efforts must emphasize not only technological refinement, but also interdisciplinary collaboration and environmental compatibility. Holistic design strategies that integrate control, durability, and socio-economic impacts will accelerate system readiness. Based on current technology trajectories and policy drivers, the following priorities are recommended for researchers, industry, and policymakers:

- Develop AI-powered control algorithms that adjust PTO damping, resonance frequency, and actuator delays in real time, maximizing energy capture under variable sea states.
- Advance MUP designs that integrate floating WECs with offshore wind, aquaculture, and ocean observation systems, sharing mooring, power conditioning, and communications infrastructure.
- Implement large-scale pilot farms in geographically diverse locations with long-term monitoring to evaluate survivability, power consistency, and ecological interaction.
- Design modular, recyclable components (especially PTO units) using composite and eco-friendly materials to reduce CAPEX and ease end-of-life management.
- Create internationally harmonized guidelines for performance testing, permitting, and EIAs, following IEC and IEA-OES standards.
- Explore non-traditional energy markets such as powering autonomous marine vehicles, hydrogen electrolyzers, or remote microgrids.

10. Conclusions

This review delivered a systematic, comparative synthesis of three principal wave energy converter classes—Point Absorbers (PA-WECs), Line Absorbers (LA-WECs), and Hybrid Systems (HS-WECs—evaluating hydrodynamic principles, PTO architectures, control approaches, techno-economic indicators, and commercialization pathways against a common set of metrics (maturity range, operational experience, capacity-factor behavior, standardization progress, indicative LCOE bands, and commercialization routes).

Distinct development trajectories emerge. PA-WEC and LA-WEC concepts show greater demonstration experience and clearer modular scaling pathways: a number of devices have advanced to full-scale sea trials and several to grid-connected demonstrators, clustering in mid-to-late TRL levels. Their relative strengths lie in tractable PTO designs and incremental cost-reduction opportunities through standardization and supply-chain scaling. Hybrid systems, by contrast, promise strategic system-level benefits—shared infrastructure, diversified revenues, and risk mitigation—but predominantly occupy earlier TRL bands (typically TRL 4–6). For hybrids, the primary challenge is multi-domain integration complexity (structural, electrical, operational and regulatory), which increases uncertainty in lifetime costs and permitting timelines.

A central methodological conclusion is that credible techno-economic benchmarking requires harmonized assumptions and transparent reporting. Wide LCOE spreads across studies largely reflect inconsistent CAPEX/OPEX definitions, discount rates, assumed lifetimes, capacity-factor baselines, and balance-of-plant scopes. Likewise, TRL statements in literature are often unsupported by uniform evidence thresholds. To support robust comparison, future work must adopt explicit harmonization protocols (standardized TRL rubrics tied to demonstrable metrics and an LCOE convention specifying discount rate, lifetime, capacity-factor baseline, and included cost components).

Three convergent opportunity areas offer immediate leverage: (1) scaling adaptive and predictive control (model-predictive and AI-assisted) from single devices to farms to improve capture and survivability; (2) adopting modular PTO interfaces and common mechanical/electrical standards to reduce manufacturing and O&M costs; and (3) embracing digitalization—digital twins, interoperable telemetry, and condition-based maintenance—to accelerate learning and reliability improvements. Priority actions to accelerate commercialization include: harmonized, grid-connected demonstrators that publish standardized performance datasets; clear TRL and LCOE reporting conventions with sensitivity bounds; coordinated standardization of PTO, mooring and electrical interfaces; phased hybrid integration roadmaps with early cross-sector stakeholder engagement; and performance-based, staged financing to de-risk first commercial rollouts.

In sum, the PA-WEC and LA-WEC pathways offer the most tractable near-term routes for incremental progress toward commercialization, whereas hybrid concepts require coordinated integration trials and harmonized evaluation frameworks to realize system-level advantages. With transparent, harmonized demonstrations, common metrics, and targeted policy-finance mechanisms, buoy-type wave technologies can progress from prototype to credible contributors within low-carbon energy systems.

CRediT authorship contribution statement

Alireza Abbasi: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Hassan Ghassemi:** Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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