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Review

From Wave Energy Converter Optimisation to Hybrid Offshore Integration: A Critical Review with the TALOS WEC as a Case Study

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Abstract

Optimising standalone wave energy converters (WECs) does not establish their performance within hybrid offshore wind–wave systems. This review develops an evidence-based framework linking WEC optimisation to hybrid integration through critical appraisal of modelling, validation, performance boundaries, and uncertainty. It synthesises 179 publications (96 primary studies) spanning WECs, offshore wind, coupled modelling, hybrid integration, and machine learning (ML) and artificial intelligence (AI), using the Technologically Advanced Learning Ocean System (TALOS) as a literature-derived case study. Published TALOS optimisation increased simulated mechanical power take-off (PTO)-level annual energy production (AEP) from approximately 345 MWh to 1311 MWh (3.8-fold) within the investigated numerical design space. This does not demonstrate electrical AEP, experimentally validated full-scale performance, or beneficial TALOS–wind integration. ML and AI can support prediction, monitoring, control, and optimisation, but require representative data, physical consistency, and validation. The synthesis identifies coupled dynamics, wave-to-wire conversion, structural and mooring constraints, reliability, and techno-economic performance as key evidence gaps. A proposed pathway prioritises uncertainty-aware modelling, experimental validation, coupled hybrid-system assessment, and offshore demonstration. Device-level optimisation gains must be independently evaluated at system level before hybrid performance or economic benefits can be claimed.

Keywords: wave energy converter; offshore wind energy; wind–wave integration; TALOS wave energy converter; power take-off optimisation; coupled modelling; techno-economic assessment; machine learning; artificial intelligence

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1. Introduction

The transition toward low-carbon energy systems requires substantial expansion of renewable electricity generation to support reductions in energy-sector greenhouse-gas emissions [1,2]. Within this broader transition, ocean waves represent a high-density renewable-energy resource with substantial theoretical and technical potential for future low-carbon electricity generation [3–6]. Wave energy converters (WECs), however, remain considerably less commercially mature than offshore wind technologies, despite sustained resource characterisation, technology development, and offshore testing activity [7,8]. Their

development continues to be constrained by high capital and operational costs, structural survivability requirements, device-specific hydrodynamic behaviour, power take-off (PTO) efficiency, control complexity, and uncertainty in long-term energy yield [9–12].

Improving WEC performance therefore requires coordinated optimisation across several strongly coupled design domains. Hull geometry influences added mass, radiation damping, excitation forces, and resonance behaviour; these hydrodynamic characteristics determine suitable PTO parameters and control strategies, while increased motion and energy absorption may introduce additional structural and survivability constraints [13,14]. Recent control co-design research further demonstrates that WEC geometry, PTO dynamics, and control laws should increasingly be treated as coupled optimisation variables rather than independent design problems [15,16].

Offshore wind provides a comparatively mature and rapidly developing reference sector for large-scale marine renewable-energy deployment [17]. For future offshore deployment, however, successful optimisation of a standalone WEC does not by itself demonstrate suitability for integration within a hybrid offshore renewable-energy system. Offshore wind turbines (OWTs), particularly floating systems, introduce aerodynamic loading, platform motion, mooring dynamics, structural-control interactions, and long-term reliability considerations that are not present in isolated WEC optimisation [18–22]. When wave and wind technologies are co-located or physically integrated, additional interactions arise through shared platform dynamics, hydrodynamic coupling, mooring loads, electrical infrastructure, control coordination, and site-dependent resource complementarity [23–25]. For clarity, this review uses "hybrid offshore wind–wave integration" to describe the process of combining offshore wind and wave-energy technologies within a common offshore energy development. The term "hybrid offshore wind–wave system" refers to the resulting arrangement, which may involve resource co-location, shared infrastructure, or physical integration. Here, "co-location" denotes deployment within the same offshore area without necessarily requiring shared structures, whereas "physical integration" refers to configurations in which wind and wave-energy technologies share a supporting structure or platform and may exhibit coupled dynamic interactions. These distinctions are maintained throughout the review to avoid treating resource co-location and mechanically coupled systems as equivalent.

This distinction between *device-level optimisation* and *hybrid-system optimisation* is central to the present review. A WEC may demonstrate substantial improvements in absorbed mechanical power or simulated annual energy production following optimisation of geometry, PTO parameters, control, or mooring configuration. Such results should not, however, be interpreted automatically as improvements in electrical wave-to-wire output, hybrid-system annual energy production, levelised cost of energy, or commercial deployability. Credible assessment of hybrid wind–wave systems requires additional consideration of coupled aero–hydro–servo dynamics, structural and mooring interactions, electrical conversion and collection, control coordination, reliability, and techno-economic performance.

Coupled numerical modelling is consequently an important bridge between standalone device optimisation and system-level offshore integration. For floating wind–wave systems, platform motions can alter wind-turbine aerodynamic loading while aerodynamic forces can modify the platform response relevant to WEC operation. These bidirectional interactions mean that the behaviour of an integrated system cannot necessarily be inferred by independently modelling its constituent technologies and combining their outputs [25–28]. The fidelity, validation level, and system boundaries adopted in coupled modelling therefore strongly influence the confidence that can be placed in reported hybrid-system benefits.

Data-driven methods, including machine learning (ML) and artificial intelligence (AI), represent an additional, but complementary, development pathway. ML approaches have

been investigated for WEC power-output prediction, condition monitoring, fault diagnosis, and optimisation [29–32], while reinforcement-learning and deep-reinforcement-learning methods have been explored for adaptive energy-maximising control, energy-storage coordination, and grid-connected WEC operation [33–35]. Their relevance to hybrid offshore systems depends not only on predictive accuracy, but also on training-data quality, generalisation beyond the training domain, physical consistency, robustness, safety, and experimental validation. Accordingly, AI and ML methods are considered in this review where they contribute directly to the progression from device-level optimisation toward deployable offshore energy systems, rather than as an independent research theme.

Although substantial literature exists on WEC technology, WEC optimisation and control, floating offshore wind, coupled modelling, and hybrid wind–wave platforms [23,24,36], these research areas are frequently assessed using different performance boundaries, modelling assumptions, validation practices, and levels of technology-development evidence. This makes it difficult to determine which findings are transferable from standalone WEC optimisation to hybrid offshore-system design, which conclusions remain dependent on numerical assumptions, and which integration pathways are still conceptual. A critical synthesis based on common evidence dimensions is therefore needed to distinguish demonstrated results from numerically supported findings and prospective system-level opportunities. To address this gap, the present review integrates evidence appraisal with a staged engineering framework that connects standalone WEC optimisation, validation of reported performance, coupled hybrid-system assessment, and the requirements for offshore deployment. Rather than treating improvements in device-level energy capture as direct evidence of hybrid-system benefits, the framework identifies the additional modelling, experimental, electrical, structural, control, and techno-economic evidence needed to support each progression stage.

The TALOS (Technologically Advanced Learning Ocean System) WEC is used in this review as a literature-derived case study through which this distinction can be examined. TALOS is a multi-axis WEC based on the relative motion of an internal oscillating mass and an external floating hull. Published TALOS studies have investigated hull geometry, PTO parameters, centre-of-gravity positioning, numerical modelling, power-output prediction, and more recently mooring and AI-based optimisation [30,37–39]. These studies provide useful evidence of how coordinated device-level optimisation can alter predicted WEC performance. However, TALOS has not yet been demonstrated as part of a fully coupled wind–wave offshore platform. It therefore provides an appropriate case study for distinguishing established device-level findings from the additional modelling, validation, electrical, structural, control, and techno-economic requirements associated with future hybrid integration. Accordingly, this review addresses the following research questions:

RQ1. Which device-level optimisation approaches have been applied to WECs, and what is the strength of the supporting numerical or experimental evidence?
RQ2. Which additional modelling, structural, mooring, control, electrical, and techno-economic requirements arise when WECs are considered for integration with offshore wind systems?
RQ3. What does the published TALOS literature demonstrate at the device level, and which proposed pathways toward hybrid offshore integration remain conceptual or unvalidated?
RQ4. How are ML- and AI-enabled methods being applied to WEC prediction, monitoring, control, and optimisation, and what limitations currently restrict their deployment in hybrid offshore systems?

Figure 1 presents the evidence-based conceptual framework connecting research questions RQ1–RQ4 to the critical synthesis developed in this review. It integrates the reviewed evidence domains, common critical-appraisal criteria, and published TALOS device-level

findings to identify the additional engineering and validation requirements associated with hybrid offshore wind–wave integration. The proposed evidence-building pathway distinguishes published device-level results from prospective system-level integration and deployment requirements.

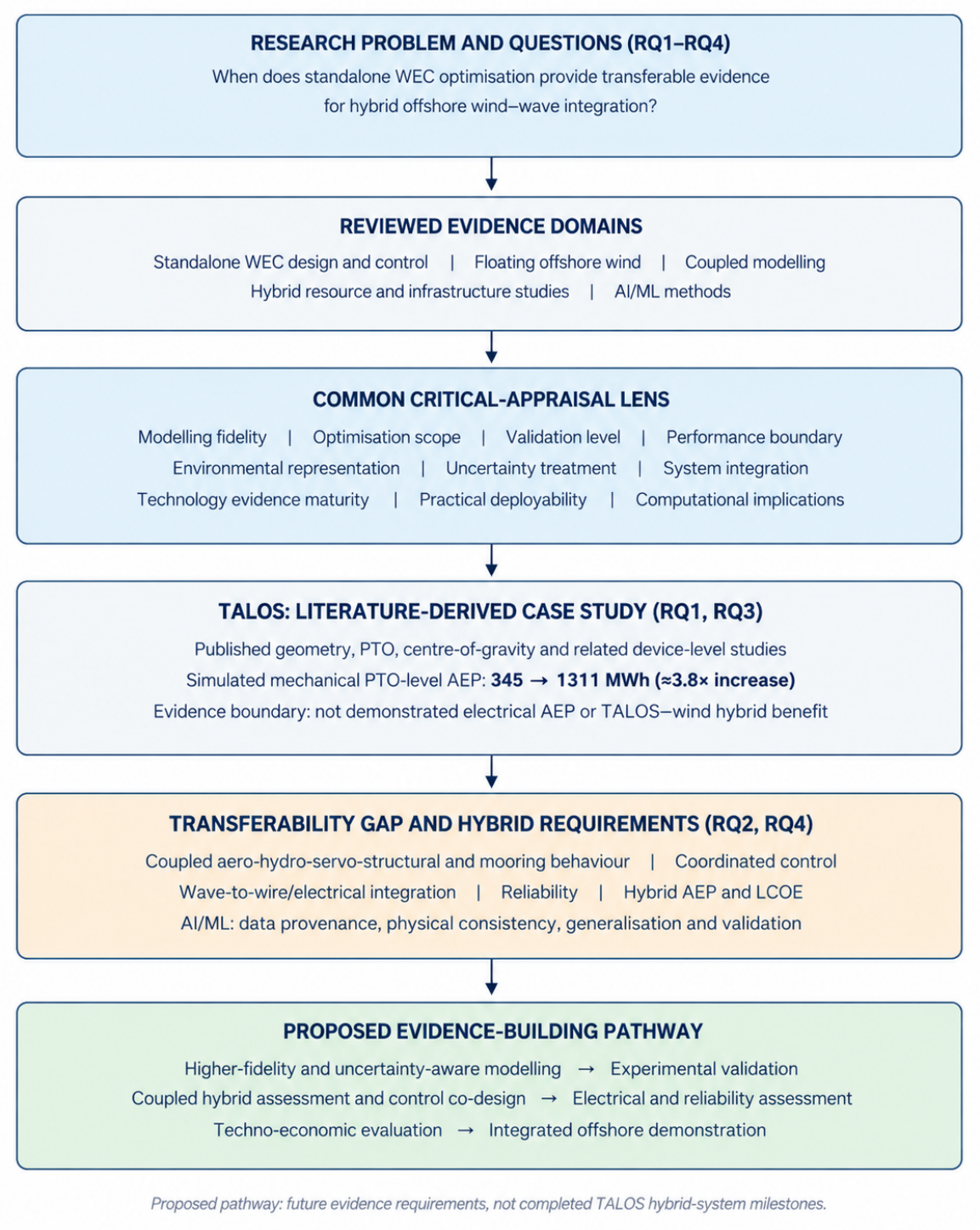


Figure 1. Evidence-based conceptual framework linking standalone WEC optimisation to hybrid offshore wind–wave integration through critical evidence appraisal, TALOS case-study assessment, and identification of system-level research gaps and validation requirements. The proposed pathway represents future research priorities rather than demonstrated TALOS hybrid-system capabilities.

The main contributions of this paper are therefore:

- a structured synthesis linking standalone WEC optimisation to the additional engineering requirements introduced by hybrid offshore integration;
- a critical comparison of the reviewed literature using common evidence dimensions including modelling fidelity, optimisation scope, validation level, performance boundary, uncertainty treatment, technology evidence maturity, and practical deployability;
- a literature-derived TALOS case study that distinguishes previously published device-level optimisation results from conceptual future hybrid-integration pathways;
- a focused assessment of ML- and AI-enabled methods according to their evidence base, validation practices, and relevance to WEC and hybrid offshore-energy applications; and
- an evidence-based identification of the modelling, experimental, wave-to-wire, control, structural, and techno-economic gaps that must be addressed when progressing from optimised standalone WECs toward validated hybrid offshore renewable-energy systems.

This paper is organised as follows. Section 2 describes the literature-search, screening, data-extraction, and critical-appraisal methodology. Section 3 examines WEC optimisation with emphasis on the design variables and evidence relevant to offshore deployment. Section 4 considers the offshore-wind characteristics that become important when moving toward integrated floating wind–wave systems. Section 5 reviews coupled modelling approaches and their principal assumptions and validation requirements. Section 6 examines resource, infrastructure, electrical, structural, and techno-economic aspects of hybrid offshore integration. Section 7 critically synthesises the published TALOS device-level evidence. Section 8 evaluates TALOS in the context of representative WEC technologies without assuming direct quantitative equivalence between heterogeneous studies. Section 9 identifies remaining evidence gaps and development priorities, and Section 10 presents the principal conclusions.

2. Review Methodology

This section describes the methodology used to construct and critically evaluate the evidence base for the review. It first defines the review design and research scope, followed by the literature-search strategy, eligibility criteria, screening procedure, and classification of records. It then describes the data-extraction process and common critical-appraisal framework used to assess modelling fidelity, optimisation scope, validation, performance boundaries, system integration, and technology evidence maturity. Finally, the synthesis approach and methodological limitations are outlined to clarify how heterogeneous numerical, experimental, operational, and techno-economic evidence is interpreted throughout the review.

2.1. Review Design and Research Scope

This study adopts a structured critical-review methodology to examine the progression from standalone WEC optimisation toward hybrid offshore wind–wave integration. The literature-search, screening, and record-selection process was documented using principles consistent with transparent systematic-review reporting practice [40]. A pooled statistical meta-analysis was not considered appropriate because the available literature is heterogeneous with respect to device architecture, environmental conditions, optimisation objectives, performance definitions, modelling fidelity, system boundaries, and validation level. Instead, the review combines a structured literature-search and screening procedure with a common evidence-extraction and critical-appraisal framework designed to evaluate both reported findings and the strength and transferability of the supporting evidence [41].

The review is guided by the four research questions defined in Section 1. Particular emphasis is placed on distinguishing standalone device optimisation from hybrid-system optimisation and on separating hydrodynamic absorption, mechanical PTO performance, electrical wave-to-wire performance, annual energy production, structural and reliability performance, and techno-economic performance. These quantities are not treated as interchangeable measures of system performance.

Published TALOS results are treated as literature-derived case-study evidence rather than as new numerical or experimental results generated within the present review. The TALOS case study is used to examine how device-level optimisation evidence relates to the additional modelling, validation, control, electrical, structural, and techno-economic evidence required for hybrid offshore integration. The conceptual framework presented in Figure 1 summarises this evidence-based approach by linking the review questions, common appraisal dimensions, TALOS case-study evidence, identified transferability gaps, and proposed research priorities for hybrid offshore wind–wave integration.

2.2. Literature Search and Baseline Reconstruction

The literature considered in this review was collected through searches of major academic databases and indexing platforms, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, SpringerLink, and Google Scholar. Institutional repositories and authoritative technical reports relevant to marine renewable energy were additionally consulted when they provided technical information on numerical modelling, technology development, resource assessment, experimental validation, or offshore-system integration.

The main publication period considered was 2000–2026. Earlier studies were retained where they provided foundational theoretical formulations, benchmark technologies, established modelling approaches, or documented technology-development evidence that remained directly relevant to the review. Publications available up to 30 June 2026 were eligible for the review. The literature search was subsequently verified for completeness within this predefined eligibility period.

Because database-specific result counts were not retained for all stages of the literature collection, the baseline search pool was reconstructed from the preserved reference libraries. Accordingly, only auditable aggregate record counts are reported, and unverified record numbers are not retrospectively assigned to individual databases. The reconstructed baseline contained 186 bibliographic records. Duplicate identification based primarily on digital object identifier (DOI), supplemented by normalised title and bibliographic matching where necessary, identified 12 duplicate records, leaving 174 unique baseline records.

A targeted update search was subsequently used to identify recent or previously uncaptured studies relevant to evidence gaps identified during the critical synthesis. Nine additional unique records were identified in the documented update-search pass, producing a combined screening pool of 183 unique records. The update search focused particularly on recent WEC control co-design, wave-to-wire modelling, coupled floating wind–wave modelling, hybrid-system optimisation, TALOS, and ML- or AI-enabled methods.

Search terms were organised according to the principal evidence streams of the review. WEC-related searches included combinations of “wave energy converter”, “WEC optimisation”, “power take-off”, “PTO control”, “wave-to-wire modelling”, “hydrodynamic optimisation”, “shape optimisation”, “control co-design”, “survivability”, “reliability”, and “mooring optimisation”. Offshore-wind and hybrid-system searches included “offshore wind turbine”, “floating offshore wind”, “aero–hydro–servo–elastic modelling”, “hybrid wind–wave energy”, “co-located wind and wave”, “hybrid offshore renewable energy”, “wave and wind complementarity”, “shared offshore infrastructure”, “hybrid control”, and “levelised cost of energy”.

TALOS-specific searches included "TALOS wave energy converter", "TALOS WEC", "multi-axis wave energy converter", "internal mass wave energy converter", "HydroChrono TALOS", "TALOS optimisation", "TALOS mooring", and "TALOS machine learning". Data-driven searches additionally included "machine learning", "artificial intelligence", "deep learning", "reinforcement learning", "surrogate modelling", "fault diagnosis", "condition monitoring", "predictive maintenance", "power-output prediction", "digital twin", "energy storage", and "grid-connected control" in combination with WEC, offshore-wind, and hybrid-system terminology.

Boolean operators were used to combine technology, modelling, optimisation, and application terms. Backward and forward citation chaining of relevant reviews and primary studies was also used to identify foundational studies and technical evidence not captured through keyword searching alone.

2.3. Eligibility Criteria

Studies were considered for the critical synthesis when they contributed direct evidence to at least one of the research questions. Relevant evidence included WEC hydrodynamic or geometric optimisation, PTO and control design, control co-design, structural reliability and survivability, mooring optimisation, wave-to-wire modelling, floating offshore-wind dynamics, coupled wind–wave modelling, hybrid offshore-platform integration, resource complementarity, electrical integration, techno-economic performance, machine-learning or AI-enabled methods, and TALOS-specific modelling or optimisation.

Peer-reviewed journal articles and conference papers containing sufficient methodological, numerical, experimental, operational, or techno-economic information were prioritised for the critical synthesis. Review papers, foundational books, standards, authoritative reports, and institutional documents were retained separately as supporting sources where they established theoretical background, terminology, benchmark formulations, historical technology development, resource context, or citation pathways.

This distinction prevents the total bibliography from being interpreted as a homogeneous set of primary studies. Sources used for contextual or foundational purposes were fully cited in the manuscript where they supported theoretical background, terminology, benchmark formulations, methodological context, or broader technology interpretation, but were not treated as primary evidence in the critical synthesis.

Records were excluded from the review evidence set when they lacked sufficient direct relevance to the defined research scope or when the preserved bibliographic information was insufficient to establish a verifiable technical source. Sources that remained relevant to the review but did not constitute primary technical evidence were retained separately as supporting/background literature rather than being classified as excluded. Duplicate records were removed during deduplication before eligibility classification and were therefore not counted as exclusions.

Table 1 summarises the principal eligibility criteria.

2.4. Screening and Evidence-Set Classification

The reconstructed literature pool was screened sequentially. Duplicate records were first removed. Titles and available abstracts or bibliographic information were then screened against the topical and methodological eligibility criteria. Potential primary studies were subsequently subjected to detailed evidence extraction using full texts where accessible. Where a full manuscript could not be retrieved, evidence obtained from publisher abstracts, accepted-manuscript records, institutional repositories, or authoritative bibliographic records was explicitly distinguished from full-text-verified evidence.

Table 1. Inclusion and exclusion criteria applied during literature screening.

Criterion	Included or Retained	Not Retained as Primary Critical-Synthesis Evidence
Topical relevance	Studies addressing WEC optimisation, floating offshore wind, coupled wind–wave modelling, hybrid offshore systems, techno-economic assessment, AI/ML applications relevant to WECs, or TALOS-specific development	Studies outside offshore renewable energy or without a direct or transferable connection to the research questions
Publication type	Peer-reviewed journal articles and recognised conference proceedings; authoritative technical reports, books, and institutional sources were retained where required for supporting or benchmark evidence	Opinion pieces, unsupported commercial material, non-technical web content, or sources from which sufficient technical evidence could not be established
Time range	Primarily 2000–30 June 2026, with earlier foundational studies retained where they introduced established theoretical, numerical, experimental, or historical evidence	Older sources superseded by more complete evidence and without continuing theoretical, technical, or historical relevance
Evidence content	Studies reporting modelling methods, optimisation variables, environmental conditions, performance boundaries, validation evidence, uncertainty, structural or reliability evidence, electrical conversion, or techno-economic methods	Records lacking sufficient technical or bibliographic information to establish their relevance or evidential basis; relevant contextual sources without primary technical evidence were retained separately as supporting/background literature
Hybrid-system relevance	Studies addressing resource complementarity, shared infrastructure, hydrodynamic or aero–hydro–servo–elastic coupling, mooring, electrical integration, coordinated control, or hybrid energy/cost assessment	Unrelated multi-energy studies without transferable relevance to offshore wind–wave integration
Case-study relevance	Studies directly addressing TALOS and relevant internal-mass or multi-degree-of-freedom (DOF) WEC concepts, including geometry, PTO, mooring, numerical modelling, prediction, and optimisation	Device-specific evidence with no relevant contribution to either the TALOS case study or the wider critical comparison

Following screening, records were classified into three groups:

1. **critical-synthesis studies**, providing direct primary technical, numerical, experimental, operational, or techno-economic evidence relevant to the research questions;
2. **supporting/background sources**, used for theoretical foundations, reviews, standards, historical development, resource context, or citation chaining; and
3. **excluded records**, which did not satisfy the scope or evidence requirements of the review.

The reconstructed baseline consisted of 186 bibliographic records. Twelve duplicate records were identified and removed, leaving 174 unique baseline records. The targeted update search identified nine additional unique records, resulting in a combined screening pool of 183 records.

Detailed evidence extraction was prioritised in two stages. The first priority set comprised TALOS studies, direct hybrid wind–wave studies, wave-to-wire and control-co-design studies, and AI/ML applications central to the research questions. The second set comprised core WEC optimisation, validation, reliability, techno-economic, and comparative-device evidence. Across these two priority sets, 97 candidate studies underwent detailed evidence extraction. Following source verification and final evidence-set classification, 96 studies were retained in the critical-synthesis set. One candidate record was reclassified as supporting/background evidence because its original technical source could not be sufficiently verified for use as primary evidence.

Following final classification of the complete 183-record screening pool, 83 sources were retained as supporting/background literature. These sources contributed foundational theory, review context, historical technology development, standards, resource context, methodological guidance, or other contextual evidence but were not treated as primary evidence in the critical synthesis. Four records were excluded: three because they lacked sufficient direct relevance to the defined review scope and one because the preserved bibliographic information was insufficient to establish a verifiable technical source.

The resulting evidence-set accounting was therefore 96 critical-synthesis studies, 83 supporting/background sources, and four excluded records from the 183 unique records subjected to classification. The 12 duplicate records were removed before eligibility classification and are therefore not counted as exclusions. Accordingly, the 179 retained records comprised 96 primary studies included in the critical-synthesis set and 83 supporting/background sources used for theoretical, methodological, contextual, or benchmark purposes. All 179 retained sources are traceable through citations in the manuscript and the reference list, while the four records excluded during eligibility classification were not included in either retained evidence category. The complete literature-selection and classification process, including the exclusion categories, is summarised in Figure 2.

2.5. Data Extraction and Evidence Classification

For each study retained in the critical synthesis, evidence was extracted according to the system boundary and research objective of the study. Extracted fields included, where reported, technology or device type, device scale, optimisation variables and objectives, optimisation algorithm, environmental conditions, modelling approach and solver, modelling fidelity, PTO representation, control method, mooring treatment, performance metric, performance boundary, reported result, validation level, experimental or operational evidence, uncertainty or sensitivity analysis, deployment evidence, techno-economic treatment, and principal limitations.

For hybrid wind–wave studies, additional fields included the degree of physical integration, floating-platform or support-structure type, wind-turbine representation, WEC configuration, hydrodynamic and aero–hydro–servo–elastic coupling, mooring interaction, electrical architecture, resource-complementarity treatment, coordinated control, and techno-economic assessment.

For ML and AI studies, extraction additionally considered the application, data provenance, dataset size where reported, input and output variables, model architecture, training/validation/test procedure, performance metrics, generalisation or out-of-distribution assessment, physical constraints, integration with numerical or experimental models, and experimental or operational validation.

Published TALOS studies were evaluated using the same framework. Numerical results reported in previous TALOS publications are therefore treated as published evidence rather than as new simulation results generated within the present review.

During evidence extraction, bibliographic metadata were also cross-checked against publisher and repository records. Where discrepancies in year, DOI, or publication details were identified in the reconstructed reference library, the verified bibliographic information was retained for subsequent correction of the manuscript reference database.

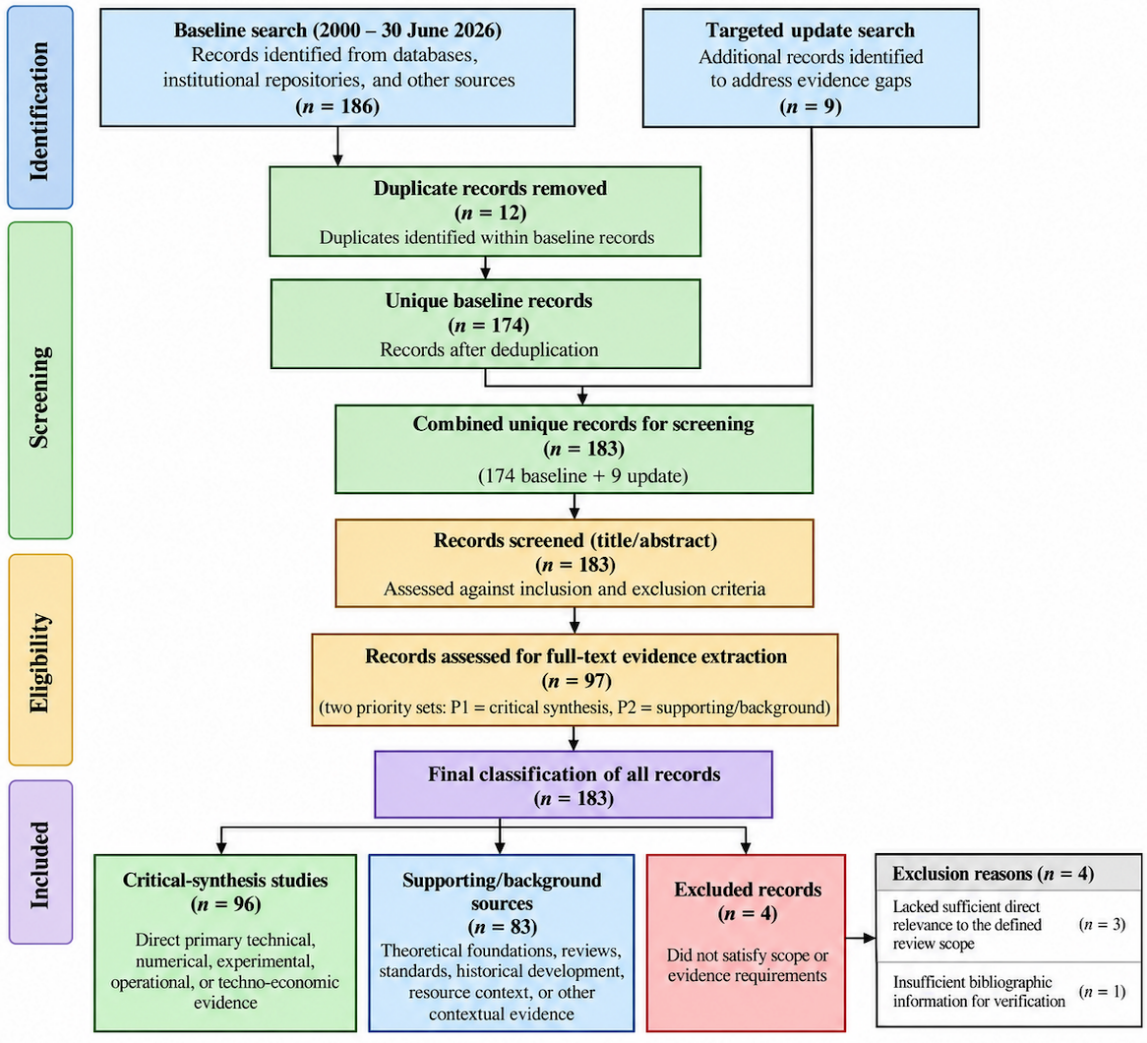


Figure 2. Literature-selection flow diagram showing the reconstruction of the baseline literature pool, targeted update search, deduplication, screening, evidence extraction, and final classification of records included in the review. Of the 183 unique records screened, 96 were retained for critical synthesis, 83 were retained as supporting/background sources, and four were excluded.

2.6. Critical-Appraisal Framework

To avoid comparison based solely on reported performance improvements, the selected studies were appraised using common evidence dimensions. The purpose of the framework is not to assign a universal quality or technology readiness score, but to identify differences in modelling fidelity, optimisation scope, system boundary, validation maturity, uncertainty, and practical relevance that affect the interpretation and transferability of published results.

The framework is particularly important when interpreting numerical performance gains. Improvements in hydrodynamic absorption or mechanical PTO output are not treated as equivalent to improvements in electrical annual energy production (AEP) or levelised cost of energy (LCOE). Similarly, an optimisation that maximises standalone WEC power is not assumed to maximise hybrid-system performance because WEC operation can alter

platform motion, structural loads, mooring response, wind-turbine dynamics, electrical requirements, and lifecycle cost.

Accordingly, technology evidence maturity is described principally through observed validation and deployment evidence rather than inferred numerical technology readiness level (TRL) scores. Cross-device comparisons likewise avoid ranking technologies using rated power, capture-width ratio, AEP, or cost where the underlying studies do not share sufficiently consistent environmental conditions, scales, conversion boundaries, and validation procedures. These appraisal dimensions also inform the proposed evidence-building pathway in Figure 1. In particular, limitations in modelling fidelity, validation, performance boundaries, uncertainty treatment, and system-integration evidence are used to identify the additional analyses and demonstrations required before device-level optimisation findings can support claims about hybrid-system performance or deployment readiness.

2.7. Synthesis Approach and Methodological Limitations

The reviewed studies exhibit substantial heterogeneity in device architecture, environmental conditions, scale, numerical formulation, optimisation objectives, performance definitions, and validation level. A pooled quantitative meta-analysis across the complete evidence base would therefore be inappropriate. Quantitative results are compared directly only where their physical definitions, system boundaries, environmental assumptions, and validation conditions are sufficiently consistent. Elsewhere, the synthesis focuses on modelling approach, optimisation scope, validation status, assumptions, uncertainty, limitations, and evidence maturity.

This principle is particularly important for cross-technology comparisons. For example, published capture-width-ratio databases provide useful contextual evidence, but values assembled from heterogeneous devices and environmental conditions are not treated as a common experimental benchmark. Similarly, device-specific AEP and cost estimates are not directly ranked where conversion boundaries, resource assumptions, availability, scale, and economic assumptions differ.

The synthesis therefore distinguishes among experimentally or operationally demonstrated findings, numerically supported findings, and conceptual or prospective integration pathways. These categories do not imply that numerical or conceptual studies lack scientific value; rather, they identify the evidential boundary within which the corresponding claim can be interpreted.

The review is subject to several methodological limitations. First, the baseline literature pool was reconstructed from preserved reference libraries, and database-specific identification counts were not available for all original searches. The review therefore reports the auditable combined baseline count rather than retrospectively assigning unverified numbers to individual databases. Second, full texts were not equally accessible for every candidate study; evidence derived from full manuscripts was therefore distinguished during extraction from evidence verified only through publisher abstracts, repositories, or authoritative bibliographic records. Third, terminology and reporting practices vary substantially between WEC, offshore-wind, control, AI/ML, and techno-economic research communities.

These limitations were mitigated through DOI- and title-based deduplication, targeted update searching, backward and forward citation chaining, use of common evidence-extraction fields, cross-checking of bibliographic metadata, and explicit reporting when quantitative comparison or transfer of results between technologies was not justified.

3. WEC Optimisation: Evidence and Relevance to Hybrid Integration

The optimisation of a WEC is inherently multidisciplinary because hydrodynamic geometry, PTO characteristics, control, structural loading, and survivability are strongly

coupled. The relevance of standalone WEC optimisation to hybrid offshore systems therefore depends not only on the magnitude of the reported energy improvement, but also on the optimisation scope, environmental representation, modelling fidelity, performance boundary, and validation level of the underlying study. This section critically examines these relationships rather than providing a general classification of WEC technologies [13–15].

3.1. Hydrodynamic and Geometric Optimisation

WEC geometry determines excitation forces, added mass, radiation damping, resonance behaviour, and ultimately the motion available for energy extraction. Parameters including draft, beam, displacement, hull curvature, tethering or restoring characteristics, and other characteristic dimensions are therefore frequently treated as optimisation variables [13,37,42,43]. Geometry optimisation is particularly important because changes intended to increase hydrodynamic absorption also modify PTO requirements, structural loading, mooring response, and control authority.

Frequency-domain potential-flow methods provide an efficient means of screening large geometric design spaces and identifying configurations with favourable response characteristics. Their formulation builds on established linear wave–body interaction theory, including descriptions of radiation, diffraction, added mass, and wave-excitation forces [44–46]. Their relatively low computational cost makes them attractive for parametric optimisation, but the resulting performance gains remain dependent on assumptions such as linear wave theory, small-amplitude body motion, and simplified viscous effects. Higher-fidelity time-domain or CFD approaches can represent nonlinear effects more explicitly, including response regimes in which viscous, large-amplitude, or breaking-wave effects become important, although their increased computational cost generally restricts the number of design variables and environmental conditions that can be explored [47–50]. Benchmark comparisons of numerical modelling approaches further demonstrate that systematic WEC performance evaluation depends on the modelling formulation and assumptions used, reinforcing the need to interpret optimisation results within their stated model-fidelity boundary [51].

Consequently, a large numerical improvement following geometry optimisation should be interpreted within the modelling boundary used to obtain it. Irregular-wave assessment commonly relies on spectral representations of the sea state, including established formulations such as the JONSWAP spectrum [52]. Improvements demonstrated under regular waves or a limited set of irregular sea states do not necessarily translate directly into annual electrical energy production or improved survivability at full scale. Site-specific wave climates, directional spreading, nonlinear loads, extreme conditions, and experimental validation become increasingly important as the design progresses toward deployment [15,16,53,54].

Recent optimisation studies increasingly treat WEC design as a coupled problem involving multiple physical and operational variables rather than isolated parameter tuning [15,16,54–56]. Geometry should therefore not be optimised independently of PTO and control parameters. A geometry that maximises unconstrained hydrodynamic response may not maximise useful electrical output once PTO force limits, motion constraints, structural loads, and conversion losses are introduced. The more relevant design objective is therefore system-level performance under realistic operational constraints rather than hydrodynamic response alone.

3.2. PTO and Wave-to-Wire Optimisation

The PTO determines how mechanical motion is converted into useful energy and strongly influences the dynamic response of the WEC. PTO design and optimisation there-

fore form a central part of WEC performance assessment [57]. Simplified numerical studies commonly represent the PTO through equivalent stiffness and damping parameters, allowing efficient investigation of impedance matching and resonance tuning [13,58]. Such representations are useful for identifying favourable mechanical operating regions but do not necessarily capture generator efficiency, hydraulic or mechanical losses, power-electronic constraints, saturation, force limits, or auxiliary consumption.

This distinction creates an important performance boundary within the WEC literature. Hydrodynamic absorbed power, mechanical energy delivered to the PTO, and electrical wave-to-wire output are related but are not interchangeable metrics [59,60]. Studies reporting improvements in mechanical PTO energy therefore provide evidence of device-level optimisation, but additional wave-to-wire modelling is required before equivalent improvements in electrical AEP can be inferred.

Variable-impedance and actively controlled PTO systems can broaden the effective operating range of a WEC across changing sea states, while the interaction between PTO dynamics and device motion can materially influence the resulting energy-conversion behaviour [61]. However, the additional energy gain must be considered alongside actuator requirements, control effort, conversion efficiency, reliability, and maintenance implications. For hybrid offshore systems, this issue becomes more important because the WEC electrical output must ultimately interact with shared power electronics, collection networks, storage, or grid-control systems. PTO optimisation is therefore transferable to hybrid-system design only when the associated electrical and operational constraints are made explicit [59,60].

Computational efficiency is also important when PTO and device parameters are embedded within broader design optimisation, since higher-fidelity time-domain evaluation can become prohibitive across large design spaces. Reduced-order or spectral-domain approaches can therefore provide useful intermediate tools for techno-economic optimisation, provided that their performance boundaries and modelling assumptions remain explicit [62].

3.3. Control and Control Co-Design

WEC control seeks to improve energy absorption by modifying the relationship between wave excitation, device motion, and PTO force. Passive fixed-parameter strategies are comparatively simple and robust but cannot remain optimal across a broad range of sea states. Reactive control, latching, declutching, and model predictive control (MPC) can improve phase alignment and energy capture, but generally require greater model accuracy, sensing, prediction, computation, and actuator authority [63–65].

The literature therefore reveals a recurring trade-off between theoretical energy maximisation and practical deployability. Control strategies that perform strongly in idealised numerical simulations may be sensitive to model mismatch, wave-prediction error, PTO saturation, communication delay, or unmodelled nonlinear dynamics. These limitations are especially relevant when control performance has not been demonstrated experimentally or under site-specific irregular sea states [33,65–67].

Control co-design attempts to address this limitation by optimising device geometry, PTO parameters, and control laws simultaneously rather than sequentially [15,16]. This represents an important progression in WEC optimisation because the optimal physical design depends on the control strategy and vice versa. Nevertheless, the maturity of such approaches varies considerably: numerical optimisation can explore large coupled design spaces, whereas experimental validation of fully integrated geometry–PTO–control optimisation remains more limited.

For future hybrid wind–wave systems, WEC control introduces a further system boundary. Maximising instantaneous WEC power may not maximise overall platform performance

if the resulting motion increases wind-turbine loads, mooring loads, electrical peaks, or fatigue damage [25,68]. Hybrid integration therefore requires progression from device-level energy-maximising control toward coordinated system-level objectives.

3.4. Structural Constraints, Mooring, and Survivability

Energy-maximising WEC designs must remain compatible with structural integrity and survivability. Increasing resonant motion or PTO force can enhance absorbed power while simultaneously increasing fatigue loading, peak structural forces, mooring demand, and PTO loading. Structural, reliability, and survivability considerations should therefore form part of the design and optimisation process rather than being assessed only after hydrodynamic performance has been maximised [14,69–71].

The reviewed literature addresses survivability through measures including design-stage screening, mooring design, PTO and motion constraints, structural-load assessment, and storm or survival operating modes [70,72–74]. However, the level of evidence varies from conceptual design and numerical load analysis to laboratory testing and, for a smaller number of technologies, offshore prototype experience [75,76]. Claims regarding survivability or reduced maintenance should therefore be interpreted according to the corresponding validation level rather than inferred from device architecture alone.

Mooring design is particularly relevant to hybrid offshore integration. For a standalone WEC, the mooring system affects station keeping and device response; on a shared floating wind–wave platform, mooring forces become part of the coupled platform dynamics and may affect both WEC energy capture and wind-turbine loading. Standalone mooring optimisation is therefore useful but cannot substitute for coupled platform-level assessment [24,74,77,78].

Experimental evidence is particularly important for determining whether numerically favourable hydrodynamic, structural, or mooring behaviour persists when nonlinear effects and physical constraints are introduced. The retained literature includes examples ranging from component- and device-scale hydrodynamic experiments to measurements of mooring response and prototype operation [76,77,79]. Such evidence does not eliminate scale effects or establish commercial readiness, but it provides a stronger validation basis than numerical optimisation alone. Progression toward deployment additionally requires structured consideration of technology performance, reliability, survivability, and validation evidence across successive development stages [80].

3.5. Critical Synthesis: Transferability to Hybrid Systems

The reviewed WEC literature demonstrates that geometry, PTO, control, mooring, and structural constraints cannot be considered independently. However, the strength of evidence differs substantially among studies because reported improvements are obtained using different model fidelities, environmental conditions, performance boundaries, and validation approaches.

Three implications are particularly important for hybrid offshore integration. First, hydrodynamic or mechanical optimisation establishes device-level potential but does not by itself demonstrate electrical or economic benefit. Second, optimisation results obtained for an isolated WEC cannot automatically be transferred to a shared floating platform because platform motion, mooring response, structural loads, and control objectives may change. Third, increasing optimisation complexity must be accompanied by appropriate validation: higher numerical performance does not necessarily indicate greater technology evidence maturity [14,24,25,69].

Accordingly, the WEC evidence considered in this review is interpreted using the critical-appraisal dimensions defined in Table 2. These distinctions provide the basis for

evaluating the TALOS literature later in the paper and for determining which aspects of standalone TALOS optimisation can reasonably inform future hybrid-system development.

Table 2. Evidence dimensions used for critical appraisal of the reviewed literature.

Evidence Dimension	Assessment Basis
Modelling fidelity	Analytical, frequency-domain, time-domain potential-flow, multibody, computational fluid dynamics (CFD), coupled aero–hydro–servo–elastic, wave-to-wire, surrogate, or other numerical approach
Optimisation scope	Single-variable, multi-variable, multi-objective, PTO/control optimisation, control co-design, geometry/layout optimisation, mooring optimisation, or system-level optimisation
Validation level	Cross-model or numerical benchmarking, laboratory experiment, wave-tank testing, hardware testing, prototype demonstration, sea trial, grid-connected demonstration, or operational validation
Performance boundary	Hydrodynamic absorption, mechanical PTO power, electrical wave-to-wire output, annual energy production, structural response, reliability, availability, lifecycle performance, or techno-economic performance
Environmental representation	Regular waves, irregular spectra, site-specific resource conditions, directional seas, combined wind–wave conditions, turbulent wind, or extreme environmental loading
Uncertainty treatment	No explicit assessment, parameter sensitivity, statistical uncertainty, probabilistic analysis, surrogate uncertainty, or uncertainty propagation
System-integration level	Standalone device, resource co-location, shared infrastructure, hydrodynamically coupled system, mechanically integrated platform, aero–hydro–servo–elastically coupled system, electrically integrated system, or techno-economically optimised hybrid system
Technology evidence maturity	Conceptual or numerical development, laboratory-scale validation, prototype testing, grid-connected demonstration, sea trial, or operational deployment; formal technology readiness level (TRL) values were not inferred where they were not explicitly reported by the source
Practical deployability	Consideration of structural loads, survivability, mooring, reliability, maintainability, electrical conversion, control constraints, availability, and lifecycle cost
Computational implications	Where reported, computational burden, surrogate-model acceleration, reduced-order modelling, or fidelity–cost trade-offs relevant to design optimisation and real-time implementation

4. Offshore Wind Requirements for Hybrid Wind–Wave Integration

The relevance of offshore wind technology to this review lies primarily in the additional dynamic, structural, mooring, and control requirements introduced when WECs are co-located with or mechanically coupled to offshore wind systems. Accordingly, this section focuses on the aspects of floating offshore wind that directly affect wind–wave integration rather than providing a general review of wind-turbine aerodynamic design.

4.1. Floating-Platform Dynamics

Unlike fixed-bottom turbines, floating offshore wind turbines respond dynamically to combined aerodynamic, hydrodynamic, and mooring loads. Integrated dynamic analyses have shown that these physical domains must be resolved together when assessing floating-system response [81,82]. Platform motion occurs in six DOF and can modify rotor inflow, tower and blade loading, drivetrain response, and control behaviour [19,20,83]. Pitch, surge, and heave are particularly relevant to hybrid wind–wave concepts because the addition of WECs can alter the hydrodynamic response, damping, inertia, and restoring characteristics of the shared platform.

The accuracy of predicted platform response also depends on the hydrodynamic formulation. Second-order wave effects can influence the response of semi-submersible floating wind turbines, while later model development has highlighted the importance of improving predictions of nonlinear and low-frequency platform behaviour [84,85]. These effects become particularly relevant when hybrid devices introduce additional hydrodynamic forcing or alter the frequency content of the shared platform response.

The development of floating wind concepts has also shown that platform geometry, hydrodynamic response, station keeping, and turbine dynamics must be assessed as an integrated system rather than as independent design problems. A range of floating support concepts has consequently been investigated, including tension-leg and taut-leg configurations, semi-submersible systems, and alternative V-shaped platform concepts [86–88]. Early WindFloat studies, for example, combined hydrodynamic and structural considerations in the development and assessment of the semi-submersible floating-wind platform [89–91].

Floating-wind development has also progressed beyond conceptual and numerical studies to offshore demonstration and operational deployment. Projects based on the Hywind and WindFloat technology families provide important practical evidence of floating-platform development under offshore operating conditions [92,93]. Such deployment evidence does not remove the need for configuration-specific dynamic analysis, but it provides a stronger operational reference than conceptual or numerical platform studies alone.

This interaction creates both opportunities and constraints. Appropriately designed WECs may contribute hydrodynamic damping or extract energy from platform-associated wave motion, whereas poorly tuned devices may amplify platform response or introduce additional structural and mooring loads. The effect is configuration- and frequency-dependent and cannot be inferred solely from standalone WEC performance [25,94].

The implication for hybrid-system design is that platform motion becomes a shared optimisation variable. WEC geometry and PTO settings that are favourable for an isolated device may not remain optimal when the WEC is dynamically coupled to a floating wind platform [25,95,96].

Early floating-wind studies also demonstrated that platform response, design trade-offs, and economic considerations are coupled rather than independent, motivating optimisation frameworks that consider dynamic behaviour alongside platform-design objectives [97].

4.2. Wind-Turbine Control and Platform Interaction

Conventional wind-turbine control regulates generator torque below rated wind speed and blade pitch above rated conditions to balance energy capture and structural protection [19,98]. For floating systems, controller behaviour is also relevant to structural durability because control strategy can materially influence fatigue loading [99]. Floating platforms introduce additional feedback because platform pitch and surge modify the apparent wind experienced by the rotor. Blade-pitch actions can consequently interact with platform motion and, under some operating conditions, contribute to destabilising aerodynamic feedback.

For a hybrid wind–wave platform, control design therefore extends beyond independent wind-turbine and WEC controllers. WEC PTO forces can alter platform motion, while wind-turbine pitch and torque control modify aerodynamic forces acting on the same structure. Independent energy-maximising controllers may consequently produce conflicting system-level responses [25,68].

This motivates coordinated or co-designed control in which wind-turbine regulation, WEC PTO control, platform-motion constraints, structural loads, and potentially electrical-power smoothing are considered within a common objective [68,96]. Such approaches remain substantially less mature than conventional standalone wind-turbine control and require coupled models capable of representing the relevant feedback paths.

4.3. Mooring, Structural Loads, and Reliability

Floating offshore wind platforms rely on mooring and anchoring systems to provide station keeping while allowing compliant motion under environmental loading [19,100,101]. Integration of WECs changes the platform mass distribution, hydrodynamic coefficients, excitation forces, and potentially the frequency content of platform motion. These changes can affect mooring-line tension, anchor loads, fatigue accumulation, and allowable excursions [24,94,95].

Structural assessment must similarly consider simultaneous wind, wave, WEC, and control-induced loads. Floating-wind structural design is governed by requirements that account for the combined environmental and structural conditions specific to floating support systems [102,103]. A hybrid concept that increases total energy production but substantially increases fatigue damage, extreme loading, or maintenance demand may not provide a net system-level benefit [104]. Reliability and accessibility are therefore central to hybrid-system assessment because offshore maintenance costs can offset benefits obtained from shared infrastructure or increased energy capture [14,22].

Economic performance provides an additional system constraint. Floating offshore wind cost is sensitive to platform concept, structural mass, installation strategy, mooring and anchoring requirements, operation and maintenance, lifetime energy production, and site conditions. Lifecycle and spatially resolved LCOE studies therefore show that floating-platform design decisions should be interpreted together with their economic consequences rather than solely through dynamic performance [105,106]. For hybrid wind–wave systems, additional WEC hardware and structural complexity must therefore deliver sufficient energy, infrastructure, or operational benefit to offset the corresponding incremental cost.

These considerations also limit the extent to which results from standalone WEC optimisation can be transferred directly to a hybrid configuration. Mooring, structural, and reliability effects must be reassessed at platform level once the WEC becomes dynamically or structurally coupled to the wind system [24,94].

4.4. Implications for WEC Integration

From the perspective of hybridisation, the principal contribution of offshore-wind modelling is therefore not a separate optimisation of blade geometry or rotor aerodynamics.

Rather, it establishes the dynamic and operational constraints within which an integrated WEC must function. These include acceptable platform motion, wind-turbine control stability, tower and blade loads, mooring tension, fatigue, electrical operation, and reliability [19,24,104].

A credible hybrid wind–wave assessment must consequently demonstrate that WEC integration does not compromise wind-turbine performance or structural integrity while quantifying any additional energy or system-level benefit [25,94,96]. This requirement motivates the coupled modelling approaches discussed in Section 5.

5. Coupled Modelling for Hybrid Wind–Wave Systems

Coupled modelling provides the principal numerical bridge between standalone WEC optimisation and credible assessment of integrated wind–wave systems. The central modelling challenge is not simply the simultaneous presence of wind and waves, but the exchange of forces, motions, and control actions among the wind turbine, floating platform, WEC, mooring system, and electrical conversion chain. The level at which these interactions are represented determines which system-level conclusions can reasonably be drawn from a study.

5.1. Levels of Coupling and Modelling Fidelity

Hybrid-system studies can be distinguished by the degree of physical coupling represented. At the simplest level, wind and wave resources may be assessed independently and their expected energy outputs combined statistically. Such co-location studies are useful for resource-complementarity and preliminary energy-yield assessment but do not represent mechanical interaction between technologies [107].

A second level considers hydrodynamic interaction among floating bodies or between WECs and a shared platform. Frequency-domain potential-flow methods are computationally efficient for evaluating radiation, diffraction, added mass, and wave-excitation effects, but generally rely on linearised assumptions and do not capture the complete nonlinear operating behaviour of the integrated system [47,49]. For floating platforms, the selected hydrodynamic formulation can materially influence the predicted response, particularly where second-order wave effects or nonlinear low-frequency behaviour become important [84,85].

Time-domain coupled models can additionally represent transient platform motion, PTO forces, control actions, and nonlinear mooring behaviour. Integrated nonlinear wind–wave formulations have provided an important basis for representing the simultaneous environmental loading acting on offshore wind turbines [108]. Coupled numerical formulations have consequently been developed to resolve the interacting wind- and wave-induced response of floating offshore systems [109]. For floating wind–wave systems, higher-fidelity frameworks may combine aerodynamic, hydrodynamic, servo-elastic, structural, and mooring models to resolve bidirectional interactions under simultaneous wind and wave excitation [24,26,110,111]. These models provide a stronger basis for system-level load and control assessment but require substantially greater model definition, computational effort, and validation.

The distinction between these levels is critical when interpreting the literature. A resource co-location study cannot substantiate claims regarding structural-load reduction, while a hydrodynamic model without an electrical conversion chain cannot establish hybrid electrical AEP or LCOE. Model fidelity must therefore be matched to the performance claim being made [59,60].

5.2. Aero–Hydro–Servo–Elastic Interaction

Floating wind turbines experience aerodynamic loading from the rotor simultaneously with wave excitation and hydrodynamic restoring forces acting on the platform. Platform surge, heave, and pitch modify the apparent wind experienced by the rotor, while variations in aerodynamic thrust alter platform motion [26,82,83,112]. When WECs are attached to or dynamically coupled with the platform, their hydrodynamic and PTO forces introduce additional feedback paths.

The effect of WEC integration is not necessarily beneficial. Depending on device placement, tuning, and environmental frequency content, WEC forces may provide additional damping to selected platform modes or may increase motion and structural loading. Consequently, improvements observed for an isolated WEC cannot establish a hybrid system benefit without evaluating the response of the complete coupled system [25,94,95].

Early combined floating wind–wave concepts similarly demonstrated that the WEC and wind-turbine subsystems cannot be assessed solely through independent power-performance calculations. Studies of the Spar–Torus Combination, for example, evaluated the dynamic response and power performance of a floating wind turbine combined with a coaxial wave-energy absorber, providing early numerical evidence of the coupled behaviour that must be considered in integrated concepts [113,114].

Dynamic investigations of other combined wind–wave configurations further reinforce that integration changes the response of the overall floating system and should therefore be assessed through coupled rather than independent subsystem models [115].

Servo-control interactions add further complexity. Wind-turbine pitch and torque control, WEC PTO control, and potentially platform or storage controllers may respond simultaneously to the same environmental disturbance. A coupled model intended to evaluate coordinated control must therefore represent not only physical forces but also the relevant control loops and actuator constraints [25,68].

5.3. Hydrodynamic, Mooring, and Layout Interactions

The spatial arrangement of WECs relative to a floating wind platform affects radiation and diffraction, local wave fields, platform response, and WEC energy absorption [24,28,116]. For multiple devices, constructive or destructive hydrodynamic interactions can alter both individual-device and array-level performance. The same configuration may also modify platform loads and mooring response. Different integration architectures have also been examined numerically, including WECs distributed around floating platforms and devices mounted around offshore-wind support structures, illustrating that hydrodynamic interaction and layout effects are strongly configuration dependent [117,118].

Mooring dynamics are particularly important because station-keeping forces act directly on the floating system and can introduce nonlinear stiffness, damping, and transient loads. Simplified quasi-static representations may be sufficient for preliminary design, whereas dynamic mooring models are more appropriate when line inertia, drag, snap loads, or strong platform–mooring interaction influence the response [74,77,78,119].

Layout optimisation must therefore consider more than WEC energy capture. Device position, PTO tuning, platform response, mooring loads, wind-turbine loading, installation constraints, and maintenance access may impose competing objectives [96]. This is one reason why optimisation of a standalone WEC geometry or PTO cannot be interpreted as optimisation of the hybrid platform.

5.4. Numerical Frameworks and Validation

Hybrid modelling commonly combines specialised numerical tools for different physical domains. The development of coupled floating-offshore models has progres-

sively integrated aerodynamic loading, platform hydrodynamics, structural response, and station-keeping behaviour within common numerical frameworks [120]. Aerodynamic and aeroelastic models can be integrated with hydrodynamic solvers, WEC models, and mooring-dynamics tools through time-domain co-simulation or common simulation environments [26,121–123]. Examples of relevant modelling capabilities include aerodynamic loading, radiation and diffraction forces, nonlinear mooring response, PTO dynamics, structural elasticity, and supervisory control.

Increasing the number of coupled physical domains does not automatically increase confidence in the results. Model credibility depends on verification of the numerical implementation and validation against analytical solutions, benchmark models, laboratory experiments, or field measurements [94,117,124,125]. Validation becomes particularly challenging for hybrid systems because experimental data for fully coupled wind–wave platforms remain comparatively limited.

Subsystem-level validation and hydrodynamic characterisation can also provide an intermediate step between standalone WEC analysis and fully coupled hybrid demonstration, as illustrated by investigations of the WEC subsystem within combined wind–wave concepts [126].

Computational cost is also an important practical consideration. Frequency-domain models allow broad parametric exploration but provide reduced representation of nonlinear and transient effects; fully coupled time-domain or CFD-based approaches offer greater physical fidelity at substantially higher computational expense. A multi-fidelity strategy may therefore be preferable, using lower-cost models for design-space exploration followed by higher-fidelity analysis of selected configurations [32,60,127].

5.5. Performance Boundaries and System-Level Metrics

The performance metric used in a coupled study must be consistent with the model boundary. Hydrodynamic models can quantify absorbed wave power and platform response, whereas mechanical PTO models estimate energy transferred through the WEC conversion mechanism. Electrical AEP requires representation of conversion efficiencies, generator or hydraulic behaviour, power electronics, availability, and site-specific environmental probabilities [59,60]. Hybrid LCOE requires an additional economic boundary including capital expenditure (CAPEX), operational expenditure (OPEX), lifetime, reliability, installation, maintenance, and shared-infrastructure assumptions.

Structural performance should likewise be assessed through quantities such as platform motion, tower-base bending moment, blade and drivetrain loads, mooring tension, fatigue damage, and extreme responses rather than inferred from energy performance alone [25,26,73,104,128].

Accordingly, this review does not treat the terms absorbed power, mechanical PTO energy, electrical AEP, and hybrid-system AEP as interchangeable. This distinction is particularly important when the published TALOS results are considered later in the paper.

5.6. Critical Synthesis and Remaining Modelling Gap

The coupled-modelling literature demonstrates a clear hierarchy of evidence. Resource-level studies can establish whether wind and wave availability is complementary at a site; hydrodynamic models can evaluate WEC–platform interactions; coupled aero–hydro–servo models can investigate platform and turbine response; and wave-to-wire and techno-economic models are required to translate physical performance into electrical and economic outcomes [24,26,59,107,114].

No single modelling level is sufficient for all hybrid-system claims. The appropriate fidelity depends on the research question, and higher-fidelity models introduce additional

computational and validation requirements. For the TALOS case considered in this review, published standalone hydrodynamic, PTO, mooring, and data-driven studies provide useful device-level evidence, but they do not constitute a coupled TALOS–wind model [30,37–39]. Demonstrating hybrid performance would require explicit representation of the interactions described in this section.

6. Hybrid Offshore Platform Integration

Hybrid offshore systems can combine wind and wave technologies through co-location, shared infrastructure, or physical integration on a common floating structure. The development of combined wind–wave concepts has produced a range of architectures with different degrees of physical, energy-conversion, and functional coupling [23,24,36,129]. The potential value of hybridisation depends on whether benefits in resource utilisation, infrastructure sharing, or power smoothing outweigh the additional structural, hydrodynamic, electrical, control, reliability, and maintenance complexity introduced by integration [23–25]. Hybridisation should therefore be evaluated as a system-level design problem rather than assumed to improve performance by combining individually optimised devices.

6.1. Resource Complementarity

Wind and wave resources are physically related but can exhibit temporal differences because the local wave field depends on wave generation, propagation, swell, and the preceding wind history. Wave energy may therefore remain elevated after local wind speed has decreased, while the degree of correlation varies substantially with location and timescale [130–133].

This behaviour can reduce variability in aggregated wind–wave generation at suitable sites, but complementarity is not an intrinsic property of every offshore location. Claims regarding smoother power output, increased effective capacity factor, or reduced storage demand require site-specific joint wind–wave data and appropriate temporal analysis. Resource complementarity alone also does not demonstrate the benefit of physically integrating WECs with a wind platform; similar smoothing may in some cases be achieved through co-location without mechanical coupling [107].

Accordingly, resource assessment represents the first level of hybrid-system evidence. It can identify locations at which combined resources are potentially favourable, but additional physical and economic modelling is required to determine whether a particular integrated platform is advantageous.

Resource uncertainty should also be propagated into system-level assessment, because estimates of annual energy production and economic performance depend on the representativeness of the environmental data used to characterise the deployment site [53].

6.2. Shared Infrastructure and Economic Performance

Infrastructure sharing is one of the principal economic motivations for offshore hybridisation. Co-located wind and wave farms have been investigated as a means of improving the competitiveness of wave energy through combined offshore development and shared use of selected infrastructure [134]. Potentially shared components include export cables, offshore substations, grid connections, installation vessels, maintenance logistics, and, depending on the physical configuration, support structures or mooring systems [135,136]. Such sharing can reduce duplicated infrastructure, but the magnitude of the saving depends strongly on platform architecture, WEC number and rating, installation strategy, reliability, accessibility, and additional structural requirements introduced by integration.

Economic assessment should therefore consider both potential savings and additional costs. Integrating WECs may increase energy production and infrastructure utilisation,

but it can also increase platform complexity, structural mass, mooring demand, power-electronic requirements, inspection needs, and failure modes. Operational expenditure and maintenance assumptions are particularly important for offshore wave-energy projects because they can materially affect financial performance [137]. Consequently, a lower hybrid LCOE cannot be inferred from infrastructure sharing alone [138,139].

Published techno-economic studies indicate that wind–wave configurations can offer economic benefits under favourable site, technology, and cost assumptions [138,140–142]. However, comparison across studies is complicated by differences in technology evidence maturity, CAPEX and OPEX assumptions, lifetime, capacity factors, discount rates, availability, and whether WEC costs are derived from commercial experience or conceptual estimates. Techno-economic conclusions should therefore be interpreted within the assumptions of each study rather than treated as universally transferable.

6.3. Physical Integration and System-Level Optimisation

Physical integration introduces stronger interactions than simple co-location. Multi-use offshore-platform concepts have provided an important development pathway for investigating how different marine renewable-energy technologies can be incorporated within shared offshore systems [143]. WECs attached to a floating wind platform can alter hydrodynamic damping, added mass, excitation forces, platform natural frequencies, and mooring loads. Their PTO forces may influence platform motion and consequently wind-turbine aerodynamic and structural response [24,25,94].

A range of integrated configurations has been investigated, including combined spar-type wind–wave systems, WECs arranged around semi-submersible platforms, combined floating vertical-axis wind-turbine and WEC concepts, oscillating water column (OWC)-based hybrid floating-wind configurations, and WEC subsystems incorporated into hybrid offshore systems [28,114,124,126,144,145].

Integration is not limited to floating multi-device concepts. Hybrid architectures have also been investigated in which a WEC is associated with an offshore-wind support structure, illustrating that the structural and hydrodynamic consequences of integration depend strongly on the selected platform and WEC architecture [146].

These interactions and configuration-dependent effects make hybrid-system design a multi-objective optimisation problem involving energy production, platform motion, fatigue and extreme loads, mooring performance, reliability, and cost [96].

Electrical integration introduces an additional system boundary. Wind and wave generators can have different power characteristics, conversion chains, voltage levels, and temporal variability. Shared collection and export systems therefore require appropriate power electronics, protection, supervisory control, and potentially storage. A complete hybrid AEP assessment should account for these conversion and availability effects rather than simply summing mechanical or hydrodynamic energy estimates [59,60].

The literature consequently supports a distinction between *co-location*, *shared-infrastructure integration*, and *fully coupled physical integration*. These levels require progressively greater modelling and validation effort and should not be treated as equivalent evidence of hybrid-system maturity [23,24,125].

Table 3 illustrates that the term “hybrid integration” encompasses substantially different levels of technical evidence. Resource complementarity or infrastructure sharing can motivate a hybrid concept, but neither is sufficient to demonstrate coupled platform performance. Similarly, hydrodynamic interaction studies can quantify changes in motion or absorbed wave power without establishing electrical AEP or economic benefit. Progressively stronger claims therefore require progressively broader modelling and validation

boundaries, culminating in fully coupled physical, electrical, operational, and techno-economic assessment.

Table 3. Levels of wind–wave offshore integration and the evidence required to support system-level claims.

Integration Level	Primary Objective	Evidence That Can Be Established	Additional Evidence Required for Stronger System-Level Claims
Resource co-location	Exploit temporal complementarity between offshore wind and wave resources	Joint resource statistics, correlation, variability reduction, preliminary combined energy potential	Technology-specific conversion models, electrical losses, availability, infrastructure requirements, and techno-economic assessment
Shared infrastructure	Reduce duplicated offshore infrastructure and improve asset utilisation	Potential sharing of export cables, substations, grid connection, installation logistics, and selected support infrastructure	Detailed CAPEX/OPEX modelling, reliability, availability, installation constraints, maintenance strategy, and lifecycle cost analysis
Hydrodynamically coupled integration	Assess interaction between WECs and the floating support structure	Changes in platform response, radiation and diffraction effects, WEC absorbed power, and selected hydrodynamic loads	Higher-fidelity nonlinear modelling, dynamic mooring response, structural-load assessment, and experimental validation
Fully coupled physical integration	Represent interactions among wind turbine, platform, WECs, controls, and mooring system	Coupled platform motion, wind-turbine loads, WEC response, PTO forces, mooring response, and controller interaction	Validated aero–hydro–servo–elastic simulation, fatigue and extreme-load assessment, coordinated control, and representative environmental conditions
Electrical and operational integration	Coordinate generation, conversion, storage, and export of wind and wave power	Electrical power flow, conversion-chain behaviour, power smoothing, storage interaction, and shared export-system performance	Wave-to-wire validation, power-electronic constraints, protection, supervisory control, availability, and operational testing
Techno-economic hybrid optimisation	Determine whether integration produces a net system-level benefit	Hybrid AEP, CAPEX, OPEX, LCOE, reliability, availability, and sensitivity to shared infrastructure	Site-specific cost data, validated component reliability, installation and maintenance assumptions, uncertainty analysis, and demonstration-scale evidence

Experimental investigations of integrated or multi-use concepts provide an important intermediate evidence level because they can reveal hydrodynamic and structural interactions that are difficult to establish from numerical optimisation alone [117,124,125].

6.4. Evidence Required for TALOS Hybrid Integration

The published TALOS literature considered in this review primarily addresses the WEC at device level, including hydrodynamic behaviour, geometry and PTO optimisation, power prediction, and mooring-related optimisation [30,37–39]. These studies provide evidence relevant to the development of TALOS as a standalone WEC, but they do not demonstrate the performance of a coupled TALOS–wind platform.

Several additional evidence layers would be required before system-level hybrid claims could be substantiated. These include site-specific joint wind–wave resource assessment; definition of a physical TALOS–wind platform configuration and device layout; coupled aero–hydro–servo-elastic simulation; dynamic mooring and structural-load assessment; wave-to-wire and shared electrical-system modelling; coordinated wind-turbine and WEC control; reliability and availability analysis; and hybrid AEP and LCOE assessment. Experimental validation would subsequently be required to establish whether the predicted interactions and performance gains persist beyond the numerical environment [25,59,94,125,126].

TALOS characteristics such as its internal moving mass, multi-degree-of-freedom response, and enclosed architecture [37,38] may motivate investigation of particular integration concepts, but these characteristics should be treated as design features rather than demonstrated hybrid-system advantages. Their value can only be established through the coupled analyses described above.

6.5. Critical Synthesis of Hybrid Wind–Wave Integration

The hybrid offshore literature indicates potential benefits from resource complementarity and infrastructure sharing, but the strength of evidence varies considerably between resource studies, conceptual platform designs, coupled numerical simulations, techno-economic assessments, and experimentally validated systems. The principal question is therefore not whether wind and wave technologies can be combined, but under which environmental, structural, operational, and economic conditions integration produces a measurable system-level benefit [24,107,125,126].

For the TALOS case study, the present evidence supports discussion of a future integration pathway rather than a demonstrated hybrid configuration [37–39]. The distinction is important: published standalone TALOS optimisation provides inputs to future hybrid design, but coupled platform performance, hybrid electrical AEP, structural benefit, coordinated control, and LCOE remain to be established. These unresolved evidence requirements are developed further in Section 9.

7. TALOS as a Case Study: Published Device-Level Optimisation Evidence

The TALOS WEC, developed at Lancaster University, is a multi-axis converter in which an internal oscillating mass moves relative to an external floating hull. The concept is designed to respond in six DOF—surge, sway, heave, roll, pitch, and yaw—with relative motion between the internal mass and hull transferred through the PTO system [38,58]. Its enclosed internal mechanism and multi-DOF architecture are notable design characteristics; however, their implications for survivability, reliability, maintainability, or hybrid-platform suitability require validation and should not be inferred from the architecture alone.

This section critically synthesises previously published TALOS modelling and optimisation studies. No new TALOS numerical simulations or experimental results are generated in the present review. Particular attention is given to the modelling boundary, optimisation variables, reported performance improvements, and limitations of the available evidence. The case study is used to illustrate the distinction between successful standalone device-level optimisation and the additional evidence required for hybrid offshore integration.

7.1. Published TALOS Modelling Framework

Published TALOS studies model the device as a two-body floating system in which an internal oscillating mass moves relative to the external hull, with this relative motion driving the PTO system [38,58,121]. Hydrodynamic interactions have been represented using linear potential-flow theory, with radiation forces formulated using the Cummins approach [121,147]. Frequency-domain hydrodynamic coefficients, including added mass, radiation damping, and wave-excitation forces, are obtained using boundary-element approaches and subsequently incorporated into time-domain simulations.

This modelling strategy is computationally suitable for parametric device-level optimisation because it enables multiple hull and PTO configurations to be evaluated without the computational expense associated with higher-fidelity CFD. Its principal limitation is the reliance on linear hydrodynamics. Viscous effects, strongly nonlinear wave–body interactions, extreme-event behaviour, and other effects that may become important at full scale are not represented explicitly. Consequently, the published optimisation results should be interpreted within this numerical modelling boundary rather than as experimentally validated full-scale performance predictions [47–49].

The PTO representation used in the published TALOS optimisation can be expressed as a linear spring–damper relationship,

$$F_{\mathrm{PTO}}(t) = -K_{\mathrm{PTO}} x_{\mathrm{rel}}(t) - B_{\mathrm{PTO}} \dot{x}_{\mathrm{rel}}(t), \tag{1}$$

where $F_{\mathrm{PTO}}(t)$ is the PTO force at time t, $x_{\mathrm{rel}}(t)$ is the relative displacement between the internal mass and hull, K_{PTO} is the PTO spring stiffness, and B_{PTO} is the PTO damping coefficient. This scalar expression represents the spring–damper relationship for a given PTO direction; the TALOS architecture contains multiple PTO elements whose responses are represented within the device model.

The published optimisation studies investigated PTO stiffness values of approximately 250–500 kN m^{-1}, with damping values including approximately 150–200 kN s m^{-1} [38]. These values represent numerical design cases rather than experimentally established operating limits.

The reported annual energy estimates were derived using irregular-wave simulations and sea-state occurrence probabilities representative of the adopted European Marine Energy Centre (EMEC) resource conditions [38]. In general form, the mechanical annual energy production can be expressed as

$$\mathrm{AEP}_{\mathrm{mech}} = T_{\mathrm{yr}} \sum_i p_i \overline{P}_{\mathrm{PTO},i}, \tag{2}$$

where $\overline{P}_{\mathrm{PTO},i}$ is the mean mechanical PTO power for sea state i, p_i is its annual probability of occurrence, and $T_{\mathrm{yr}} = 8760$ h.

The subscript "mech" is used here deliberately to distinguish the published PTO-level energy estimates from electrical wave-to-wire AEP. Generator efficiency, power-electronic losses, auxiliary consumption, availability, and grid-interface losses are not represented in these values. They should therefore not be interpreted as annual electrical energy delivered to the grid [59,60].

A further limitation for independent assessment is that some numerical details required for complete reproduction of the published AEP estimates, including simulation duration, time-step selection, and the number of irregular-wave realisations, are not consistently reported across the accessible TALOS sources. The numerical results are consequently treated here as published device-level evidence rather than independently reproduced results.

7.2. Published Hull-Geometry Optimisation

Hull geometry strongly influences WEC excitation forces, added mass, radiation damping, hydrostatic restoring behaviour, and resonance characteristics. As discussed in Section 3, optimisation based solely on resonance at a single wave frequency is generally insufficient for broadband irregular-wave environments, motivating assessment across representative sea-state distributions [11,148].

Published TALOS investigations considered modifications to the original hull geometry, including shortening the hull and removing the extended tail section [37,38]. The tail had originally contributed to the mass distribution and stability characteristics of the device, but the numerical optimisation indicated that changes to the hull geometry could modify pitch response and increase relative motion between the external hull and internal oscillating mass.

Sheng and Aggidis [38] reported that the shortened and tailless configurations produced substantially higher simulated mechanical energy capture than the original geometry under the environmental conditions and modelling assumptions considered. These results demonstrate the sensitivity of TALOS performance to geometric design within the published numerical model. They do not, however, establish equivalent improvement under nonlinear full-scale conditions or experimentally validated operation. The hull configurations considered in the published TALOS studies are illustrated in Figure 3.

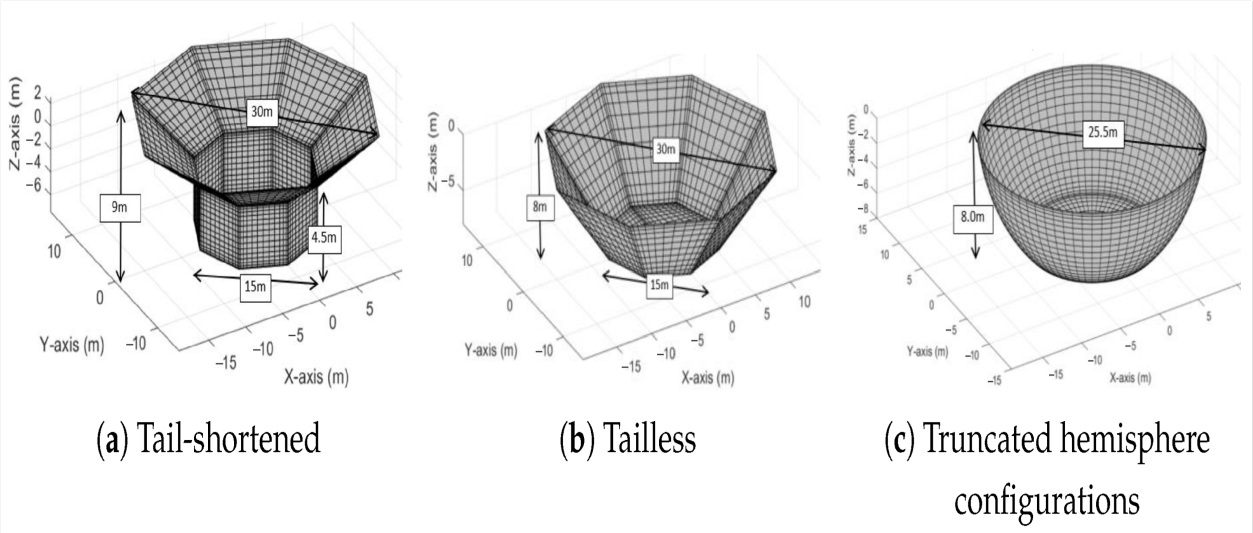


Figure 3. TALOS hull configurations considered in published geometry studies: (**a**) tail-shortened, (**b**) tailless, and (**c**) truncated hemispherical configurations. Geometry illustration reproduced from Sheng and Aggidis [38], with permission; the configurations are also reported by Nasr Esfahani et al. [58].

7.3. Published PTO Optimisation

The published TALOS studies also investigated the sensitivity of mechanical energy capture to PTO stiffness and damping [38]. This optimisation is important because the PTO parameters affect the amplitude and phase of relative motion between the internal mass and hull and therefore the amount of mechanical energy transferred through the PTO.

Within the investigated numerical design space, softer spring settings were reported to improve performance relative to the original harder PTO configuration. Sheng and Aggidis [38] considered soft spring stiffness values including approximately 350 kN m^{-1} and 250 kN m^{-1}, together with damping values including approximately 150 kN s m^{-1}. The reported results indicate that the effect of PTO tuning depended on the hull configura-

tion, reinforcing the need to consider geometry and PTO parameters jointly rather than as independent optimisation problems.

The largest reported mechanical AEP among the configurations summarised in Table 4 was approximately 1.311 GWh for the tailless TALOS configuration with the soft PTO setting, compared with approximately 345 MWh for the original TALOS configuration with the hard PTO setting [38]. This corresponds to an approximately 3.8-fold increase in *simulated mechanical PTO-level AEP within the published numerical design space*. It should not be interpreted as a 3.8-fold improvement in electrical AEP, commercial energy yield, or hybrid-system performance. The reported 3.8-fold improvement is derived from numerical optimisation rather than a direct experimental comparison of the baseline and optimised TALOS configurations. The reviewed optimisation evidence does not establish full-scale experimental validation of this AEP improvement.

Table 4. Published simulated mechanical PTO-level AEP values for selected TALOS configurations, compiled from the results reported by Sheng and Aggidis [38]. The values use the environmental weighting adopted in the published study and exclude detailed electrical wave-to-wire conversion and full-scale experimental validation.

Configuration	PTO Setting	Reported Mechanical AEP
Original TALOS	Hard PTO	345 MWh
Original TALOS	Soft PTO	612 MWh
Short TALOS	Hard PTO	865 MWh
Short TALOS	Soft PTO	1.274 GWh
Tailless TALOS	Hard PTO	846 MWh
Tailless TALOS	Soft PTO	1.311 GWh

The result is nevertheless significant as device-level evidence because it demonstrates the strong interaction between geometry and PTO tuning in the TALOS numerical model. Its transfer to practical energy production requires additional representation of the wave-to-wire conversion chain, nonlinear losses, operational constraints, availability, survivability, and experimental validation [59,60].

7.4. Published Centre-of-Gravity Assessment

The vertical centre-of-gravity position affects hydrostatic restoring moments and the rotational response of floating WECs. Published TALOS analyses examined the sensitivity of device performance to centre-of-gravity position as part of the broader device-level design investigation [38].

Within the reported numerical cases, a centre-of-gravity position of approximately 1.25 m below the reference water level was associated with favourable pitch response and energy capture. This finding should be interpreted as an optimum within the investigated numerical configuration and environmental assumptions rather than as a universally optimal full-scale design value. Changes in hull mass distribution, PTO characteristics, mooring system, structural design, or hybrid-platform configuration could alter the preferred centre-of-gravity position. TALOS-specific investigation of the effects of mooring lines further indicates that station-keeping characteristics form part of the device-level performance problem rather than an entirely independent design consideration [149].

This is particularly relevant to future hybrid integration because any physical incorporation of TALOS within, or mechanical coupling to, a floating wind platform would be expected to modify the mass, inertia, hydrostatic, and mooring characteristics of the overall system. The standalone centre-of-gravity result therefore provides a device-level design reference but would require re-optimisation within a coupled hybrid configuration [24,25].

7.5. Published Performance Evidence and Its Boundaries

Table 4 summarises the mechanical AEP values reported for the principal TALOS hull and PTO configurations considered by Sheng and Aggidis [38]. The values are compiled here as literature evidence and were not generated or independently recalculated in the present review.

The progression from 345 MWh to 1.311 GWh is therefore evidence of substantial improvement within the published standalone numerical model, but the performance boundary must remain explicit. The reported values represent mechanical energy at the PTO level rather than electrical energy exported to the grid [59,60]. Moreover, the optimised configurations have not yet been validated through full-scale experimental operation.

The principal evidence limitations include the use of predominantly linear hydrodynamic modelling, incomplete representation of viscous and strongly nonlinear effects, the absence of a detailed wave-to-wire conversion model, limited evidence under extreme survival conditions, and lack of full-scale experimental validation. These limitations do not invalidate the numerical optimisation; rather, they determine the strength and scope of the conclusions that can be drawn from it [47–49,59].

7.6. Critical Assessment and Relevance to Hybrid Integration

The published TALOS literature demonstrates that coordinated modification of hull geometry, PTO parameters, and mass distribution can substantially affect simulated standalone WEC performance [38,58]. Within the evidence framework adopted in this review, these findings constitute *numerically supported device-level optimisation evidence*. They should be distinguished from experimentally demonstrated performance and from system-level hybrid evidence.

This distinction is particularly important when considering TALOS for integration with floating offshore wind. None of the device-level AEP values in Table 4 represents a coupled TALOS–wind configuration [38]. The published values therefore provide no direct evidence of hybrid electrical AEP, wind-turbine load reduction, platform-motion mitigation, shared-mooring performance, coordinated wind–wave control, or hybrid LCOE.

The appropriate role of the TALOS case study is consequently not to demonstrate that TALOS is already suitable for hybrid offshore deployment, but to identify which device-level optimisation capabilities have been established and which evidence layers remain missing. Progression toward a credible hybrid configuration would require nonlinear and experimentally validated standalone modelling, detailed wave-to-wire analysis, definition of the physical TALOS–wind configuration, coupled aero–hydro–servo–elastic and mooring analysis, coordinated control, site-specific resource assessment, structural and fatigue evaluation, and hybrid AEP and techno-economic assessment. These requirements connect the published TALOS evidence to the hybrid-integration framework developed in Section 6 and form the basis of the development pathway discussed later in this review [24,25,59,125,126].

8. Comparative Evidence Assessment

This section places the published TALOS evidence in the context of representative WEC technologies, including Pelamis, OWC systems, PS Frog and related pitching–surging internal-mass concepts, and SeaREV. The purpose is not to rank these technologies according to energy performance, survivability, cost, or scalability, because the available studies differ substantially in device scale, environmental conditions, PTO architecture, conversion boundaries, performance metrics, numerical assumptions, and validation level. Instead, the comparison evaluates the nature and maturity of the available evidence using the critical-appraisal dimensions defined in Section 2.

Direct comparison of reported annual energy production (AEP), capture efficiency, or nominal power would be misleading unless the devices were assessed under consistent sea states, water depths, scales, conversion boundaries, availability assumptions, and numerical or experimental procedures. Environmental parameters such as water depth can themselves materially influence WEC performance [150]. Accordingly, numerical performance values are discussed only where they clarify the evidence available for an individual technology and are not used to construct a cross-technology ranking. Greater emphasis is placed on conversion principle, PTO architecture, modelling and experimental evidence, validation maturity, deployment experience, performance boundary, and the principal limitations affecting comparison.

8.1. Basis for Cross-Technology Comparison

The selected technologies represent distinct approaches to wave-energy conversion. Pelamis is an articulated attenuator in which relative motion between connected floating sections drives the PTO system [151–153]. OWC systems convert oscillation of an internal water column into reciprocating airflow through an air turbine and encompass a broad family of fixed, shoreline, breakwater-integrated, and floating configurations [154–158]. PS Frog and related pitching–surging concepts employ an internal reaction mass to exploit rotational and translational body motion [159,160]. SeaREV similarly uses an internal inertial mechanism, typically represented by an eccentric or pendular rotating mass enclosed within a floating hull [161,162]. TALOS applies the internal-mass principle through a multi-degree-of-freedom architecture in which relative motion between the external hull and internal oscillating mass is transferred through multiple PTO elements [38,58].

These architectural differences reflect the wider diversity of WEC principles, device realisations, and development pathways reported across the wave-energy literature [7,163]. They influence hydrodynamic response, PTO design, structural loading, control requirements, and maintenance strategy, and also make simple comparison using a single performance indicator inappropriate. For example, a mechanical PTO-level AEP obtained from a numerical model cannot be compared directly with grid-connected electrical output from a deployed device without accounting for conversion efficiency, environmental conditions, availability, scale, and other system boundaries.

The comparison therefore follows the evidence-oriented approach established in Section 2. Particular attention is given to: (i) the physical conversion principle and PTO architecture; (ii) the representative scale and evidence basis; (iii) the type and level of numerical, experimental, prototype, deployment, or operational validation available; (iv) the performance boundary of the reported results; and (v) the principal limitations preventing direct quantitative comparison.

8.2. Cross-Technology Evidence Assessment

Table 5 summarises the evidence considered for TALOS and the representative WEC technologies using a common set of descriptive criteria: conversion principle, primary motion and PTO architecture, representative scale or evidence basis, validation and deployment evidence, reported performance boundary, and the principal limitation affecting cross-technology comparison. The table deliberately avoids qualitative ratings such as “high”, “moderate”, or “low” and does not assign inferred technology-readiness levels, because such rankings would imply a degree of comparability not supported by the heterogeneous literature. Where a quantity cannot be established consistently from the source literature, it is not inferred for the purpose of comparison.

Table 5. Evidence-based comparison of TALOS and representative WEC technologies. The comparison emphasises observed evidence and validation boundaries rather than inferred technology-readiness scores or cross-technology performance rankings. Reported performance quantities are not directly ranked because the underlying studies differ in scale, environmental conditions, PTO and conversion boundaries, availability, modelling assumptions, and validation procedures.

Technology	Conversion Principle	Primary Motion/PTO	Representative Scale/Evidence Basis	Validation/ Deployment Evidence	Reported Performance Boundary	Principal Limitation for Comparison
TALOS	Floating internal-mass WEC	Multi-DOF relative motion between hull and internal mass; multiple internal PTO elements	Device-level numerical hydrodynamic, geometry, PTO, centre-of-gravity, prediction, and mooring studies	Predominantly numerical development evidence, including cross-model numerical assessment; no full-scale operational validation of the optimised configuration	Hydrodynamic response, mechanical PTO power, and simulated mechanical PTO-level AEP; published optimisation includes an increase from 345 MWh to 1.311 GWh within the investigated numerical design space	No harmonised full-scale electrical AEP, experimental validation of the optimised design, or coupled TALOS–wind system evidence [30,38,39,58]
Pelamis	Articulated floating attenuator	Relative motion between articulated floating sections; hydraulic PTO	Large floating articulated device supported by numerical, laboratory, prototype, and full-scale offshore-development evidence	Full-scale prototype testing and grid-connected offshore deployment provide an observed validation boundary beyond numerical and laboratory assessment	Hydrodynamic, mechanical, electrical, operational, and lifecycle evidence has been reported across different studies	Different scale, PTO architecture, sea states, operational assumptions, and performance definitions prevent direct comparison with TALOS mechanical PTO-level AEP [151–153]
OWC	Oscillating-water-column *technology class*	Oscillating internal water surface produces reciprocating airflow through an air-turbine PTO	Includes shoreline, fixed, breakwater-integrated, floating, single-chamber, and multi-chamber configurations investigated at substantially different scales	Analytical, numerical, laboratory, prototype, and field evidence exists across the OWC technology class	Reported quantities include hydrodynamic efficiency, chamber response, airflow and pressure response, turbine performance, and, for some configurations, electrical or operational output	OWC is a technology class rather than a single standardised device; geometry, turbine, deployment configuration, scale, and environmental conditions vary substantially among studies [61,155,156,158]

Table 5. *Cont.*

Technology	Conversion Principle	Primary Motion/PTO	Representative Scale/Evidence Basis	Validation/ Deployment Evidence	Reported Performance Boundary	Principal Limitation for Comparison
PS Frog/related pitching–surging concepts	Internal reaction-mass WEC	Pitching and surging body motion drives an internal reaction mass and PTO	Analytical and numerical development supported by scaled wave-tank investigation of the pitching–surging/reaction-mass principle	Scale-model experimental evidence supports the conversion principle and self-orienting behaviour; survivability and full-scale performance remain less established	Hydrodynamic response and mechanical energy-capture behaviour under the tested/ modelled conditions	No harmonised full-scale electrical AEP or operational evidence directly comparable with TALOS; scale, PTO implementation, and environmental assumptions differ [159,160]
SeaREV	Floating inertial WEC	Internal eccentric or pendular rotating mass coupled to the PTO	Successive numerical and experimental development generations of an enclosed inertial WEC concept	Numerical optimisation and experimental-development evidence is available, but not a directly comparable commercial operational dataset	Hydrodynamic/ mechanical performance, control behaviour, and development-stage energy and economic estimates have been reported	Different inertial architecture, scale, control assumptions, environmental conditions, and development-stage economic assumptions prevent direct ranking against TALOS [161,162]

The comparison highlights a substantial distinction between *reported performance* and *evidence maturity*. Pelamis, for example, provides full-scale offshore and grid-connected development evidence that is not available for the optimised TALOS configuration [153], whereas the TALOS literature provides detailed numerical evidence regarding the sensitivity of device performance to geometry, PTO parameters, mass distribution, prediction methods, and mooring-related design choices [30,38,39]. These evidence types answer different questions: numerical optimisation establishes behaviour within a defined model and design space, whereas experimental, prototype, grid-connected, and operational evidence progressively test whether predicted behaviour persists under physical and deployment constraints. They should therefore not be collapsed into a single qualitative performance or maturity score.

Similarly, OWC should be interpreted as a technology class rather than as a single standardised comparator. Fixed, shoreline, breakwater-integrated, floating, single-chamber, and multi-chamber OWC systems differ in geometry, air-turbine configuration, scale, deployment environment, and performance boundary. The dynamics and control of the air-turbine PTO introduce an additional source of configuration-dependent behaviour [61]. The broader OWC evidence base spans analytical and numerical modelling, laboratory testing, prototype development, and field experience, including investigations of power extraction from integrated tubular OWC configurations [75,76,164–168]. This breadth of evidence is valuable for assessing conversion principles and validation pathways, but it does not support assignment of a single representative energy-capture, survivability, rated-power, or cost value to the OWC class.

The wider WEC literature also illustrates how prototype testing can expose performance and deployment issues that are not represented fully in device-level numerical optimisation. Prototype development across different conversion principles, including overtopping concepts such as Wave Dragon and the Sea Slot-cone Generator, provides evidence of the progression from hydrodynamic design and component assessment toward physical experimental and offshore-development stages [169,170].

Demonstration-stage studies of other WEC concepts further extend this evidence base by examining device behaviour beyond purely numerical or laboratory-scale assessment [171]. Such evidence is valuable for identifying deployment-related behaviour, although results remain specific to the device architecture, scale, site, and operating conditions investigated.

PS Frog and SeaREV provide more direct architectural context for TALOS because they exploit internal reaction or inertial masses. The available PS Frog evidence includes scaled experimental investigation of the pitching–surging conversion principle [159,160], whereas SeaREV is supported by successive numerical and experimental development studies [161,162]. Nevertheless, differences in DOF, PTO configuration, device scale, control, environmental conditions, and performance definitions remain too large for a harmonised quantitative ranking against TALOS.

Published cross-device capture-width-ratio databases provide useful context for understanding the range of performance reported for different WEC concepts [148]. However, such databases aggregate results obtained using different device scales, sea states, modelling or experimental procedures, control assumptions, and data sources, with extrapolation required for some concepts. They are therefore treated here as literature-normalised contextual evidence rather than as a harmonised experimental benchmark. Capture-width ratio is consequently not used to rank TALOS against Pelamis, OWC, PS Frog, or SeaREV.

The same limitation applies to published cost and techno-economic estimates. Values reported for different WEC technologies originate from different development periods, levels of technology-development evidence, deployment scales, resource assumptions, financing conditions, availability assumptions, and cost boundaries [138–141]. Development-stage energy-cost estimates for concepts such as SeaREV and historical economic assessments of deployed or prototype devices therefore provide useful evidence regarding economic challenges, but they are not interpreted here as directly comparable LCOE rankings [153,162].

8.3. Interpretation of the Published TALOS Performance Improvement

The published TALOS optimisation results reported in Section 7 show an increase from approximately 345 MWh for the original hard-PTO configuration to approximately 1.311 GWh for the tailless configuration with the softer PTO setting [38]. This corresponds to an approximately 3.8-fold increase in simulated mechanical PTO-level AEP within the numerical design space investigated in the published study.

This result provides evidence of the sensitivity of TALOS performance to coordinated geometry and PTO optimisation within the published numerical design space, but it does not establish that TALOS has higher energy capture than Pelamis, SeaREV, PS Frog, or OWC technologies. No common experimental campaign or harmonised numerical benchmark has evaluated these technologies using identical sea states, scale treatment, PTO and electrical-conversion assumptions, availability, control strategy, and performance definitions. The approximately 3.8-fold increase is therefore an *intra-device numerical optimisation result*, not an *inter-device performance benchmark*.

The distinction is equally important for technology evidence maturity. A large improvement obtained within a numerical optimisation framework does not necessarily imply greater readiness for deployment than a technology exhibiting a smaller reported numerical improvement but supported by laboratory, prototype, or full-scale operational evidence. Performance improvement and evidence maturity are therefore treated as separate dimensions throughout this review.

8.4. Architectural Insights and Evidence Limitations

The selected technologies nevertheless provide useful architectural context for interpreting the TALOS concept. Pelamis demonstrates the engineering implications of an externally articulated floating architecture, while OWC systems illustrate an alternative conversion principle in which mechanical motion is transferred through an oscillating water column and air turbine. PS Frog and SeaREV are particularly relevant to TALOS because they demonstrate alternative approaches to extracting energy through internal reaction or inertial masses.

TALOS differs from these concepts through its multi-DOF internal-mass architecture and the coordinated numerical optimisation of hull geometry, PTO characteristics, and mass distribution reported in the published literature [38,58]. The enclosed location of its internal mechanism is a physical design characteristic, but evidence currently available does not justify concluding that this architecture necessarily provides superior reliability, maintainability, survivability, or lifecycle cost relative to the other technologies considered here.

Similarly, the multi-DOF response of TALOS provides additional design and control variables, but it also increases the number of coupled dynamic interactions that must be characterised. Potential gains in energy capture therefore need to be assessed together with PTO loading, structural response, fatigue, mooring behaviour, nonlinear hydrodynamics, survivability, reliability, maintainability, control requirements, electrical conversion, availability, and wave-to-wire efficiency. Device optimisation based primarily on absorbed or mechanical power can therefore identify promising design directions without demonstrating that the same configuration is optimal when structural, operational, electrical, and lifecycle constraints are introduced. These considerations reinforce the distinction between numerical optimisation potential and experimentally demonstrated system performance [14,59,78].

Higher-fidelity numerical approaches, including CFD models, can provide additional insight into nonlinear free-surface and viscous effects for selected WEC configurations, although their greater computational cost limits their routine use across large optimisation spaces [172,173].

More generally, experimental WEC studies show the importance of testing hydrodynamic behaviour under physical conditions that can expose nonlinear, viscous, and scale-dependent effects not represented completely by simplified numerical models [79,174]. Such evidence does not by itself establish full-scale operational performance, but it provides a stronger validation boundary than numerical optimisation alone.

8.5. Critical Synthesis of Cross-Technology Evidence

The cross-technology evidence does not support a defensible ranking of TALOS, Pelamis, OWC systems, PS Frog, and SeaREV according to energy capture, survivability, scalability, reliability, or cost. The underlying studies differ too substantially in device scale, environmental conditions, modelling assumptions, PTO representation, performance boundary, and validation maturity for such rankings to be meaningful.

The comparison is nevertheless informative when interpreted in terms of evidence type and maturity. Pelamis provides valuable full-scale deployment evidence for an articulated offshore WEC architecture, while OWC technologies are supported by a broad numerical, experimental, and field literature across multiple configurations. PS Frog and SeaREV provide relevant evidence for reaction-mass and inertial conversion principles, including experimental development at model or device scale [159–162]. Published TALOS studies, by contrast, provide increasingly detailed numerical evidence of the sensitivity of a multi-DOF internal-mass WEC to geometry, PTO characteristics, mass distribution, power-prediction methods, and mooring-related design choices [30,38,39,58].

The approximately 3.8-fold mechanical AEP improvement reported between selected original and optimised TALOS configurations [38] should therefore be interpreted within the published TALOS numerical design space rather than as evidence that TALOS outperforms the other technologies considered here. Establishing such a comparison would require either a harmonised numerical benchmark or a common experimental methodology using consistent environmental conditions, scale treatment, performance boundaries, and validation criteria.

From the perspective of this review, the principal value of the cross-technology assessment is therefore to identify differences in evidence type, system boundary, validation maturity, and deployability rather than differences in nominal performance. For TALOS, the next evidence requirements are not further qualitative ranking against heterogeneous WEC concepts, but higher-fidelity nonlinear modelling, experimental validation of the optimised configuration, wave-to-wire assessment, structural and mooring validation, reliability and survivability assessment, and ultimately coupled wind–wave modelling, coordinated control, electrical integration, and techno-economic evaluation. These requirements provide the basis for the integration pathways and research priorities considered in Section 9.

9. Evidence Gaps and Development Pathways for TALOS Hybrid Integration

The preceding sections distinguish between published standalone TALOS optimisation evidence and the substantially broader evidence required to demonstrate successful integration within a hybrid offshore renewable-energy system. The principal research need is therefore not simply further optimisation of individual TALOS parameters, but progression through increasingly complete levels of physical modelling, experimental validation, electrical conversion, coupled-system analysis, control, reliability assessment, and techno-economic evaluation.

This section synthesises these requirements into a development pathway. It first identifies the principal limitations of the current standalone TALOS evidence, then critically evaluates the role of machine-learning and artificial-intelligence methods, and finally defines the additional evidence required to progress from numerical device optimisation toward a validated hybrid wind–wave system.

9.1. Standalone TALOS: Remaining Validation and Modelling Gaps

The published TALOS literature provides numerical evidence that hull geometry, PTO parameters, centre-of-gravity position, mooring characteristics, and data-driven optimisation can materially affect predicted device performance [38,39,58,149]. However, as established in Section 7, the strength of these findings is constrained by the modelling and validation boundary within which they were obtained.

A first priority is experimental validation of the optimised device configurations. Numerical improvements in mechanical PTO-level AEP should be evaluated through appropriately scaled physical testing and, ultimately, prototype sea trials. Such testing is required not only to validate energy capture but also to characterise nonlinear motion, PTO loading, structural response, mooring behaviour, control limitations, and survivability under irregular and extreme environmental conditions. Experimental studies of multi-DOF WEC concepts demonstrate the value of progressively validating numerical predictions under increasingly representative conditions [175].

A second priority is progression beyond predominantly linear hydrodynamic assumptions. Linear potential-flow models provide computationally efficient tools for broad design-space exploration but do not explicitly represent all viscous, strongly nonlinear, breaking-wave, or large-amplitude effects that may influence full-scale behaviour [47–49]. Benchmark

comparisons of numerical WEC modelling approaches further reinforce that systematic performance evaluation remains dependent on the selected modelling formulation and its associated assumptions [51]. Comparative modelling studies also indicate that the accuracy of linearised descriptions can deteriorate as controlled device motions increase, reinforcing the need to match model fidelity to the response regime being investigated. For a multi-DOF internal-mass system such as TALOS, nonlinear coupling among hull motion, internal-mass dynamics, PTO forces, and mooring response may therefore become increasingly important as motion amplitudes increase.

Higher-fidelity time-domain models should therefore be used selectively to investigate viscous corrections, nonlinear wave–body interactions, directional irregular seas, dynamic mooring response, PTO constraints, and extreme environmental loading. CFD-based studies provide one route for resolving selected nonlinear free-surface and viscous effects that are simplified or omitted in lower-order hydrodynamic models [172,173]. The objective is not necessarily to replace lower-order models, but to establish a multi-fidelity workflow in which computationally efficient models support broad optimisation and selected designs are subsequently evaluated using higher-fidelity numerical and experimental methods. Reduced-order and surrogate models can further accelerate this process, provided that their training domain, approximation error, and uncertainty are explicitly characterised and that higher-fidelity models or experiments remain the reference for validation [32,127].

9.2. Wave-to-Wire, Reliability, and Lifecycle Evidence

A further evidence gap concerns the conversion boundary between mechanical PTO energy and useful electrical output. As discussed in Section 7, the principal published TALOS AEP values represent simulated mechanical PTO-level energy rather than complete electrical wave-to-wire production. Detailed assessment therefore requires representation of generator or conversion-system efficiency, power electronics, PTO force and motion limits, auxiliary consumption, electrical losses, control constraints, availability, and grid-interface requirements [59,60].

This distinction becomes increasingly important when comparing alternative device configurations. A geometry or PTO setting that maximises mechanical energy transfer may not maximise net electrical output if it increases conversion losses, actuator demand, component loading, or downtime. Wave-to-wire modelling should therefore be integrated with future TALOS optimisation rather than applied only as a post-processing efficiency factor.

This also changes the optimisation objective itself. A design selected on the basis of maximum absorbed or mechanical PTO power may cease to be optimal when generator characteristics, PTO saturation, electrical losses, power-electronic constraints, component loading, availability, and reliability are introduced. Future TALOS optimisation should therefore progress from hydrodynamic or mechanical-power objectives toward wave-to-wire and lifecycle-aware objectives [14,59].

Reliability and lifecycle evidence are similarly required before architectural features can be translated into economic claims. The enclosed internal mechanism of TALOS reduces direct seawater exposure of internal components as a matter of device architecture, but the available evidence does not establish a quantitative reliability, maintenance, or lifecycle-cost advantage relative to alternative WEC concepts. Such claims require failure-mode analysis, component reliability data, inspection and maintenance modelling, accessibility assessment, replacement strategy, and ultimately operational experience [71].

Reliability-based WEC optimisation studies further demonstrate that maximum energy capture alone is not necessarily an appropriate design objective when structural reliability, failure probability, component loading, and lifecycle cost are considered [14,69]. For TALOS, this implies that the geometry and PTO combinations producing the highest

simulated mechanical energy should eventually be re-evaluated under structural, reliability, and maintenance constraints rather than being treated automatically as the preferred deployable configuration.

Techno-economic assessment should consequently include manufacturing, installation, mooring, electrical infrastructure, inspection, maintenance, component replacement, availability, decommissioning, and uncertainty in long-term resource conditions [12,138,142]. These analyses are necessary to determine whether improvements in predicted energy capture translate into reductions in LCOE or other system-level economic benefits.

9.3. Machine-Learning and AI-Enabled Methods

ML and AI methods are relevant to the development pathway considered in this review when they address specific limitations of physics-based optimisation, monitoring, control, or system operation. Their value should therefore be evaluated according to the application, data source, validation strategy, generalisation capability, physical constraints, and deployment requirements rather than treated as an independent indicator of technological advancement [29].

Four application areas are particularly relevant: surrogate modelling and power prediction, condition monitoring and fault diagnosis, adaptive control, and system-level supervisory optimisation. Across these applications, the present review considers not only the algorithm employed but also the provenance and size of the training data where reported, model architecture, training and validation procedure, quantitative performance metrics, generalisation beyond the training domain, physical constraints, and the distinction between numerical, experimental, and operational validation.

9.3.1. Prediction and Surrogate Modelling

For TALOS, machine-learning-based power prediction has been investigated using response data generated from numerical models, with environmental and device-response variables used to estimate PTO power [30]. Such models can reduce computational demand during design-space exploration and may provide efficient surrogates for repeated numerical simulations. More broadly, data-driven predictive modelling and optimisation are being investigated as tools for exploring WEC design and performance relationships without requiring repeated evaluation of the highest-cost physical models [176].

The principal limitation is that a surrogate model inherits the validity domain of the data used for training. A model trained predominantly on numerical TALOS data cannot independently validate the physical model from which those data were generated. Its predictive performance outside the training range, under different sea states, nonlinear operating conditions, component degradation, or experimental conditions therefore requires separate assessment.

Ensemble-learning approaches have also been investigated for WEC power forecasting across coastal locations [177]. These methods are relevant to resource assessment and operational forecasting, but site transferability remains an important issue because wave climates, device characteristics, and available measurements can differ substantially between locations.

Recent surrogate-assisted studies also demonstrate how data-driven models can reduce the computational burden of coupled wind–wave optimisation. Wei et al. [32] compared Gaussian-process regression (GPR), multilayer-perceptron (MLP) neural networks, and support-vector regression (SVR) using a numerical database generated with coupled OpenFAST–AQWA simulations of a floating wind–wave hybrid system. The MLP-based surrogate achieved coefficients of determination exceeding 0.96 for all ten predicted response and performance variables and was subsequently combined with a genetic algorithm (GA)

to optimise WEC PTO settings with respect to platform response and power performance. This provides direct evidence that surrogate modelling can make coupled hybrid-system optimisation computationally more tractable. However, the reported predictive accuracy remains conditional on the fidelity and coverage of the underlying numerical database; surrogate accuracy should therefore not be interpreted as independent physical validation of the coupled system [32].

9.3.2. Condition Monitoring and Fault Diagnosis

Machine-learning methods have been applied to fault diagnosis and condition monitoring using operational wave-energy data [31]. This application is particularly relevant to offshore technologies because maintenance access is weather-dependent and unplanned intervention can contribute substantially to lifecycle cost.

For TALOS, condition-monitoring applications remain a future development requirement rather than an established capability. Useful implementation would require representative sensor data covering normal operation, component degradation, and relevant failure modes. Models would also need to distinguish actual faults from changes in environmental conditions and operating state. Consequently, condition-monitoring performance demonstrated on another WEC architecture cannot be assumed to transfer directly to TALOS without device-specific data and validation.

9.3.3. Learning-Based Control

Reinforcement-learning and related adaptive-control approaches offer a potential means of adjusting WEC control actions under changing environmental conditions [33,178]. Importantly, the available evidence spans different validation levels. Experimental reinforcement-learning studies have demonstrated energy-capture improvements under controlled wave-tank conditions, whereas more recent deep reinforcement learning (DRL) studies have used high-fidelity CFD or numerical-control environments to investigate real-time control under irregular waves. Deep-reinforcement-learning studies on Archimedes Wave Swing systems have additionally considered energy-storage coordination and grid-connected control [34,35]. These studies demonstrate increasingly sophisticated control architectures, but their validation boundaries and device-specific assumptions differ substantially and they do not constitute direct evidence of equivalent TALOS performance.

Recent studies using soft actor–critic (SAC) architectures are particularly relevant because they examine adaptive control without requiring perfect future-wave prediction. Su et al. [179] coupled SAC with a CFD numerical wave flume for real-time latching control of an Edinburgh Duck WEC under irregular waves. In the reported test conditions, the learned controller increased energy-capture efficiency by 8.85% relative to a predictive benchmark and by 17.3% relative to a non-predictive benchmark; generalisation was additionally examined under extreme waves and different water depths. Nevertheless, these results remain CFD-based rather than experimental or offshore validation [179].

Wen et al. [180] similarly combined an OpenFOAM-based CFD model with SAC control for a point-absorber WEC. In the reported open-water case, the learned policy achieved an average power of 0.63 W compared with 0.61 W for MPC and 0.33 W for resistive control, while also constraining device motion. Tests under unseen wave conditions and a wall-included environment provided additional numerical evidence of generalisation. These studies strengthen the case for learning-based WEC control, but numerical generalisation remains distinct from experimental robustness and offshore deployment.

Recent TALOS-specific work has combined mooring-related analysis with AI-based time-domain optimisation of PTO parameters under site-specific sea conditions [39]. This extends the TALOS evidence base beyond the earlier geometry and fixed-PTO studies and

demonstrates the usefulness of data-driven optimisation within the device-level numerical framework. It does not, however, constitute experimental validation of an autonomous real-time TALOS controller or coordinated wind–wave control.

For deployment, learning-based controllers must operate subject to PTO force and displacement limits, structural constraints, sensor noise, model uncertainty, communication and computation requirements, and safe behaviour outside the training distribution. Energy maximisation alone is therefore insufficient as an optimisation objective [29].

A further issue is that the control objective changes when a WEC becomes part of a hybrid floating system. Published hybrid studies show that control strategies that increase WEC power can simultaneously alter platform motions and loads, creating a trade-off between wave-energy maximisation and wind-platform stability [25,68]. Consequently, a controller that is optimal for a standalone WEC cannot be assumed to remain optimal after integration. Future TALOS control design should therefore be formulated as a constrained multi-objective or control-co-design problem in which wave power, wind-turbine performance, platform motion, mooring loads, structural response, and actuator limits are considered simultaneously.

9.3.4. Hybrid Supervisory Control

At the hybrid-system level, AI methods could potentially coordinate wind generation, WEC operation, storage, curtailment, and grid export. Such supervisory control could use forecasts of wind and wave conditions to balance energy production against structural loading, storage state, power-electronic constraints, and grid requirements.

This application remains largely prospective for TALOS. A credible implementation would first require a validated coupled hybrid-system model and clearly defined controllable variables. AI cannot substitute for the absence of a physical TALOS–wind configuration, coupled dynamics, electrical architecture, or validated system constraints. Hybrid AI control should therefore be viewed as a later stage in the development pathway rather than evidence that hybrid integration has already been demonstrated.

Deployment would additionally require fail-safe behaviour, constraint handling, interpretable supervisory logic, robust sensing and communication, and fallback control strategies for conditions outside the training distribution. These requirements are particularly important offshore, where unsafe exploratory control actions or loss of communication cannot be treated in the same manner as errors within an offline numerical environment.

Table 6 demonstrates that apparently similar AI applications can rest on substantially different evidence bases. These range from numerically generated training data and CFD environments to wave-tank experiments and measured operational plant data. Consequently, high predictive accuracy or improved simulated energy capture should be interpreted together with dataset provenance, sample coverage, validation procedure, generalisation tests, and physical validation. Methods developed for AWS or other WEC architectures provide valuable methodological evidence but should not be interpreted as TALOS-specific validation. Algorithm choice alone is therefore an insufficient measure of readiness for offshore deployment.

Across these applications, recurring deployment challenges include training-data quality, extrapolation beyond the training domain, interpretability, sensor reliability, computational requirements, actuator constraints, uncertainty, and safe operation under extreme conditions. AI and ML should therefore complement physics-based modelling and experimental validation rather than replace them.

Table 6. Critical assessment of representative ML and AI applications relevant to WEC development and future TALOS hybrid integration.

Application	Model/Architecture	Data Source/Scale	Validation/Reported Performance	Relevance to TALOS/Hybrid Systems	Principal Limitation
TALOS power prediction	Machine-learning surrogate/power prediction	Numerically generated TALOS response data	Validation primarily within the available numerical-data domain	Rapid prediction and surrogate-assisted design exploration	Does not independently validate the underlying physical TALOS model; extrapolation requires assessment [30]
Data-driven WEC optimisation	Predictive/data-driven modelling and optimisation	WEC performance data within the investigated modelling framework	Validation dependent on the data and operating domain used to develop the predictive model	Illustrates the broader use of data-driven methods for WEC design-space exploration and optimisation	Transferability depends on device architecture, data coverage, model fidelity, and validation outside the training domain [176]
TALOS parameter optimisation	AI-assisted optimisation of PTO parameters with mooring-related modelling	Numerical, site-specific TALOS modelling	Numerical device-level optimisation	Extends TALOS optimisation toward coordinated mooring/PTO design	Not equivalent to experimental real-time control or coupled TALOS–wind optimisation [39]
Hybrid surrogate optimisation	MLP, GPR, and SVR surrogate models; MLP selected for GA-based optimisation	Numerical database generated using coupled OpenFAST–AQWA simulations across operational conditions; dataset size not reported in the evidence extracted for this review	MLP achieved $R^2 > 0.96$ for all ten predicted outputs; surrogate subsequently used for multi-objective PTO optimisation	Directly relevant to computationally efficient optimisation of coupled floating wind–wave systems and future TALOS–wind studies	Accuracy remains conditional on the numerical training database; no independent experimental validation of the coupled hybrid system [32]
Condition monitoring	ML-based fault diagnosis	Measured operational wave-energy data	Application-specific operational dataset	Relevant to future predictive maintenance and reliability management	Transfer to TALOS requires TALOS-specific sensors, fault data, and validation [31]
WEC adaptive control	Reinforcement-learning control	Numerical training/development with experimental validation in the FloWave wave basin	Experimental testing reported an approximately 11.3% improvement in conversion efficiency under the investigated conditions	Provides experimental evidence that learning-based WEC control can improve energy capture	Device- and test-condition-specific; generalisation and transfer to TALOS remain unverified [33]

Table 6. *Cont.*

Application	Model/Architecture	Data Source/Scale	Validation/Reported Performance	Relevance to TALOS/Hybrid Systems	Principal Limitation
Non-predictive DRL control	Soft actor–critic reinforcement learning coupled with CFD latching control	Irregular waves generated in parallel CFD numerical-wave-flume environments using a Pierson–Moskowitz spectrum	Energy-capture efficiency increased by 8.85% relative to a predictive benchmark and 17.3% relative to a non-predictive benchmark; generalisation tested under extreme waves and different water depths	Demonstrates adaptive WEC control without reliance on perfect future-wave prediction	CFD-based numerical validation; transfer to TALOS and experimental/offshore robustness remain unverified [179]
CFD–DRL point-absorber control	OpenFOAM CFD coupled with a soft actor–critic controller	CFD-generated wave–structure interaction data for open-water and wall-included point-absorber environments	Reported open-water average power of 0.63 W compared with 0.61 W for MPC and 0.33 W for resistive control; additional tests used unseen waves and a wall-included environment	Demonstrates adaptive PTO control and numerical generalisation under changing hydrodynamic conditions	Device- and CFD-specific validation; experimental and offshore deployment remain unverified [180]
Storage-integrated control	Deep reinforcement learning with WEC energy storage	Archimedes Wave Swing (AWS)-based numerical/control framework	Architecture-specific numerical assessment	Relevant to future WEC power smoothing and storage coordination	Not TALOS-specific; electrical and control architecture differs [34]
Grid-connected control	Twin-delayed deep reinforcement learning	Grid-connected AWS numerical/control framework	Architecture-specific numerical assessment	Relevant to future generator-side and grid-interface control	Transfer to TALOS requires a defined and validated TALOS wave-to-wire model [35]
Regional power forecasting	Ensemble-learning prediction	Site-dependent wave/resource and WEC data	Dependent on training locations and environmental range	Relevant to site assessment and operational forecasting	Site transferability and device-specific generalisation require evaluation [177]

9.4. From Standalone TALOS to a Coupled Hybrid System

Progressing from the current TALOS evidence base to a hybrid wind–wave system introduces a sequence of additional requirements. Resource complementarity should first be established using site-specific joint wind–wave data [107,133]. A physical hybrid configuration must then be defined, including the number and location of TALOS devices relative to the wind platform, structural interfaces, mass distribution, and station-keeping arrangement.

Once the configuration is defined, coupled aero–hydro–servo–elastic modelling is required to determine how TALOS hydrodynamic and PTO forces affect platform motion, wind-turbine loads, mooring response, and control behaviour. The TALOS PTO parameters

and device placement would then need to be re-optimised within this coupled system because the optimum obtained for the standalone WEC cannot be assumed to remain optimal after integration [24–26,95,114].

This requirement is supported more generally by hybrid wind–wave studies in which WEC control or PTO settings that improve wave-energy extraction can simultaneously modify platform motions and wind-turbine response [25,68]. Hybrid optimisation should therefore seek a system-level compromise rather than simply embedding the standalone maximum-power TALOS configuration into a wind platform.

Electrical integration requires a further modelling layer. A hybrid system must define the TALOS wave-to-wire conversion chain, electrical collection architecture, wind and wave power interfaces, shared export capacity, protection, curtailment, storage where applicable, and supervisory control. Only after these elements are represented can hybrid electrical AEP and power-smoothing benefits be quantified credibly [59,60].

Finally, structural, reliability, lifecycle, and techno-economic analyses are required to determine whether additional wave-energy production offsets the added platform complexity and cost. Hybrid LCOE should therefore be calculated from a system boundary that includes the additional WEC hardware, structural modifications, mooring changes, electrical infrastructure, installation, maintenance, availability, and any infrastructure shared with the wind system [138–142].

9.5. Evidence-Based Development Roadmap

The evidence reviewed in this paper supports a staged development pathway rather than an immediate transition from numerical TALOS optimisation to hybrid deployment. This progression is consistent with the broader need for marine-energy technologies to accumulate increasingly representative performance, reliability, survivability, and validation evidence as development advances [80]. The TALOS-specific stages synthesised from the evidence reviewed here are summarised in Table 7.

Table 7. Evidence-based development pathway from published standalone TALOS optimisation toward validated hybrid wind–wave integration.

Stage	Development Level	Required Evidence	Indicative Outputs	Status Relative to Published TALOS Evidence
1	Standalone numerical optimisation	Hydrodynamics, hull geometry, PTO parameters, mass distribution	Mechanical PTO performance and sensitivity to design variables	Published TALOS evidence available [38,58]
2	Higher-fidelity and multi-fidelity standalone modelling	Nonlinear hydrodynamics, viscous effects, dynamic mooring, extreme conditions, PTO constraints, and validated surrogate/reduced-order models	More robust motion, load, and mechanical-energy predictions with quantified fidelity–computational-cost trade-offs	Partially developed; further high-fidelity and experimental validation required [32,39,121,127]

Table 7. *Cont.*

Stage	Development Level	Required Evidence	Indicative Outputs	Status Relative to Published TALOS Evidence
3	Experimental standalone validation	Scaled physical testing followed by prototype/sea-trial evidence	Validation of energy capture, loads, control behaviour, and survivability	Required for optimised configurations; analogous WEC development pathways demonstrate the value of progressive physical validation [76,79]
4	Wave-to-wire and reliability assessment	Generator/conversion model, power electronics, losses, availability, failure modes, maintenance	Electrical AEP, efficiency, reliability, and lifecycle evidence	Not established for the optimised TALOS configurations reviewed here [59,60,69]
5	Hybrid configuration and resource assessment	Physical TALOS–wind layout, site-specific joint resource, structural and mooring concept	Defined hybrid architecture and design conditions	Conceptual/future requirement for TALOS; analogous hybrid configurations have been investigated for other WEC–wind concepts [24,126]
6	Fully coupled hybrid modelling and control co-design	Aero–hydro–servo–elastic interaction, WEC PTO, dynamic mooring, device placement, coordinated wind–wave control, and system-level constraints	Platform response, turbine loads, WEC output, mooring loads, structural response, and control trade-offs	Not demonstrated for TALOS–wind integration; coupled-system and control-interaction evidence exists for other hybrid configurations [25,26,68]
7	Hybrid electrical and techno-economic optimisation	Wave-to-wire and shared electrical architecture, hybrid electrical AEP, CAPEX, OPEX, availability, reliability, LCOE, and uncertainty propagation	Quantified system-level energy, reliability, and economic benefit with explicit uncertainty bounds	Not demonstrated for TALOS–wind integration; broader hybrid techno-economic studies provide methodological precedents [138,141,142]
8	Hybrid experimental demonstration	Integrated prototype testing and representative offshore operation	Validated hybrid performance, reliability, and operational evidence	Long-term development requirement

The roadmap makes explicit that completion of one stage does not provide evidence for all subsequent stages. In particular, the published improvement in standalone mechanical PTO-level AEP [38] establishes Stage 1 evidence but does not establish hybrid electrical or economic performance. Likewise, AI-assisted numerical optimisation can strengthen individual stages but cannot substitute for missing physical, electrical, experimental, or techno-economic validation.

This staged interpretation provides a more conservative basis for assessing TALOS than treating architectural features or numerical optimisation gains as direct indicators of hybrid suitability. At present, the published evidence supports continued development of TALOS as a numerically optimised multi-DOF WEC and provides inputs for future hybrid-system design [30,38,39,58]. Demonstration of a beneficial TALOS–wind configuration remains dependent on the additional evidence layers identified in Table 7.

10. Conclusions

This review critically examined the progression from standalone wave energy converter (WEC) optimisation toward hybrid offshore wind–wave integration, using TALOS as a literature-derived case study. By synthesising evidence across common appraisal dimensions, the review identified a fundamental distinction between device-level performance improvement and the evidence required to establish hybrid-system benefits. Geometry, power take-off (PTO) characteristics, control, mooring, structural response, and environmental conditions are interdependent, supporting coordinated rather than isolated optimisation [13,16,54,56]. The principal conclusion is that improved simulated mechanical energy capture alone does not establish electrical performance, structural reliability, economic viability, or deployment readiness.

Published TALOS studies illustrate this evidence boundary. Coordinated optimisation of hull geometry and PTO parameters, alongside investigations of centre-of-gravity positioning, demonstrates the sensitivity of device-level performance to interacting design variables. The reported simulated mechanical PTO-level annual energy production (AEP) increased from approximately 345 MWh for the original hard-PTO configuration to 1311 MWh for the tailless soft-PTO configuration, representing an approximately 3.8-fold difference within the investigated numerical design space [38]. This result does not establish equivalent improvements in electrical AEP, experimentally validated full-scale performance, or beneficial TALOS–wind integration. Furthermore, differences in modelling assumptions, performance boundaries, and validation maturity prevent defensible performance rankings between TALOS and other WEC technologies, including Pelamis, oscillating water columns, PS Frog, and SeaREV.

For hybrid offshore wind–wave systems, resource complementarity and shared infrastructure offer potential benefits but do not independently demonstrate improved integrated-system performance [23,24,107,129]. Physical integration introduces coupled aerodynamic, hydrodynamic, structural, mooring, PTO, control, and electrical interactions that may alter standalone-device optima [25,26,95,108]. For TALOS, the reviewed evidence supports investigation of prospective hybrid configurations rather than a demonstrated integrated system [37,38,58,149]. Machine learning and artificial intelligence may assist surrogate modelling, prediction, condition monitoring, control, and optimisation, but their usefulness remains conditional on representative data, physical consistency, generalisation, and appropriate validation [29–33,176].

Future research should prioritise the validation of published device-level optimisation findings and progressive expansion of the assessment boundary to include wave-to-wire electrical conversion, structural and mooring constraints, reliability, and coupled wind–wave dynamics. Subsequent investigations should evaluate specific hybrid configurations using coordinated control, uncertainty-aware modelling, site-specific hybrid AEP, and lifecycle techno-economic assessment, supported by experimental validation and, ultimately, integrated offshore demonstration [51,149]. For TALOS, the immediate priority is therefore not simply further maximisation of standalone mechanical PTO energy but establishing whether reported device-level gains persist under realistic operating constraints and translate into measurable technical and economic benefits at the hybrid-system level.

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Abbreviations

The following abbreviations are used in this manuscript:

AEP	Annual Energy Production
AI	Artificial Intelligence
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
DOF	Degrees of Freedom
DRL	Deep Reinforcement Learning
GPR	Gaussian-Process Regression
LCOE	Levelised Cost of Energy
ML	Machine Learning
MLP	Multilayer Perceptron
MPC	Model Predictive Control
OPEX	Operational Expenditure
OWC	Oscillating Water Column
OWT	Offshore Wind Turbine
PTO	Power Take-Off
SAC	Soft Actor–Critic
SVR	Support-Vector Regression
AWS	Archimedes Wave Swing
TALOS	Technologically Advanced Learning Ocean System
TRL	Technology Readiness Level
WEC	Wave Energy Converter

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