Oxford Open Energy, 2026, 5, oiag011
https://doi.org/10.1093/ooenergy/oiag011
Published: 28 July 2026
Review

OXFORD

Wave energy converter survivability and lessons from offshore wind: a critical review

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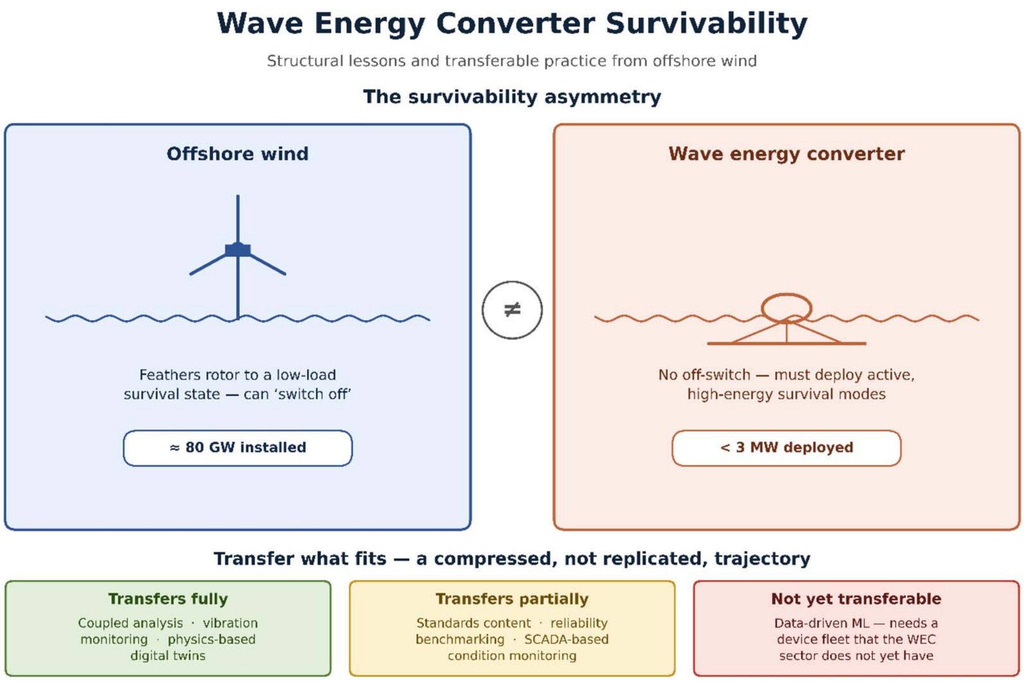
Abstract

Ocean wave energy remains pre-commercial after four decades, with under 3 megawatts deployed against some 80 gigawatts of offshore wind. Cost and efficiency explanations are incomplete: structural and station-keeping failure recur in documented wave energy converter (WEC) terminations. This review examines WEC structural integrity over 2016–2026 and Preferred Reporting Items for Systematic reviews and Meta-Analyses asks what the sector can learn from offshore wind. The methodology is two-part. Part A is a Preferred Reporting Items for Systematic reviews and Meta-Analyses 2020 systematic review of the WEC literature (Scopus, Web of Science, IEEE Xplore) plus grey literature; Part B is a purposive review of five pre-defined offshore wind practice areas. Together these draw on 150 references (117 in-window 2016–2026; 33 foundational). Addressing RQ1, WEC failures parallel early offshore wind in three respects: subsystem failure dominates primary-structure failure; the gap between codified and observed design loads persists; and condition monitoring is now the operational response to residual risk. They diverge in two critical ways: offshore wind can feather its rotor into a low-load survival state, whereas WECs must use active, high-energy survival configurations with their own failure modes; and offshore wind has the fleet scale that underpins reliability benchmarking. Addressing RQ2, transferability against four criteria (physical analogy, data availability, regulatory maturity, economic feasibility) shows that reliability benchmarking, standards content, and Supervisory Control and Data Acquisition-based monitoring transfer only partially, while vibration monitoring and coupled analysis transfer fully. Digital-twin methodology transfers asymmetrically: physics-based models suit single-prototype validation, whereas data-driven monitoring is constrained by the absence of a WEC fleet. We argue for a compressed rather than replicated trajectory and identify four priority research directions.

Received: 21 April 2026. **Revised:** 21 July 2026. **Accepted:** 23 July 2026

Graphical abstract



Lay summary

Wave energy—capturing power from ocean waves—has been studied for >40 years; yet, very little has been built: under 3 megawatts of wave devices operate worldwide, against roughly 80 gigawatts of offshore wind. This review asks why, and finds that the obstacle is not cost alone but survival-wave machines repeatedly suffer structural damage or lose their moorings in harsh seas. Comparing wave-energy research from 2016 to 2026 with the earlier history of offshore wind, we identify a fundamental difference: a wind turbine can ride out a storm by turning its blades edge-on and effectively switching off, whereas a wave device cannot switch off the waves and must rely on other survival measures that create their own ways to fail. Wave energy therefore cannot simply copy offshore wind. Some wind-sector tools transfer well—design standards, certain monitoring methods, and physics-based computer models—while data-hungry artificial-intelligence methods do not, because they need a large fleet of devices that wave energy still lacks. We argue that the sector should follow a shortened development path, adopting proven offshore-wind practice and prioritizing survival in extreme conditions.

Keywords wave energy converter, structural integrity, survivability, offshore wind, digital twin, hybrid systematic review

Introduction

Ocean wave energy represents one of the last largely untapped renewable energy resources, with a global theoretical potential exceeding 2 TW and energy densities ∼13 times higher than those of wind [1–4]. Yet, despite more than four decades of research and development, the total installed wave energy capacity worldwide remains negligible. As of 2021, actively operating wave energy projects amounted to merely 2.31 MW [2], a figure that stands in stark contrast to the ∼80 GW of offshore wind capacity installed over a comparable development timeline [5]. This disparity demands explanation. The conventional narrative attributes the slow commercialization of wave energy converters (WECs) to their high levelized cost of energy (LCOE) and low power conversion efficiency. However, a growing body of evidence suggests that a primary barrier is more fundamental: WEC devices have repeatedly failed to demonstrate adequate structural integrity and survivability in real sea conditions. A survey conducted by Ocean Energy Europe identified improving reliability and survivability—not reducing costs or increasing efficiency—as the foremost priority for advancing ocean energy technology [6]. This finding is echoed by the trajectory of commercial WEC ventures: companies such as Pelamis Wave Power [7], Aquamarine Power [8], Wavebob, AWS Ocean Energy, and Oceanlinx have all ceased operations, with structural failures or inadequate survivability cited as contributing factors in several cases [2, 9]. The significance of structural integrity for WEC commercialization can be understood through the concept of a "binary factor" proposed by Sheng [6]: while energy conversion efficiency can be incrementally improved through learning curves and economies of scale, a device that suffers catastrophic structural failure produces zero energy. In economic terms, a single unplanned structural failure offshore can consume the entire capital investment, as retrieval, repair, and redeployment costs in the marine environment are prohibitively high. This is not merely an engineering challenge but a commercial one: survivability risk dominates the expected-return calculation of any investor contemplating a WEC array, and until that risk can be quantified with confidence, capital flows into the sector will remain constrained.

Existing reviews and the remaining gap

The WEC literature contains several comprehensive reviews that have addressed structural integrity as part of broader treatments of wave energy technology [10–15]. Sheng [6] provided an insightful discussion of reliability and survivability challenges within a comprehensive review of wave energy conversion technologies. Guo and Ringwood [2] examined WEC commercialization trajectories and identified survivability as a critical development factor. Garcia-Teruel and Forehand [16] noted that structural loads have not been systematically incorporated into hull geometry optimization, a finding subsequently extended by Guo and Ringwood [17] in their survey of geometric optimization approaches. The foundational reliability survey of Coe *et al.* [18], drawing on the combined engineering experience of Sandia National Laboratories and the US National Renewable Energy Laboratory, established the three-pathway failure taxonomy that continues to organize the field. More recently, a wave of 2023–2026 reviews has revisited the WEC landscape from multiple angles. Khojasteh *et al.* [19] performed a 20-year bibliometric analysis of wave and tidal energy research. Chitumwa *et al.* [20] reviewed the viability and development of WEC technology. Huang *et al.* [21] synthesized progress on built-in WECs, and Samuel *et al.* [22] reviewed motion responses of floating-breakwater WEC hybrids. Mortazavizadeh *et al.* [23] reviewed fault diagnosis and condition monitoring specifically for the WEC sector. Arrosyid *et al.* [24] applied PRISMA methodology to WEC design and performance optimization. Most recently still, a comparative state-of-the-art review has synthesized point-absorber, linear-absorber, and hybrid system classes [25–27], a bibliometric synthesis has mapped the entire global WEC research base from 2005 to 2024 across >70 countries [28], and parallel reviews have addressed machine-learning applications [26], capture-width databases [29], and multi-purpose offshore systems [30]. Despite this extensive coverage, three critical gaps remain unaddressed. First, to the authors' knowledge, no existing review has compiled a **structured deployment-outcome inventory** that catalogs publicly documented WEC deployments at prototype scale or above against a common coding scheme for structural outcome. In the absence of such an inventory, the field lacks a common reference point for basic indicators of WEC structural outcome frequency or the relative vulnerability of different WEC types—indicators of a kind that have become routinely available for offshore wind in recent years [31]. Second, no review has provided a **systematic cross-type survivability comparison** that evaluates the structural integrity characteristics of different WEC categories against common criteria drawn from empirical failure evidence rather than expert judgment. Third, and most significantly, no review has conducted a **structured cross-industry comparison between WEC and offshore wind** regarding structural integrity development pathways. Given that offshore wind has successfully navigated the transition from prototype demonstration to commercial maturity, the lessons embedded in that experience—in design standards evolution, condition monitoring deployment, maintenance strategy development, and digital-twin adoption—represent a potentially transformative knowledge resource for the wave energy sector. Yet, this cross-pollination has not been systematically examined.

Objectives and research questions

This review aims to fill the third and most significant of these gaps by addressing two focused research questions:

RQ1: How do WEC structural failure patterns documented in the 2016–2026 literature compare with the early-stage failure history of the offshore wind industry?

RQ2: Which structural integrity practices from the offshore wind sector are transferable to WEC development, which require adaptation, and which are constrained by fundamental asymmetries between the two technologies?

By addressing these questions, this review seeks to provide the wave energy community with an evidence-based understanding of where structural integrity currently stands relative to a useful comparator, a concrete catalog of transferable knowledge from a more mature marine renewable technology evaluated against explicit criteria, and a prioritized research agenda that identifies the most impactful near-term actions.

Contribution and paper structure

The contribution of this review is methodological as well as empirical. Methodologically, the review adopts an explicit two-part design (detailed in Section 2): Part A is a PRISMA 2020 [32] systematic review of the WEC structural integrity literature of 2016–2026, and Part B is a structured comparative review of five pre-defined offshore wind practice areas, based on purposive selection of landmark references within each area. The two parts address different research questions with different evidentiary requirements and are not claimed to follow the same methodological standard—an asymmetry that the review states openly rather than concealing under a uniform "systematic review" label. Empirically, the review synthesizes evidence from 150 references (117 within the 2016–2026 window and 33 foundational pre-2016 references) into a thematic classification table mapping 30 landmark references to themes, findings, and limitations (Table 2) and a structured transferability matrix (Table 4) evaluated against four criteria: physical analogy, data availability, regulatory maturity, and economic feasibility. The matrix provides, to the authors' knowledge, the first explicit criterion-referenced inventory of cross-industry transfer opportunities for the WEC sector, intended as a starting point for subsequent refinement rather than a final assessment. The remainder of this paper is organized as follows. Section 2 details the two-part methodology, including the PRISMA 2020 flow for Part A, the a priori practice frame and purposive selection rule for Part B, the source hierarchy applied to grey literature, and the coding protocol used for the deployment-outcome inventory of Section 3. Section 3 addresses RQ1 by characterizing the WEC structural failure record from the 2016–2026 Part A literature and contrasting it with the early-stage offshore wind experience. Section 4 addresses RQ2 by presenting the five offshore wind practice areas of Part B and evaluating each for WEC transferability. Section 5 synthesizes the findings into the cross-industry comparison matrix, addresses the strategic question of whether the WEC sector should replicate or compress the offshore wind trajectory, and examines the role of emerging digital-twin and fault-tolerant control methodologies. Section 6 concludes with the research agenda implied by the synthesis and acknowledges the limitations of the review.

Methodology

Overall design: a two-part review

The research questions set out in Section 1 have different evidentiary requirements and therefore call for different methodological strategies. RQ1 asks what the WEC structural integrity literature of 2016–2026 documents about failure patterns and compares that record to the early development phase of offshore wind. This question demands comprehensive, reproducible coverage of the WEC literature; the relevant literature is finite, the topic is well defined, and systematic-review discipline is both feasible and appropriate. RQ2 asks which structural integrity practices from the mature offshore wind sector are transferable to WECs. This question does not require a comprehensive review of offshore wind—offshore wind is an established industry with a literature far larger than the WEC literature, and no single review can survey it adequately. What it requires instead is the identification of a small number of landmark practices, each represented by consolidated, highly cited sources, against which the WEC experience can be contrasted. The review therefore adopts a two-part design that is explicit about this asymmetry rather than attempting to subsume both questions under a single methodological framework.

Part A (addressing RQ1) is a systematic review of the WEC structural integrity literature of 2016–2026, supplemented by hand-searched grey literature and standards. Part A follows PRISMA 2020 reporting guidance [32] and is fully accounted for in the flow diagram of Fig. 1.

Part B (addressing RQ2) is a structured comparative review of offshore wind structural integrity practices. Part B is purposive in selection and is not claimed to be a systematic review of offshore wind; rather, it selects a pre-defined set of five practice areas and, within each, draws on landmark references identified by citation metrics and topical fit. The rationale for this approach, the selection criteria, and the bias-mitigation measures used are detailed in Section 2.4 below.

A brief integrative synthesis combines the two parts in Section 5, where the comparison against the four transferability criteria introduced in Section 1.3 is performed. This explicit two-part framing departs from a number of recent marine-renewable reviews that have applied PRISMA methodology uniformly to cross-sector comparisons without distinguishing between question types. The authors consider that such uniform framing overstates the systematic character of the underlying search where one of the compared literatures is too large to be reviewed comprehensively, and prefer to state the asymmetry openly. The approach is consistent with recent methodological guidance on hybrid and integrative review designs in the engineering sciences [32].

Inclusion window and rationale

The formal inclusion window for both Part A and Part B is 1 January 2016 to 31 March 2026. The lower bound was chosen so as not to duplicate the generation of WEC reviews published between 2010 and 2015—notably [10, 33]—while still spanning the decade during which several high-profile WEC ventures ceased operations and during which offshore wind reached commercial scale. A set of canonical references predating the window is cited contextually in Sections 1, 3, and 4 to establish historical continuity; these foundational sources were not included in the formal screening pipeline of Part A and are flagged as such in Supplementary Material S1 (column B).

Part A: systematic review of the wave energy converter structural integrity literature

Databases and search strings

Part A drew on three databases: Scopus, Web of Science Core Collection, and IEEE Xplore. The primary Scopus search string combined device-descriptor and structural-topic keyword groups:

TITLE-ABS-KEY ((“wave energy convert∗” OR “WEC” OR “oscillating water column” OR “point absorber” OR “overtopping” OR “attenuator”) AND (“structural” OR “surviv∗” OR “reliab∗” OR “fatigue” OR “mooring” OR “extreme load” OR “extreme wave” OR “snap load” OR “slamming” OR “failure” OR “limit state” OR “corrosion” OR “biofouling” OR “digital twin” OR “condition monitor∗”))

Equivalent search strings were constructed for Web of Science Core Collection and IEEE Xplore using native syntax conventions. The complete set of search strings, database settings, date-of-search, and number of records returned by each is reported in Supplementary Material S2 to permit reproduction.

Screening

The Scopus string returned 623 records, the equivalent Web of Science string returned 412 records, and the IEEE Xplore string returned 187 records. After duplicate removal across all three sources, 758 unique records entered title-and-abstract screening. Of these, 638 were excluded at the screening stage (312 because structural integrity was not the primary focus; 194 because the investigation was confined to laboratory or sub-scale conditions below TRL 3; and 132 because the focus was grid integration, techno-economic analysis, or ecosystem effects without direct structural-integrity content). A total of 120 records passed screening for full-text assessment. At the full-text stage, a further 27 records were excluded at full-text review (18 for substantially duplicated content with other included sources by the same research group, 3 for full-text retrievability, 4 for non-English body text, and 2 for superseded standard editions; see Supplementary Material S2, Sheet 3), yielding 93 included articles for synthesis in Part A. The TRL-3 exclusion applied to studies confined to sub-scale hydrodynamic or performance investigation; Froude-scaled wave-basin and tank studies were retained where they provided validation of numerical methods for structural response under extreme or long-term loading (inclusion criterion ii), as with the focused-wave-group snap-load experiments of Hann *et al.* [34].

Inclusion and exclusion criteria

Records were included if they satisfied at least one of: (i) reporting of empirical data on structural failures, loads, fatigue, or reliability of WECs at prototype scale or larger; (ii) development or validation of numerical methods directly applicable to WEC structural response under extreme or long-term loading; (iii) review of survivability, reliability, condition monitoring, or digital-twin methodologies with explicit application to floating marine energy devices; or (iv) publication of technical standards or guidance documents applicable to WEC structural design. Records were excluded if their focus was confined to hydrodynamic performance optimization without structural implications, to grid integration or electrical-system design, or

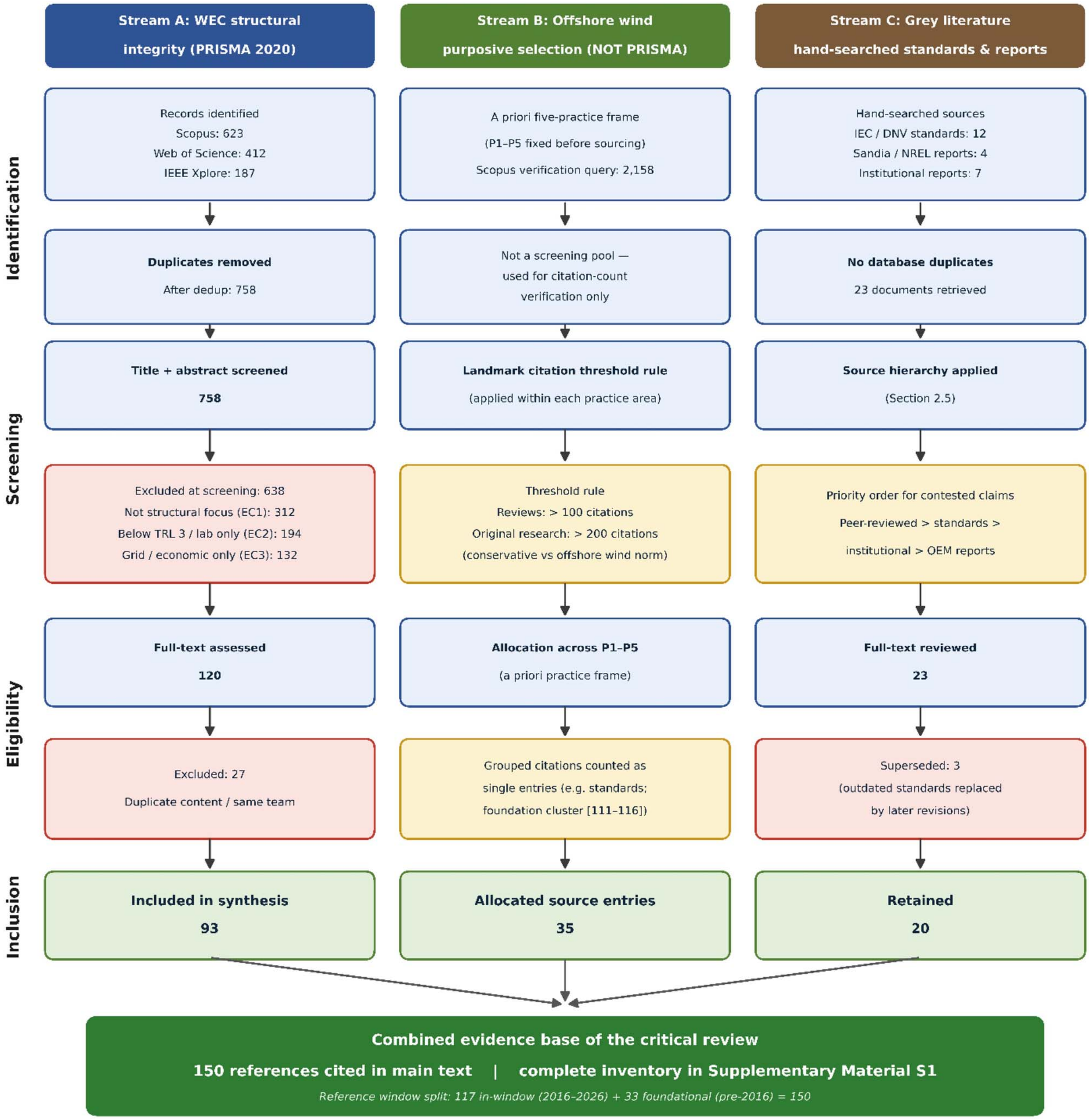


Figure 1 Three-column PRISMA flow diagram tracking the WEC systematic search (Stream A: 758 screened, 120 full-text, 93 included), the offshore-wind purposive selection (Stream B: 35 source entries), and hand-searched standards and reports (Stream C: 20 retained), combining into the review's 150 cited references (117 in-window, 33 foundational).

to small-scale laboratory investigations lacking full-scale relevance. Policy-focused or techno-economic studies were included only where they provided evidence of deployment outcomes or of the commercial consequences of structural failure. Records for which the authors could not obtain the full text despite multiple attempts were excluded and logged. The full PRISMA 2020 flow for Part A is reported in Fig. 1. Primary screening was performed by the first author and checked by the second author, with disagreements resolved by discussion against the explicit criteria. Because a coder-and-checker workflow does not yield independent per-rater decision vectors, Cohen's κ could not be computed from it directly; it was instead obtained from a separate retrospective exercise in which the two authors independently re-coded the full-text records as include or exclude, blind to the original decisions and to each other's ratings. This re-assessment covered 101 of the 120 full-text records; the 19 omitted records were all cases excluded at the full-text stage in the original screening and were not carried into the blind re-coding. Inter-rater agreement was almost perfect [Cohen's $\kappa = 0.86$, 95% CI (0.75, 0.97); observed agreement of 94.1%]. Because clear excludes are under-represented in the re-assessed set, giving an include-heavy prevalence (prevalence index 0.41) that can depress κ relative to raw agreement, the prevalence-and-bias-adjusted κ (PABAK = 0.88) and the low bias index (0.06) are reported as robustness checks; all three statistics lie in the "almost perfect" band. The six disagreements—borderline records that one author judged includable and the other excludable—were resolved by discussion as in the primary screening.

Part B: structured comparative review of offshore wind practices

Rationale for purposive selection

As noted in Section 2.1, the offshore wind literature is too large to be reviewed comprehensively within a single paper whose principal focus is WECs. A systematic review of offshore wind would, moreover, duplicate existing work [31, 35–39] without producing new insight into the target question of transferability to WECs. Part B therefore adopts a purposive selection strategy in which the sampling frame is determined a priori, by topic, rather than empirically, by keyword.

Practice areas identified a priori

Five practice areas were identified a priori, on the basis of prior familiarity with both literatures and of the published structural-integrity taxonomies [18, 31], as the offshore wind practices whose transferability to WECs is most often invoked in the literature:

- **P1** Quantitative reliability benchmarking (failure-rate and repair-time statistics)
- **P2** Standards-based structural design (IEC, DNV, and derived recommended practices)
- **P3** Condition monitoring and structural health monitoring
- **P4** Reliability-based fatigue design
- **P5** Coupled multi-physics analysis and design load case matrices

Digital-twin methodology, although cross-cutting, is treated as a subtopic within P3 rather than as a sixth practice, because its instrumentation and modeling dependencies are contiguous with second- and third-generation condition monitoring. This five-practice frame, fixed before Part B sourcing began, is the principal mechanism by which Part B limits post-hoc cherry-picking. Additional practices (for example, installation-vessel logistics; blade design; electrical balance-of-plant) were considered during the planning stage and excluded because their transferability to WECs is either negligible (blades have no direct WEC analog) or already well covered in existing marine-renewable literature.

Source selection within each practice area

Within each of the five practice areas, sources were selected to represent (i) the landmark foundational references most frequently cited by downstream work; (ii) the most recent authoritative review or state-of-the-art assessment; and (iii) where applicable, the relevant technical standards. Landmark status was operationalized using an adaptive citation threshold: Scopus citation counts of >100 for review articles and >200 for original research articles, relaxed for references published after 2022, which were eligible for inclusion below threshold where they provided essential current-generation coverage that no higher-cited reference supplied [40]. These thresholds are conservative relative to the offshore wind citation norm and are intended to identify references whose influence is consolidated rather than emerging, while the post-2022 exception prevents the rule from systematically excluding the most recent methodological advances. Where a practice area yielded multiple candidate landmarks (for example, P1 yielded the Carroll *et al.* study [31] and several derivative analyses), the most frequently cited was selected, with complementary sources retained to represent subsequent extension and verification. A Scopus query combining offshore-wind device descriptors and structural-topic keywords was used to generate the candidate pool (TITLE-ABS-KEY(("offshore wind" OR "offshore wind turbine") AND ("failure rate" OR "reliability" OR "fatigue" OR "monopile" OR "condition monitor*" OR "structural health" OR "digital twin"))); this returned 2158 records (Scopus; March 2026). The purpose of this query was not to generate a comprehensive screening pool but to support citation-count-based selection and to verify that no high-citation records outside the authors' prior knowledge had been overlooked. Application of citation thresholds and allocation across the five practice areas yielded the 35 allocated source entries used in Part B (corresponding to 53 individual references in Supplementary S1 when grouped clusters are expanded) (counting grouped citations such as the foundation-engineering cluster [41–46] and the DNV/IEC standards set as single entries within their assigned practice areas). The full list of Part B sources, with practice-area allocation and citation-count rationale, is provided in Supplementary Material S1 (sheet "Bibliography", Stream B entries).

Explicit acknowledgement of methodological limits

Part B is not a systematic review and the authors make no claim that its selection is exhaustive or fully reproducible. What is reproducible is the a priori practice frame, the citation-threshold rule, and the full list of sources. A different author team working from the same frame and thresholds would be expected to return a closely overlapping but not identical set; a fully systematic treatment of offshore wind structural integrity practices is a distinct research project and is not attempted here.

Grey literature: standards, reports, and source hierarchy

The review draws on technical standards and grey-literature reports alongside peer-reviewed sources. The sources consulted were standards from the International Electrotechnical Commission and Det Norske Veritas [47–58]; technical reports from the US Department of Energy national laboratories (Sandia, NREL) [59–62]; and industry and institutional reports from Ocean Energy Europe [5], the Carbon Trust [63], the World Forum Offshore Wind [3], EMEC, and Wave Energy Scotland [64], together with international benchmarking from GWEC [4], IEA-OES [65], and IRENA [66]. To mitigate the risk of overweighting non-peer-reviewed material, the review adopts an explicit source hierarchy for contested claims:

1) Peer-reviewed journal articles with independent replication or validation take priority.
2) Published technical standards from IEC and DNV take second priority, with currency of issue date considered (where a standard has been superseded, the most recent issue is cited and the previous issue referenced only where the older content remains methodologically relevant).
3) Government-laboratory technical reports (Sandia, NREL) take third priority for empirical content that is not yet peer-reviewed but is authored by funded laboratories with documented peer-review of their internal reports.
4) Trade-association and industry reports (OEE, Carbon Trust, WFO, GWEC, IEA-OES, IRENA) are used for statistical and contextual information that is not available in peer-reviewed form;

where a statistic is contested, the peer-reviewed source is preferred.

5) Developer press releases and corporate technical communications are used only for factual deployment information (device, location, date, rated capacity, status) and are not used as authority for interpretive or causal claims. Where a developer communication conflicts with a peer-reviewed retrospective account, the peer-reviewed account takes precedence and the conflict is noted.

Standards listed above were selected for inclusion on the basis of direct relevance to marine-energy or offshore-wind structural design; reports were selected on the basis of authoritative provenance and empirical content (for example, failure-rate databases, standards-gap analyses, or deployment-outcome summaries). The complete list of grey-literature sources, with organizational provenance and rationale for inclusion, is provided in Supplementary Material S1 (Stream C entries). The implications of this reliance on the open record for failure-mode coverage are discussed in Section 6.3.1.

Data extraction and failure-mode coding

For each included article, data were extracted on device type, deployment context, structural issue addressed, method employed, and findings relevant to the research questions. Where studies reported failure events, failure modes were coded using an adapted version of the Coe *et al.* taxonomy [18], covering mooring and anchoring, primary structure and hull, PTO mechanical interface, foundation or substructure (for bottom-mounted devices), control and end-stop systems, and secondary components such as power cables and sensors. Offshore wind failure data were coded using the Carroll *et al.* taxonomy [31], which separates minor repairs, major repairs, and major replacements. The WEC deployment-outcome inventory reported in Table 1 (Section 3) is constructed separately from the literature synthesis and carries its own coding protocol. Each entry was classified as F (structural or station-keeping failure contributing to project termination), D (premature decommissioning for non-structural or end-of-life reasons), O (currently operational or recently operational), or U (unknown or status ambiguous at the time of writing). The operational definitions and the source hierarchy used to resolve borderline cases are as follows:

- F requires documented evidence in a peer-reviewed retrospective account, a published incident report, or a developer communication explicitly attributing termination to structural or station-keeping causes. Where a project was terminated after a structural incident but the termination decision was also reported to be influenced by commercial or financial considerations, the code F is retained and the compound nature of the termination is recorded in the "Primary failure mode" column.
- D is assigned where termination is explicitly reported as commercial, end-of-operational-life, or programmatic, without an accompanying structural incident in the open literature. It does not imply the absence of structural issues during operation; it implies that no catastrophic structural event was the documented trigger.
- O is assigned where the device is reported as operational within the past eighteen months of the review cut-off (October 2024–March 2026) by at least one source in the hierarchy above.
- U is assigned where the status is ambiguous in the open literature or where a program has been publicly paused without an announced termination decision.

Table 1 classifications were performed by the first author and checked by the second author. The full inventory, with source attribution for each classification, rationale for borderline cases, and the authors' resolution where sources conflict, is provided in Supplementary Material S2. The limitations of this inventory—small sample size, reliance on publicly documented deployments, and the inherent interdependence of structural and commercial termination drivers—are discussed in Section 3.5 and summarized in the caveats below Table 1.

Synthesis approach

The synthesis adopts a two-stage structure. Section 3 addresses RQ1 by characterizing WEC failure patterns from the Part A literature and contrasting them with the early-development offshore wind experience as recorded in foundational references [67–69]. Sections 4 and 5 address RQ2 by presenting the five practice areas of Part B and subjecting each to a transferability assessment. Transferability is evaluated against four explicit criteria introduced in Section 1.3: (i) physical analogy (does the WEC load regime resemble the offshore wind regime closely enough for the practice to apply?); (ii) data availability (does the WEC sector have, or can it plausibly acquire, the data on which the offshore wind practice depends?); (iii) regulatory maturity (is there a standards framework within which the practice can be deployed?); and (iv) economic feasibility (is the practice proportionate to WEC capital costs?). A thematic classification of landmark references is provided in Table 2 (end of Section 4), and the transferability matrix is reported in Table 4 and discussed in Section 5.

Reproducibility, limitations, and supplementary material

The methodology described above has four explicit limitations that the authors wish to record openly rather than have pointed out by readers.

First, Part B is purposive. A different author team might select a slightly different landmark set within the five practice areas, and a different team might plausibly identify six or four practice areas rather than five. The authors consider that the a priori practice frame and the citation-threshold rule make the result stable at the level of headline conclusions, but not at the level of individual reference selection.

Second, primary screening in both Part A and Part B was performed by the first author and checked by the second author rather than by parallel independent rating. To address this, a retrospective blind dual re-assessment of the full-text stage was performed, yielding a Cohen's κ of 0.86 (almost perfect agreement on the Landis and Koch scale; Section 2.3.2). The residual methodological uncertainty is therefore concentrated not in Part A screening but in Part B source selection, which remains purposive by design.

Third, the deployment-outcome inventory (Table 1) is small. Twenty-six deployments are still too few to support formal reliability statistics in the sense of Carroll *et al.* [31], and the inventory is therefore presented as a structured descriptive instrument rather than as a statistical database. Indicators derived from it—the F-code share (7 of 26 tabulated deployments), for example—should be read as descriptive, not inferential.

Fourth, the review terminates in March 2026. Very recent publications, particularly those in press at the cut-off, may be incompletely represented. Where known references were in press at the cut-off

Table 1 Documented WEC deployments at prototype scale or above (TRL ≥ 5, rated capacity $\geq$10 kW) showing structural outcome.

Device	Developer	Type	Rated capacity	Test site	First deploy	Status	Outcome	Primary failure mode
Pelamis P1/P2	Pelamis Wave Power	Attenuator	750 kW	EMEC, UK	2004/2010	Terminated 2014	F	Mooring/hinge-joint structural
Oyster 800	Aquamarine Power	Oscillating surge	800 kW	EMEC, UK	2012	Terminated 2015	F	Structural and commercial
Wavebob	Wavebob Ltd	Point absorber	250 kW (demo)	Galway Bay, Ireland	2007	Dissolved 2013	F	Commercial following demonstrator issues
Oceanlinx Mk3	Oceanlinx	OWC	1 MW	Port Kembla, Australia	2014	Company liquidated 2014	F	Foundation/towing
Pico OWC	Pico Plant consortium	Fixed OWC	400 kW	Azores, Portugal	1999	Decommissioned 2018	D	Long-service; storm damage recorded 2016
LIMPET	Voith Hydro Wavegen	Fixed OWC	500 kW	Islay, Scotland	2000	Decommissioned 2018	D	End of operational life
CETO 5/6	Carnegie Clean Energy	Submerged PA	240 kW/1 MW	Garden Island, Australia	2014/2018+	Program paused	U	Commercial; partial deployments
Penguin WEC	Wello Oy	Asymmetric rotating	500 kW (design)	EMEC, UK	2012	Lost at sea 2018	F	Mooring/station-keeping
C3/C4 (CorPower)	CorPower Ocean	Point absorber	300 kW	Aguçadoura, Portugal	2018/2023	Ongoing	O	— (monitoring in progress)
WaveStar C5	Wave Star A/S	Multi-point absorber	600 kW (full)	Hanstholm, Denmark	2009	Decommissioned 2013	D	Commercial
Islay OWC (Voith)	Voith (predecessor)	Fixed OWC	250 kW	Islay, Scotland	1991	Decommissioned	D	End of life
Mighty Whale	JAMSTEC	Floating OWC	110 kW	Gokasho Bay, Japan	1998	Decommissioned 2002	D	Research program conclusion
OceanEnergy OE35	OceanEnergy Ltd	Floating OWC	500 kW (grid)	WETS, Hawaii/Ireland	2021	Ongoing	O	—
Mocean Blue X	Mocean Energy	Hinged-raft attenuator	10 kW (demo)	EMEC, UK	2021	Ongoing	O	—
Marmok-A-5	IDOM/Oceantec	Floating OWC	30 kW (demo)	BiMEP, Spain	2016	Ongoing (program paused)	U	—
Laminaria WEC	Laminaria	Multi-DOF submerged	200 kW (demo)	EMEC, UK	2019	Program continuing	O	—
Bombora mWave	Bombora Wave Power	Flexible membrane	1.5 MW (commercial design)	Peniche, Portugal	2023+	Ongoing	O	—
Oscilla Power Triton	Oscilla Power	Heave–surge PA	400 kW (demo)	Hawaii, USA	2023	Ongoing	O	—
Eco Wave Power (Gibraltar)	Eco Wave Power	Shoreline flap	100 kW (grid)	Gibraltar	2016	Ongoing	O	—
Toftestallen OWC	Kvaerner Brug	Fixed OWC	500 kW	Toftestallen, Norway	1985	Destroyed 1988	F	Foundation: steel–concrete bolted-connection failure in storm
Tapchan	Norwave A/S	Overtopping (tapered channel)	350 kW	Toftestallen, Norway	1985	Destroyed (late 1980s)	F	Storm damage to channel/reservoir structure
Wave Dragon (NB)	Wave Dragon ApS	Floating overtopping	~20 kW (1:4.5 prototype)	Nissum Bredning, Denmark	2003	Decommissioned post-2005	D	Storm/mooring incident 2005; program wind-down
Archimedes Wave Swing	Teamwork Technology/AWS	Submerged point absorber	2 MW	Aguçadoura, Portugal	2004	Decommissioned 2004	D	Submergence/installation stability
Mutriku	EVE/Voith Hydro	Breakwater OWC	296 kW	Mutriku, Spain	2011	Operational	O	— (operational since 2011)
OPT PB150	Ocean Power Technologies	Point absorber	150 kW	Invergordon, Scotland	2011	Program ended	D	Programmatic; Reedsport array not completed
Seabased Sotenäs	Seabased/Fortum	Point-absorber array (36 units)	~1 MW	Sotenäs, Sweden	2015	Closed ~2018	D	Funding-driven closure; deployment difficulties

Note: Compiled from Coe *et al.* [18], Sheng [6], Guo and Ringwood [1], Ocean Energy Europe [5], and developer press releases. Outcome codes: O = operational or recently operational; F = structural failure contributing to project termination; D = premature decommissioning for non-structural commercial reasons; U = unknown/under deployment at time of writing.

Table 2 Thematic classification of landmark references: theme, key finding, and limitation.

#	Reference	Section(s)	Theme	Key finding (as cited in this review)	Limitation/gap
1	B. Guo and J. V. Ringwood (2021) [2]	1.1, 3.1	WEC deployment record	Review of wave energy technology from a research and commercial perspective	Review/synthesis article; empirical contribution is the categorization rather than primary data
2	W. Sheng (2019) [6]	1.1, 3.1, 3.5, 4.1	WEC vs early offshore wind comparison	Review of wave energy conversion and hydrodynamics modeling technologies: a review	Review/synthesis article; empirical contribution is the categorization rather than primary data
3	R. G. Coe, Y. H. Yu, and J. van Rij (2018) [18]	1.1, 3.1, 3.2, 3.5, 4.1, 4.6, 6.2	Pathway I—extreme-event failure	Three-pathway failure taxonomy (extreme/fatigue/interface) adopted as organizing framework for the sector	Qualitative synthesis; no quantitative fleet statistics
4	E. J. Ransley *et al.* (2017) [71]	3.2, 4.6	Pathway I—extreme-event failure	OpenFOAM focused-wave CFD loads on cylinder and hemispherical point absorber exceed linear theory by factors of 2–4	Single geometry per study; no multi-directional sea states
5	C. Windt *et al.* (2018) [72]	3.2, 4.3, 4.6	Pathway I—extreme-event failure	CFD-based numerical wave tanks for WEC are mature but computationally prohibitive for full DLC campaigns	Does not resolve the accuracy–cost trade-off
6	E. Katsidoniotaki *et al.* (2022) [73]	3.2, 4.3	Pathway I—extreme-event failure	Loads on a point-absorber WEC in extreme waves	Single-study contribution; independent replication across teams/devices not yet established
7	P. R. Thies *et al.* (2014) [80]	3.3, 3.5, 4.4, 4.6	Pathway II—fatigue/mooring	Field tension measurements from SWMTF reveal factor-of-12 fatigue-life variation across nominally similar mooring configurations	Single site; short monitoring period
8	S. H. Yang *et al.* (2017) [84]	3.3, 3.4, 4.6	Pathway II—fatigue/mooring	Biofouling can reduce mooring fatigue life by ∼80% and annual energy by ∼20% at a North Sea WEC site	Numerical only; experimental validation limited
9	M. Hann, D. Greaves, and A. Raby (2015) [34]	3.3, 4.6	Pathway II—fatigue/mooring	Experimental focused-wave groups produce mooring snap tensions exceeding 3× the nominal mean	Wave-basin only; one mooring configuration
10	J. Davidson and J. V. Ringwood (2017) [89]	3.3, 4.6	Pathway II—fatigue/mooring	Descriptive review of mooring modeling approaches (lumped-mass, FE, quasi-static, CFD)	No comparative benchmarking across codes
11	S. Xu *et al.* (2019) [90]	3.3, 4.6	Pathway II—fatigue/mooring	Comprehensive review of WEC mooring design and its proliferation of incompatible approaches	Descriptive synthesis; round-robin validation absent
12	M. Penalba *et al.* (2017) [107]	4.1, 4.3, 4.6	P1—reliability benchmarking	Review of mathematical modeling of wave energy converters: nonlinear approaches	Review/synthesis article; empirical contribution is the categorization rather than primary data
13	P. R. Thies *et al.* (2012) [92]	3.4, 4.6	Pathway III—interface/secondary	First methodology for power-cable mechanical-load and fatigue-life assessment for floating marine energy	Laboratory rig; no full-scale operational validation
14	Y. Liu, G. Xu *et al.* (2023) [23]	1.1, 3.4, 3.5, 4.1, 4.6, 5.3	Pathway III—interface/secondary	Survey of fault-diagnosis and fault-tolerant control methods for WECs	Review only; deployment-ready implementations absent
15	G. Papini *et al.* (2024) [106]	4.1, 4.6, 5.3	P1—reliability benchmarking	Fault-tolerant PTO control strategies for WECs	Simulation-level; hardware demonstration pending
16	J. Carroll *et al.* (2016) [31]	1.1, 3.1, 4.1, 4.6, 6.2	P1—reliability benchmarking	8.3 failures per turbine-year across ∼350 multi-MW offshore turbines over 1768 turbine-years (6.2 minor +1.1 major +0.3 replacement)	Single consortium data; repair/cost allocation proprietary

(continued)

Table 2 Continued.

#	Reference	Section(s)	Theme	Key finding (as cited in this review)	Limitation/gap
17	J. Carroll *et al.* (2017) [35]	4.1, 4.6	P1—reliability benchmarking	O&M accounts for ∼30% of offshore wind LCOE; failure-rate assumptions dominate cost projection	Derived from same dataset as [31]; not independent
18	H. A. Said and J. V. Ringwood (2021) [93]	3.4	Pathway III—interface/secondary	Grid integration aspects of wave energy—overview and perspectives	Single-study contribution; independent replication across teams/devices not yet established
19	L. Arany *et al.* (2017) [94]	3.5, 4.2, 4.4, 4.6	WEC vs early offshore wind comparison	10-step monopile design procedure; serviceability (not ultimate) limit state is dimension-governing	Legacy onshore-turbine SLS assumptions not fully justified from first principles
20	S. Ambühl *et al.* (2015) [109]	4.2, 4.4, 4.6, 6.2	P2—standards-based design	Calibrated fatigue design factors for WECs differ materially from those imported from offshore wind or oil and gas	Single device (Wavestar); welded and bolted details only
21	International Electrotechnical Commission *et al.* (2019) [51]	4.2, 6.2	P2—standards-based design	Specifies design requirements for IEC TS 62600-2: marine energy—design requirements for marine energy systems	Technical specification rather than full standard in the WEC context; relies on cross-reference to adjacent sectors
22	W. Yang *et al.* (2014) [96]	3.5, 4.3, 4.6	WEC vs early offshore wind comparison	Vibration-based condition monitoring established as primary wind-turbine monitoring discipline	Pre-SCADA era; drivetrain focus only
23	P. Tchakoua *et al.* (2014) [97]	3.5, 4.3	WEC vs early offshore wind comparison	Comprehensive review of wind turbine condition monitoring: state-of-the-art review, new trends, and future challenges	Review/synthesis article; empirical contribution is the categorization rather than primary data
24	M. Martinez-Luengo *et al.* (2016) [98]	3.5, 4.3	WEC vs early offshore wind comparison	Review of structural health monitoring of offshore wind turbines: a review through the statistical pattern recognition paradigm	Review/synthesis article; empirical contribution is the categorization rather than primary data
25	A. Stetco *et al.* (2019) [99]	3.5, 4.3, 4.6, 5.3	WEC vs early offshore wind comparison	Machine-learning methods applied to wind-turbine condition monitoring	Fleet-size dependent; not transferable to pre-commercial WEC sector
26	E. Branlard *et al.* (2024) [40]	3.5, 4.3, 4.5, 4.6, 5.2, 5.3, 6.1, 6.2	WEC vs early offshore wind comparison	Kalman-filter-based digital twin validated against full-scale TetraSpar floating prototype SCADA data	Single prototype; limited operating-condition coverage
27	J. Velarde *et al.* (2020) [121]	4.4, 4.6	P4—reliability-based fatigue	Thickness effect becomes a dimensioning consideration for large-diameter monopile fatigue design	Specific to monopile geometry
28	J. T. Horn and B. J. Leira (2019) [122]	4.4, 4.6	P4—reliability-based fatigue	Reliability treatment of offshore wind turbines extended to stochastic availability	Offshore-wind specific; WEC transfer not attempted
29	E. J. Ransley *et al.* (2019) [132]	4.5	P5—coupled analysis	A blind comparative study of focused wave interactions with a fixed FPSO-like structure (CCP-WSI Blind Test Series 1)	Single-study contribution; independent replication across teams/devices not yet established
30	F. F. Wendt *et al.* (2019) [133]	4.5	P5—coupled analysis	Ocean Energy Systems wave energy modeling task 10	Single-study contribution; independent replication across teams/devices not yet established

Note: Entries cross-referenced to manuscript sections and to the failure-pathway framework of Fig. 2 (Pathways I–III, WEC evidence) and the practice-area frame of Section 2.4.2 (P1–P5, offshore wind). The table is deliberately restricted to landmark references for readability. Three patterns visible across the 30 entries motivate the synthesis that follows in Section 5. First, Part A entries covering Pathways I–III (rows 2–15) are dominated by numerical methods applied to single devices or single sites, with limited multi-device or multi-site validation—a limitation pattern that explains why the WEC sector has not yet produced reliability benchmarks comparable to those of offshore wind. Second, Part B offshore-wind practice entries (rows 16–30) are dominated by methodology that has been validated at fleet scale, which is precisely the resource the WEC sector lacks. Third, across both parts, the most frequent limitation reported is not a methodological error but a restriction of the evidentiary base (single device, single site, single code, review-only), consistent with a sector that is still acquiring the empirical foundation its practice requires.

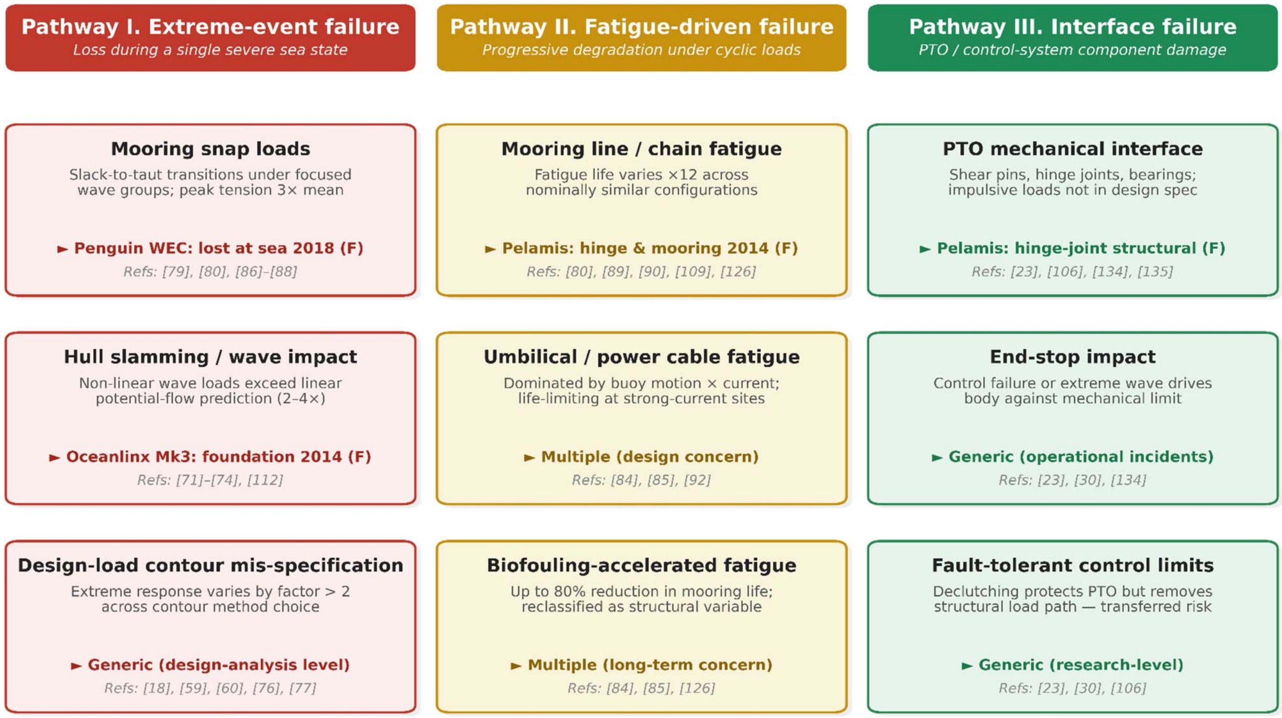


Figure 2 Three-column taxonomy of WEC structural failure modes—extreme-event failure (e.g. mooring snap loads, hull slamming), fatigue-driven failure (e.g. mooring and umbilical fatigue), and interface failure (e.g. PTO and end-stop damage)—with representative failed devices named.

their available metadata is recorded in Supplementary Material S1 with the status flag.

Wave energy converter structural failure patterns: evidence from 2016–2026

The empirical record

Two observations dominate the structural integrity record of the wave energy sector between 2016 and 2026. The first is that the number of full-scale deployments remains small, so that the statistical base for quantitative failure-rate estimation is unavoidably thin. The second is that, where deployment has occurred, structural or station-keeping failures have recurred across almost every major device archetype, and their consequences have repeatedly been disproportionate—loss of the device, loss of the developer, or both [6, 18]. The combination of sparse data and severe consequences appears to account, at least in part, for why the WEC literature of the past decade has emphasized survivability analysis, extreme-response prediction, and mooring design alongside—and in some cases ahead of—hydrodynamic optimization [70]. The foundational reliability survey by Coe *et al.* [18], drawing on the combined engineering experience of Sandia National Laboratories and the US National Renewable Energy Laboratory, identified three structurally distinct failure pathways that remain the organizing framework for the decade that followed: extreme-event failure (loss of the device during a single storm), fatigue-driven failure (progressive degradation of cyclically loaded components, particularly mooring and power-umbilical systems), and interface failure (damage to power-take-off or control components arising from unanticipated structural response). The 2016–2026 literature supplies new empirical content for each pathway without fundamentally altering the taxonomy. Figure 2 summarizes this three-pathway taxonomy together with the device-level evidence from Table 1.

Summary statistics. Of the 26 deployments tabulated, 8 are currently operational or recently operational (O), 2 have ambiguous or paused status (U), and 16 have been terminated; of the terminated deployments, 7 are coded F (structural or station-keeping failure contributing to termination) and 9 are coded D (decommissioning for non-structural or end-of-life reasons). As descriptive, non-inferential indicators, F-coded deployments represent 7 of 26 tabulated deployments and 7 of 16 terminated deployments. The inventory has been extended retrospectively to the first full-scale European prototypes of the mid-1980s (caveat 6); the F-share is essentially unchanged from the smaller 2016-window baseline of 5 of 19, which indicates that the descriptive failure indicator is stable to inclusion of the foundational historical record rather than an artifact of a small sample. Coding is provided by the authors using the protocol described in Section 2.6 and Supplementary Material S2; the F/D boundary depends on the relative contribution of structural causes versus commercial or end-of-life considerations to the termination decision, and in several cases both contributed (see caveat 1 below).

Caveats and limitations of the inventory. (i) Classification of F versus D involves author judgment, as several projects listed as D experienced structural or operational difficulties that contributed to the commercial decision to decommission even where no single catastrophic failure can be isolated. Two of the D-coded entries illustrate this judgment directly: the Pico OWC sustained storm damage in 2016 yet remained in service until its 2018 end-of-life decommissioning, while the Archimedes Wave Swing prototype encountered submergence and installation-stability difficulties. These are retained as D because no catastrophic in-service structural failure was the documented termination trigger, but both are acknowledged as borderline F/D cases whose classification a reader may reasonably contest. The coding protocol, source hierarchy, and decisions for borderline cases are provided as Supplementary Material S2. (ii) The inventory is confined to publicly documented deployments reported in peer-reviewed literature, standards or regulatory documents, and developer communications. Proprietary developer testing and deployments not reported in the open literature are omitted. (iii) The sample size is small relative to formal reliability analysis of the kind produced for offshore wind [31]; the percentages reported should be read as descriptive indicators rather than as statistical estimates of population failure rate. Recent deployments (2021 onwards) are classified primarily on developer communications (Tier 5 sources in the S2 hierarchy) pending peer-reviewed retrospective analysis; such classifications are flagged borderline in Supplementary S2 Sheet 7. This limitation is further developed in Section 3.5 and Section 6.3. 4. "Structural failure" (F) covers both primary-structure damage and station-keeping (mooring) failures, consistent with the failure taxonomy adopted in Section 3. 5. The boundary between "terminated" projects and "paused" or "restructured" commercial programs is inherently fluid; several entries coded D reflect commercial dissolutions that followed sustained operational difficulties, and the inventory does not imply that the commercial failure and the structural performance are independent events. 6. The inventory is extended retrospectively to 1985 to incorporate foundational full-scale European prototypes (for example, the Toftestallen oscillating-water-column and Tapchan plants, the Wave Dragon and Archimedes Wave Swing prototypes, and the Mutriku breakwater plant); these pre-window entries are descriptive context only and were not part of the Part A systematic screen, which is confined to the 2016–2026 window.

Extreme-event failure and the problem of design loads

The consensus of the 2016–2026 CFD and experimental literature is that WEC survival-condition loads are dominated by strongly nonlinear wave–structure interactions that are inadequately captured by the linear potential-flow models still widely used in design [71–74]; this conclusion rests on the numerical-methods foundations synthesized earlier by Li and Yu [75]. Ransley *et al.* [71] demonstrated using OpenFOAM-based simulations of focused-wave impacts on a truncated cylinder and a hemispherical point absorber that peak structural loads under focused-wave events can exceed linear-theory predictions substantially, and that higher-order wave formulations and accurate free-surface treatment are essential to reproducing the loading. Windt *et al.* [72] reviewed CFD-based numerical wave tank techniques for WECs and concluded that while the methods had matured to the point of operational usefulness, their computational cost continued to preclude their routine use in full design-load-case campaigns. The environmental contour approach, which reduces the multidimensional joint distribution of sea-state parameters to a representative curve for design-condition selection, has been extensively debated in the 2016–2026 period [18, 76, 77]. Edwards and Coe [77], comparing five contour methods applied to the Reference Model 3 point absorber, found that extreme PTO force predictions varied by more than a factor of two depending on contour selection alone, and that this variation exceeded the uncertainty introduced by choice of structural model for most load cases. This finding is structurally significant: it implies that design-load uncertainty at the environmental-description stage can dominate the subsequent structural analysis, and that apparent convergence between competing structural models may mask the upstream ambiguity. A distinct but related literature has concentrated on survival strategies that reduce the design load rather than withstand it. Wavestar-type submergence during extreme sea states [78] and the active-mooring peak-load mitigation concept of Luxmoore *et al.* [79] exemplify this approach. Luxmoore *et al.* [79] demonstrated on a physical test rig that an intelligent active mooring system can reduce peak mooring tensions by roughly 50% without compromising minimum breaking load, and provided the first systematic reliability qualification of such a system outside the oil and gas industry. The success of the approach, however, is conditional on predictive control of sea-state evolution, which remains a research-level capability.

Fatigue and mooring: the persistent dominant failure mode

Mooring-system fatigue is the failure mode for which the 2016–2026 literature provides the most consistent empirical signal. The field measurements of Thies *et al.* [80], while falling just outside the formal search window, remain the benchmark study against which subsequent numerical work has been calibrated. Thies *et al.*'s [80] analysis of mooring-line tensions from the South West Mooring Test Facility quantified accumulated fatigue damage under site-specific wave climates and showed that predicted fatigue life could vary by a factor of twelve between mooring configurations that were superficially similar. Complementary experimental and numerical investigations by Paredes *et al.* [81], Palm *et al.* [82], and Harnois *et al.* [83] have since established the validation baseline for the software tools now in routine use. Later studies have extended this finding in two directions.

First, the role of biofouling on mooring-line and umbilical fatigue life has been demonstrated numerically to be disproportionately large. Yang *et al.* [84], applying a coupled hydrodynamic–structural model to a WEC system under operational sea states at a North Sea site, reported that biofouling growth could reduce mooring-line fatigue life by ∼80% while simultaneously reducing annual energy output by up to 20%. The same study [84] reports parallel findings for power cables and for taut-moored configurations, with the latter subsequently validated against experimental data by the same group [85]. These findings indicate that biofouling, conventionally treated as an operational nuisance, should be reclassified as a structural-integrity variable comparable in effect to sea-state severity.

Second, the treatment of mooring snap loads, where a slack line becomes suddenly taut, has moved from a recognized concern to a quantitatively characterized phenomenon. Hann *et al.* [34] first demonstrated experimentally that snap loads under focused-wave groups could exceed the nominal mean tension by factors of three or more. Subsequent analytical and experimental work [86–88] has confirmed the prevalence of snap events in both slack and hybrid mooring configurations, and has shown that mixture-distribution statistical models substantially outperform single-distribution fits of rainflow-counted tension amplitudes for fatigue-damage estimation. The contribution of snap loading to accumulated mooring fatigue damage has consistently been found to exceed that predicted by frequency-domain or quasi-static methods.

The mathematical modeling review of Davidson and Ringwood [89] and the comprehensive mooring design review of Xu *et al.* [90]

collectively map the proliferation of mooring modeling approaches—lumped-mass, finite-element, quasi-static, and coupled CFD formulations—and make the critical point that method selection continues to be determined more by legacy and software availability than by demonstrated fitness for the problem. The lack of round-robin validation across codes is a methodological weakness of the sector that the offshore wind community has, by contrast, begun to address systematically through initiatives such as the IEA Wind Task 30 OC series. The comparative numerical study of Touzon *et al.* [91] represents a first step in this direction for the WEC mooring community, but remains an exception rather than the norm.

Interface and secondary-component failure

Failures at the interface between the primary structure and the power-take-off, and of secondary components such as power umbilicals, sensors, and hatches, have received less attention than mooring but are arguably responsible for a larger share of downtime-inducing incidents when judged against the limited available operational records. Thies *et al.* [92] first identified power-cable fatigue as a critical failure mode for floating marine energy systems and established methodology for mechanical-load and fatigue-life assessment that has guided subsequent work. Yang *et al.* [84] extended this framework by coupling the hydrodynamic response of the moored buoy to a parallel fatigue assessment of the power cable, showing that cable fatigue life is strongly sensitive to current loading and biofouling growth, and that in sites with strong tidal flows the cable rather than the mooring may become the life-limiting component. The downstream grid-integration interface—where umbilical reliability ultimately determines revenue continuity—is reviewed comprehensively by Said and Ringwood [93].

The so-called end-stop problem, in which control-system failure or extreme waves drive the oscillating body against its mechanical limit, is structurally analogous to snap loading in moorings: a nominally low-energy event concentrated in a short time window that transmits impulsive loads to components not designed for them. The review of fault detection and control methodologies for WEC systems by Mortazavizadeh *et al.* [23] in *Energies* surveys the growing literature on fault-tolerant control, in which the PTO is reconfigured in response to detected abnormalities to protect the primary structure. Fault-tolerant control remains a research-level capability; its practical deployment requires a level of sensor integration and model fidelity that has so far been demonstrated only in laboratory or simulation environments.

Comparison with the early offshore-wind failure record

The critical question RQ1 poses is whether WEC structural failure patterns in the 2016–2026 decade resemble those recorded during the early development of offshore wind, and the comparison—set out schematically in Fig. 3—yields a nuanced answer. Three parallels emerge clearly.

First, the dominance of subsystem failure over primary-structure failure is common to both sectors. The early offshore wind reliability surveys of Tavner *et al.* [67], Ribrant and Bertling [68], and Faulstich *et al.* [69], all foundational pre-window references, together with subsequent reviews [36–38], converged on the finding that blade, gearbox, generator, and converter failures dominated the failure-count record, while catastrophic tower or foundation failures were rare. The WEC record, to the extent that the available evidence permits an analogous tabulation [6, 16], shows an equivalent pattern: mooring, umbilical, and PTO-interface failures dominate the count, and catastrophic loss of the primary hull is a rarer event, typically associated with mooring-system failure as a proximate cause rather than with primary-structure collapse. The structural and economic implication is that improving commercial viability in both sectors has depended less on oversizing the primary structure than on reducing the failure rate of interface components.

Second, the gap between design load assumptions and observed loads has been an enduring concern in both sectors. The 10-step monopile design procedure of Arany *et al.* [94] explicitly identifies serviceability limit states, rather than ultimate limit states, as the dimension-governing requirement for offshore wind monopiles, and notes that the originating SLS requirements may derive from legacy onshore turbine practice rather than from first-principles offshore engineering [95]. The WEC analog is the over-sensitivity of fatigue-life estimates to environmental-contour selection [77] and to mooring-configuration choice [80]. In both sectors, the underlying problem is that design basis documents codify methods whose empirical validation is still in progress.

Third, both sectors have converged on condition monitoring and, latterly, digital-twin methodologies as the operational response to residual failure risk that cannot be eliminated by structural redesign. Offshore wind arrived at this response earlier [96–99] and is now implementing it at scale [40, 100, 101]. Parallel methodology is emerging rapidly in the adjacent floating offshore wind sector [102, 103], and the WEC community has begun to engage with comparable approaches at review level [23], though full deployment remains some years behind.

A single important asymmetry must be recorded. The offshore wind sector developed its structural integrity practices in parallel with a fleet growth rate that guaranteed statistical populations of turbines sufficient to support reliability benchmarking by 2010. The WEC sector has not experienced equivalent fleet growth; its statistical base for quantitative reliability analysis is still essentially pre-commercial. This asymmetry determines which offshore wind practices are transferable to WECs and which are not, and it is the central subject of Section 4.

Structural integrity practices from offshore wind: a critical inventory

Quantitative reliability benchmarking

The single most consequential contribution of the offshore wind sector to its own commercial maturation has been the generation of publishable, large-sample reliability statistics. The seminal Carroll *et al.* [31] study, drawing on operational data from ∼350 modern multi-MW offshore turbines across 5 to 10 European wind farms over 1768 turbine-years, reported an overall failure rate of 8.3 failures per turbine per year, decomposed into 6.2 minor repairs, 1.1 major repairs, and 0.3 major replacements. The corresponding O&M cost analysis by the same authors [35] showed that O&M can account for 30% of offshore wind lifetime LCOE and that failure-rate assumptions dominate O&M-cost projections. Subsequent work has refined these estimates [36–38] and extended them to 15 MW turbines [104] and to floating offshore wind [105]. Reviews of reliability, availability, and maintainability across both offshore wind and tidal applications [39] confirm that the discipline of standardized failure reporting has become a prerequisite for commercial maturation.

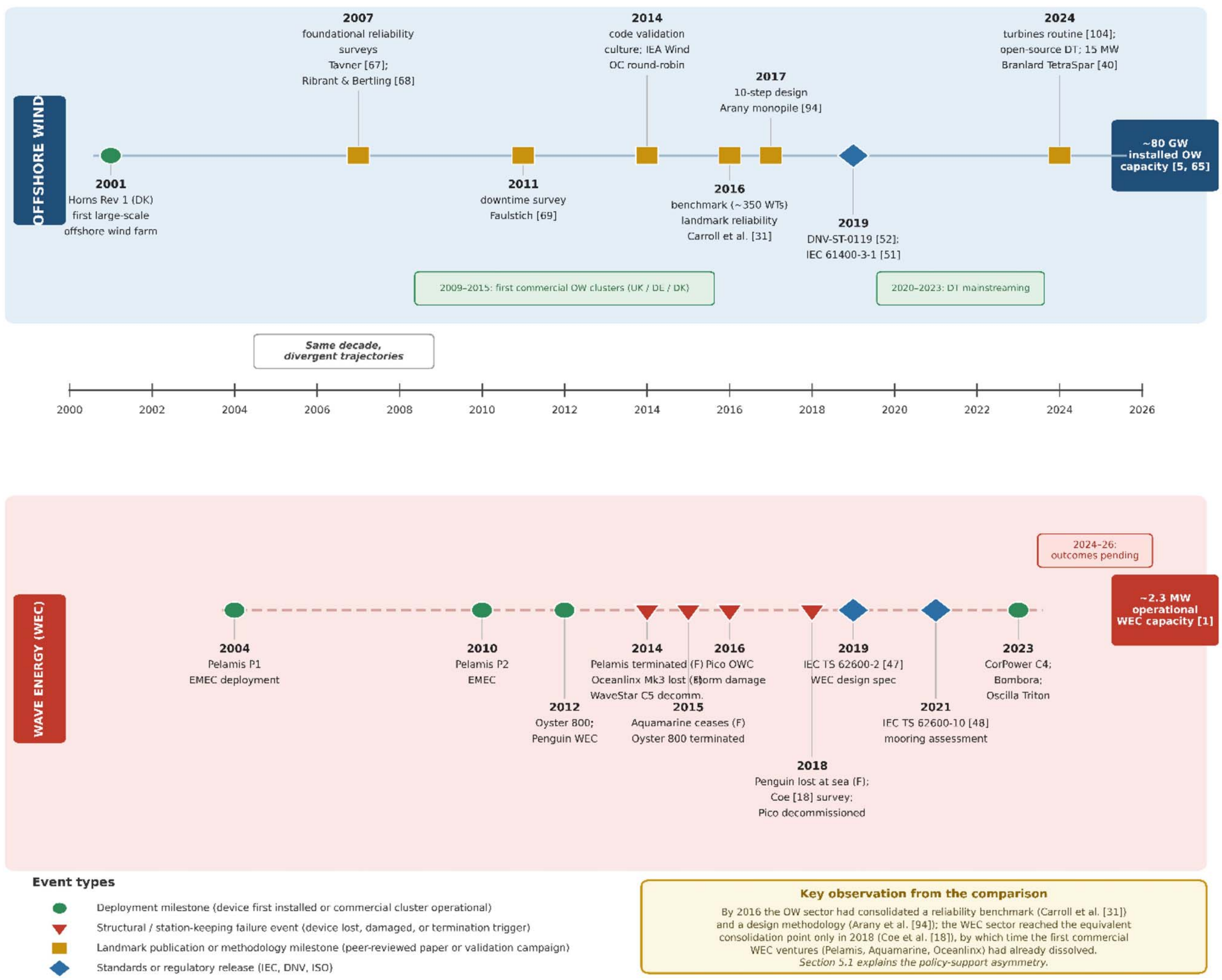


Figure 3 Dual-band 2000–2026 timeline comparing offshore wind (upper) and wave energy (lower), marking deployments, failures, key publications, and standards. Offshore wind consolidated reliability methods by about 2016 (~80 GW); wave energy reached a comparable point only by about 2018, after several flagship devices had failed (~2.3 MW).

The transferability of this practice to WECs is, in principle, high: the methodology depends on a consistent failure-event taxonomy and a sufficiently large fleet-hour database, both of which are intellectually rather than technologically demanding to reproduce. In practice the transferability is low, because the WEC sector has no fleet that would yield comparable operational hours. The 2.31 MW of operational wave energy capacity reported for 2021 [6] citing Ocean Energy Europe statistics is two orders of magnitude below the threshold at which failure statistics of the Carroll *et al.* type become meaningful. The WEC sector has no realistic prospect of duplicating the offshore wind benchmarking approach within the next decade at current deployment rates. What is transferable is the "discipline" of the approach: the use of a common failure taxonomy, the separation of minor repairs, major repairs, and major replacements, and the linkage of failure rate data to LCOE projection. The reliability survey of Coe *et al.* [18] adopts this discipline qualitatively; the systematic reviews that would complete the program for the WEC sector [23, 106] on condition monitoring are recent and still limited in scope. A near-term priority for the WEC community, identifiable from this comparison alone, and echoed in multiple recent reviews [17, 23, 106, 107], is the establishment of a voluntary failure-reporting consortium analogous to that which generated the Carroll *et al.* dataset, even if it operates at an order of magnitude smaller scale.

Standards-based design with a long operational history

Offshore wind structural design is anchored in a small number of widely adopted standards: IEC 61400-3-1 for fixed-bottom turbines [51], DNV-ST-0119 [52] and DNV-RP-0286 [58] for floating structures, DNV-RP-C205 [56] for environmental loads, and DNVGL-RP-0416 [57] for corrosion protection. Position mooring is governed by DNV-OS-E301 [53] with chain-specific provisions in DNVGL-OS-E302 [54], and DNVGL-ST-0164 [55] for tidal turbines is the closest WEC analog. These documents embody decades of offshore platform experience, adapted for the specific loading and fatigue regime of wind turbines. The 10-step monopile design procedure of Arany *et al.* [94] and its precursors [108] operationalize the standards into engineering practice, supported by an extensive foundation-engineering literature [41–46] that documents the calibration of these methods against field data. The WEC standards framework is comparatively thin. IEC TS 62600-2 [47] codifies design requirements for marine energy systems and IEC TS

62600-10 [48] addresses mooring assessment, but the documents are technical specifications rather than full standards and rely extensively on cross-reference to oil and gas or offshore wind codes. Where WEC-specific design values diverge from these borrowed sources—notably for fatigue safety factors on mooring components, on which the work of Ambühl *et al.* [109] has provided an empirical foundation—the divergence is not yet codified in accessible standards.

The transferability assessment for this practice is partial. The principle of standards-based design transfers fully and has already been instantiated in the IEC TS 62600 series. The specific content of offshore wind standards transfers only where the load regime justifies it. Cyclic fatigue loading on steel structures is sufficiently similar in mechanism across the two sectors that S–N curves and safety-factor methodologies borrow well; extreme wave loading on floating, hydrodynamically active bodies is not closely analogous to the blade-rotor-tower coupled response of a wind turbine, and direct borrowing is inappropriate. The landscaping study of Wave Energy Scotland [64] is a constructive attempt to identify where gaps in WEC-specific guidance are most acute, and suggests that structural forces on PTO-interface components and on overtopping structures are under-served by the current standards.

Condition monitoring and digital-twin methodology

Offshore wind condition monitoring has evolved through three generations [38, 96–98]. The first generation, dominated by vibration monitoring of main bearings and gearboxes, established the vocabulary and the commercial business model. The second generation, grounded in Supervisory Control and Data Acquisition (SCADA)-based statistical anomaly detection, dramatically reduced cost per turbine and enabled fleet-wide deployment [99, 110]. The third generation, now in active development, integrates physics-based digital twins with operational data to produce real-time estimates of load history, fatigue accumulation, and remaining useful life [40, 100, 101, 111]. Branlard *et al.* [40] validated a Kalman-filter-based digital twin against measurements from the full-scale TetraSpar floating prototype and demonstrated the feasibility of real-time tower-load estimation from standard SCADA signals. The transferability of the three generations differs markedly. First-generation vibration monitoring transfers directly to WEC drivetrains; commercial hardware is available and the cost per device is proportionate even for small fleets. Second-generation SCADA-based statistical monitoring transfers in principle but is constrained by the WEC sector's limited volume of historical operational data, which is the statistical resource on which the second generation depends. Third-generation digital-twin methodologies, originating in the aerospace structural-life-prediction literature [112], transfer conceptually and offer a compelling near-term opportunity for the WEC sector precisely because their physics-based component can be validated against low-volume, high-fidelity prototype data, an approach that is difficult to apply in mature industries with established statistical baselines. This asymmetry maps directly onto the two landmark references of Table 2: the fleet-dependent machine-learning monitoring surveyed by Stetco *et al.* [99] exemplifies the data-driven mode that does not transfer to the pre-commercial WEC sector, whereas the physics-based prototype digital twin of Branlard *et al.* [40] exemplifies the mode that does. The recent floating offshore wind digital-twin literature [113–119] provides a template and, in the open-source TetraSpar implementation of Branlard *et al.* [40], a concrete starting point. A caveat is necessary. The verification of physics-based digital twins depends on the accuracy of the underlying numerical model, and the nonlinear nature of WEC hydrodynamic response at survival conditions—precisely the conditions at which monitoring matters most—pushes current models to their limits [72, 74, 107]. Digital-twin methodology is transferable, but the numerical modeling infrastructure on which it depends requires further maturation for the WEC case.

Fatigue design for ultra-high-cycle regimes

Offshore wind monopiles operate in the ultra-high-cycle fatigue regime, with cycles to failure typically exceeding 10^8 over a 20-to-25-year design life [94, 120, 121]. Fatigue design guidance has been adapted from oil and gas S–N curves through industry joint-development projects such as SLIC, and is now embedded in DNV and IEC standards. Horn and Leira [122] extended the reliability treatment to include stochastic availability, and Velarde *et al.* [121] demonstrated that for large-diameter monopiles the thickness effect—the reduction in fatigue strength with increasing plate thickness—has become a dimensioning consideration. Recent work has further considered correlated wind–wave–current loads on floating wind turbines [123] and fatigue-life assessment of structural details [124], and the corrosion–fatigue interaction in the splash zone [125] has been identified as a coupling that offshore wind standards do not yet fully address. The fatigue design landscape for WECs is fragmented. Ambühl *et al.* [109] established the reliability-based foundation for WEC fatigue design factors and demonstrated that calibrated factors differ materially from those carried over from offshore wind or oil and gas. The field data of Thies *et al.* [80] and the numerical work that followed [86, 126] provide an empirical foundation, but the integration of these individual contributions into a codified fatigue design practice for WEC mooring, umbilical, and primary-structure components is incomplete. Transferability is asymmetric. The methodology of reliability-based fatigue design calibration transfers from offshore wind to WECs fully; the calibrated safety factors do not, because the load spectra are different in both spectral content (WEC mooring sees more frequent low-magnitude cycles) and extreme statistics (WEC mooring sees proportionally more snap events). The most useful near-term contribution the offshore wind experience can make to the WEC sector is methodological: the institutional practice of producing design factors through transparent, reproducible calibration exercises should be imported, even where the numbers themselves must be recalibrated.

Floating structure coupled analysis

Floating offshore wind has, over the 2016–2026 period, developed a mature coupled-analysis practice that combines hydrodynamic, structural, mooring, and aerodynamic analysis in a single simulation framework, typically OpenFAST or equivalent [40, 127–129]. The scope of the analysis extends across the design load case matrix prescribed by IEC 61400-3-2 and includes both extreme and fatigue conditions. The WEC coupled-analysis tradition is longer established at the device level—WEC-Sim and similar platforms have been in use since 2014 [59, 60]—but narrower in scope. Full design load case matrices of the kind prescribed for offshore wind are rare, and the coupling of the hydrodynamic solver to the mooring solver, to the control system, and to the structural-response solver remains uneven across available tools [130, 131]. The blind-comparison exercise of Ransley *et al.* [132]

and the numerical benchmarking study of Wendt *et al.* [133] under IEA OES Task 10 are the WEC counterparts of the offshore wind OC series, and their findings indicate that inter-code scatter remains significant for survival-condition response. The transferability of the offshore wind coupled-analysis practice is high. The WEC sector possesses the component tools; what it lacks is the institutional discipline of comprehensive design load case execution and the round-robin validation culture that has characterized offshore wind. Both are acquirable, and their absence is not a technological obstacle.

Synthesis of the reviewed literature

Table 2 presents a thematic classification of landmark references from both Part A (WEC structural integrity, Pathways I–III) and Part B (offshore wind practices, P1–P5), mapping each to its dominant theme, key empirical or methodological finding, and limitation as critically assessed in this review. The entries are a reviewer-oriented distillation of the evidence base drawn from the full 150-reference classification; the complete annotated classification (all 150 cited references with theme, finding, and limitation) is provided as Supplementary Material S1, which records the allocation of each cited reference to its review stream (Part A, Part B, grey literature, standards, or foundational). Table 3 consolidates the principal quantitative results that underpin the narrative of Sections 3 and 4, providing a single reference point for the values discussed across the review.

Cross-industry synthesis: what transfers and what does not

Table 4 summarizes the transferability assessment in schematic form. The remainder of this section develops the synthesis thematically, drawing on review-level evidence [17, 75, 107] and addressing three questions that the enumeration in Section 4 raises but does not answer: how to explain the persistence of structural failure as a dominant commercialization barrier for WECs; whether WEC developers should aim to replicate the offshore wind commercialization trajectory or attempt to compress it; and what role emerging methodologies, in particular digital twins and fault-tolerant control, should play in either strategy.

Why structural failure persists as a commercialization barrier

The argument of Section 3—that WEC failure patterns broadly parallel the early offshore wind record—invites the question of why the WEC sector has not traversed the same commercialization trajectory. Three explanations, each partial, emerge from the cross-comparison.

The first is a structural difference in load regime. Offshore WECs lack a standardized low-load survival state equivalent to blade feathering for the severe sea states they are designed to exploit. They are not, however, without survival options: the active strategies that do exist—full or partial submergence [78], PTO declutching or latching [134–136], pressure-relief or by-pass valves in oscillating-water-column chambers [137], and variable-ballast or draft adjustment—reconfigure the device into a high-energy hydrodynamic or geometric survival mode rather than shedding load as a feathered rotor does. These modes have been implemented on specific devices such as Pelamis [7] and Oyster [8], and reviewed more broadly at device-class level for OWC [137, 138] and bent-duct-buoy [139] configurations; they remain, however, far from generic across the sector. The implication is that WEC design must either oversize for rare events (economically penal) or implement active survivability (technologically challenging), while offshore wind avoids both horns of the dilemma by virtue of its controllable rotor. On the available evidence, this asymmetry appears to reflect a genuine technological difference between the two sectors rather than a maturity gap alone.

The second is a financial-structural difference. The offshore wind learning curve was sustained by policy instruments—feed-in tariffs, contracts for difference, and regulated lease rounds—that created predictable revenue streams for developers whose devices survived the first deployment. The wave energy sector has not enjoyed equivalent support. Failed WEC deployments, therefore, have not generated successor deployments in the way that failed early offshore wind deployments did, and the cumulative operational hours that underpin reliability learning have accumulated correspondingly slowly. This observation, supported by the techno-economic analyses of Guo *et al.* [140], Astariz and Iglesias [141], and Magagna and Uihlein [142], implies that structural integrity improvement and market-design reform are coupled problems. Isolated engineering advances will not close the commercial gap; they must be matched by financial instruments that reward survivable designs with continuing revenue.

The third is methodological. The offshore wind sector benefited from the transfer of oil and gas structural engineering practice—S–N curves, environmental contour methods, reliability-based design—at a point when its deployed fleet was still small. The WEC sector has inherited the methods but has not had the operational scale necessary to calibrate them for its own load regime. As Sections 3.2 and 4.4 have argued, the result is that design-load and fatigue-factor uncertainty now dominates the structural analysis. The WEC sector thus appears to be in the position—on the basis of the reviewed literature—of having current-generation numerical tools while remaining empirically thin in fleet-scale operational data.

Should the wave energy converter sector replicate or compress the offshore wind trajectory?

The natural response to the observation that WECs face early-offshore-wind failure patterns is to argue that they should be allowed to traverse the same learning curve, at the same pace. The 2016–2026 literature suggests this response is too comfortable. A replication strategy implies that WECs require another decade of full-scale prototype deployments, each contributing operational hours and failure events to a gradually thickening reliability database. In purely technical terms this strategy is defensible, and the roadmap implied by the reliability-methodology transfer discussed in Section 4.1 is consistent with it. In economic terms the strategy is hard to sustain: each prototype deployment commits capital that, on the historical record of Pelamis, Aquamarine, Wavebob, AWS Ocean Energy, and Oceanlinx [143], is unlikely to be recovered. The feedback loop that sustained offshore wind—each failure a contained loss compensated by policy instruments—is not available. A compression strategy would substitute numerical and laboratory methods for operational hours, using digital twins, physics-based simulation, and accelerated component testing to produce equivalent confidence in structural integrity with a fraction of the fleet hours. Several elements of this strategy are already visible in the 2016–2026 literature. The component reliability test rigs of Thies *et al.* [144] and the DMaC test facility at Exeter, the active-mooring system reliability-testing methodology of Luxmoore

Table 3 Quantitative evidence synthesized from the 2016–2026 WEC structural-integrity literature (upper block) and the parallel offshore-wind literature (lower block).

#	Pathway/Area	Metric	Value reported	Source	Evidence base
1	Pathway I—extreme-event	CFD vs linear-theory peak load ratio	2–4×	Ransley *et al.* [71]	OpenFOAM focused-wave impact on truncated cylinder and hemispherical point absorber
2	Pathway I—extreme-event	Extreme PTO-force variation across contour methods	>2×	Edwards & Coe [77]	Reference Model 3 point absorber; five environmental-contour methods
3	Pathway I—extreme-event	Non-linear to linear response ratio (slamming)	2–4×	Katsidoniotaki & Göteman [73]	OpenFOAM extreme-wave simulation, point absorber
4	Pathway II — fatigue/mooring	Mooring fatigue-life variation across configurations	×12	Thies *et al.* [80]	South West Mooring Test Facility field tension data
5	Pathway II—fatigue/mooring	Biofouling-induced mooring-life reduction	∼80%	Yang *et al.* [84]	Coupled hydrodynamic–structural model, North Sea
6	Pathway II—fatigue/mooring	Biofouling-induced annual energy reduction	up to 20%	Yang *et al.* [84]	Same coupled model
7	Pathway II—fatigue/mooring	Snap-load peak/nominal-mean tension ratio	>3×	Hann *et al.* [34]	Wave-basin focused-wave groups
8	Pathway III—interface	Fault-tolerant control laboratory readiness	Simulation/lab only	Papini *et al.* [106]; Liu *et al.* [23]	Reviewed PTO reconfiguration strategies
9	P1—reliability benchmarking	Offshore-wind failure rate	8.3/turbine-year	Carroll *et al.* [31]	∼350 multi-MW turbines; 1768 turbine-years
10	P1—reliability benchmarking	Failure-rate decomposition	6.2 minor +1.1 major +0.3 replacement	Carroll *et al.* [31]	Same dataset
11	P1—reliability benchmarking	O&M share of offshore-wind LCOE	∼30%	Carroll *et al.* [35]	Same consortium, cost model
12	P2—standards-based design	Governing limit state (OW monopile)	SLS, not ULS	Arany *et al.* [94]	10-step monopile design procedure
13	P3—condition monitoring	Digital-twin validation	Kalman-filter; tower loads from SCADA	Branlard *et al.* [40]	TetraSpar floating prototype
14	P4—fatigue design	Design-life fatigue cycles (OW)	$>10^8$ over 20–25 year	Arany *et al.* [94]; Velarde *et al.* [121]	Ultra-high-cycle regime; thickness effect
15	P5—coupled analysis	WEC inter-code response scatter (survival)	Significant	Ransley *et al.* [132]; Wendt *et al.* [133]	IEA OES Task 10 blind-comparison
16	Sector scale	Operational WEC capacity, ∼2021	∼2.31 MW	Ocean Energy Europe [5]; Sheng [6]	Global reported operational fleet
17	Sector scale	Installed offshore-wind capacity, ∼2024	∼80 GW	GWEC [4]	Global cumulative
18	Sector scale	Fleet-scale ratio (OW/WEC)	∼35 000×	Derived from [4, 6]	Capacity ratio at time of review

et al. [79], and the digital-twin methodology of Branlard *et al.* [40] and its antecedents [112, 118, 119] collectively suggest that a compression strategy is feasible in principle. Its weak link, which neither the offshore wind literature nor the WEC literature has fully addressed, is validation: the confidence with which a digital-twin-based reliability assessment can substitute for a fleet-hour-based assessment depends on the accuracy of the underlying physical model, and at survival conditions the models remain imperfect. The synthesis of this review suggests that a compressed trajectory, pursued with explicit epistemic honesty about what is substituted for what, may be more tractable for the WEC sector than a pure replication of the offshore wind learning curve. The compression must not be rhetorical—a digital twin labeled as such while functioning merely as a static design calculation—and must be accompanied by a parallel program of physical-test validation. The recent open-source digital-twin demonstrations for floating offshore wind [40] provide a template for the transparency this requires.

The role of emerging methodology

Two emerging methodologies merit specific comment: digital twins and fault-tolerant control. Digital-twin methodology offers the WEC sector two distinct benefits. The first is the capacity to infer operational loads on deployed prototypes that are instrumented less comprehensively than the twin requires, using virtual-sensing techniques

Table 4 Transferability of offshore wind structural integrity practices to WECs against four criteria. Condition monitoring (P3) is shown as four rows reflecting distinct monitoring approaches (first-generation vibration, SCADA-based statistical, and physics- and data-driven digital twins); the other four practice areas (P1, P2, P4, P5) each occupy a single row.

Practice (offshore wind)	Physical analogy	Data availability	Regulatory maturity	Economic feasibility	Overall
Quantitative reliability benchmarking	High	Low	Medium	Medium	Partial (discipline transfers; data do not)
Standards-based design (IEC 61400-3; DNV-ST-0119)	Medium	Medium	Medium (IEC TS 62600 series)	High	Partial (framework transfers; content requires WEC calibration)
First-generation vibration CM	High	High	High	High	Full
SCADA-based statistical CM	Medium	Low	Medium	High	Partial (fleet-size constrained)
Digital-twin (physics-based)	High	High	Developing	High	Conditional (validation-constrained)
Digital-twin (data-driven/ML)	Medium	Low	Developing	Medium	Low (fleet-size constrained)
Reliability-based fatigue calibration	High	Medium	Medium	High	Methodology transfers; factors do not
Coupled analysis & DLC matrix	High	High	Medium	High	Full (institutional practice gap)

such as Kalman-filter-based state estimation [40, 100]. This benefit is immediate and technology-ready; its implementation is primarily a matter of adapting floating-wind-developed code to WEC hull forms. The second benefit is the generation of reliability predictions that can substitute partially for fleet-hour statistics [145]. This benefit is longer-term and depends on the validation program discussed in Section 5.2. Fault-tolerant control, reviewed by Papini *et al.* [106] and by Liu *et al.* [23], with broader wave-energy-control perspective from Ringwood [136], offers a complementary benefit: the capacity to reconfigure device operation in response to detected component degradation, extending operational availability and protecting downstream components from secondary damage. The offshore wind sector has implemented fault-tolerant approaches at the pitch-system and yaw-system levels and more recently at the drivetrain level [99]. The WEC sector has begun to follow [134, 135], but the full scope of fault-tolerant control for a device whose primary function requires that it be structurally loaded by the sea—rather than shielded from it—remains to be defined. The end-stop problem is the paradigmatic case: the natural fault-tolerant response is to declutch the PTO, but declutching removes the load path that protects the primary structure from resonant amplification, potentially transferring rather than eliminating the failure risk. Fault-tolerant control strategies for WECs are therefore best understood as part of the survivability analysis, not as an add-on to it.

Conclusions, limitations, and research agenda

Summary of principal findings

This review has addressed two research questions. RQ1 asked how the WEC structural failure record compares with the early offshore wind experience. The analysis of Sections 3 and 4 indicates that the WEC and early offshore wind failure records appear to resemble one another in three respects on the reviewed literature: the apparent dominance of subsystem over primary-structure failure, the persistent gap between codified design loads and empirical loads, and the convergence on condition monitoring as an operational response to residual risk. They differ in three important respects (developed in Section 5.1): WECs face a survivability problem that offshore wind avoids by rotor controllability; the WEC sector has not enjoyed the financial-policy support that converted early offshore wind failures into learning rather than exit; and, relatedly, the WEC sector has not accumulated the fleet-scale operational hours needed to calibrate reliability and fatigue methods inherited from oil-and-gas and offshore-wind practice.

RQ2 asked which offshore wind structural integrity practices are transferable to WECs. The transferability assessment of Section 4, summarized in Table 4, distinguishes three outcomes. Practices that transfer fully include first-generation vibration condition monitoring, the physics-based component of digital-twin methodology [40, 112–114, 118, 119], and the institutional discipline of coupled analysis with design load case matrices [146]. Practices that transfer partially include reliability benchmarking (the discipline transfers; the data do not), standards-based design (the framework transfers; the specific numerical content does not), SCADA-based condition monitoring (methodology transfers; fleet-scale is insufficient), and reliability-based fatigue calibration (the calibration method transfers; the safety-factor values must be recalibrated). Few if any practices transfer without some degree of adaptation on the evidence reviewed.

The research agenda implied by the synthesis

The review suggests four priority research directions for the WEC sector, arranged by time horizon and institutional scope in Fig. 4.

The first is the establishment of a voluntary failure-reporting consortium, analogous to but smaller than the database underpinning the Carroll *et al.* [31] analysis, that would standardize failure taxonomy and accumulate operational data across developers and test sites. Such a consortium need not involve commercial confidentiality concessions of the kind that constrained the offshore wind database; anonymized reporting at component rather than device level would provide substantial statistical value.

The second is a structured program of WEC-specific fatigue design factor calibration, extending the methodological foundation of Ambühl *et al.* [109]. This program would need to encompass mooring components in the snap-load regime, umbilical cables under combined wave and current loading, and PTO-interface components subjected to impulsive loads.

The third is the integration of physics-based digital-twin methodology, adapted from the floating offshore wind template, into deployed WEC prototypes. The adaptation is not trivial—WEC survival conditions push hydrodynamic models harder than floating wind survival conditions—but the potential benefit in compressing the learning curve is substantial, and the open-source precedents [40] materially lower the barrier to entry.

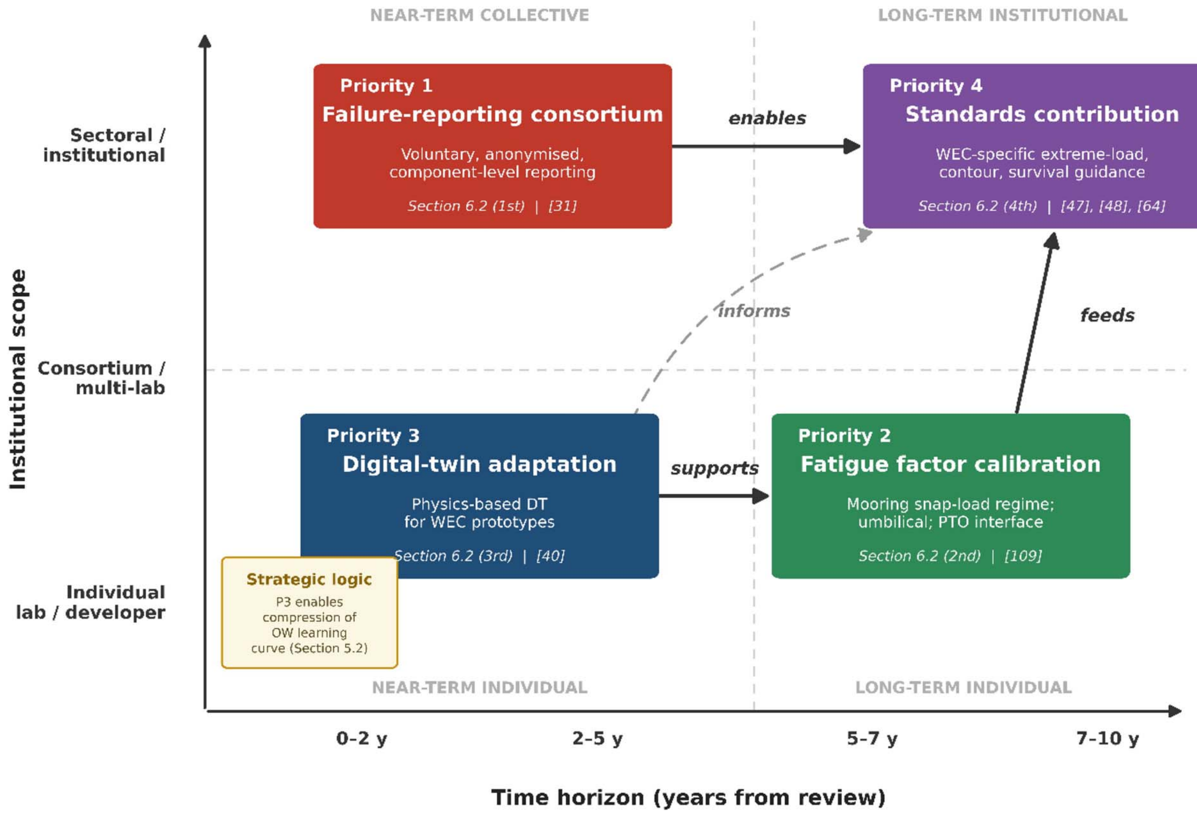


Figure 4 Quadrant roadmap placing four research priorities by time horizon (0–10 years) and institutional scope: (1) failure-reporting consortium, (2) fatigue-factor calibration, (3) physics-based digital-twin adaptation, (4) WEC-specific standards. Arrows link them—1 enables 4; 3 supports 2 and informs 4; 2 feeds 4.

The fourth is the development of a WEC-specific standards contribution that complements the IEC TS 62600 series [47–50] with detailed guidance on extreme-load assessment, environmental contour selection, and survival-mode design. Multi-criteria prioritization frameworks [147] could support the selection of which standards-development topics to pursue first. The landscaping study of Wave Energy Scotland [64] identifies the gaps this guidance would fill; the design-response methodology of Coe *et al.* [18] provides much of the technical content; what is required is the institutional mechanism to codify it.

Limitations

The review has three limitations that should be acknowledged. First, the 2016–2026 search window excludes much of the foundational WEC literature, which has been cited contextually but not formally screened; a future review might usefully broaden the window to capture the earlier phases of the learning curve more systematically. Second, the comparison with offshore wind is necessarily asymmetric, because offshore wind has a developed fleet and WECs do not; the conclusions drawn from this asymmetry are conditional on it, and would require reassessment if WEC deployment rates were to accelerate materially. Third, the grey-literature component of the search (Stream C) relies on organizational publications whose coverage is not uniform; relevant proprietary technical reports, particularly from device developers, were not accessible and may contain evidence that would alter specific conclusions.

Publication and proprietary bias

The evidence base assembled in this review is subject to a structural bias that warrants explicit acknowledgement. The deployment-outcome inventory (Table 1) and the Part A corpus draw almost exclusively on the open record: peer-reviewed literature, public funding-body reporting, and organizational grey literature. In the wave energy sector, however, much of the most informative evidence on structural failure, mooring-line incidents, and hull or seal degradation is held privately by device developers under commercial confidentiality, and a substantial share of public developer reporting is self-authored—the principal record of the OPT PB150 program, for example, is a developer-prepared technical report [148]. The open record is therefore likely to understate both the frequency and the diversity of failure modes, since unsuccessful outcomes are disproportionately the ones not published. This is a survival bias in the literal archival sense, and it cuts against the descriptive failure indicators reported here being treated as anything more than a lower bound.

The contrast with offshore wind is instructive. There, the maturation of a large operational fleet has supported the emergence of intermediary institutions that synthesize commercially sensitive failure data into an anonymized, sector-level evidence base. Specialist marine-energy underwriters now publish multi-year claims analyses, reporting that contractor error and component defect, rather than catastrophic structural failure, dominate offshore-wind claims by both frequency and value, and identifying subsea cables as the single largest loss category [149]. Classification societies play a parallel role: third-party certification frameworks for marine energy converters exist precisely to give financiers, insurers, and utilities independent assurance of structural and station-keeping integrity, transferring lessons from offshore oil and gas into the renewable sector [150]. No equivalent claims pool or actuarial feedback loop yet exists for wave energy, because the deployed population is too small and too fragmented to sustain one. The absence of this data-sharing infrastructure is itself a barrier to the sector's learning curve, and it reinforces the case made in Section 6.2 for pre-competitive, consortium-level reporting of structural and survivability outcomes.

Closing remark

The central argument of this review is that, on the reviewed evidence, the commercial viability of wave energy conversion appears to be meaningfully constrained by structural integrity and survivability concerns alongside better-recognized cost and efficiency challenges; that the structural integrity challenge is in significant part a methodological one of translating an intellectually mature body of offshore-sector engineering practice into a WEC-specific idiom; and that this translation is partly under way but remains incomplete. The 2016–2026 literature supplies the technical components of the translation. What remains is the institutional work of integrating them—through standards contributions, consortium reliability databases, and open-source digital-twin implementations—into a form that future WEC prototype deployments can use.

Acknowledgements

The authors thank the anonymous reviewers for their constructive comments, and acknowledge the institutional support of Rambhai Barni Rajabhat University and Kasetsart University, Sriracha Campus.

Author contributions

Kornpaphop Ruttanawijit (Conceptualization [equal], Data curation [equal], Investigation [equal], Methodology [equal], Validation [equal], Writing—original draft [equal]) and Yodchai Tiaple (Conceptualization [equal], Methodology [equal], Project administration [equal], Supervision [equal], Validation [equal], Writing—review & editing [equal])

Supplementary material

Supplementary material is available at *Oxford Open Energy* online.

Conflicts of interest

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

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability

No primary data were generated in this study. All data supporting the findings of this review are drawn from published peer-reviewed literature, technical standards, and grey-literature reports cited in the reference list. A complete inventory of the 150 references cited in this review (117 in-window; 33 foundational) is provided as Supplementary Material S1. The coding protocol and source decisions for the deployment-outcome inventory in Table 1 are provided as Supplementary Material S2.

AI use statement

During the preparation of this manuscript, the authors used AI tools (ChatGPT and Claude) for language refinement, grammar checking, and figure formatting assistance. No AI tools were used for data analysis, interpretation, or formulation of research conclusions. All outputs were critically reviewed and edited by the authors, who take full responsibility for the content and integrity of the work.

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Oxford Open Energy, 2026, **5**, oiag011
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