

Article

Evaluation and Optimization of Wave Energy Converters: A Systematic Perspective on Methods and Design Optimization Research Trend

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Abstract. The escalating global demand for renewable energy positions wave power as a critical sustainable resource. However, the widespread adoption of Wave Energy Converters (WECs) is impeded by challenges in optimizing hydrodynamic efficiency and reducing lifecycle costs. This paper provides a comprehensive review of the technological evolution of WECs, focusing on design optimization methods and emergent trends. A three-step methodology was employed, integrating descriptive analysis, bibliometric mapping, and a systematic review of optimization strategies. Our findings reveal a significant research trajectory towards hybrid energy systems, which co-locate WECs with offshore wind platforms to enhance energy capture and economic viability. The study underscores the pivotal role of advanced computational techniques, such as hybrid optimization algorithms, in elevating WEC performance. Nevertheless, critical gaps persist, primarily the lack of extensive experimental validation for numerical models and the need for algorithms with faster convergence. This review synthesizes the current state-of-the-art, offering valuable insights to direct future research toward more efficient and commercially viable WEC technologies.

Keywords: Wave energy converter, optimization design, hybrid energy systems, power take-off, research trend

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1. Introduction

The global demand for renewable energy sources has been steadily increasing, driven by the urgent need to mitigate climate change and reduce dependency on fossil fuels [1], [2], [3]. Among these, ocean wave energy has gained significant attention due to its high energy density and reliable nature, especially when compared to more unpredictable sources like solar and wind. Waves provide a consistent and predictable source of power, making them an attractive option for sustainable energy generation [4], [5], [6]. According to Mira et al. [7], the stability and forecastability of wave energy are key advantages, offering a viable alternative to more variable energy sources.

Wave Energy Converters (WECs) are the primary technology used to capture and convert the mechanical energy from ocean waves into electricity [8], [9], [10]. However, while WECs hold great promise, there are several challenges that hinder their widespread adoption. These challenges are largely related to optimizing their efficiency and reducing the high costs associated with deployment. The interactions between ocean waves, the environment, and the converter systems are complex, which makes it difficult to achieve the desired energy output with cost-effectiveness [11], [12]. As Martins et al. [13] highlight, these systems require significant advancements in design and optimization to overcome the technical hurdles that currently limit their economic viability. In addition to the technical challenges, the cost of deploying WECs remains a major barrier to their commercialization, especially when compared to more established renewable technologies like offshore wind turbines [14], [15], [16]. While wave energy has immense potential, it often faces tough competition from offshore wind, which has already reached a more mature stage in terms of technology and market adoption [17], [18], [19], [20].

One promising solution to these challenges is the development of hybrid energy systems that combine offshore wind turbines with WECs [21], [22]. These hybrid systems take advantage of both wave and wind energy, which often coexist in the same regions, thus providing a more stable and reliable source of renewable power. Integrating WECs with semi-submersible wind platforms allows for shared infrastructure, such as moorings and support structures, thereby reducing overall costs and improving the efficiency of energy extraction [23], [24], [25]. Jin et al. [26] demonstrated that hybrid systems can generate more energy while maintaining system stability, particularly in regions where both wind and wave resources are abundant.

Despite the growing number of review articles on Wave Energy Converters (WECs), most existing studies tend to focus on a single review methodology, such as descriptive analysis [33, 34], bibliometric mapping [35, 39], or systematic technical review [36–38, 40, 41]. While these works have significantly contributed to understanding WEC technological development, they often emphasize long-term historical perspectives spanning decades and do not specifically isolate the most recent five-year research trajectory, where rapid advancements in hybrid systems, multi-objective optimization, and computational intelligence have occurred. Furthermore, previous reviews rarely integrate quantitative bibliometric mapping with structured methodological evaluation frameworks that allow cross-comparison of optimization techniques and validation practices. In contrast, the present study focuses explicitly on the most recent five-year period (2020–2025) to capture emerging trends, rapid algorithmic evolution, and the growing convergence between hydrodynamic optimization, techno-economic assessment, and hybrid renewable integration. By combining descriptive analysis, bibliometric analysis, and systematic evaluation within a single structured framework, this review aims to provide a more comprehensive and up-to-date synthesis of WEC optimization research.

Table 1. Comparative Summary of Previous Review Studies and the Present Study on Wave Energy Converter Optimization

Authors	Number of Papers Evaluated	Source of Database	Period of Analysis	Type of Review	Scope
Foteinis and Tsoutsos [33]	39	ScienceDirect, Springer	2010-2016	Descriptive Analysis	Mediterranean
Ahamed et al. [34]	31	ScienceDirect	2010-2019	Descriptive Analysis	Worldwide
Galparsoro et al. [35]	49	Scopus	2006-2020	Bibliometric Analysis	Worldwide
Golbaz et al. [36]	40	Scopus	1974-2021	Systematic Analysis	Worldwide
Rosati et al. [37]	40	ScienceDirect	1991-2021	Systematic Analysis	Worldwide
Shadmani et al. [38]	11	ScienceDirect	2020-2023	Systematic Analysis	Worldwide
Khurshid et al. [39]	74	Scopus, Web of Science, Google Scholar	2000-2023	Bibliometric Analysis	Worldwide
Gaspar et al. [40]	17	ScienceDirect	2011-2023	Systematic Analysis	Worldwide
Yang et al. [41]	194	Springer, IEEE, Web of Science, ScienceDirect	2013-2023	Systematic Analysis	Worldwide
This paper	36	Scopus	2020-2025	Descriptive Analysis, Bibliometric Analysis, Systematic Analysis	Worldwide

To assess the current state of technological advancements and optimization strategies for WECs, this review adopts a three-stage methodology combining descriptive analysis, bibliometric analysis, and systematic review. Descriptive analysis is employed to provide an overview of the literature [36], [37], [38], especially for five newest year period that can identifying a broad range of studies on WEC technologies and their optimization also identifying the most recent research acceleration and topical shifts. Bibliometric analysis is then applied to quantify the academic influence within the field, highlighting key authors, influential works, and research trends [39], [40]. Then the systematic analysis stage focuses on a more detailed examination of selected studies, evaluating their methodologies and optimization strategies in depth [37], [41]. This three-stage approach follows the methodology of review paper used in previous reviews of WEC technologies are summarized in Table 1. By adopting this structure, the review offers a comprehensive evaluation of the WEC field, drawing on both quantitative and qualitative insights. This paper integrated approach differs from prior previous reviews that summarized in Table 1, which predominantly relied on a single methodological lens. By combining quantitative trend mapping with qualitative methodological benchmarking, the present study not only captures the five-year research momentum but also bridges the gap between theoretical optimization development and practical performance validation.

As shown in Table 1, previous reviews generally examined either long historical periods or employed a single methodological approach. In contrast, this paper provides an in-depth evaluation of 36 core publications, systematically distilled from an initial pool of 6,024 records extracted from the Scopus database over the latest five-year window (2020–2025). This selection was achieved through a rigorous three-step inclusion and exclusion procedure. Crucially, each filtering stage was meticulously analyzed to preserve the macroscopic trends of the entire dataset, thereby concentrating on the most recent acceleration phase of WEC optimization research without losing the broader context. Moreover, unlike earlier works that were limited to descriptive, bibliometric, or systematic methods individually, this study integrates all these three approaches into a unified analytical framework. This enables a multi-layered assessment covering research productivity trends, intellectual structure evolution, and detailed methodological benchmarking. Such integration enhances transparency, comparability, and reproducibility while offering a clearer identification of research gaps related to algorithm convergence speed, experimental validation availability, and techno-economic feasibility.

This study contributes to the existing literature on WEC optimization in three main aspects. First, it introduces an integrated review framework that combines descriptive analysis, bibliometric mapping, and systematic technical evaluation within a single methodological structure, enabling a more comprehensive understanding of recent research developments. Second, the study

provides a structured classification and comparative assessment of optimization approaches used in WEC research, including parametric, deterministic, and stochastic methodologies, highlighting their respective objectives, constraints, and validation strategies. Third, the review extends beyond purely technical evaluation by examining emerging hybrid renewable configurations, particularly wind–wave integrated systems, and discussing their potential techno-economic implications. Through this combined perspective, the present study aims to bridge the gap between algorithm development, system-level performance evaluation, and practical deployment considerations in modern WEC research.

To systematically assess the current state of technological advancements and optimization strategies for WECs, this study is structured around three core objectives:

1. to identify and quantify the latest five-year research trends in WEC optimization, including hybrid wind-wave integration and advanced computational algorithms;
2. to classify and compare optimization methodologies based on their objective functions, constraints, validation approaches, and performance metrics; and
3. to critically evaluate existing research gaps, particularly regarding experimental validation, convergence efficiency, and techno-economic integration.

Through bibliometric analysis, this paper identifies prolific authors, influential publications, keyword co-occurrences, and geographical research distribution. These insights provide a macroscopic view of how the intellectual structure of WEC optimization has evolved in the most recent innovation cycle. As highlighted by Paiva et al. [42], bibliometric methods are instrumental in capturing the dynamics of academic attention and technological focus over time. However, bibliometric trends alone cannot fully explain methodological effectiveness. Therefore, the bibliometric findings are complemented with systematic technical assessment to enable structured cross-comparison of optimization strategies.

To achieve these goals, a systematic literature search was conducted using major academic databases, followed by data cleaning and filtering to ensure relevance and accuracy. The selected documents were analyzed using bibliometric techniques, such as co-authorship networks, co-citation analysis, and keyword mapping that employing tools like VOSviewer. This enabled the identification of major research clusters and thematic concentrations within the WEC field. The bibliometric findings were integrated with qualitative assessments to provide deeper insight into recent optimization strategies. Mehdipour et al. [43] emphasize the potential of advanced optimization methods, including hybrid algorithms, in enhancing WEC efficiency, reducing operational costs, and improving energy capture. Complementing this, studies like Ahmed et al. [44] have demonstrated how innovations such as S-

shaped floaters significantly contribute to optimizing the mechanical power take-off (PTO) system. These analyses offer a comprehensive understanding of how technological advancements align with the need to overcome technical and economic barriers in the implementation of WECs.

2. Methodology

This study adopts a three-stage research methodology framework, as illustrated in Fig. 1, to comprehensively evaluate and analyze the development and optimization of Wave Energy Converters (WECs) from a bibliometric and systematic review perspective. Each stage of the methodology was designed to progressively refine and assess relevant scientific literature to ensure a high level of academic rigor and objectivity in the evaluation.

In Stage 1, the research commenced with a descriptive analysis involving the identification and collection of journal articles from the Scopus database. Scopus was selected due to its wide coverage of peer-reviewed literature across disciplines, a feature that has been widely acknowledged in bibliometric analyses for its reliability in identifying relevant studies across various fields [45]. Additionally, Scopus has been employed extensively for the analysis of renewable energy technologies, including wave energy harvesting, with several studies highlighting its use in optimizing energy harvesting systems and understanding emerging trends [46]. Furthermore, Scopus is also recognized for its critical role in identifying key contributors and collaboration networks in the field of offshore renewable energy systems, such as hybrid energy sources and optimization methods, which are essential for advancing sustainable energy solutions [33].

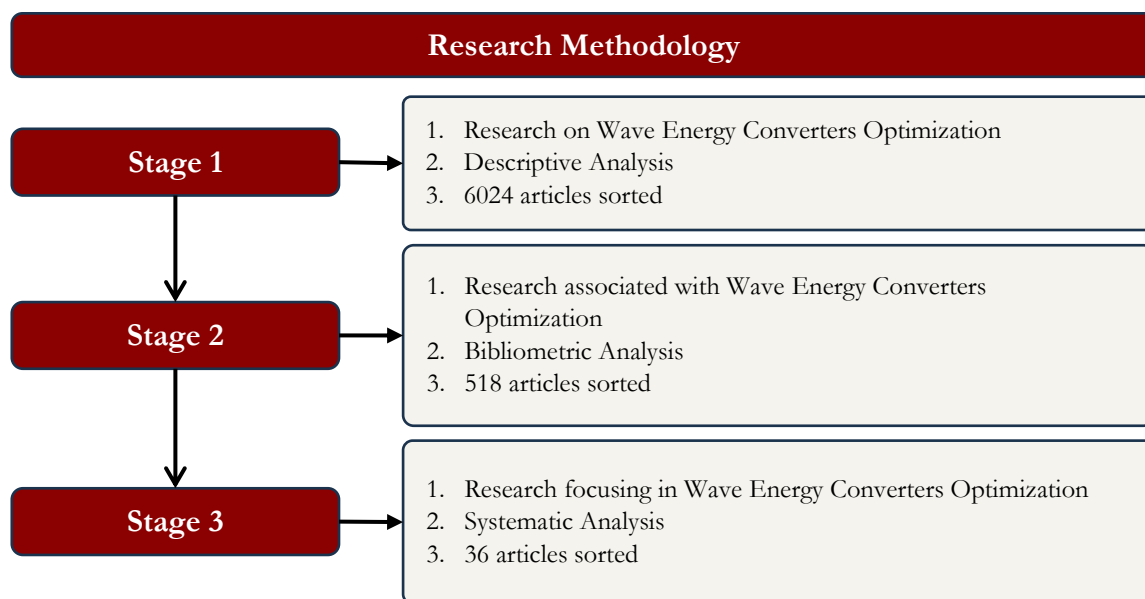


Fig. 1. Research Methodology Framework

The literature identification process focused on publications from the most recent five-year period (2020–2025) and was conducted using the Scopus database in May 2025. To ensure comprehensive coverage of Wave Energy Converter (WEC) optimization studies, the initial identification stage applied three complementary keyword combinations targeting the TITLE, ABSTRACT, and KEYWORDS fields. These queries were designed to capture the main technical themes commonly associated with WEC optimization research, namely system dynamics, power take-off mechanisms, and optimization methodologies. The search strings were defined as follows:

1. TITLE-ABS-KEY ("wave energy converter" AND "degree of freedom") AND DOCTYPE (ar OR re) AND PUBYEAR > 2020 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))
2. TITLE-ABS-KEY ("wave energy converter" AND "power take off") AND DOCTYPE (ar OR re) AND PUBYEAR > 2020 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))
3. TITLE-ABS-KEY ("wave energy converter" AND "optimization") AND DOCTYPE (ar OR re) AND PUBYEAR > 2020 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))

The combined results of these three queries produced 6024 records, which constituted the initial dataset used for the Stage 1 descriptive analysis. At this stage, the purpose of the search was to obtain a broad overview of the research landscape related to WEC technologies within the defined keyword scope. This initial dataset enabled the identification of the overall publication volume, research activity trends, and thematic coverage of recent WEC studies. This dataset was subsequently used to perform the descriptive analysis in Stage 1, which aimed to identify publication trends and general research directions in recent WEC optimization studies.

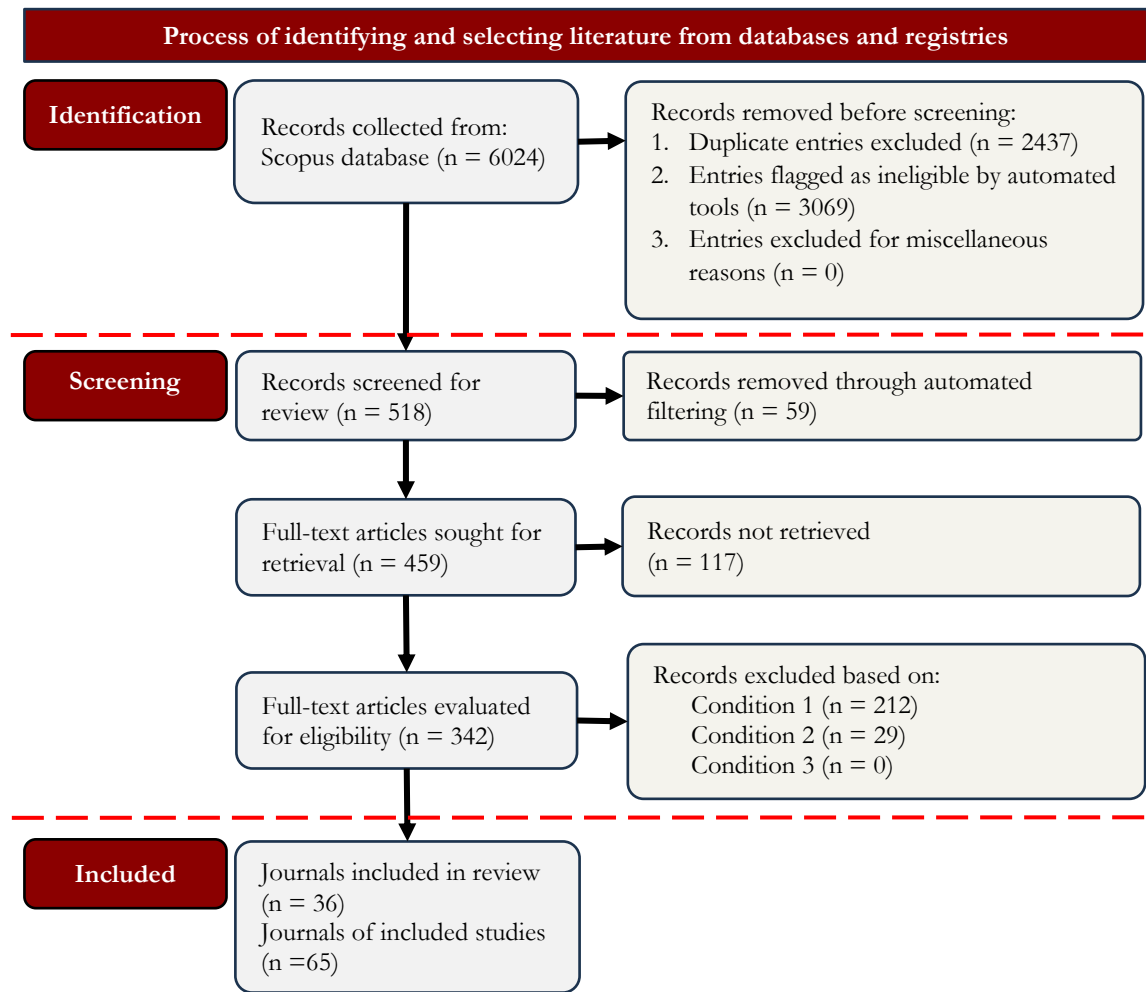


Fig. 2. Flow Diagram of Screening Process Study of WEC

Subsequently, a data cleaning process was conducted to prepare the dataset for Stage 2 bibliometric analysis. As illustrated in Fig. 2, duplicate records were automatically detected and removed, resulting in the exclusion of 2437 duplicate entries. In addition, 3069 records were flagged as ineligible by automated filtering tools, primarily due to metadata inconsistencies or indexing limitations within the database. After this cleaning process, 518 records remained, which were used as the primary dataset for bibliometric analysis.

Stage 2 involved conducting a bibliometric analysis of the 518 screened records using VOSviewer, a widely recognized software tool for constructing and visualizing bibliometric networks. Bibliometric analysis refers to the quantitative evaluation of academic publications to identify patterns, trends, and relationships within a specific research field [47], [48]. Through VOSviewer, co-

occurrence of keywords, co-authorship patterns, citation analysis, and thematic clustering were examined. This process enabled the identification of the most frequently studied optimization themes, key research contributors, institutional collaborations, and evolving technological focuses in WEC research. The bibliometric analysis provided a macro-level understanding of the intellectual structure and knowledge landscape surrounding WEC optimization. The use of VOSviewer for bibliometric analysis in diverse fields, including renewable energy and wave energy, has been widely applied, as demonstrated by recent studies in ocean energy research and renewable energy technology, where it has proven to be an effective tool in uncovering research trends and collaboration patterns [39], [49], [50].

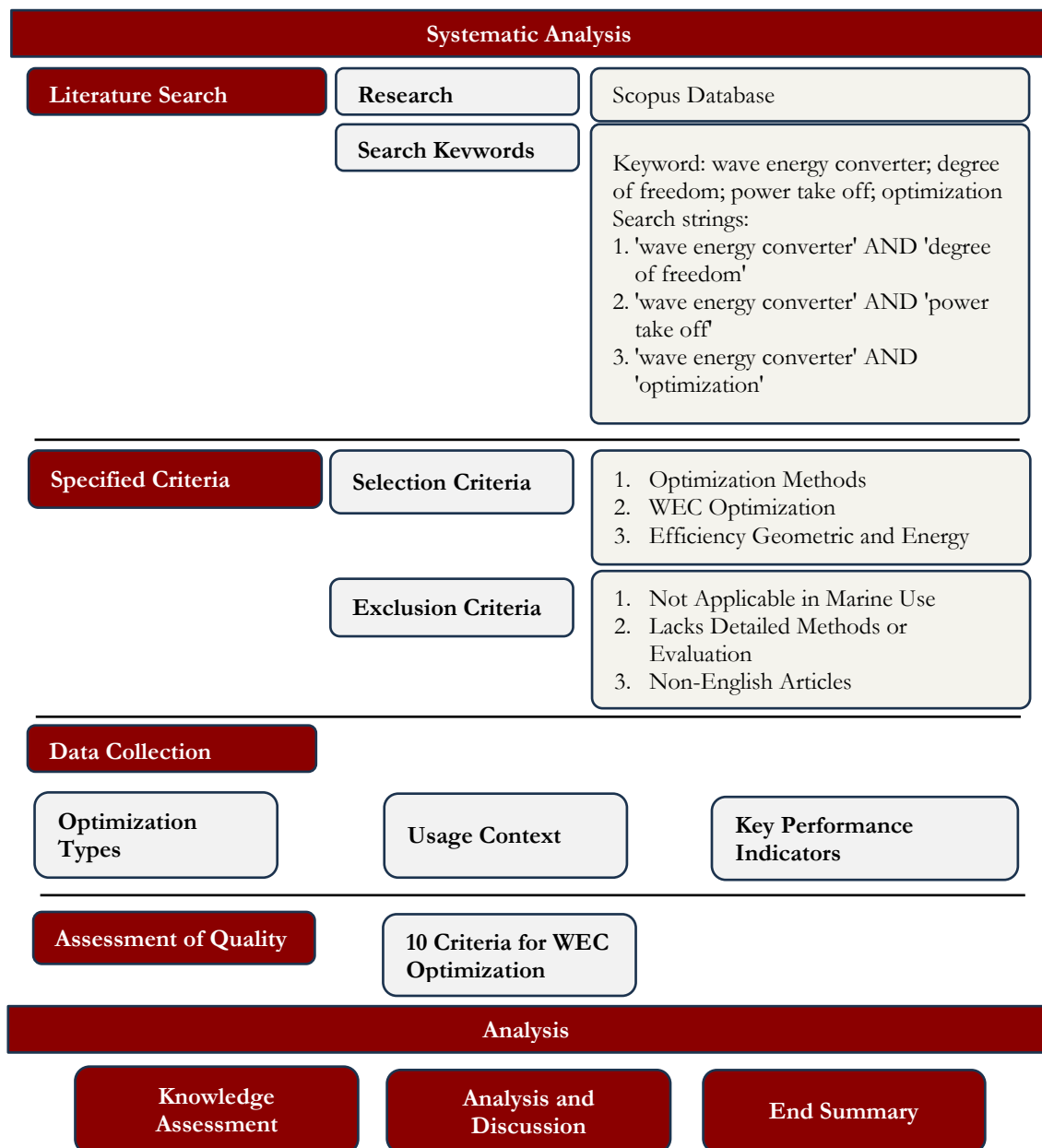


Fig. 3. Systematic Analysis Framework

Table 2. Explanation of Criteria for Evaluating WEC Designs [51]

No.	Item	Description
1	High Energy Efficiency	The primary aim is to optimize the conversion of wave energy into electrical output by enhancing energy absorption efficiency and minimizing system losses through effective design and control mechanisms.
2	Low Computational Cost	Optimization techniques must be computationally efficient, ensuring accurate results without excessive processing demands, thereby supporting practical implementation.
3	Multi-Objective Capability	To balance competing objectives such as maximizing energy output, maintaining structural durability, and minimizing cost, multi-objective optimization frameworks are employed to generate balanced, Pareto-optimal solutions.
4	Robustness to Wave Variations	Systems must be engineered to function dependably under a wide spectrum of ocean wave conditions, including unpredictable and severe scenarios, to maintain consistent performance.
5	Applicability to Various WECs	Optimization approaches should be flexible and scalable to suit different WEC designs, enhancing their suitability for diverse marine deployment conditions.

6	Improved System Stability	Ensuring dynamic stability in operational marine settings is critical to avoid performance fluctuations and maintain the structural safety of the converter.
7	High Convergence Speed	Optimization methods should be capable of reaching optimal or near-optimal solutions swiftly, facilitating efficient iterations in the design and testing cycle.
8	Innovative Methodology	Cutting-edge methods including artificial intelligence, machine learning, and heuristic algorithms are leveraged to push the boundaries of optimization in WEC technologies.
9	Wide Software Compatibility	The ability to integrate with multiple industry-standard simulation platforms such as ANSYS, WAMIT, and MATLAB ensures broader applicability and smoother implementation of optimization models.
10	Experimental Validation Availability	Verification through laboratory testing or real-world deployment is essential to evaluate the practical effectiveness of the optimization strategy and to support further refinements.

Following the bibliometric stage, the dataset was further refined to support Stage 3 systematic analysis. An automated filtering process first removed 59 records that did not satisfy the predefined document classification criteria. Subsequently, 117 records could not be retrieved at the full-text stage due to access limitations or incomplete indexing information. After these filtering steps, 342 full-text articles were retained and evaluated for eligibility, forming the candidate pool for systematic review. The inclusion criteria emphasized articles that specifically addressed WEC optimization methods, examined efficiency in relation to geometry and energy output, and demonstrated methodological clarity. The exclusion criteria were: (1) not applicable to marine energy use; (2) lacking detailed methods or evaluation; and (3) non-English articles. These criteria were defined in accordance with systematic review principles proposed by Page et al. [52], [53], emphasizing transparency and replicability in literature selection. Based on the predefined exclusion criteria, 212 articles were excluded because they were not directly related to marine energy applications, and 29 articles were excluded due to insufficient methodological details or evaluation procedures. Following the eligibility assessment, 36 journal articles were selected for in-depth systematic analysis using a PRISMA-aligned framework. In addition, 65 supporting journal articles were incorporated to strengthen the broader literature discussion and contextual analysis, as illustrated in Fig. 3. Each selected study was examined based on its optimization approach, application context (experimental, simulation, or offshore testing), and the performance indicators used for evaluation.

Furthermore, a 10-criteria framework proposed by Arrosyid et al. [51], summarized in Table 2, was employed as a structured descriptive tool to examine how each study addressed key aspects of WEC optimization. The criteria were used to identify recurring methodological characteristics, common design considerations, and dominant research themes within the selected literature. This approach enabled the analysis to highlight prevailing trends, methodological strengths, and areas that remain underexplored, particularly in relation to efficiency improvement, robustness, computational feasibility, and experimental validation. This stage provided a deeper and

more structured understanding of recent innovations and research directions in WEC optimization. Through this integrative three-stage methodology, the study achieves a balanced combination of breadth and depth in capturing the evolution of research and innovation in the field.

3. Results and Discussion

3.1. Descriptive Analysis

The descriptive analysis is the first stage process in research methodology in Fig. 1, aimed at assessing the volume of publications related to WEC and their optimization from the Scopus database. This search, covering the period from 2020 to 2025, yielded a total of 6024 publications initially. These articles spanned a broad spectrum of topics within WEC technology, including design considerations, energy capture, and the mechanics of power take-off systems. The substantial number of publications underscores the growing importance of wave energy as a renewable resource and highlights the expanding body of research in optimizing wave energy systems to meet global energy demands more efficiently. However, the analysis then honed in on 2955 articles directly related to the design of WECs. This refined subset, representing approximately 49% of the total publications, emphasizes the critical focus of these studies within the broader field of wave energy research. While there is significant interest in wave energy technologies, nearly half of the research specifically tackles optimization issues such as design improvements, energy output maximization, and cost reduction strategies. This finding suggests that despite the widespread interest in wave energy, a large portion of the research is concentrated on refining its efficiency and operational performance.

Based on Fig. 4, publications on WEC topics were 487 in 2020, slightly decreasing to 485 in 2021. This was followed by a notable increase to 557 publications in 2022, indicating growing interest and activity. In 2023, the number dipped slightly to 535 publications, while in 2024, the number saw the most significant surge with 648 publications, reflecting heightened focus and investment in WEC optimization and renewable energy research. The obvious decline to 243 publications in 2025 is primarily

due to data collected only up to May, representing less than half of the year. Therefore, the 2025 figure likely underrepresents the total annual output and is expected to rise as more studies are published and indexed later in the year. This fluctuation underscores the dynamic and evolving nature of research in the WEC field.

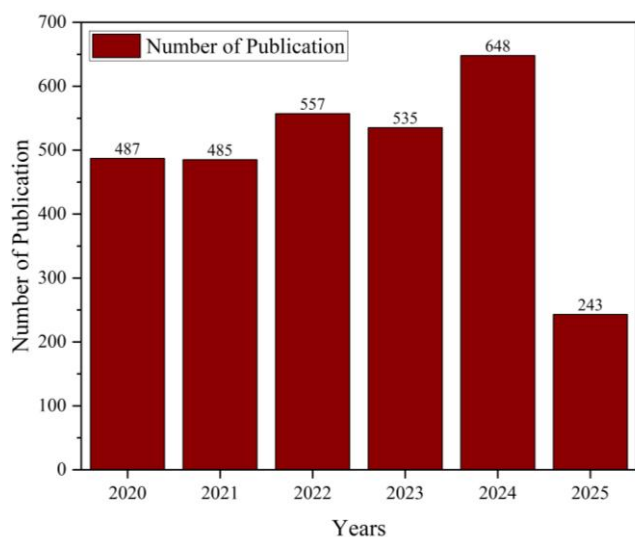


Fig. 4. Annual Publication with WEC Topic Based on Scopus Database

Figure 5 illustrates the number of publications across different research areas, with a particular emphasis on the distribution of publications within engineering and energy sectors that categorize 20 distinct research areas, showcasing the volume of publications in each field. Notably, Engineering and Energy emerge as the dominant areas, with energy-related publications accounting for as many as 2,101 articles, followed closely by engineering publications, which total 1,192. These two fields together constitute a significant portion of the overall research output, highlighting the increasing focus on technical and energy-related advancements, particularly the optimization of energy systems such as WECs. In contrast, fields like Environmental Science and Mathematics also show considerable interest, with publications numbering 953 and 473, respectively. Although these areas reflect notable engagement, their publication volumes are still substantially lower than those of energy and engineering. Fields such as Physics and Astronomy, Computer Science, and Materials Science demonstrate moderate involvement, with 309, 270, and 226 publications, respectively. On the other hand, disciplines like Social Sciences, Medicine, and Pharmacology, Toxicology, and Pharmaceuticals are comparatively underrepresented, with the number of publications in these fields being significantly smaller with 67, 8, and just 1, respectively.

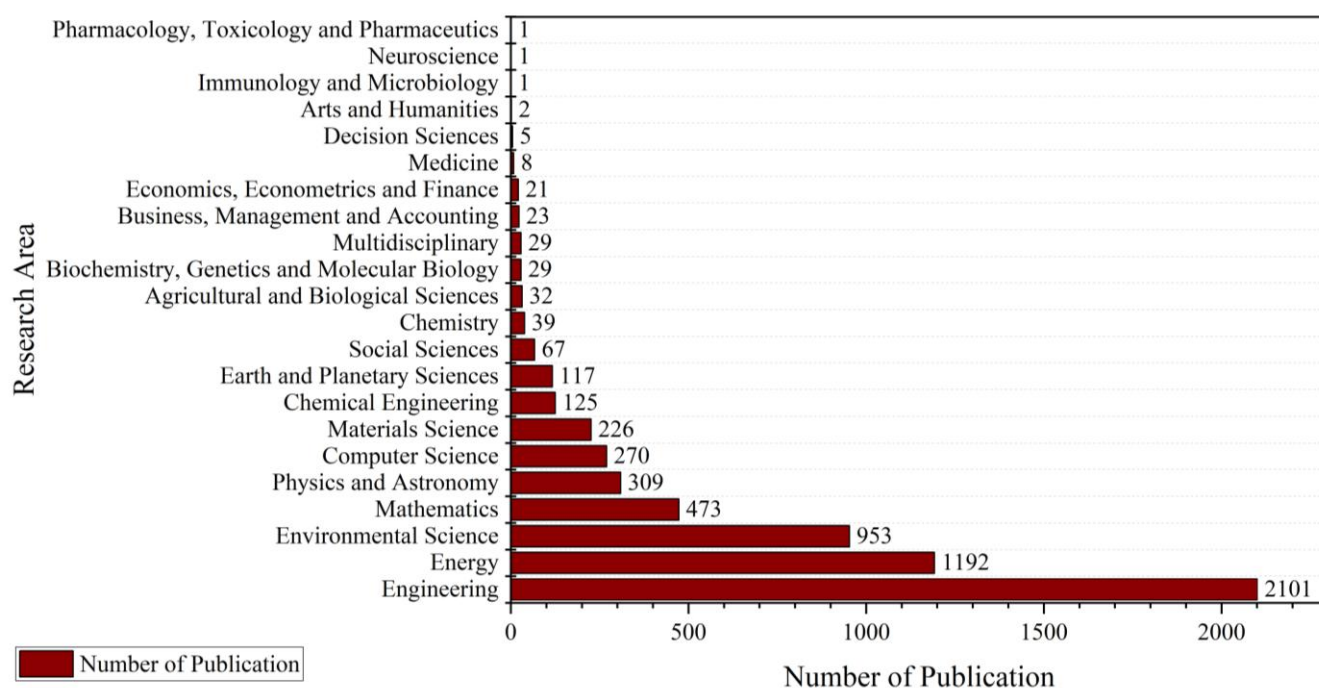


Fig. 5. Research Area Distribution by Number of Publications

This distribution suggests that the field of WEC research, particularly focused on energy and engineering optimization, is drawing considerable attention, aligning with broader global trends toward renewable energy technologies and their optimization. The relatively high number of publications in Environmental Science further supports this focus, as environmental considerations are integral to the development of sustainable energy solutions. Thus, the significant concentration of

publications in engineering and energy reflects the ongoing push for advancements in energy systems, while the modest representation from other fields points to a broader interdisciplinary approach, with contributions from materials science, physics, and social sciences, among others. This emphasizes the growing recognition of WECs as a key component in renewable energy technologies and the need for multidisciplinary research to enhance their effectiveness and deployment.

3.2. Bibliometric Analysis

The bibliometric analysis in this study is designed to identify the most influential research papers in the field of WEC Optimization, using data from the Scopus database. VOSviewer software processes this data to create network visualizations, where the nodes represent authors and the size and color of each node reflect citation metrics [54], [55]. This approach highlights the most cited and influential works in the field by visualizing networks based on direct citations and fractional counting methods to prevent the dominance of papers with excessive citations [56].

In Figure 6, the bibliometric network visualizes the research literature on WEC optimization. The size and color of the author nodes indicate the citation frequency, with larger font sizes and brighter colors or yellow indicating more frequently cited works. This figure shows a network of connected articles, where each node represents a prominent research paper or author. The central nodes, such as Gomes et al. [57] and Shi et al. [58], are the most influential and heavily cited, while peripheral nodes represent research with fewer citations but still relevant to the field. The nodes are clustered in a way that suggests thematic connections, with the central position of certain papers indicating their pivotal role in driving further research on WEC optimization. The yellow nodes

represent the areas with the highest concentration of citations, showing where the most important research in this field is concentrated. The paper by Gomes et al. [57] stands out as one of the central contributions in this topic, with its substantial citation frequency. This centrality suggests that Gomes et al. [57] work has played a crucial role in shaping the direction of subsequent research in WEC optimization.

Figure 7 depicts the evolution of publication sources over time in the context of WEC optimization research. This bibliometric visualization employs citations as the type of analysis and journals as the unit of analysis, with thresholds set at a minimum of five documents and 20 citations per source. Using fractional counting, the network highlights *Renewable Energy* as the central and most influential publication outlet in this field. The color gradient, ranging from blue (2020) to yellow (2025), effectively illustrates the temporal progression of research outputs. Notably, there is a discernible increase in publications in journals such as *Applied Energy* and *Energy Conversion and Management*, indicating a growing scholarly interest in the specialized and advanced aspects of WEC optimization. The connectedness of these publication sources reveals how journals have increasingly focused on more specialized and advanced topics within the broader fields of renewable energy and ocean engineering.

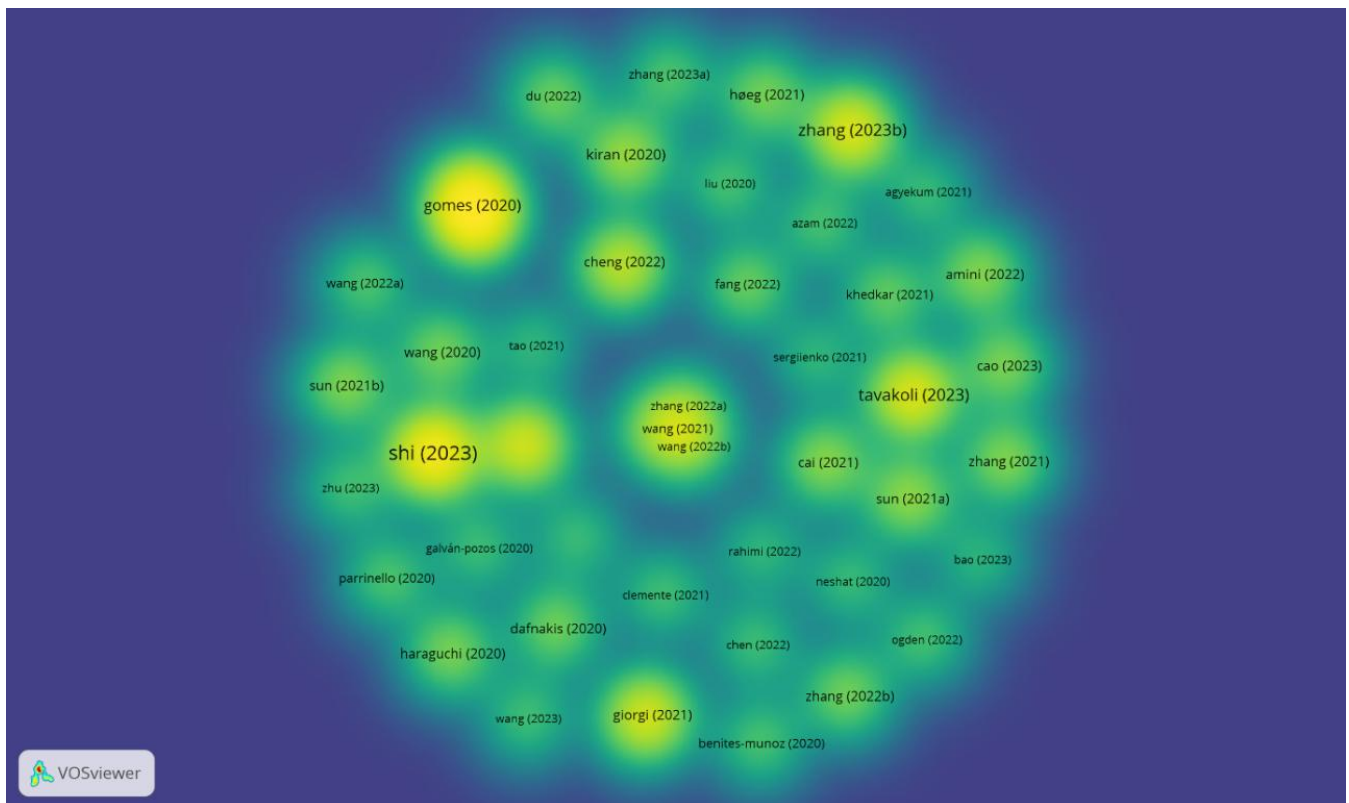


Fig. 6. Prominent Research Literature on WECs Optimization Topics

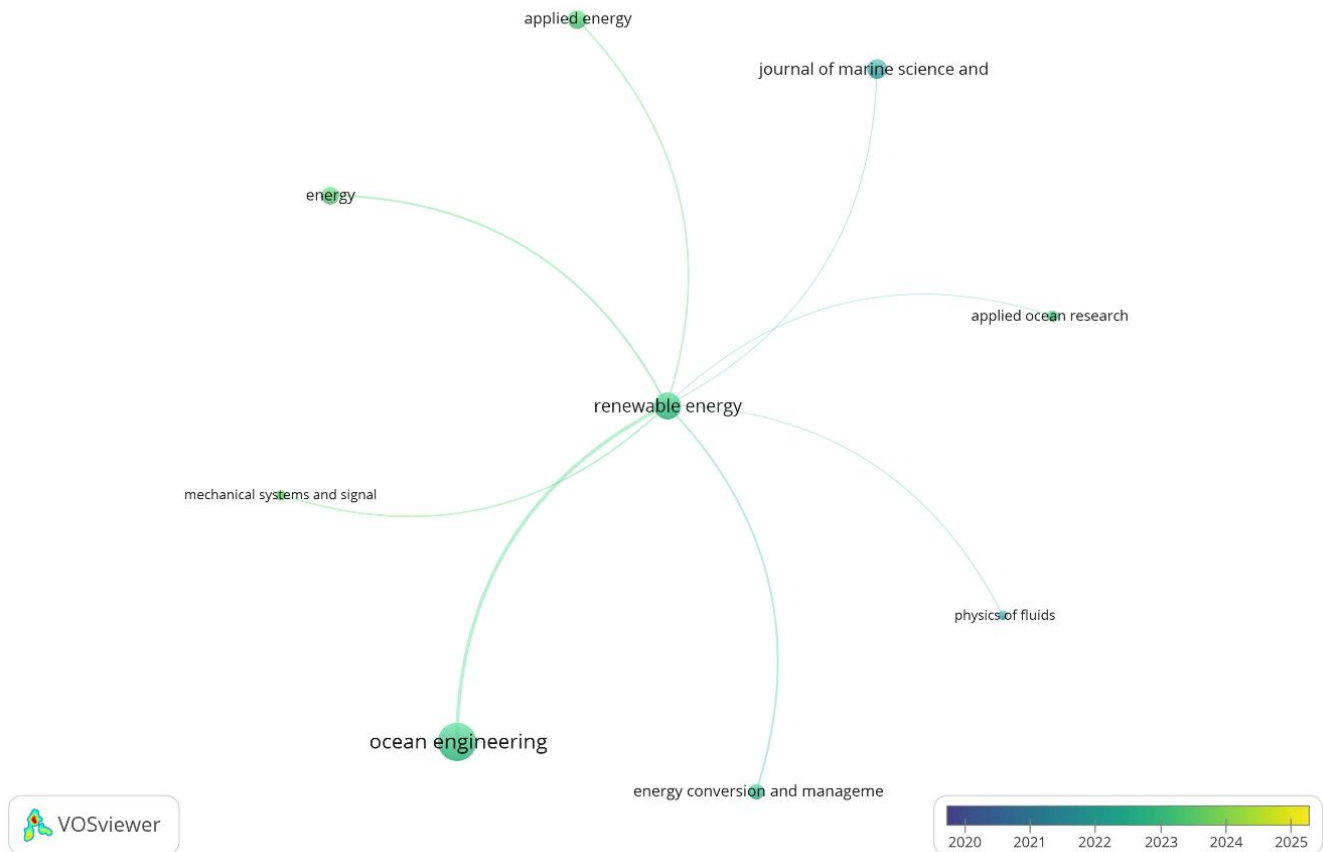


Fig. 7. Publication Sources on WECs Optimization Over Time

In addition to citation-based analysis, keyword co-occurrence mapping and country collaboration networks offer critical insights into the thematic structure and geographical distribution of research in WEC optimization. Using VOSviewer, this study evaluated 22 interlinked author keywords with a minimum occurrence threshold of five, applying the fractional counting method recommended by Miraj et al. [59] and Hu et al. [45]. As visualized in Fig. 8, three major thematic clusters emerge. The red cluster focuses on structural and functional integration, featuring keywords such as “wave energy converter,” “floating breakwater,” and “hybrid system.” The green cluster highlights technical performance and sustainable energy themes, connecting terms like “wave energy,” “hydrodynamic performance,” and “renewable energy.” Meanwhile, the blue cluster represents control-oriented technological advancements, with keywords such as “wave energy conversion,” “power take-off,” “point absorber,” and “model predictive control.” The node size and proximity indicate both the frequency of occurrence and the strength of inter-keyword relationships, revealing a complex yet coherent thematic landscape. These keyword linkages also reflect the strategic focus of key authors, whose recurring use of these terms signifies their central role in shaping the evolution of WEC optimization research. This confirms the multidisciplinary nature of the

field, combining ocean engineering, energy systems, and intelligent control strategies.

Building upon this thematic understanding, Figure 8 presents a network visualization of international collaboration in WEC optimization research, also generated using the fractional counting method. Here, each node represents a country, with node size reflecting the volume of collaborative research outputs, and link thickness indicating the strength of bilateral cooperation. The figure shows China and the United Kingdom as the dominant centers of global collaboration, forming the green cluster with strong ties to countries such as Japan, Ireland, Portugal, and Italy. Their central positions suggest leadership in setting research agendas and fostering transnational innovation in marine renewable energy. The United States, while also significant, occupies a separate red cluster, collaborating closely with Australia, Iran, and South Korea, indicating regional research dynamics. Additionally, nations like Sweden and Portugal act as intermediaries bridging different clusters, reflecting a diverse and globally integrated research community. Together, Fig. 8 and Fig. 9 offer a comprehensive overview of the intellectual and collaborative landscapes in WEC optimization, highlighting both the topical priorities and the geographical networks that drive innovation in this crucial area of renewable energy.

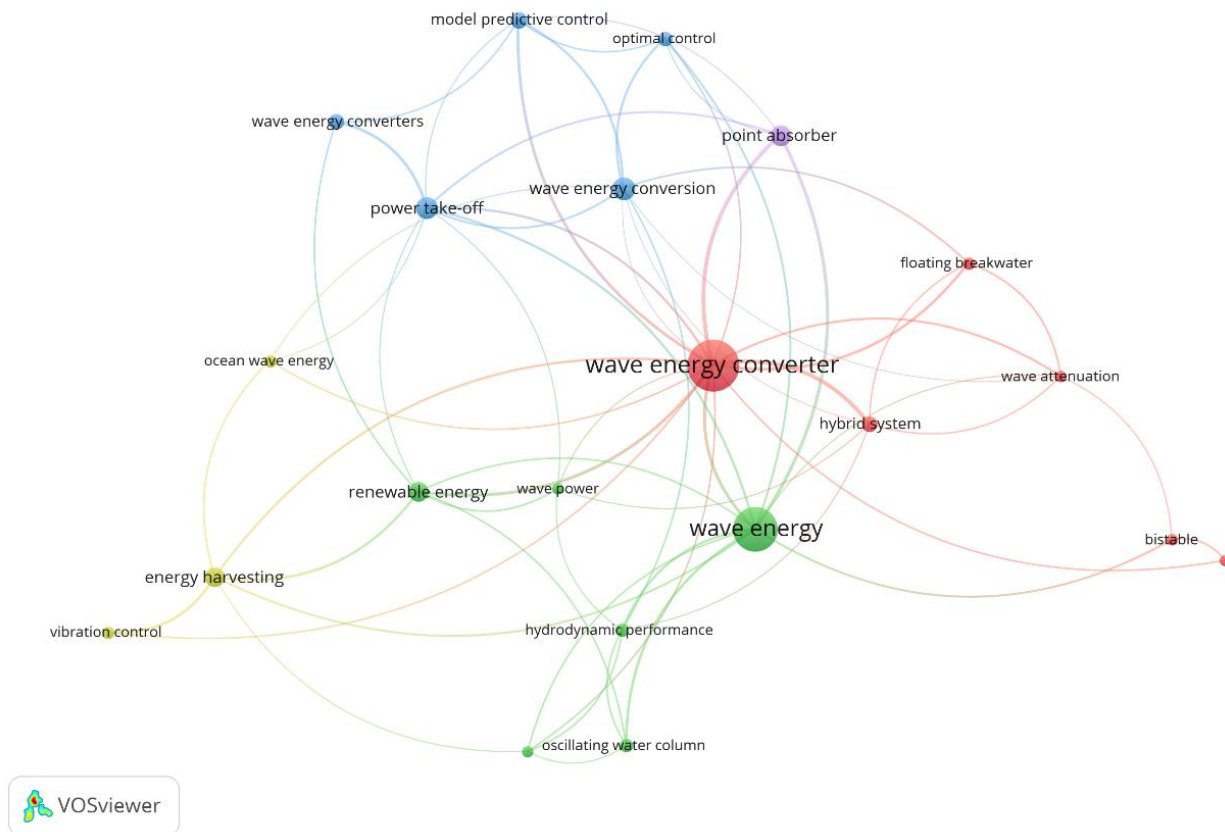


Fig. 8. Network Visualization of Keyword Relationships Using VOSviewer

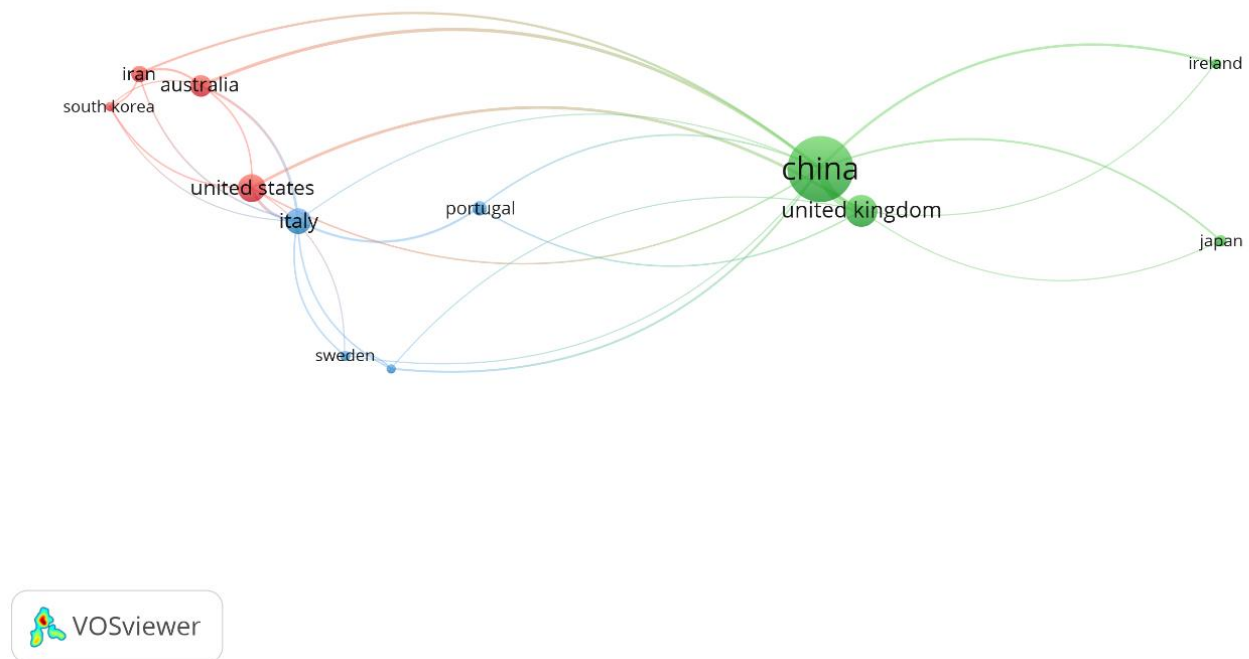


Fig. 9. Co-Authorship Countries Using VOSviewer

3.3. Systematic Analysis

This review adopts a systematic analysis method based on the framework proposed by Arrosyid et al. [51], as illustrated in Fig.3. The process consists of four key stages: literature search, criteria specification, data collection, and quality assessment. Each step was carefully followed to ensure the reliability and comprehensiveness of the findings. The literature search was conducted using the Scopus database, employing a structured query that combines several relevant keywords and Boolean operators. The search string used was: 'wave energy converter' AND 'degree of freedom' AND 'power take off' AND 'optimization'. This string was designed to capture a broad but focused set of publications related to WECs, their degrees of freedom, power take-off (PTO) systems, and optimization approaches. From this process, 36 journal articles published between 2020 and 2023 were identified as being highly relevant to the topic of WEC optimization as the results of the bibliometrics analysis before were selected for further analysis.

Selection of the final 36 studies was based on specific inclusion and exclusion criteria. The selection criteria required that the articles: presented a clear optimization

methodology, focused on WEC optimization, and addressed geometric and energy efficiency aspects. Meanwhile, exclusion criteria eliminated studies that: were not applicable to marine environments, lacked detailed explanations of methods or evaluations, or were published in languages other than English. This rigorous screening process ensured that the studies analyzed were both relevant and methodologically robust.

Once selected, each paper was examined in terms of the optimization method applied, the type of WEC addressed, and its fulfillment of ten key evaluation criteria. These criteria, as defined by Arrosyid et al. [51] in Table 2, included high energy efficiency, low computational cost, multi-objective capability, robustness to wave variations, applicability to various WEC types, improved system stability, high convergence speed, use of innovative methodology, wide software compatibility, and availability of experimental validation. These aspects were extracted to form a comparative analysis and enable benchmarking across different approaches and technologies. The information was synthesized into Table 3, which lists the optimization method, WEC type, and criteria satisfaction for each study.

Table 3. Evaluation Framework Comparison Drawn from WEC Studies

No. Ref.	Authors	Optimization Technique	Type of WEC	Consideration Aspect									
				1	2	3	4	5	6	7	8	9	10
1	Haraguchi and Asai [60]	Tuned Inertial Mass (TIM) system	Point absorber WEC	O	O	O	O	O	O	O	O	O	X
2	Dafnakis et al. [61]	Adjusting PTO coefficients and mass density of the buoy	Submerged cylindrical point absorber WEC	O	O	O	O	X	O	X	O	O	X
3	Neshat et al. [62]	Bi-level optimisation framework combining global and local search methods	Fully submerged, cylindrical WEC with three tethers	O	O	O	O	O	O	O	O	O	O
4	Parrinello et al. [63]	Extremum-seeking (ES) control	Heaving point absorbers	O	O	O	O	O	O	O	O	O	O
5	Gomes et al. [57]	Time-domain simulation of a slack-moored Spar-buoy OWC	Slack-moored Spar-buoy OWC	O	O	O	O	O	X	O	O	O	O
6	Liu et al. [64]	Improving the PTO system design and electrical damping coefficients	Direct drive and linear generators WEC	O	X	O	O	O	O	O	X	O	O
7	Kiran et al. [65]	Optimizing the use of piezoelectric materials	Oceanic WEC (OWEC)	O	O	O	O	O	O	O	O	O	O
8	Wang et al. [66]	Time-domain wave-to-wire model	Point absorber WEC	O	O	O	O	O	O	O	O	O	O
9	Galván-Pozos and Ocampo-Torres [67]	Six degrees of freedom in the WEC-SGP system	Point absorber WEC	O	X	O	X	O	O	O	O	O	O
10	Zhang et al. [68]	Numerical modeling with potential flow theory to optimize breakwater size, WEC array layout, and placement	Oscillating Buoy (OB) WEC	O	O	O	O	O	O	O	O	O	O
11	Giorgi et al. [69]	Nonlinear Froude-Krylov force model	Pitch WEC	O	O	O	O	O	O	O	O	O	O
12	Cai and Zhu [70]	Frequency tuning by adjusting the positions of two independent masses in the DMP oscillator	Point absorber WEC	O	O	O	O	O	O	O	O	O	O

13	Clemente et al. [71]	Numerical modelling of the E-Motions WEC in the ANSYS AQWA environment	E-Motions WEC	O	O	O	O	O	O	X	O	O	O
14	Sun et al. [72]	Configuration of point-absorber arrays and adjusting their arrangement to optimize wave energy capture	Point absorber WECs	O	O	O	O	O	O	X	O	O	O
15	Sergiienko et al. [73]	Model predictive control (MPC)	Submerged multi-degree-of-freedom WEC	O	X	O	O	O	O	X	O	O	X
16	Khedkar et al. [74]	Reactive control theory for the gyroscopic specifications	Inertial sea WEC (ISWEC)	O	X	O	O	O	O	X	O	O	X
17	Høeg and Zhang [75]	Modeling approach by correctly capturing gyroscopic effects in a time-domain model	Floating offshore wind turbines (FOWT)	X	O	X	O	O	O	X	O	O	X
18	Wang and Ringwood [76]	Inner-layer PTO control optimization and outer-layer geometric and ballast optimization	Three-body hinge-barge WEC	O	O	O	O	X	O	X	O	O	O
19	Sun et al. [77]	Structural optimization through simulations of buoy spacing, placement modes, and actuating arm lengths	Floating array-buoy WEC	O	O	O	O	O	O	O	O	O	O
20	Tao et al. [78]	Response surface method combined with boundary element method (BEM) solvers and optimization algorithms	A 3-DOF buoy WEC with surge, pitch, and heave motion	O	O	O	O	O	O	O	O	O	O
21	Amini et al. [79]	Modified Genetic-Surrogate-fminsearch, numerical and metaheuristic methods	Point absorber WEC	O	X	O	O	O	O	O	O	O	X
22	Fang et al. [80]	Integration of a mechanical rectification mechanism	Vibration Energy Harvesting Systems (VEHS)	O	O	O	X	O	X	O	O	O	O
23	Chen et al. [81]	Bang-bang control	Heaving WEC	O	O	O	O	O	O	X	O	O	X
24	Ogden et al. [82]	WEC-Sim's optimization	Point absorber WEC	O	O	O	O	O	O	X	O	O	O
25	Rahimi et al. [83]	Optimization of PTO system parameters (damping and stiffness)	Two-body point absorber (2B-PA) WEC	O	O	O	O	O	O	O	O	O	O
26	Du et al. [84]	Self-bias voltage optimization	Oscillating Water Column (OWC)	O	O	O	O	O	O	O	O	O	O
27	Wang et al. [85]	Relative motion, phase control, and gap distance optimization	Dual-oscillating water column (OWC)	O	O	O	O	O	O	O	O	O	O
28	Cheng et al. [86]	Parametric study of the geometric design	Multi-degree-of-freedom (MDOF)	O	O	O	O	O	O	O	O	O	O
29	Azam et al. [87]	Simulations using ANSYS AQWA	Floating buoy-type WEC	O	O	O	O	O	O	O	O	O	O
30	Cao et al. [88]	Magnetic coupling and symmetrical magnet arrangement in the piezoelectric energy harvester (PEH)	Hybrid wind energy converter (WEC)	O	O	O	X	O	O	O	O	X	O
31	Wang et al. [89]	Frequency domain optimization	Two-body counter-rotating WEC (CR-WEC)	O	O	O	O	O	O	X	O	O	O
32	Zhu et al. [90]	Matching-method of eigen functions	Point absorbing WEC, coupled with a floating wind turbine.	O	O	O	O	O	O	O	O	O	X
33	Zhang et al. [91]	Numerical simulations using ANSYS/AQWA software to model hydrodynamic interactions	Wavestar point-absorption WEC	O	O	O	O	O	O	O	O	O	X
34	Zhang et al. [92]	Multi-DOF optimization approach	Oscillating Body WEC (OBWEC), particularly a parallel configuration (PCWEC) with multi-DOF	O	O	O	O	O	O	X	O	O	O
35	Bao et al. [93]	Coupled dynamics model of the multi-DOF WEC with hybrid PTO systems	Multi-DOF WEC (PUWEC)	O	O	O	O	O	O	O	O	O	O

As shown in Table 3, high energy efficiency (Criterion 1) is nearly universal, reflecting the primary objective of maximizing energy capture. However, experimental validation (Criterion 10) and high convergence speed (Criterion 7) are less consistently addressed. Methodological comprehensiveness is exemplified by

studies such as Neshat et al. [62], Parrinello et al. [63], Wang et al. [66], Zhang et al. [68], and Bao et al. [93] which satisfy nearly all criteria. To further clarify the methodological landscape, Table 4 categorizes these studies by algorithmic approach, hybrid configuration, and design objectives.

Table 4. Research Framework and Design Objectives from WECs Studies

No. Ref.	Optimization Category	Hybrid Configuration	Objective Function	Key Constraints
1	Parametric	WEC + Tuned Inertial Mass (TIM).	Maximize power absorption across a broad frequency band.	Physical dimensions and mass ratios of the inertial disk.
2	Parametric	Submerged Buoy (PF vs CFD Hybrid Analysis).	Accurate prediction of hydrodynamic coefficients and power.	3-DoF motion (Heave, Surge, Pitch) in submerged conditions.
3	Stochastic / Metaheuristic	Multi-mode (Surge-Heave-Pitch) submerged WEC.	Maximize Mean Power; Minimize LCOE.	Geometry (radius/height), tether angles, site-specific sea states.
4	Deterministic	WEC + Extremum Seeking (ES) Control.	Maximize mean extracted power via PTO damping tuning.	None (unconstrained), but adaptable to physical PTO limits.
5	Parametric	Spar-buoy OWC + Slack Mooring.	Optimize turbine damping for maximal pneumatic power.	Slack-mooring stiffness, air chamber volume, and turbine speed.
6	-	PTO Mechanism Survey (Various).	Maximize PTO efficiency and reliability.	Mechanical friction, leakage (hydraulic), and heat dissipation.
7	-	Piezoelectric + Electromagnetic Hybrid.	Maximize power density ($\mu\text{W}/\text{cm}^3$) and material durability.	Material fatigue, low voltage output, and fluid-structure coupling.
8	Parametric	WEC + Optimized Electric Load (Wave-to-Wire).	Maximize time-averaged electric power (Wave-to-Wire).	Generator voltage limits, cable losses, and buoy stroke limits.
9	Parametric	6-DoF Stewart-Gough Platform WEC.	Track planned trajectories for maximum 6-DoF energy harvest.	Leg length limits, singular configurations, and ball-joint angles.
10	Parametric	WEC array + Floating Breakwater (FB).	Maximize power absorption and wave attenuation (Capture Width).	Coupled motion constraints between WEC and breakwater.
11	Parametric	Prismatic Floating Platform (Integrated)	Computational speed for real-time control optimization	Geometric constraint (prismatic floating platforms)
12	Parametric	Double-mass Pendulum (DMP) Oscillator	Maximize resonance at ultra-low frequencies (< 1 Hz)	Pendulum mechanical limits and ultra-low-frequency resonance
13	Parametric	E-Motions (Rolling Platform WEC)	Maximize Annual Energy Production (AEP)	Platform design (eight hull variants) and PTO characteristics
14	Parametric	FABWEC (Floating Array-Buoys)	Maximize capture width ratio and efficiency	Physical dimensions of the FABWEC floating frame
15	Deterministic	Submerged Multi-mode (CETO-inspired)	Maximize total power production subject to constraints	Maximum control force, stroke, and stroke rate
16	Parametric	ISWEC (Internal Gyroscope in Boat Hull)	Power conversion efficiency and hull-wave synchronization	Fluid-structure interaction and multi-phase flow dynamics
17	Parametric	Hybrid Wind-Wave (Floating Offshore Wind Turbine)	Accuracy of dynamic response and stability under loads	Gyroscopic matrix and coupled mechanical-hydrodynamic constraints
18	Stochastic / Metaheuristic	Three-body Hinge-Barge (McCabe Wave Pump)	Maximize time-averaged power in irregular wave climates	Barge lengths and ballast positioning (technical/physical)
19	Parametric	Semi-submersible + Point-absorber Array	Maximize wave energy capture efficiency	Multi-floater hydrodynamic interference and platform spacing
20	Stochastic / Metaheuristic	3-DOF Multi-mode Buoy (Heave, Pitch, Surge)	Maximize mean output power per unit mass	Stability (avoiding overturning) and resonance frequency matching
21	Deterministic and Stochastic	WEC + Hydraulic PTO System	Maximize captured power; minimize PTAP ratio	Piston area, accumulator volume, and pre-charge pressure
22	Parametric	Inertial Pendulum + Rectification	Maximize peak output power and efficiency	Freight train vibration frequency (3–10 Hz)

23	Deterministic	FOWT + 3 Heaving WECs	Maximize power while reducing structural loads	PTO force limits and stroke displacement
24	-	WEC-Sim (Wind-Wave Capability)	User-defined (Power, Load, or Cost)	Hydrodynamic and PTO constraints
25	Parametric	Two-Body Point Absorber	Maximize time-averaged mechanical power	Dimensionless damping and stiffness coefficients
26	Parametric	DE WEC + Ancillary Wind Turbine	Maximize energy gain per cycle (J)	DE film breakdown voltage and pre-stretch ratio
27	Parametric	Dual-unit Heaving OWC	Maximize overall power extraction efficiency	Lip-wall draft, chamber breadth, and gap distance
28	Parametric	Platform-Integrated Multi-DOF WEC	Maximize Capture Width Ratio (CWR)	Platform stability and buoy stroke
29	Parametric	Spinning Top Resonant Buoy	Maximize absorbed power in low energy density seas	Buoy draft and diameter ratios
30	Parametric	Wind-Piezoelectric-Electromagnetic	Maximize voltage and power density	Bridge installation space and starting torque
31	Parametric	Two-Body Hybrid using Counter-rotating inner and outer bodies for deep-sea power.	Maximize absolute power capture in deep-sea conditions.	Limited working stroke and absolute motion limits of the PTO system.
32	Parametric	Array Hybrid using OC4-DeepCwind semi-submersible platform + heaving WEC array.	Maximize energy capture width while minimizing platform heave.	Physical boundary conditions of the fluid domain and viscous damping.
33	Parametric	Parallel Config Hybrid using Multi-absorber parallel structure with integrated multiple PTOs.	Maximize the Energy Cost-Efficiency Indicator (ECEI) and power density.	Kinematic limits of the UPS-UP parallel structure and structural stiffness.
34	Parametric	Wind-Wave Hybrid using SPIC semi-submersible FWT integrated with 8 Wavestar WECs.	Maximize absorbed power and minimize negative interaction factors (q).	Platform pitch stability and safe operating limits for the Wavestar arms.
35	Parametric	Hybrid PTO using combination of a piston PTO (Heave) and U-shaped column (Pitch).	Maximize total captured power (P_t) and capture width ratio (CWR).	PTO damping coefficients, piston friction, and U-column stiffness.

The classification presented in Table 4 reorganizes the reviewed studies into three principal academic categories: parametric approaches, deterministic algorithms, and stochastic (metaheuristic) optimization methods, in order to provide a clearer methodological distinction between design evaluation and automated search-based optimization. The majority of the reviewed studies fall under the parametric category, where optimization is conducted through systematic parameter variation, analytical evaluation, or comparative simulation without employing an automated search algorithm. These studies typically involve geometry sweeping, PTO coefficient tuning, damping adjustment, or structural configuration testing using numerical solvers such as BEM, CFD, or time-domain simulations. Examples include the Tuned Inertial Mass system by Haraguchi and Asai [60], slack-moored OWC simulations by Gomes et al. [57], array configuration analysis by Sun et al. [72], and hybrid wind-wave numerical evaluations using ANSYS/AQWA tools. Although some of these works use the term “optimization,” the procedure is primarily iterative evaluation rather than algorithm-driven global search.

The deterministic category consists of mathematically structured optimization or control algorithms that compute optimal solutions based on gradient-based or model-based formulations. This includes extremum-seeking control [63], model predictive control (MPC) strategies [73], bang-bang control [81], and Sequential

Quadratic Programming methods applied to PTO systems. These approaches rely on explicit cost functions and dynamic models to converge toward locally or globally optimal operating conditions while respecting physical constraints such as stroke limits and control force bounds.

In contrast, the stochastic category comprises automated search-based optimization techniques, including metaheuristic and surrogate-assisted frameworks. Studies such as the bi-level optimization framework by Neshat et al. [62], the surrogate-genetic hybrid model by Amini et al. [79], and response-surface-based optimization methods [78] employ probabilistic exploration strategies to address multi-objective problems such as maximizing absorbed power while minimizing Levelized Cost of Energy (LCOE). These approaches are particularly advantageous when the design space is nonlinear, high-dimensional, or multimodal.

This reclassification clarifies that while algorithmic optimization is increasingly present in WEC research, the field remains predominantly driven by parametric performance evaluation. The transition from parameter sweeping toward fully automated stochastic optimization reflects an emerging shift toward techno-economic integration and multi-objective design strategies. To further evaluate the practical implications of these approaches, Table 5 presents a comparative assessment of reported technical performance improvements and validation levels.

Table 5. Technical Performance and Validation from WECs Studies

No. Ref.	Energy Gain / Performance Data	Capacity Factor / Operational Consistency	Validation Level
1	40% higher power in irregular waves vs. standard WEC.	Broadens the effective frequency bandwidth significantly.	-
2	CFD predicts lower power than PF due to viscous drag.	Viscous effects reduce motion in resonance by 15-25%.	-
3	20-40% increase in power compared to single-mode (Heave).	Improved stability in the variable Mediterranean wave climate.	Numerical simulation (10 sea states); compared with 7 metaheuristics.
4	15-20% gain in extracted energy without wave forecasting.	Continuous adaptation ensures peak performance in non-stationary seas.	Numerical simulation (1-DoF buoy); verified with reference maps.
5	Capture Width Ratio (CWR) peaks at ~0.4-0.5.	High consistency; OWC works well in both regular/irregular waves.	Physical model tests (1:35 scale) in a wave flume.
6	Direct Drive: ~90-95% efficiency; Hydraulic: ~70-85%.	Indirect (Hydraulic) systems have better energy storage (Accumulators).	Literature survey and comparative performance metrics.
7	PZT density up to 116 $\mu\text{W}/\text{cm}^3$; EM is much higher.	PZT provides energy in low-frequency/calm sea conditions.	Experimental laboratory prototypes (various PZT types).
8	5.4% to 10.2% increase in net electric power.	Stable voltage output through active resistance control.	Time-domain simulation using full-scale experimental sea data.
9	Theoretical capture from all six directions of motion.	Captures surge, sway, and yaw energy often lost by 1-DoF buoys.	Numerical kinematic and dynamic analysis (Theoretical).
10	61% Efficiency (Max); exceeding standalone WEC limits.	High consistency due to "Wave Focusing" behind the FB.	3D Frequency-domain modeling; verified with WEC-Sim.
11	Significant gain via real-time control enablement	High consistency through nonlinear analytical modeling	Comparison against state-of-the-art mesh-based NLFK methods
12	25% increase in CWR (based on two-body baseline)	Tunable resonance for ultra-low-frequency waves	Shaking table and wave flume experimental tests
13	52% Capture Width Ratio (CWR) (Max)	1040 MWh Annual Energy Production (AEP)	Numerical modeling verified against proof-of-concept experiments
14	38% higher than basic/standalone model	High synergistic energy capture across the array	Hydrodynamic simulation and physical lab experiments
15	20–30% potential power increase (MPC prediction)	Better consistency by penalizing peak control forces	-
16	Optimal efficiency at hull length $\lambda/3$ to $\lambda/2$	Enhanced consistency via proportional control	-
17	Significant load reduction (torsion/yaw stability)	Improved structural stability in operational conditions	-
18	67.6% improvement in energy production	Higher operational consistency via control-informed design	5-DOF mathematical model with site-specific wave data
19	11.1% Overall Efficiency (Max); 35.2% Hydraulic Efficiency	Consistent performance across staggered array floaters	Experimental testing in a towing tank (regular/irregular waves)
20	Increased from <20% (standard) to higher optimized CWR	Improved adaptation to multiple wave directions	Numerical simulation (BEM) validated by experimental statistical data
21	Up to 15% power increase via optimization	38% reduction in PTAP ratio	-
22	1.04 W Peak Power; 68.29% Efficiency	Consistent power during train movement	Experimental & Prototype Testing
23	~6% increase in total power	Increased stability; 17.1% pitch reduction	-
24	Varies by application (typically 5-10%)	Improved modeling accuracy	Review of various validation levels
25	Improved capture via relative motion	Better performance in deep water	Numerical (BEM/CFD) & Experimental
26	1.4 J per cycle (at 120mm deformation)	Constant bias voltage provided by wind	Theoretical modeling & validation
27	Optimized efficiency vs standalone	Dual units capture wider wave spectrum	Theoretical (Linear Potential Theory)
28	Significant CWR increase across frequencies	Multi-DOF capture improves consistency	Numerical (CFD) & Physical Experiment
29	6.9 W absorbed power in low seas	Higher resonance bandwidth	Numerical (ANSYS AQWA)
30	Max 19.24 mW output reported	Improved low-speed performance (starts at 2.5 m/s)	Experimental & Field Testing

31	>100% (theoretical) compared to non-optimized baseline.	Improved reliability for deep-sea sensors/equipment.	Experimental Verification with Prototype tank testing with a 0.36m diameter scale model.
32	30% reduction in platform heave (indirect energy/stability gain).	Broadened frequency bandwidth for energy extraction.	-
33	Higher energy capture per unit area than traditional WECs.	Not explicitly quantified but shows higher frequency adaptability.	-
34	Peak power capture of ~110 kW per WEC unit reported.	Enhanced operational consistency via wind-wave energy smoothing.	Numerical simulation using coupled hydrodynamic analysis using ANSYS-AQWA.
35	49.8% increase compared to single-DOF systems.	Improved consistency across varying wave frequencies.	Numerical & Experimental using 1:10 scale tank testing validated against simulation.

The metrics in Table 5 confirm that optimization significantly enhances energy capture and operational consistency. For example, Tao et al. [78] and Zhang et al. [68] reported substantial increases in Capture Width Ratio (CWR), while Bao et al. [93] demonstrated a 49.8% increase over single-DOF systems. Control-based approaches by Parrinello et al. [63] and Fang et al. [81] achieved stable improvements under irregular sea states.

However, validation remains predominantly numerical (BEM, CFD, and time-domain), with few studies incorporating experimental tank testing such as Sun et al. [72] and Bao et al. [93], highlighting a gap between simulation and deployment. To address hybrid wind-wave configurations specifically, Table 6 provides a practical and economic impact analysis.

Table 6. Practical Impact and Critical Analysis from WECs Studies

No. Ref.	Practical Contribution	Economic Impact	Key Insight
1	Broadened bandwidth; 30% - 50% power increase in off-resonance.	Potential for smaller buoys to harvest the same energy as larger ones.	Mechanical "tuning" can substitute for expensive active control.
2	Proves PF is sufficient for small waves, but CFD is vital for large waves.	Improved reliability of power estimates for investors.	Overestimating power (via PF) leads to poor economic planning.
3	Identified optimal buoy (r=5m, h=2m) for Mediterranean, reducing LCOE.	LCOE Optimized with 5m radius found to be most cost-effective.	Multi-mode harvesting is essential for low-energy sea regions.
4	Real-time adaptation to changing sea states without wave prediction.	Reduced need for expensive wave-sensing LIDAR or buoys.	Model-free control is a robust alternative to complex MPC.
5	Validated that air compressibility effects are negligible at small scales.	Mooring costs analyzed; slack mooring reduces peak tension forces.	Accurate time-domain modeling is critical for OWC mooring design.
6	Provided a roadmap for selecting PTOs based on deployment depth.	Direct drive has lower OPEX; Hydraulic has higher CAPEX.	PTO choice is the primary driver of WEC reliability and cost.
7	Identified PZT as viable for low-power sensors in remote buoys.	Low CAPEX for PZT; useful for self-powered ocean sensors.	Hybridizing PZT and EM can power offshore IoT and monitoring.
8	Increases electrical efficiency by 5-10% by considering transmission losses.	Reduced OPEX by preventing generator overheating/overvoltage.	Electrical losses must be included in the optimization, not just hydrodynamics.
9	Enables 6-DoF harvesting, capturing energy from complex motions.	High CAPEX due to 6 hydraulic/electric legs; high maintenance.	SGP design maximizes energy capture per unit area of the sea surface.
10	Proposed WEC-breakwater integration reaches 61% efficiency.	LCOE Reduction in Mooring Foundation sharing between FB and WECs.	Integrated systems provide coastal protection while generating power.
11	4 orders of magnitude faster calculation for real-time control	10,000x reduction in computational cost for control	Real-time nonlinear control is viable for prismatic WECs
12	Enabling WECs to harvest energy from slow-moving waves	Dual-functionality as energy harvester and damper	Ultra-low-frequency tuning (<1Hz) is possible via DMP
13	Identifying optimal hull shapes for roll-induced power capture	Hull selection optimizes the energy-to-cost ratio	Rolling motion is highly effective for energy in deep water
14	38% higher power output than basic model via structural tuning	Low building difficulty and construction cost	Structural optimization of spacing doubles efficiency
15	Guidance for PTO machinery sizing and controller tuning	PTO size and cost reduction via penalty tuning in MPC	Controller settings directly dictate the PTO machinery cost
16	High-fidelity modeling of internal gyroscopic PTO physics	Retrofitting abandoned ships reduces manufacturing costs	Resonance matching between hull and wave is the key driver
17	Efficient time-domain tool for structural stability design	Cost-effective for deep-sea (>60m) deployment	Gyroscopic effects from wind rotors stabilize the platform yaw
18	Integrated geometric and control optimization for long-term use	Significant CAPEX savings via optimized barge/ballast sizing	Joint optimization of geometry and control is essential for ROI
19	Optimized staggered array layouts for higher energy density	Shared mooring and pontoons reduce unit construction costs	Staggered arrangements are superior for array-type WECs

20	Efficient methodology for 3-DOF buoy geometric design	Power/mass ratio used as an economic viability metric	Releasing more degrees of freedom significantly boosts capture
21	Reduces LCOE by up to 38% through optimal PTO settings	~38% reduction in LCOE	Optimized PTO settings are critical for economic feasibility
22	68.29% efficiency; peak power of 1.04 W for rail sensors	Zero-energy monitoring for rail freight	Mechanical rectification doubles the effective capture cycle
23	34.6% reduction in platform heave; 11% reduction in fatigue	11.21% reduction in tower fatigue damage	WECs act as passive/active dampers for wind turbines
24	Standardizes WEC modeling; supports AI and metaheuristic plugins	Reduced R&D costs through open-source	Multi-physics coupling is the future of WEC optimization
25	Defines optimal damping ranges for two-body point absorbers	Reduced hull size for equivalent power	Accurate viscous damping is vital for power prediction
26	Wind turbine eliminates the need for external DE bias batteries	Eliminates battery replacement costs	Wind energy solves the self-bias challenge of DE harvesters
27	Optimizes phase control between dual water columns	Potential for shared infrastructure	Phase difference between units can be tuned for peak power
28	Significantly broadens the frequency bandwidth of efficient capture	Shared mooring and platform costs	Integrating buoys and OWCs on one platform reduces LCOE
29	Identified "Spinning Top" shape as superior for low-wave energy	High efficiency in low-energy density zones	Geometry optimization can double power in marginal sea states
30	Enables self-powering for sensors at 2.5 m/s wind	Lower maintenance for bridge monitoring	Hybridization of three mechanisms ensures power in low-wind
31	Theoretical power output can more than double ($> 100\%$ gain) after parameter optimization.	Efficient power supply for deep-sea exploration, reducing battery costs.	Absolute motion PTO avoids stroke limitation issues found in traditional two-body WECs.
32	Integration reduced platform heave motion by up to 30%, enhancing stability.	Potential for significant LCOE reduction through large-scale integration.	WECs act as passive dampers for the wind platform while simultaneously generating power.
33	Parallel configuration provides superior structural stiffness and higher power density.	Uses the "Energy Cost-Efficiency Indicator" for LCOE optimization.	Parallel structures offer a more robust mechanical solution for multi-DOF energy capture.
34	Identified that Layout A provides the most consistent power (approx. 110 kW peak).	Shared mooring and platform infrastructure reduces LCOE.	Proper WEC layout is critical to avoid negative hydrodynamic interaction effects.
35	Achieved 49.8% increase in energy conversion compared to traditional single-DOF WECs.	Higher power per unit mass reduces overall CAPEX.	Multi-DOF PTO systems are significantly more efficient than traditional heave-only devices.

Table 6 underscores the role of infrastructure sharing and PTO optimization in WEC commercial viability. Fig. 10 summarizes research quality across all 36 studies. While 35 studies satisfied criteria for energy efficiency, multi-objective optimization, and software compatibility, a gap remains in convergence speed and experimental validation that addressed by only 25 and 26 studies, respectively. This suggests that while sophisticated algorithms are proposed, practical verification and computational efficiency are often secondary. Future research should prioritize faster optimization techniques and physical prototyping to bridge the simulation-deployment gap.

The reviewed literature reflects a maturing field. Dominant trends include simulation-based optimization that evidenced by Wang et al. [66] and Wang et al. [89], and a shift toward metaheuristic hybrids, such as the bi-level framework by Neshat et al. [62]. Control-based strategies like Extremum Seeking [63] and Bang-Bang control [81] provide necessary real-time responsiveness. Structural optimization is equally prominent, with Tao et al. [78] and Sun et al. [77] refining buoy arrangements. Emerging directions include material-level innovation, such as the piezoelectric materials explored by Kiran et al. [65] and magnetic coupling by Cao et al. [88].

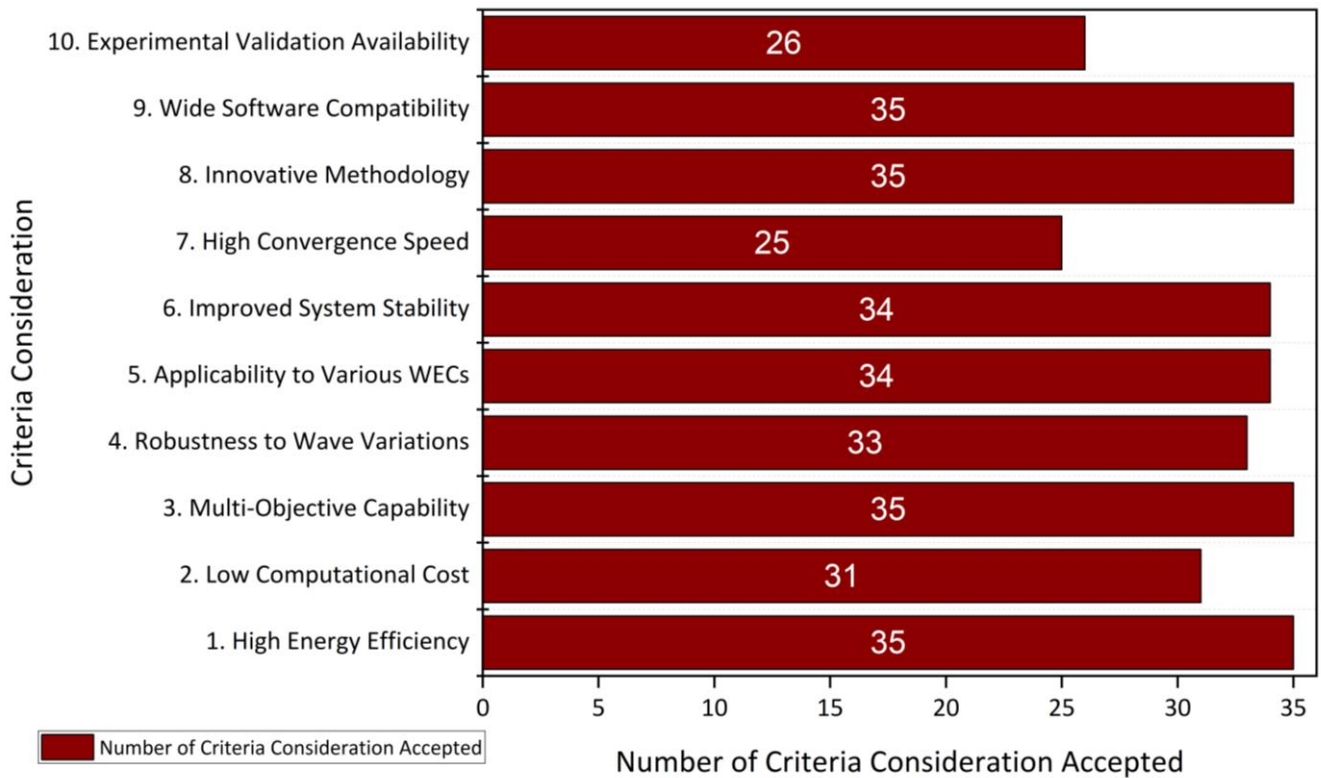


Fig. 10. Comparison of Number of Criteria Consideration Acceptance from the 36 Journals

Point absorber WECs remain the most analyzed configuration due to their simplicity and adaptability. Oscillating Water Columns (OWCs) are also prevalent, with Gomes et al. [57], Du et al. [84], and Wang et al. [85] examining varied mooring and PTO settings. Complexity increases with Multi-Degree-of-Freedom (MDOF) systems, as studied by Bao et al. [93] and Cheng et al. [86], which improve adaptability to ocean variability. Hybrid systems integrating wind or multi-source elements by Cao et al. [88] and Zhu et al. [90], and innovative designs like counter-rotating systems [89] further expand the design space.

Nine studies achieved perfect scores across all ten evaluation criteria defined by Arrosyid et al. [51], specifically the bi-level framework by Neshat et al. [62], the extremum-seeking control by Parrinello et al. [63], the wave-to-wire model by Wang et al. [66], the oscillating buoy layouts by Zhang et al. [68], the nonlinear Froude-Krylov model by Giorgi et al. [69], the frequency tuning by Cai and Zhu [70], the structural array optimization by Sun et al. [72], the response surface methodology by Tao et al. [78], and the coupled dynamics model by Bao et al. [93], all of which serve as benchmarks for integrated and validated wave energy research.

3.4. Discussion on the Findings

The collective findings from the descriptive, bibliometric, and systematic analyses offer a comprehensive understanding of the current research landscape and innovation trajectory in Wave Energy Converter (WEC) optimization. The descriptive analysis reveals a significant global momentum, with research

output increasing steadily between 2020 and 2025 and reaching a peak in 2024. This growth is primarily concentrated within the engineering and energy sectors, which together account for a substantial portion of the output, specifically 2,101 energy-related and 1,192 engineering articles, though a gradual shift toward interdisciplinary participation from environmental science (953 publications) and computer science is evident. Bibliometric mapping further elucidates the intellectual structure of the field, identifying influential citation hubs such as Gomes et al. [57] and Shi et al. [58] that have shaped subsequent research directions, while journals like *Renewable Energy* and *Applied Energy* serve as the central dissemination platforms. These bibliometric results also highlight three major thematic streams: structural-functional integration, performance optimization, and advanced control strategies, with international collaboration networks led by China and the United Kingdom showing strong ties to Japan, Ireland, and Portugal.

The systematic analysis, conducted using the structured framework by Arrosyid et al. [51], underscores a clear priority toward multi-objective optimization and software compatibility, as 97% of the core studies (35 out of 36) successfully satisfied these criteria. However, a notable research gap persists in practical applicability; only 72% of studies (26 out of 36) incorporate real-world experimental validation, and just 69% (25 out of 36) address algorithmic convergence speed. In the domain of multi-objective design, the field has transitioned toward high-fidelity frameworks where researchers like Neshat et al. [62] utilize bi-level optimization to reconcile global and local searches, and Wang and Ringwood [76] employ two-

layer strategies to simultaneously optimize geometry and power take-off (PTO) control. This methodological comprehensiveness is further exemplified by Parrinello et al. [63] and Bao et al. [93], whose models demonstrate excellence in real-time control adaptability, with Bao et al. [93] reporting a 49.8% increase in energy conversion compared to traditional single-degree-of-freedom (DOF) systems.

Furthermore, several innovations regarding design optimization can also be implemented in various optimization models such as Response Surface

Methodology (RSM) [94], [95], [96] and multi-objective optimization [97]. These models often incorporate trending multi-objective optimization approaches to reconcile conflicting goals, such as maximizing energy extraction while minimizing structural volume or capital expenditure. The efficacy of these advanced methodologies is evidenced in Table 7 below for comparison, particularly focusing on technical gains in WEC systems as shown in the recent studies comparison.

Table 7. Technical Performance Comparison and Optimization Impacts in WEC Recent Studies

Authors	WEC Type	Optimization Method	Energy Gain	Validation Level
Li et al. [98]	Dual-chain Point Absorber	RSM & Hydrodynamic Analysis	40% increase in mechanical power; optimized for low energy flux regions.	Numerical & Theoretical
Arrosyid et al. [99]	Multi-cylinder Floating Absorber	ANN-MOGA & TOPSIS	Achieved CWR of 0.865; 22.3% efficiency boost with 4.9% cost increment.	Numerical (BEM)
Mirzaei et al. [100]	OWC (Dual-slope seabed)	MFS & Spectral Analysis	Efficiency peaks at $\eta=0.55$; superior performance at high amplitudes ($A_i/d=0.04$).	Experimental & Meshless Numerical
Vipin et al. [101]	Hybrid OWC-Piezoelectric	ML (XGBoost) & RSM	Peak power output of 7912 W/m; identified chamber length as the primary driver.	Numerical (Boundary Element)

The empirical results from these recent studies underscore a transition from generalized theoretical models toward specialized, site-specific structural designs. By integrating trending multi-objective optimization (MOO) frameworks and advanced computational methods, such as Artificial Neural Networks (ANN) and machine learning that achieved substantial improvements in both capture width ratio and mechanical power output. For instance, the geometric refinement of dual-chain systems using Response Surface Methodology (RSM) yielded a 40% increase in mechanical power, specifically optimized for the low energy flux characteristics of the South China Sea [98]. Similarly, the adoption of a multi-objective approach combining ANN and Multi-Objective Genetic Algorithms (MOGA) in multi-cylinder absorbers achieved a Capture Width Ratio (CWR) of 0.865, resulting in a 22.3% efficiency boost with only a 4.9% increase in cost [99].

Furthermore, structural innovations like the dual-slope seabed design demonstrated superior energy retention by reducing destructive interference, significantly outperforming flat-bottom configurations at high wave amplitudes ($A_i/d = 0.04$) [100]. The shift toward high-fidelity modeling is further exemplified by hybrid OWC-Piezoelectric devices, where XGBoost machine learning models identified critical geometric parameters to reach a peak power output of 7912 W/m [101]. Such multi-parameter refinement aligns with the broader industry trend of enhancing techno-economic viability through superior hydrodynamic performance,

effectively bridging the gap between numerical simulation and practical marine deployment.

Significant contributions to techno-economic assessment indicate that commercial viability is increasingly driven by infrastructure sharing and strategic cost reduction. For instance, Amini et al. [79] demonstrated that systematic optimization of hydraulic PTO settings can achieve a 38% reduction in the Levelized Cost of Energy (LCOE), while Neshat et al. [62] identified optimal buoy dimensions (5m radius) that optimize cost-effectiveness for low-energy regions. Furthermore, researchers have achieved massive gains in computational efficiency, such as the 10,000-fold (four orders of magnitude) reduction in calculation costs for real-time control reported by Giorgi et al. [69], which facilitates more cost-effective iterative design cycles. Economic feasibility is also enhanced by integrated configurations, such as the WEC-breakwater systems analyzed by Zhang et al. [68], which reach 61% maximum efficiency while sharing mooring foundations to reduce capital expenditure.

Sustainability metrics have become a foundational component of the literature, supported by 953 publications linking WEC development to environmental science and coastal ecological balance. This focus is reflected in multi-source integration studies by Cao et al. [88] and Zhu et al. [90], who demonstrate that merging wind and wave platforms enhances energy density and platform stability that specifically reducing platform heave by up to 30%. Additionally, material-level innovations,

such as the piezoelectric materials explored by Kiran et al. [65], offer potential for self-powered marine monitoring with power densities reaching 116 W/cm^3 . Despite these advancements, the dominance of point absorber WECs that valued by Cai and Zhu [70] and Ogden et al. [82] for their simplicity, and Oscillating Water Columns (OWCs) highlights a field still rooted in adaptable, reliable typologies. Ultimately, the trajectory of WEC optimization suggests that bridging the divide between numerical simulation and physical deployment will require a dedicated focus on enhancing experimental validation and developing faster, adaptive algorithms essential for real-time control in highly variable marine environments.

A broader comparison across the optimization strategies discussed in this review reveals important methodological contrasts in terms of applicability, computational demand, and practical implementation. Parametric and deterministic approaches remain widely adopted due to their clear physical interpretability and relatively low computational cost, making them particularly suitable for preliminary design studies and control parameter tuning. However, these approaches often encounter limitations when addressing highly nonlinear multi-degree-of-freedom dynamics or complex hydrodynamic interactions within integrated WEC systems. In contrast, stochastic and metaheuristic frameworks, such as surrogate-based optimization, evolutionary algorithms, and machine learning-assisted models, demonstrate stronger capabilities in exploring large design spaces and identifying optimal design solutions. These methods enable more comprehensive design exploration but may introduce higher computational requirements and sensitivity to algorithmic parameterization, which can restrict their direct application in real-time operational control.

The synthesis of recent studies also indicates that the field is gradually shifting toward hybrid optimization frameworks that combine physical modeling with data-driven techniques. Such integration allows researchers to retain the interpretability of deterministic models while benefiting from the exploration capability of stochastic search methods. At the same time, the literature consistently highlights the need to strengthen experimental validation and field-scale demonstrations to confirm the reliability of optimization outcomes derived from numerical simulations. Expanding the use of surrogate modeling, adaptive control algorithms, and hybrid renewable configurations may therefore represent promising pathways for improving both the technical performance and techno-economic feasibility of WEC systems. Strengthening methodological consistency and establishing comparable evaluation metrics across studies would further support the transition from theoretical optimization research toward scalable marine energy deployment.

4. Conclusions

This study provides a comprehensive synthesis of the Wave Energy Converter (WEC) optimization landscape from 2020 to 2025, utilizing a robust three-stage methodology comprising descriptive analysis, bibliometric mapping, and a systematic review. The findings highlight a significant global research momentum that peaked in 2024, driven primarily by the engineering and energy sectors, while increasingly drawing interdisciplinary contributions from environmental and computer sciences. Bibliometric analysis identifies China and the United Kingdom as dominant collaboration hubs, with research efforts concentrated on structural-functional integration, performance optimization, and advanced control strategies.

The systematic evaluation of 36 core studies reveals that while 97% of recent research successfully incorporates multi-objective optimization and wide software compatibility, point absorber WECs remain the most favored configuration due to their inherent simplicity and adaptability. A pivotal trend identified is the transition toward hybrid energy systems, particularly those co-locating WECs with offshore wind platforms, which enhance energy density and platform stability while significantly reducing the Levelized Cost of Energy (LCOE) through shared infrastructure. Furthermore, the integration of advanced computational techniques, such as hybrid metaheuristic algorithms and real-time control strategies like Model Predictive Control (MPC), has demonstrated substantial performance gains, with some models reporting up to a 49.8% increase in energy conversion efficiency compared to traditional single-degree-of-freedom systems.

Despite these technological advancements, critical gaps persist that challenge the commercial viability of WECs. Only 72% of the evaluated studies included real-world experimental validation, and only 69% addressed the convergence speed of optimization algorithms. To bridge the gap between theoretical optimization and practical deployment, this study proposes several concrete research directions:

1. Development of Model-Free Adaptive Control where future research should pivot toward model-free or hybrid AI-driven control strategies (e.g., Deep Reinforcement Learning) that can adapt to stochastic marine environments without the heavy computational overhead of traditional MPC.
2. Techno-Economic Multi-Objective Optimization where optimization frameworks must move beyond purely hydrodynamic metrics to integrate Levelized Cost of Energy (LCOE) and maintenance reliability as primary objective functions.
3. Cross-Scale Validation Protocols by establishing standardized experimental protocols for tank testing at 1:10 or 1:30 scales to validate the high-fidelity numerical results that found in recent studies.

4. Integration of material innovation by exploring the synergy between structural geometry and smart materials, such as piezoelectric polymers, which offers a promising pathway for self-powered auxiliary systems in remote offshore monitoring. Addressing these recommendations is essential to transform WEC systems from promising numerical concepts into scalable, commercially viable renewable energy solutions.

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