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Ocean Wave Energy Conversion and Policy Frameworks

A Scoping Review of Technological Readiness, Regulatory Instruments, and Deployment Challenges

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Abstract

Ocean wave energy represents a promising yet underutilized renewable energy source with significant potential to support global energy transitions, particularly in coastal and island regions. Despite substantial technological progress in wave energy conversion (WEC) systems, large-scale deployment remains limited. The existing literature is predominantly technology-oriented, while systematic syntheses focusing on policy and governance dimensions remain fragmented. This study conducts a policy-oriented scoping review to map the body of research on ocean wave energy conversion, with a particular emphasis on policy instruments, regulatory frameworks, and governance challenges that influence deployment and commercialization. Following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines, peer-reviewed studies published between 2015 and 2025 were identified from Scopus, Web of Science, and IEEE Xplore. The review results indicate that public research and development funding, technology-specific market incentives, and integrated marine spatial planning are critical enablers of wave energy deployment. Conversely, regulatory complexity, policy instability, and institutional fragmentation remain persistent barriers, especially in developing and archipelagic contexts. This scoping review highlights key policy gaps and underscores the need for coherent, stable, and context-sensitive governance frameworks to facilitate the sustainable commercialization of ocean wave energy.

Keywords: *Energy Policy; Marine Governance; Marine Spatial Planning; Ocean Wave Energy; Scoping Review; Wave Energy Conversion*

Introduction

Ocean wave energy has gained increasing attention as a promising renewable energy source due to its high energy density, relative predictability, and extensive global availability, particularly along western coastlines and in island and archipelagic regions [1], [2], [3]. Unlike solar and wind energy, which are highly dependent on diurnal and seasonal variability, wave energy is generated by the cumulative transfer of wind energy over large oceanic areas, resulting in more stable and predictable power output. These characteristics position wave energy as a potential baseload-supporting resource capable of enhancing the reliability and resilience of diversified renewable energy portfolios [3], [4]. As global energy systems transition toward low-carbon configurations, such attributes have strengthened the strategic relevance of wave energy within broader marine renewable energy agendas.

Over the past two decades, substantial technological advancements have been achieved in wave energy conversion (WEC) systems. Research and development efforts have produced a wide range of device typologies, including oscillating water columns, point absorbers, attenuators, and overtopping devices, each designed to harness wave energy through distinct mechanical and hydrodynamic principles [4], [5], [6]. These innovations have been supported by improvements in power take-off systems, control strategies, and materials engineering, contributing to gradual increases in conversion efficiency and survivability. Nevertheless, despite this technological progress, the commercialization and large-scale deployment of wave energy technologies remain limited. Globally, deployment is largely confined to pilot projects and demonstration-scale installations, with only a few devices approaching higher technology readiness levels [7], [8].

The persistent discrepancy between technological potential and real-world implementation suggests that technical maturity alone is insufficient to enable widespread adoption of wave energy. Increasingly, scholars argue that non-technical factors play a decisive role in shaping renewable energy deployment outcomes. Energy transitions are now widely understood as socio-technical processes, in which technological innovation is deeply intertwined with policy frameworks, regulatory regimes, and governance structures [9], [10]. For emerging marine technologies such as wave energy, these institutional dimensions are particularly critical. High capital costs, long development timelines, environmental uncertainties, and complex maritime jurisdictions expose projects to significant financial and regulatory risks, making them highly sensitive to policy stability and governance quality [8], [11].

Policy instruments such as public research and development funding, market-based incentives, and marine spatial planning frameworks have been identified as key enablers capable of reducing uncertainty and facilitating technology learning. Conversely, fragmented regulatory systems, lengthy licensing procedures, and inconsistent policy support can significantly hinder project development and discourage private investment. As a result, the success or failure of wave energy initiatives often reflects the effectiveness of the surrounding policy and governance environment rather than purely technological performance.

Although a growing body of literature has reviewed the technical performance, hydrodynamics, and economic feasibility of WEC systems [1], [5], [6], comprehensive syntheses focusing on policy, regulation, and governance dimensions remain fragmented and underdeveloped. Existing reviews tend to prioritize engineering perspectives, while policy-oriented insights are scattered across energy policy, marine governance, and sustainability journals. This fragmentation limits cumulative knowledge building and constrains the ability of policymakers to draw evidence-based lessons for wave energy deployment. Moreover, the absence of integrative policy-focused reviews hampers cross-country learning and obscures how institutional contexts shape divergent deployment trajectories. Consequently, there is a clear need for systematic mapping approaches that consolidate policy, regulatory, and governance insights to better inform strategic decision-making in emerging wave energy sectors.

To address this gap, the present study conducts a scoping review that systematically maps the policy-oriented literature on ocean wave energy conversion. By synthesizing research on regulatory instruments, governance challenges, and deployment implications, this review aims to clarify how policy frameworks shape the trajectory of wave energy development. In doing so, it contributes to a more integrated understanding of wave energy as a socio-technical system and provides policy-relevant insights to support the sustainable commercialization of marine renewable energy technologies.

Material and Methods

A. Scoping Review Design

This study adopted a scoping review methodology to systematically map and synthesize the existing literature addressing policy, regulatory, and governance dimensions of ocean wave energy conversion. Scoping reviews are particularly appropriate for emerging and interdisciplinary research fields, where evidence is heterogeneous and conceptual boundaries are still evolving. The review process was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR), ensuring methodological rigor, transparency, and reproducibility throughout all stages of the review [8]. This approach enabled a comprehensive overview of how policy frameworks influence the development and deployment of wave energy technologies, without imposing restrictive quality appraisal criteria typical of systematic reviews.

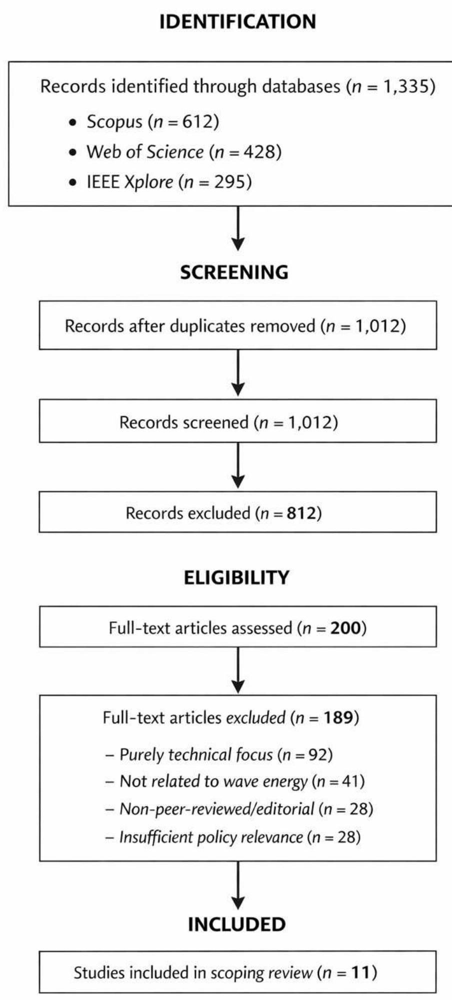

Fig. 1. PRISMA-ScR flow diagram illustrating the study selection process for the policy-oriented scoping review on ocean wave energy conversion.

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B. Data Sources and Search Strategy

Relevant literature was identified through structured searches of three major academic databases: Scopus, Web of Science, and IEEE Xplore. These databases were selected to capture interdisciplinary research spanning energy policy, marine governance, and renewable energy systems [8], [12]. The search strategy combined wave energy–related terms (e.g., "ocean wave energy," "wave energy conversion," and "WEC") with policy-oriented keywords such as "policy," "regulation," "governance," "incentives," and "marine spatial planning." Boolean operators and truncation were applied to enhance search sensitivity while maintaining relevance. Only peer-reviewed journal articles published in English between 2015 and 2025 were included to ensure the contemporary relevance of policy discussions and regulatory frameworks.

C. Study Selection and Data Analysis

Following database searches, all records were imported into reference management software for duplicate removal and screening. Titles and abstracts were first assessed against predefined inclusion and exclusion criteria, followed by full-text screening of potentially relevant articles. Data extraction focused on policy instruments, regulatory frameworks, institutional arrangements, and geographical contexts associated with wave energy deployment. The extracted data were analyzed using thematic analysis, an approach well-suited for identifying recurring policy patterns, governance challenges, and regulatory gaps across diverse study contexts [13], [14]. Fig. 1 presents the PRISMA-ScR flow diagram summarizing the study selection process. In total, 1,335 records were identified, 200 articles were assessed at the full-text stage, and 11 studies were ultimately included in the final scoping review.

Results

Table 1 summarizes the peer-reviewed studies included in this policy-oriented scoping review on ocean wave energy conversion. The table presents key information on publication year, geographical focus, study type, policy orientation, and principal findings. Overall, the included studies highlight the central role of policy instruments, regulatory frameworks, and governance arrangements in shaping wave energy deployment, with a strong empirical emphasis on European contexts and limited representation from developing and archipelagic regions.

Table 1. Summary of Included Studies in the Policy-Oriented Scoping Review of Ocean Wave Energy Conversion

No.	Author(s)	Year	Region / Country Focus	Study Type	Policy Focus	Key Findings
1	Astariz & Iglesias [5]	2015	Europe	Review	Policy & market frameworks	Public R&D funding and coordinated EU policies are critical for early-stage wave energy deployment.
2	Uihlein & Magagna [8]	2016	Europe	Review	Governance & policy mix	Lack of technology-specific incentives limits the commercialization of wave energy.
3	Mir-Artigues et al. [15]	2015	Europe	Policy analysis	Feed-in tariffs	Stable and long-term feed-in tariffs reduce investment

No.	Author(s)	Year	Region / Country Focus	Study Type	Policy Focus	Key Findings
						risk for emerging renewables.
4	Pruditsch [13]	2017	UK, EU	Comparative study	Governance models	Integrated governance structures accelerate marine energy deployment.
5	Balta-Ozkan et al. [16]	2013	Global	Conceptual	Commercialization barriers	Policy uncertainty and regulatory delays remain key non-technical barriers.
6	Trainer [12]	2018	Europe	Policy pathways	Policy instruments	Demonstration support and public procurement stimulate technology learning.
7	Aswad et al. [17]	2013	Global	Policy report	Innovation & regulation	Ocean energy requires tailored regulatory and financial frameworks distinct from wind/solar.
8	Nasiri et al. [14]	2022	EU	Empirical	Policy mix	Balanced policy mixes outperform single-instrument approaches.
9	Mouraviev [18]	2021	Southeast Asia	Regional analysis	Governance capacity	Institutional fragmentation constrains marine renewable deployment.
10	D'Amore et al. [19]	2021	Developing economies	Review	Policy gaps	Weak regulatory certainty limits private sector participation.
11	Noname et al. [20]	2009	Global	Market analysis	Policy & market trends	Policy learning from Europe is unevenly transferred to Global South contexts.

Table 2 synthesizes the key policy instruments and governance themes identified across the reviewed literature on ocean wave energy conversion. It outlines the main regulatory, institutional, and planning mechanisms discussed in relation to wave energy deployment and summarizes their reported effects. The table highlights how supportive policy instruments can enable early-stage development, while regulatory complexity, institutional fragmentation, and policy instability frequently emerge as critical barriers to large-scale implementation.

Table 2. Policy Instruments and Governance Themes Identified Across the Reviewed Literature

Policy/ Governance Theme	Description	Reported Effect on Wave Energy Deployment
Public R&D Funding	Government-funded research, pilot, and demonstration programs	Strongly enables early-stage technology development and risk reduction
Feed-in Tariffs / Contracts for Difference	Guaranteed pricing mechanisms for electricity generation	Increases investor confidence, but is often absent for wave energy
Marine Spatial Planning (MSP)	Integrated planning of marine space and activities	Reduces regulatory conflict and licensing uncertainty
Licensing & Permitting Procedures	Environmental and maritime approval processes	Complex and fragmented procedures delay project implementation
Institutional Coordination	Alignment among ministries and agencies	Poor coordination increases transaction costs
Policy Stability	Long-term consistency of renewable energy policies	Policy volatility discourages private investment
Stakeholder Engagement	Community and stakeholder involvement	Improves social acceptance and project legitimacy

The scoping review reveals that policy-oriented research on ocean wave energy conversion is predominantly concentrated in European contexts, with limited empirical evidence from developing and archipelagic regions. As summarized in Table 1, most studies emphasize the importance of public R&D funding, regulatory certainty, and integrated governance frameworks in enabling early-stage deployment. Table 2 further synthesizes the policy instruments and governance themes recurring across the literature. Collectively, the findings indicate that technological readiness alone is insufficient for commercialization without coherent policy support, streamlined regulatory processes, and institutional coordination. These results underscore the need for context-sensitive policy frameworks, particularly for coastal and island regions in the Global South.

A. Policy Instruments Supporting Wave Energy Development

The reviewed literature consistently identifies public research and development (R&D) funding as the most critical policy instrument supporting wave energy development, particularly during early technological stages [8], [17], [21]. European countries such as the United Kingdom, Portugal, and Norway have implemented long-term public funding schemes to support prototype testing and demonstration projects, significantly reducing technological and financial risks [7], [8].

Market-based incentives, including feed-in tariffs and contracts for difference, are also discussed as important enablers of private sector participation [16], [22]. However, several studies emphasize that wave energy is often excluded from technology-specific incentive schemes, which are predominantly designed for mature renewables such as wind and solar [12], [14]. This policy misalignment contributes to investor uncertainty and slows down commercialization.

B. Regulatory and Environmental Governance Frameworks

Regulatory complexity emerges as one of the most frequently cited barriers to wave energy deployment. Licensing and permitting procedures typically involve multiple authorities responsible for maritime safety, environmental protection, and coastal management, leading to prolonged approval timelines and increased transaction costs [11], [23].

Marine spatial planning (MSP) is widely recognized as a key governance instrument capable of reducing regulatory uncertainty and facilitating coexistence between wave energy projects and other marine uses [24], [25]. Studies show that jurisdictions with established MSP frameworks tend to experience more predictable and transparent approval processes, enhancing developer confidence [12], [25].

C. Institutional and Governance Challenges

Institutional fragmentation and lack of inter-agency coordination are recurring governance challenges identified across the literature [13], [16]. In many countries, wave energy governance spans multiple ministries and regulatory bodies, resulting in overlapping mandates and ambiguous decision-making authority [11], [18]. This institutional complexity increases regulatory uncertainty, prolongs permitting processes, and ultimately discourages private investment in wave energy projects.

Policy uncertainty, particularly abrupt changes in renewable energy support schemes, further undermines long-term investment and technology learning [17], [26]. Although less frequently discussed, public acceptance and stakeholder engagement are increasingly recognized as essential governance dimensions, especially in coastal communities concerned about environmental impacts and seascape alterations [27].

D. Geographical Distribution of Policy-Oriented Studies

The geographical distribution of policy-focused wave energy research is heavily skewed toward Europe, with limited empirical evidence from Asia, Africa, and small island developing states [13], [26]. This imbalance is notable given that many developing and archipelagic countries possess substantial wave energy resources but lack tailored policy frameworks and institutional capacity [18], [19], [28].

Recent studies have begun to highlight policy gaps in Southeast Asia and other developing regions, emphasizing the need for context-sensitive governance models rather than direct policy transfer from European experiences [18], [19].

Discussion

A. Policy–Technology Misalignment in Wave Energy Development

The findings of this scoping review reinforce the growing consensus that the slow deployment of ocean wave energy is not primarily driven by technological immaturity, but rather by persistent misalignments between technological progress and policy support frameworks. While several wave energy conversion (WEC) technologies have achieved advanced technology readiness levels and demonstrated operational feasibility in pilot projects, policy instruments have largely remained generic, short-term, or poorly adapted to the specific risk profiles of marine energy technologies [8], [21], [16]. Unlike solar and wind energy, wave energy faces higher capital intensity, longer development cycles, and greater environmental and regulatory uncertainty, all of which require differentiated policy treatment.

The reviewed studies indicate that existing renewable energy support schemes often fail to accommodate the early-stage characteristics of wave energy. Feed-in tariffs, auction mechanisms, and market-based incentives designed for mature technologies frequently disadvantage WEC projects due to higher costs and unproven performance at scale [14],[22]. As a result, technological innovation advances in isolation from market deployment, leading to a persistent "valley of death" between demonstration and commercialization. This misalignment suggests that energy transitions should be understood not only as technological processes but as socio-institutional transformations requiring coordinated policy adaptation.

B. Governance, Regulatory Integration, and Spatial Planning

A dominant theme emerging from European case studies is the critical role of governance coherence and regulatory integration in enabling wave energy deployment. Countries with relatively successful wave energy initiatives demonstrate strong coordination across energy policy, maritime regulation, and environmental governance [7], [12], [24]. Integrated marine governance, particularly through marine spatial planning (MSP), has proven effective in reducing regulatory fragmentation and clarifying site allocation for wave energy projects [24], [25]. By providing a coordinated spatial and institutional framework, MSP also helps mitigate conflicts with fisheries, shipping, and conservation interests while enhancing regulatory predictability.

Conversely, fragmented governance structures and overlapping regulatory mandates significantly increase administrative complexity and project uncertainty. The literature highlights that wave energy projects are often subject to multiple permitting regimes spanning energy authorities, maritime agencies, and environmental regulators, each operating under different timelines and criteria [10], [16]. Such institutional fragmentation disproportionately affects emerging technologies, where investors are highly sensitive to regulatory risk and procedural delays.

This review also reveals that governance challenges are not limited to formal regulation but extend to coordination failures among public institutions. The absence of a dedicated lead agency for marine energy frequently results in policy ambiguity and inconsistent decision-making [8], [12]. These findings underscore the importance of integrated regulatory frameworks that align national energy strategies with maritime governance and environmental objectives, rather than treating wave energy as a marginal or experimental activity within broader renewable energy policies.

C. Implications for Developing and Archipelagic Contexts

For developing and archipelagic countries, such as Indonesia, the policy and governance challenges identified in this review are particularly salient. Wave energy offers strategic potential to enhance coastal and island energy security, reduce dependence on diesel-based generation, and support decentralized energy systems in remote regions [18], [19], [28]. However, the reviewed literature suggests that without coherent marine energy policies and institutional capacity, these opportunities are unlikely to translate into tangible outcomes.

Unlike European contexts, many developing countries face additional constraints, including limited regulatory experience with marine renewables, weak inter-agency coordination, and insufficient technical expertise within public institutions [19], [28]. Generic renewable energy policies often prioritize land-based technologies and fail to address the spatial, environmental, and infrastructural specificities of wave energy. This policy bias contributes to the marginalization of marine energy options despite favorable natural conditions.

The findings point to several critical policy implications. First, technology-specific policy instruments such as targeted demonstration funding, risk-sharing mechanisms, and adaptive tariff schemes are essential to accommodate the high uncertainty, capital intensity, and learning needs associated with early-stage wave energy deployment [14], [22]. Second, streamlined regulatory processes and the institutionalization of marine spatial planning can reduce uncertainty and lower entry barriers for developers [24], [25]. Third, long-term policy stability is indispensable for attracting private investment and enabling cumulative learning effects in both technology and governance [7], [21]. Finally, institutional capacity building and adaptive governance approaches should be prioritized in developing coastal regions to ensure that wave energy development aligns with local socio-environmental contexts and long-term sustainability goals [19], [28].

Conclusion

This scoping review systematically examined the policy and governance dimensions of ocean wave energy conversion research published between 2015 and 2025. The findings confirm that the slow diffusion of wave energy technologies cannot be attributed solely to technological limitations, but is strongly shaped by the adequacy of policy instruments, regulatory coherence, and governance capacity. Supportive, technology-specific, and stable policy frameworks emerge as decisive enablers for moving wave energy from pilot projects to commercial deployment. At the same time, fragmented regulation, policy volatility, and weak institutional coordination continue to constrain development, particularly for emerging marine technologies. Notably, the literature remains heavily concentrated on European experiences, revealing a substantial knowledge gap regarding policy implementation in developing and archipelagic regions. Future research should therefore prioritize comparative, policy-oriented, and context-sensitive analyses to inform adaptive governance strategies capable of unlocking the wave energy potential in diverse coastal settings while supporting long-term sustainability and energy security objectives.

Conflict of Interest

The authors declare no conflict of interest.

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