

A Review of Ocean Wave-Based Renewable Energy Systems: Global Research Trends, Challenges, and Sustainability Opportunities

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Abstract. The urgent global transition to clean energy, in line with Sustainable Development Goals (SDGs) 7 and 13, highlights ocean wave energy as a promising yet underutilized renewable resource. This study presents a bibliometric-based review of global research trends, challenges, and sustainability opportunities of ocean wave-based renewable energy systems. Results show a significant increase in publications from 2000 to 2023, with the United States, China, and the United Kingdom leading contributions. Research themes have evolved from general technical issues to multidisciplinary studies addressing technology, environmental impact, and policy. Dominant topics include wave energy converters, sustainable development, and integration with climate action strategies. The most cited works emphasize technological innovation, hybrid systems, and socio-economic frameworks. In terms of SDGs, wave energy research strongly aligns with SDG 7 (Affordable and Clean Energy), while also contributing to SDG 9 (Industry, Innovation, and Infrastructure), SDG 13 (Climate Action), and SDG 14 (Life Below Water).

1 Introduction

Within the framework of the Sustainable Development Goals (SDGs), particularly goals 7 (Affordable and Clean Energy) and 13 (Climate Action), the transition to clean energy is a global imperative that cannot be postponed. Wave energy, as a renewable resource, offers significant potential to support the decarbonization agenda, reduce carbon emissions, and ensure sustainable energy availability. Furthermore, the development of ocean energy aligns with sustainable development efforts in coastal areas vulnerable to climate change [1].

Renewable energy development in recent decades has been dominated by solar and wind technologies, which have been commercially proven and widely implemented in various countries [2]. However, despite their widespread use, limitations related to intermittency and

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land affordability make the search for clean energy alternatives increasingly urgent. In this context, wave energy presents itself as a relatively underutilized resource, despite its abundant capacity and potential to complement the global renewable energy portfolio.

Wave-based energy is believed to have advantages due to its predictability and widespread distribution in coastal areas. Various conversion technologies have been developed, such as point absorbers, oscillating water columns, and overtopping devices, which convert the kinetic and potential energy of waves into electrical energy [3]. However, the implementation of these technologies still faces significant challenges, ranging from conversion efficiency and high operational costs to infrastructure resilience in the face of extreme marine environmental conditions.

To understand the direction and development of wave energy research globally, a bibliometric approach is an appropriate method. Bibliometric analysis can map publication trends, collaboration patterns among researchers, dominant keywords, and emerging research focuses [4]. This approach provides a comprehensive overview of how wave energy technology is positioned within the context of renewable energy research, while identifying countries, institutions, and key researchers with significant contributions [5].

However, there are still under-explored research gaps. Most studies emphasize laboratory-scale technical aspects, while the economic, policy, sustainability, and large-scale implementation strategies are relatively neglected. This article offers a novel approach by presenting a comprehensive bibliometric-based review of global wave energy research trends, key challenges faced, and potential sustainability opportunities. Thus, this study is expected to fill the research gap and provide a new direction for the development of ocean wave energy in the future. This Research was conducted following the research question

- 1 How are the research trends related to wave-based renewable energy?
- 2 How does the impact of the publication of wave-based renewable energy?
- 3 How can sustainability opportunities help wave-based energy achieve the Sustainable Development Goals (SDGs)?

2 Method

Bibliometric analysis was conducted to map global research trends on ocean wave energy in the context of renewable energy and sustainability. The keywords used in the search were TITLE-ABS-KEY (ocean wave energy OR wave power) AND TITLE-ABS-KEY (renewable energy) AND TITLE-ABS-KEY (SDGs OR sustainable development goals OR sustainability OR sustainable). The initial stage began with defining keywords, namely formulating relevant terms, so that the scope of the literature is in accordance with the research objectives. Next, the Scopus research database was selected, and then the data collection stage was carried out by downloading publications that met the criteria. The collected data were then analyzed using bibliometric methods, which were then discussed in the analysis and discussion stages (Fig. 1).



Fig. 1. Bibliometric analysis stage

3 Result and Discussion

3.1 Research Trends Related to Wave-Based Renewable Energy

Fig. 2 shows the development of publications related to ocean wave-based renewable energy systems from 2000 to 2024. In the initial period (2000–2007), the number of publications was still very low (0–2 articles per year), indicating that this topic was not yet widely of interest. The positive trend peaked in 2019 with more than 10 articles, followed by a sharp spike in 2020–2023, reaching a peak of more than 20 articles in 2023. The drastic decline in 2025 most likely does not indicate a real trend, but rather the result of data that has not been fully indexed in databases. Publication data were collected from the Scopus database using keywords related to ocean wave energy. The data extraction process was conducted on October 3, 2025, so publications from 2025 have not yet been fully indexed, potentially contributing to the decrease in the number of publications for that year.

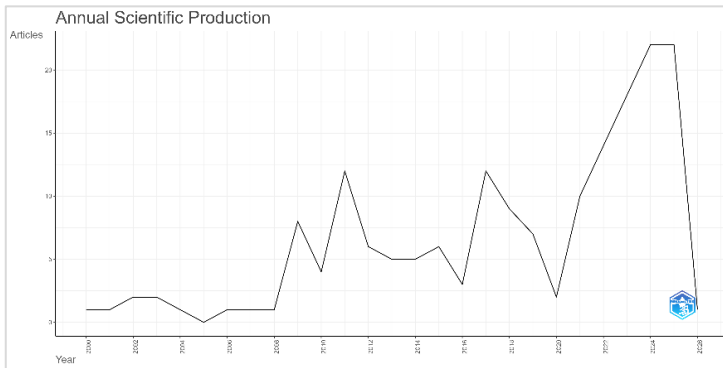


Fig. 2. Annual scientific production of wave-based renewable energy

Based on Fig. 3, it is clear that research on ocean wave-based renewable energy systems is spread across various countries, with the largest contribution coming from the United States (100 publications), followed by China (83) and the United Kingdom (63) as the three main global research centers. This distribution shows that ocean wave energy research has become a global concern, with developed countries dominating, but also followed by the involvement of developing countries, indicating the potential to encourage innovation and energy sustainability.

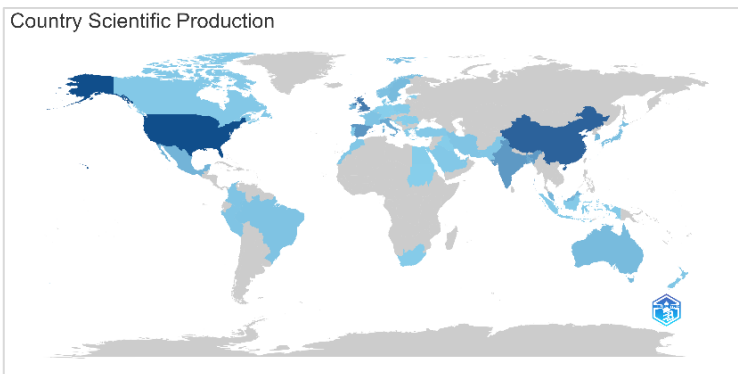


Fig. 3. Countries scientific production of wave-based renewable energy

Based on the Fig. 4 an analysis of research trends in wave-based renewable energy over the past decade shows a significant evolution from general issues to increasingly specific and integrative studies. The 2017–2019 period marked a period of rapid growth, dominated by topics such as wave energy converters, marine renewable energy, and integration with oceanography, demonstrating a shift toward technological application and its contribution to the Sustainable Development Goals (SDGs). This trend intensified in 2020–2022, with an increase in publications on ocean energy, tidal energy, and environmental impact and renewable resources, demonstrating a focus on practical implementation and environmental impact. In the latest period (2023–2024), research topics are increasingly oriented towards sustainable energy and ocean-wave energy as part of a sustainability-oriented global energy system, while also emphasizing the position of ocean wave energy not only as a technical innovation, but also a strategic solution in climate change mitigation and hybrid energy integration in the future.

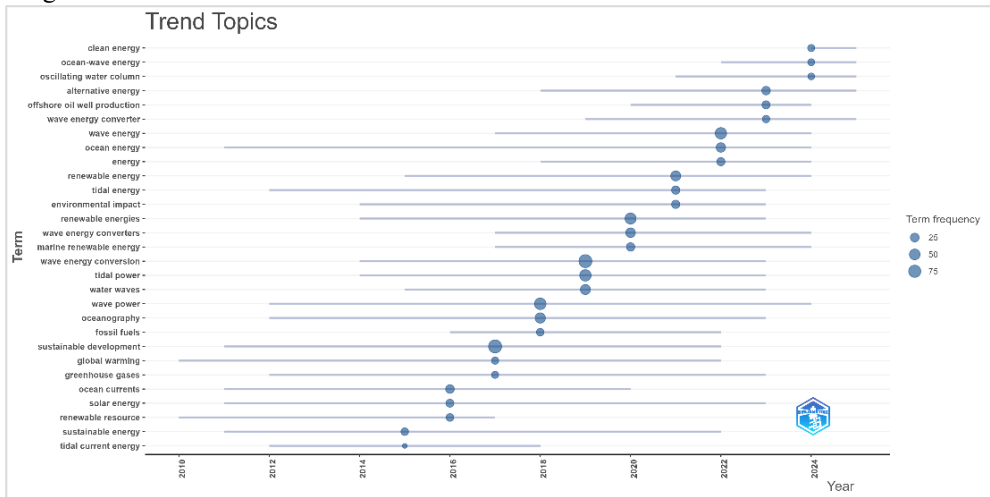


Fig. 4. Trend topics of wave-based renewable energy over decade

The visualization on Fig. 5 reveals that the dominant terms in wave-based renewable energy research are wave energy conversion and sustainable development, which occupy the largest positions and thus become core themes in academic discourse. Other prominent terms, such as tidal power, wave power, oceanography, renewable energy, and renewable energies, indicate a focus on the technical aspects of ocean energy conversion and its relationship to sustainable development issues. Furthermore, the presence of keywords such as environmental impact, climate change, and fossil fuels emphasizes that research is not solely technology-oriented but also considers the global context of climate change mitigation and energy transition. Thus, this word cloud illustrates that wave energy research has developed into a multidisciplinary field, encompassing technological, environmental, and policy aspects, as well as opportunities for collaboration in supporting energy sustainability.



Fig. 5. Word cloud of wave-based renewable energy

The thematic map analysis on the Fig. 6 shows that wave-based renewable energy research focuses on basic themes such as sustainable development, wave energy conversion, and wave power, which serve as the primary foundation of the field but still require strengthening in technical and policy aspects. At the same time, alternative energy, marine renewable energy, and environmental impact emerged as driving themes showing high relevance and rapid development, indicating the dominant direction of current research on marine energy diversification and environmental sustainability issues. Meanwhile, niche themes such as environment, emissions, and nuclear fuels occupy more specialized and developing areas of study, although their contribution is not as central to the mainstream discourse. On the other hand, themes such as energy efficiency, planning, and computational fluid dynamics remain in the emerging or declining themes category, thus can be interpreted as growing research areas that have not yet become a primary focus, or are actually tending to experience declining relevance.

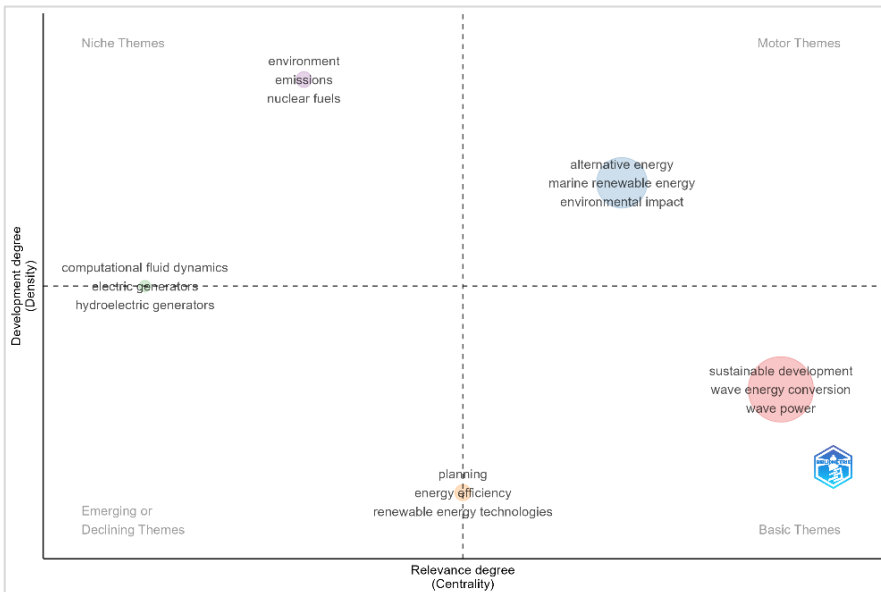


Fig. 6. Thematic map of wave-based renewable energy

This study shows that wave energy conversion and sustainable development are the most dominant terms and the center of connection, emphasizing their role as the core of the research. The blue cluster focuses on technical aspects such as wave power, water waves,

oceanography, wave energy converters, and oscillating water columns, emphasizing the technological and scientific dimensions of marine energy. The red cluster highlights the connection to global issues such as renewable energies, climate change, environmental protection, investments, and economics, thus illustrating the sustainability, policy, and socio-economic impact dimensions of marine energy. Meanwhile, the green cluster links marine energy with other renewable energy sources such as solar energy, geothermal energy, fossil fuels, greenhouse gases, and energy efficiency, indicating the direction of integration and cross-technology comparison in the energy transition (Fig. 7).

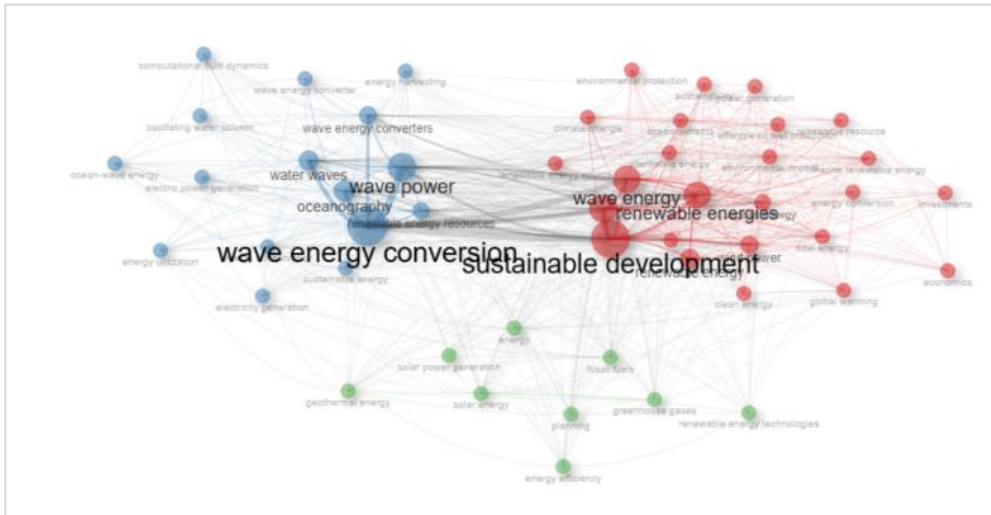


Fig. 7. Co-occurrence network of wave-based renewable energy

3.2 Impact of Publication Wave-Based Renewable Energy

Based on Table 1 an analysis of the ten most influential publications on ocean wave-based renewable energy systems reveals three main research trends. First, global reviews focus on the status, prospects, and cross-integration of ocean energy with other renewable sources. Second, technical research emphasizes the development and validation of innovative prototypes such as hybrid nanogenerators and energy harvesting technologies for specific applications. Third, several studies highlight socioeconomic and policy dimensions, including economic feasibility assessments and risk-based decision-making frameworks. These findings confirm that wave energy research is evolving toward a multidisciplinary approach that combines technology, policy, and global sustainability aspects.

Table 1. Top 10 most cited publications over the decade.

No	Author (Year)	Citations	Research Focus	Geographical Scope	Methodology
1	Melikoglu (2018)	376	Comprehensive review of tidal, wave, OTEC, salinity gradients; barriers & opportunities [6]	Global	Literature review & comparative analysis
2	Liu et al. (2021)	311	Integration of IoT, 5G, and energy harvesting [7]	Global/Urban	Review of technologies & application case mapping
3	Borthwick (2016)	199	Broad overview of marine renewable	Global	Conceptual review &

No	Author (Year)	Citations	Research Focus	Geographical Scope	Methodology
			energy (offshore wind, tidal, wave, salinity, biomass) [8]		sustainability perspective
4	Rehman et al. (2023)	129	Comparative review of wind & ocean energy (efficiency, costs, technologies) [9]	Global	Systematic review of technologies & cost analysis
5	Dalton et al. (2015)	72	Economic frameworks for ORE: public vs private perspectives [10]	Global/Europe-focused	Literature synthesis & methodological review
6	Xu et al. (2023)	71	Development of iTEHG prototype for omnidirectional wave harvesting [11]	Case study: Sanya Bay, China	Experimental design & field validation
7	Shezan et al. (2023)	71	Hybrid microgrids with solar, wind, ocean, geothermal integration [12]	Global	Review & comparative analysis of control methods
8	Qi et al. (2021)	69	Applied technology: capsule-structured harvester for bridge monitoring sensors [13]	Case study: Sea-crossing bridges (China)	Experimental prototype & performance testing
9	Abaei et al. (2017)	65	Decision-making framework for WEC siting under uncertainty [14]	Regional (Tasmania, Australia)	Bayesian modelling & multi-criteria decision analysis
10	Khan et al. (2022)	64	Review of wave, tidal, osmotic & thermal energy; socio-economic analysis [15]	Global	Literature review & technosocioeconomic assessment

Based on the bibliometric mapping shows in Table 2, several major external challenges emerge in the development of ocean wave energy. These insights emphasize the need for future research to focus not only on technological improvement but also on strengthening economic models, ecological assessment, and regulatory support to accelerate the adoption of wave energy technologies.

Table 2. Ocean wave energy Challenge Area.

No.	Challenge Area	Evidence From Bibliometric Data (Keyword & PageRank)	Key Issues Identified
1	Economic Feasibility & Investment	economics PR = 0.007; investments PR = 0.01 (very low)	High installation costs, and commercial financing is not yet stable
2	Environmental & Ecological Impact	environmental impact PR = 0.019; environmental protection PR = 0.008	The impact on marine ecosystems is unclear
3	Policy & Regulatory Framework	<i>energy policy</i> PR = 0.018 (very low)	Marine regulations & grid integration are not yet strong and licensing is complex.

3.3 Sustainability Opportunities of Wave-Based Energy

Interpreting from Table 3 The mapping of keywords to SDGs highlights the central role of SDG 7 (Affordable and Clean Energy), which dominates the discourse with terms such as

renewable energy, clean energy, and multiple marine-based technologies, reflecting the strong technical and sustainability focus of ocean energy research.

Table 3. Keywords analysis on Sustainable Development Goals (SDGs).

SDGs Point	Keyword
SDG 7 (Affordable and Clean Energy)	renewable energy, clean energy, wind power, tidal power, ocean energy, wave energy conversion, wave energy converter, electricity generation, solar energy, geothermal energy, renewable energy technologies
SDG 8 (Decent Work & Economic Growth)	investments, economics, energy policy
SDG 9 (Industry, Innovation & Infrastructure)	energy policy, offshore oil well production, computational fluid dynamics, oscillating water column, energy utilization
SDG 12 (Responsible Consumption & Production)	energy efficiency, planning
SDG 13 (Climate Action)	climate change, global warming, sustainability, greenhouse gases, fossil fuels
SDG 14 (Life Below Water)	marine renewable energy, ocean currents, environmental impact, environmental protection, oceanography, water waves, ocean-wave energy

An analysis of the ten most influential articles shows that the contribution of wave-based renewable energy research is closely linked to SDG 7 (Affordable and Clean Energy), as all publications directly address clean energy as a primary focus. The dimension of SDG 9 (Industry, Innovation, and Infrastructure) also appears strongly in seven articles, particularly regarding technological innovation and the integration of ocean energy systems with electricity infrastructure. Meanwhile, aspects of SDG 13 (Climate Action) are identified in four studies emphasizing climate change mitigation through clean energy transitions, and SDG 14 (Life Below Water) is only discussed in two articles highlighting marine environmental impacts.

Social aspects are less common, with only three publications explicitly addressing the relationship between ocean energy and communities and sustainable urban development (SDG 11). In terms of impact, the majority of studies highlight the environment (9 articles) and the economy (8 articles), while social impacts are limited (3 articles). This indicates that ocean energy research remains predominantly focused on the environmental dimension, while the social dimension remains relatively needs to be studied (Fig. 8).

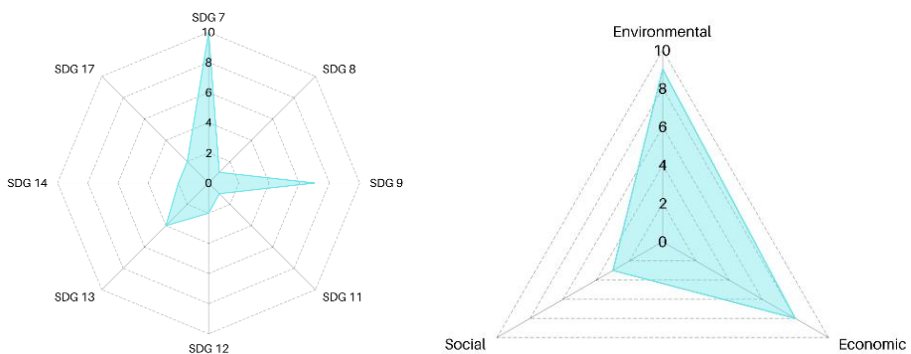


Fig. 8. SDGs point and impact of wave-based renewable energy

Table 4. Impact of literature based on the 10 most cited publications over the decade.

No	Author (Year)	SDG Points	Impact
1	Melikoglu (2018)	SDG 7, 13, 14	Environmental & Economic
2	Liu et al. (2021)	SDG 7, 9, 11	Social, Environmental & Economic
3	Borthwick (2016)	SDG 7, 13, 14	Environmental & Social
4	Rehman et al. (2023)	SDG 7, 9, 12	Economic & Environmental
5	Dalton et al. (2015)	SDG 7, 8, 17	Economic & Social
6	Xu et al. (2023)	SDG 7, 9	Environmental & Economic
7	Shezan et al. (2023)	SDG 7, 9, 12	Social, Economic & Environmental
8	Qi et al. (2021)	SDG 7, 9	Environmental & Economic
9	Abaci et al. (2017)	SDG 7, 9, 13	Economic & Environmental
10	Khan et al. (2022)	SDG 7, 13, 17	Environmental & Economic

Table 4 and Table 5 shows that ocean and renewable energy research strongly supports the SDGs through three main impacts. SDG 7 drives clean energy access with environmental decarbonization, economic affordability, and social inclusion. SDG 9 advances sustainable infrastructure via eco-friendly engineering, cost-efficient innovation, and resilient IoT systems. SDG 11 links energy-harvesting to smart cities with social empowerment and reduced footprints. SDG 13 highlights emission cuts and investment planning, while SDG 14 stresses ecological protection and governance in marine renewables.

Table 5. Sustainable Development Goals (SDGs) through wave-based renewable energy.

SDG Point	Impact	Explanation
SDG 7 Affordable & Clean Energy	Environmental	Ocean energy (wave, tidal, OTEC, salinity gradients) is recognized as a large-scale clean energy resource that supports global decarbonization [6]. Hybrid harvesters (TENG/PENG/EMG) enhance distributed renewable generation for sustainable cities [7].
	Economic	Comparative reviews highlight cost efficiency, technological maturity, and competitiveness with fossil fuels [6], [9]. Techno-economic frameworks support long-term affordability [10].
	Social	IoT-powered energy harvesting in smart cities strengthens access to sustainable electricity for communities [7].
SDG 9 Industry, Innovation & Infrastructure	Environmental	Engineering R&D in wave energy converters, oscillating water columns, and CFD modelling supports eco-friendly marine infrastructure development [14].
	Economic	Innovation in hybrid microgrids and energy converters improves techno-economic viability and lowers costs of integration [9], [11], [12].
	Social	IoT and sensor applications in infrastructure (bridges, smart cities) enhance resilience and monitoring through self-powered systems [7], [13].
SDG 11 Sustainable Cities & Communities	Social	Energy-harvesting IoT technologies (triboelectric, piezoelectric, electromagnetic) enable distributed power for urban infrastructure, supporting sustainable smart cities [7].
	Environmental	Applications in urban monitoring reduce energy demand from fossil-based grids, lowering urban carbon footprints [7].
SDG 13 Climate Action	Environmental	Ocean energy contributes to emissions reduction and climate mitigation if deployed at scale, reducing fossil reliance [6], [8].

SDG Point	Impact	Explanation
	Economic	Socio-economic assessments and risk-based siting methodologies reduce investment barriers and improve climate-oriented planning [14], [15].
SDG 14 Life Below Water	Environmental	Reviews stress ecological monitoring and impact assessment of marine energy devices to protect ecosystems while scaling marine renewables [6], [8].
	Social	Governance and policy frameworks are needed to balance marine biodiversity protection with renewable energy expansion [6].

4 Conclusion

This study confirms that ocean wave-based renewable energy research has experienced rapid growth over the past two decades, reflecting its increasing role in the global energy transition. The bibliometric findings highlight three key insights. Research trends show a shift from technology-focused studies toward multidisciplinary approaches integrating sustainability, policy, and environmental considerations. Publication impact reveals that the most influential works emphasize innovation in wave energy converters, hybrid harvesting systems, and techno-economic frameworks, yet social dimensions and large-scale implementation strategies remain underdeveloped. Sustainability opportunities demonstrate strong alignment with SDG 7, while also contributing to SDGs 9, 13, and 14, particularly in clean energy access, climate change mitigation, and marine ecosystem protection. Overall, wave energy holds significant potential as a complementary renewable resource. To fully realize this potential, future research should address underexplored areas such as socio-economic impacts, governance, and large-scale deployment strategies, thereby strengthening its contribution to global sustainability and the achievement of the SDGs.

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