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Posted Date: 11 September 2024

doi: 10.20944/preprints202409.0921.v1

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Article

Wave and Tidal Energy: A Patent Landscape Study

Mohamadreza Pazhouhan [1], Amin Karimi Mazraeshahi [1], Mohammad Jahanbakht [2,*], Kourosh Rezanejad [3] and Mohammad H. Rohban [4]

1. Sharif University of Technology, Iran; mohamadreza.pazhouhan@sharif.edu; mohammad.karimi78@sharif.edu
2. The University of Texas at Arlington, Frenesim Das Ondas, LDA (Wave To Energy), 2650-463, Amadora, Portugal
3. Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Frenesim Das Ondas, LDA (Wave To Energy), 2650-463, Amadora, Portuga; kourosh.rezanejad@tecnico.ulisboa.ptl
4. Department of Computer Engineering, Sharif University of Technology, Tehran 14588-89694, Iran; rohban@sharif.edu

* Correspondence: mohammad.jahanbakht@uta.edu

Abstract: Wave and tidal energy, recognized as vital renewable resources, harness the ocean's kinetic and potential power. This study aims to provide an in-depth patent analysis of the technological landscape within these sectors. We applied a dual approach: first, a descriptive analysis was conducted to explore patent publication trends, technology lifecycle stages, patent activity by country, top assignees, and IPC classifications. Our analysis provided a detailed overview of the sector's growth and the key players involved. Second, we utilized topic modeling, specifically BERTopic enhanced with large language models (LLMs), to identify and fine-tune key technological themes within the patent data. In this study, we identified seven distinct clusters each for wave and tidal energy using this approach. This method led to a novel categorization of the patents, revealing latent themes within the patent data. Although our categorization differs from traditional methods, it provides deeper insights into the thematic focus of the patents, highlighting emerging trends and areas of innovation within wave and tidal energy technologies to better exploit and optimize ocean energy conversion infrastructure.

Keywords: Wave Energy; Tidal Energy; Patent Analysis; Topic Modeling; Large Language Models; BERTopic

1. Introduction

The global need to transition to sustainable energy systems is more urgent than ever. As Chu et al. [1] state, the world must undertake "another industrial revolution," shifting from reliance on fossil fuels to renewable energy sources to mitigate the risks of climate change. Oliveira et al. [2], in a detailed review of renewable energy technologies, emphasize the significant role that renewable energy resources can play in meeting the world's growing energy demand. Among these, marine renewable energy sources—particularly wave and tidal power—stand out as promising yet underexploited resources. These sources not only expand the renewable energy mix [3], but they also offer advantages such as predictability and energy density [4]. These characteristics could play a critical role in building a more resilient and low-carbon energy infrastructure.

Wave and tidal energy represent two of the most promising sources of marine renewable energy, utilizing the immense and consistent power of oceanic movements. Wave and tidal power harness the immense and consistent movements of the ocean; wave energy captures the energy from surface waves, while tidal energy exploits the predictable rise and fall of sea levels. Historically, significant strides in wave energy were made in the late 20th century, for instance Falnes and Løvseth [5] detailed early technical advancements and theoretical frameworks for energy extraction from ocean waves. More recently, Melikoglu [6] provided a comprehensive global review of the status and future prospects of ocean energy sources including wave and tidal energy, emphasizing technical reviews and resource considerations. In another, study Pelc and Fujita [7] also contributed to the understanding of the potential and environmental impacts of these energy sources, emphasizing their role in sustainable energy development.

The significance of wave and tidal energy lies in their potential to contribute to a sustainable energy future. Resource assessments, such as those by Liu, et al. [8] and Reikard, et al. [9], have quantified the vast potential of wave and tidal energy. Khare and Bhuiyan [10] using a technical review, stressed the importance of these energy forms in achieving long-term energy sustainability. Additionally, their potential to meet global energy demands is substantial. For instance, in developing countries, Kabir, et al. [11] and Khojasteh, et al. [12] discussed how these energy sources could significantly enhance energy security. In other nations, research by O'Hagan, et al. [13], Wimalaratna, et al. [14], Segura, et al. [15], Lehmann, et al. [16] demonstrated their potential to supplement existing energy infrastructures and reduce dependency on fossil fuels.

Despite notable progress in wave and tidal energy development, significant engineering, economic, and institutional challenges must still be addressed before large-scale commercialization [7, 17]. Moreover, these renewable technologies face several obstacles that hinder their widespread adoption. Environmental concerns, as noted by Felix, et al. [18], Hutchison, et al. [19], and Vazquez and Iglesias [20], include impacts on marine ecosystems and coastal processes. Economic and socio-economic assessments by Dalton, et al. [21] and Melikoglu [6] pointed out key financial and regulatory barriers associated with these technologies. Socioeconomic assessments further emphasize the need for comprehensive regulatory frameworks to facilitate development and deployment [22].

Meanwhile, technical challenges continue to pose significant barriers to the advancement of wave and tidal energy technologies. Research by Mwasilu and Jung [4], Corsatea [23], and Waters and Aggidis [24] has highlighted key issues. Corsatea [23] discusses the challenges within the marine energy sector, particularly the need for stronger synergies between institutions and technology developers to transition from the pre-development phase to commercialization and fully optimize ocean energy conversion infrastructure.

While significant strides have been made in understanding the technical, environmental, and economic aspects of wave and tidal energy, a critical gap persists in the literature regarding a comprehensive analysis of the patent landscape for these technologies. This study fills that gap by providing a comprehensive analysis of the patent landscape for wave and tidal energy technologies. By employing a dual approach, the study combines descriptive patent analysis and topic modeling, specifically using BERTopic enhanced by large language models (LLMs), to extract and analyze the content of relevant patents. The descriptive analysis focused on trends in patent publications, stages of the technology lifecycle, patent activity by country, top assignees, and IPC classifications. This provided a detailed overview of the sector's growth, emphasizing the leading players and identifying China as the leader in patent activity. These findings position wave and tidal energy technologies at the middle life cycle stage. In parallel, the use of topic modeling techniques identified seven distinct clusters each for wave and tidal energy, uncovering latent themes within the patent data that traditional classification methods do not reveal. This novel categorization of the data offers deeper insights into the thematic focus of innovations, illuminating emerging trends and key areas of technological advancement.

This research is closely connected to ongoing initiatives aimed at improving and optimizing ocean energy conversion infrastructure, which seeks to tap into the immense energy resources of the world's oceans using technologies such as and wave and tidal energy conversion systems.

2. Literature Review

2.1. Wave and Tidal Energy

The field of wave and tidal energy has been extensively explored through multiple research perspectives that provide a broad understanding of its potential and challenges. Bibliometric reviews are instrumental in summarizing the evolution and current state of research. For instance, Kulkarni and Edwards [25] conducted an extensive review that examines renewable offshore marine energy development and its impact on marine species. Similarly, Khojasteh, et al. [26] and Tavakoli, et al. [27] provided insights into the academic directions, collaborations, and thematic clusters within the domain, using bibliometric techniques to map the research landscape. In their work, Hu, et al. [28] and Liang, et al. [29] also contributed on this by identifying emerging research fronts and assessing the impact of various technological advancements in ocean renewable energy and blue economy. Their studies pinpoint critical innovations and the geographical distribution of research activities, offering a global perspective on the field. Kabil, et al. [30] and Pires Manso, et al. [31] also enriched the literature by analyzing coastal tourism trends in blue economy.

In addition ,Agyekum, et al. [32] investigated the societal and policy implications of wave and tidal energy, addressing the interaction between technology, policy frameworks, and the social environment. This multi-faceted approach underscores the complexity and interdependence of various factors influencing the adoption and implementation of marine energy technologies. Guo and Ringwood [33] explored both the research and commercial perspectives of wave energy. Their work provides a balanced view of the technological innovations driving the sector and the market dynamics that affect its commercialization. They discuss the readiness levels of different technologies, the investment landscape, and the pathways to market adoption, offering a comprehensive overview that bridges the gap between research advancements and commercial viability.

Another stream of research delves into resource assessment, an essential process for determining the scope and scale at which these technologies can be implemented. Resource assessments are vital for determining the scale at which these technologies can be deployed. In a study, the worldwide wave power resource is calculated to be around 2.11 ± 0.05 terawatts (TW), with roughly 4.6% being harvestable through the selected Wave Energy Converter (WEC) setup [34]. In another study, the global theoretical wave energy potential is projected to be nearly 29,500 terawatt-hours per year (TWh/year), while the total potential for tidal energy is estimated at approximately 26,000 TWh/year [26, 35, 36]. Additionally, Guillou et al. [37] highlight the importance of detailed resource assessments in exploiting wave energy, focusing on the potential of different geographic regions and data sources.

Economic considerations are crucial for the development and scaling of wave and tidal energy technologies and have been well studied in the literature. Astariz and Iglesias [38] evaluated the economic factors of wave energy, detailing its costs and comparing its levelized cost with other energy sources to assess profitability and competitiveness. Furthermore, Denny [39] provided a comprehensive analysis of the economics of tidal energy, examining the break-even capital costs required for tidal generation to be viable and highlighting the challenges it faces compared to other renewable energy sources. Additionally, the study [40] explores the optimization of wave energy converters, focusing on balancing technological performance with economic considerations by using techno-economic optimization via genetic algorithm.

In another stream of research, Khare and Bhuiyan [10] provided a detailed technical overview of tidal energy technology. Their study covers the principles of energy conversion, the design and operation of energy converters, and the performance metrics used to evaluate these systems. They also address the integration of marine energy into existing power grids and the technical challenges that must be overcome to enhance efficiency and reliability. Waters and Aggidis [24] provide a comprehensive review of tidal range technologies, illustrating the evolution from traditional barrage schemes to newer, less invasive methods such as tidal lagoons, reefs, and fences. In addition to tidal range technologies, Li and Zhu [41] review the state-of-the-art in tidal current energy harvesting technologies, emphasizing that while these technologies offer a promising renewable energy source, they are still in early development stages. Among the key challenges are technical barriers to full-scale deployment and the need for comprehensive life cycle assessments to evaluate environmental impacts and inform sustainable energy practices. Overcoming these technical issues will require continued innovation and collaboration across the sector to make wave and tidal energy more viable on a commercial scale.

2.2. Technology Analysis Using Patents

In exploring the technological landscape of a specific domain of technology, patent analysis emerges as a crucial tool for understanding innovation and development stages. Patents are attractive to researchers and policymakers because they provide a quantitative measure for otherwise difficult-to-gauge phenomena such as innovation, knowledge transfer, collaboration, and advancements in technology [42]. Patents are vital for delineating the technological landscape and assessing innovation within a domain. They provide a detailed record of technological advancements and are used to track the evolution of specific technologies. Studies by Abraham and Moitra [43], Ernst [44], Basberg [45], Song [46], and Kim [47] highlight the role of patents in mapping technological domains and gauging the innovation output of industries. Patents offer a quantitative measure of innovation, revealing trends and shifts in technological focus over time.

Patent analysis serves as a powerful tool for technology landscaping, enabling the identification of innovation, knowledge spillovers, collaboration, and technological space [42]. For instance, Jiang, et al. [48] demonstrate how patent data can be used to visualize the competitive landscape and innovation trajectories within renewable energy sectors. Additionally, patent analysis is a critical tool in technology management, offering insights into technological trends, competitive intelligence, and innovation pathways. This process involves examining patent data to identify emerging technologies [49-52], assess technological advancements [53], and predict future trends [54, 55]. The importance of patent analysis in technology forecasting has been well-documented. For instance, Lee [56] in a review article, discusses how patent along with scientific papers can be used in technology forecasting. Additionally, Bengisu and Nekhili [57] illustrate the role of patent analysis in forecasting emerging technology using science and technology databases. Daim, et al. [50] further elaborate on the methodological advancements in patent analysis as well as bibliometrics studies for forecasting emerging technologies.

The first patent for a wave energy converter was filed in the 18th century [58]. However, in the field of wave and tidal energy, hundreds of related patents have been issued throughout the 20th century [7, 59, 60]. Recent years have seen a notable increase in patent filings related to wave and tidal energy. This surge in patent filings indicates growing interest and investment in wave and tidal energy technologies. The European Commission's 2022 report shows the number of patents filed, underscoring the momentum in this sector [61].

Despite extensive patent analyses in other renewable energy areas like wind [62], solar [63, 64], thermal [65], and hydrogen [66, 67], wave and tidal energy remain relatively underexplored. This gap presents an opportunity for targeted patent analysis to uncover innovation patterns and identify technological milestones specific to wave and tidal energy. Studying patents, we can understand development stages, spot emerging trends, and evaluate the overall landscape of these promising renewable energy sources. This knowledge is essential for advancing these technologies toward better exploitation and optimization of these technology sectors.

Several tools and methodologies are used for patent analysis, ranging from traditional statistical methods to advanced text mining techniques. Abbas, et al. [68] provide a comprehensive overview of these tools that showed their applications in various domains. Text mining, in particular, has become a popular approach for patent review which allows for the extraction of valuable information from large datasets. Tseng, et al. [69] illustrate the effectiveness of text mining in uncovering hidden patterns and trends within patent data.

However, new methods for patent analysis have emerged recently, including machine learning and natural language processing (NLP) techniques. Advanced computational tools such as artificial technologies can also be used in patent analysis [70]. Lupu [71] discusses the integration of machine learning algorithms in patent analysis, highlighting how they enhance the accuracy and efficiency of identifying emerging technological trends and innovations. Building on these advancements, the next section delves into topic modeling, BERTopic and Large Language Models (LLMs) that we used in our study.

2.3. Topic Modeling in Patent Analysis

Topic modeling is an advanced text mining technique that has gained prominence in patent analysis. It involves the use of algorithms to identify and cluster topics within a corpus of documents, revealing the underlying thematic structure. The Latent Dirichlet Allocation (LDA) model was developed by Blei, et al. [72] and is a popular topic modeling method that has been employed in many different technology sectors. In a study Wang, et al. [73] applied topic modeling to analyze LTE patents that uncovered key technological themes and trends. Similarly, Zhang, et al. [74] used topic modeling to explore the blockchain technology roadmap and Choi and Woo [75] used this method to map the progression and anticipate emerging directions in hydrogen technology patents. Most recently Ghaffari, et al. [76] utilized topic modeling to study patents related to vehicle tires, demonstrating its versatility and applicability across different technology sectors.

2.4. BERTopic

BERTopic [77] is a recent advancement in topic modeling that combines the strengths of BERT (Bidirectional Encoder Representations from Transformers) [78] embeddings with traditional clustering algorithms to improve the coherence and interpretability of topics. Grootendorst [77] outlines the architecture of BERTopic, emphasizing its ability to generate high-quality topics by leveraging contextual information from BERT. BERTopic has several advantages, including its ability to handle large and diverse datasets, provide dynamic topic modeling, and generate interpretable topics.

The application of BERTopic spans various areas for instance, An, et al. [79] used BERTopic to gain customer insights from product reviews, demonstrating its utility in consumer research. Chagnon, et al. [80] applied it to scientific articles. [81] explored mental health issues in academia using BERTopic, illustrating its potential in social science research.

Egger and Yu [82] further supported the use of BERTopic and demonstrated its advantages and limitations over other topic modeling algorithms like LDA, NMF, and Top2Vec. They found that BERTopic excels in handling short, unstructured text data, such as Twitter posts, due to its robust embedding approach. The algorithm's ability to support multilingual analysis, automatically determine the number of topics, and provide hierarchical topic reduction makes it particularly powerful for diverse datasets. These features collectively justify the use of BERTopic for topic modeling this study, where data may be complex and multifaceted. Figure 1 illustrates the modular architecture of BERTopic, which illustrates how the framework is structured to process and analyze large text datasets.

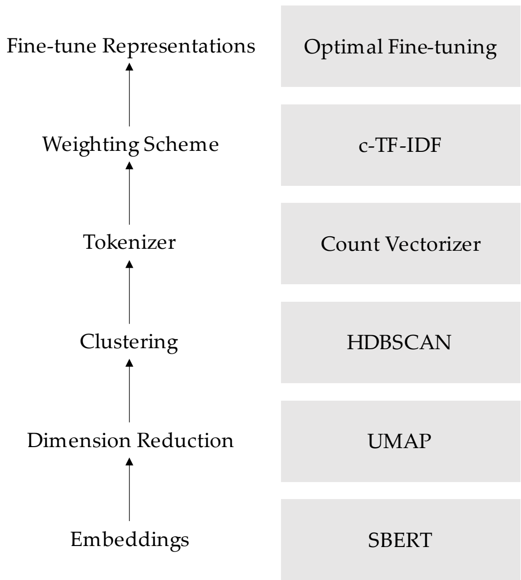

Figure 1. BERTopic modular architecture.

2.5. Large Language Models

Large language models (LLMs) have revolutionized text analysis, particularly patent analysis. Examples of these models are as GPT-3 [83] and BERT [78]. Devlin, et al. [78] introduced BERT, a transformer-based model that has set new benchmarks in NLP tasks by providing deep contextual understanding of text. These models have immense potential in patent analysis such as text generation, summarization, and information extraction.

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George and Sumathy [84] examine the impact of large language models (LLMs) in their study on an integrated clustering and BERT framework for enhanced topic modeling. Lee and Hsiang [85] emphasize the potential of LLMs in enhancing the accuracy of patent classification. Patent analysis, augmented by advanced text mining techniques and LLMs, offers a powerful framework for technology and innovation assessment. The integration of methods such as topic modeling and BERTopic, along with the capabilities of LLMs, provides a comprehensive approach to uncovering hidden patterns and trends within wave and tidal energy sector.

3. Materials and Methods

3.1. Methodology

The methodology employed in this research, as outlined in Figure 2, involves a structured approach designed to systematically analyze patent data of wave and tidal energy. The process begins with data collection, data preprocessing, and descriptive analysis, followed by topic modeling using BERTopic, fine-tuning representations using Large Language Models (LLMs), and culminates in evaluation, interpretation, and the practical application of the findings.

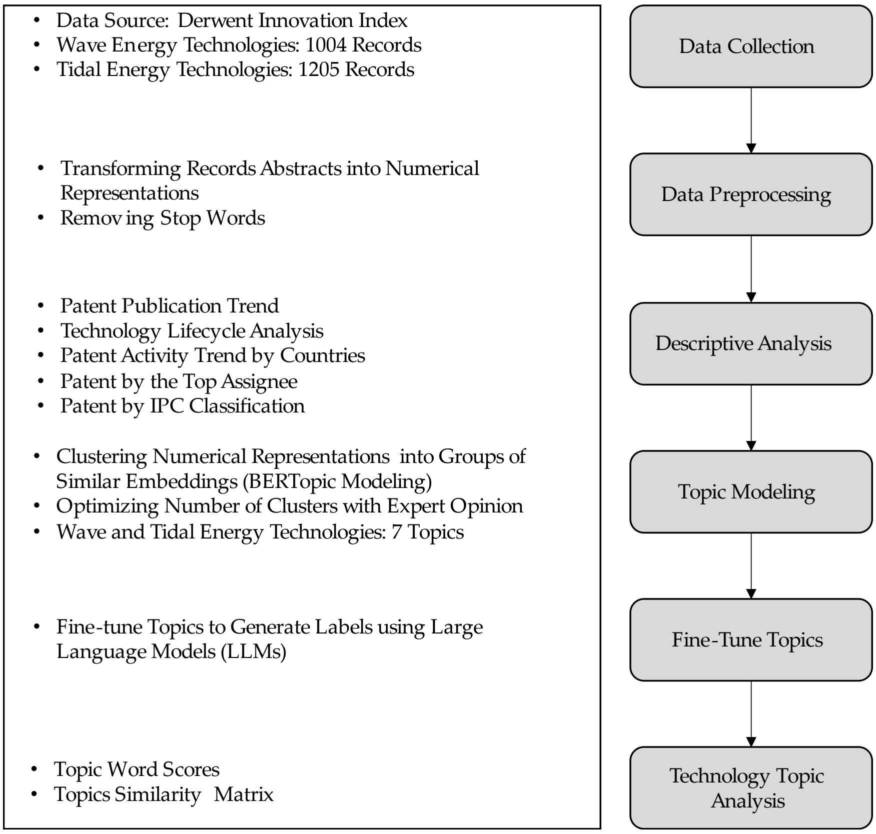


Figure 2. Research methodology.

3.2. Data Source

The variability in patenting practices and systems across different countries or regions [86] can complicate cross-country comparisons and analyses of patent data. To address the challenges posed by variability in patenting practices, the Derwent Innovation Index was chosen as the main source of patent data for our research due to its extensive coverage, strong analytical capabilities, and vast historical data. The Derwent Innovation Index creates distinct patent families for each innovation to expedite the discovery process. This is achieved by combining over 14.3 million basic inventions from nearly 60 global patent-issuing agencies.

The database consists of two primary indexes—DWPI (Derwent World Patents Index) and DPCI (Derwent Patent Citations Index). The DWPI organizes global patent filings into families, facilitating the accurate tracing of the patent's country of origin and its dissemination. Due to these advantages, we selected Derwent Innovation as our source of patent data.

3.3. Data Collection

In this study, we utilized a keyword-based approach to identify patents related to wave and tidal energy technologies. Building upon the search terms from Khojasteh et al. [26] we refined and expanded these keywords with a particular focus on technological innovations, incorporating expert opinions to ensure a comprehensive identification and analysis of relevant patent documents. The detailed search query is provided in the appendix. This search strategy was designed to capture all patents that mention wave and tidal energy within their topic sections, including abstracts, titles, keywords, and author keywords. This approach ensures that our analysis encompasses a wide range of innovations within these sectors.

By using this search method, we extracted 1004 patents related to wave energy technologies and 1205 patents pertained to tidal energy technologies. Our approach ensures that our analysis covers a broad spectrum of technologies within the wave and tidal energy sectors.

3.4. Data Preprocessing

The data preprocessing step involved gathering a comprehensive dataset of patents from the Derwent Innovation Index database, forming the basis for subsequent analyses. Initial preprocessing tasks, including cleaning, standardizing text, removing noise and punctuation, and eliminating stopwords, were manually conducted. The preprocessing was then further improved by BERTopic, which automatically carried out tasks including tokenization, which divides text into discrete words or tokens, and lemmatization, which reduces words to their basic or root forms. Additionally, BERTopic vectorizes the processed text using advanced language models like BERT, creating numerical representations of the text that capture semantic meaning.

3.5. Topic Modeling with BERTopic

Following data preprocessing, the next phase involved applying the BERTopic library to perform topic modeling on the cleaned patent data. BERTopic uses transformer-based models to generate topic representations from the high-dimensional patent embeddings. To improve the interpretability of these embeddings, we applied a dimensionality reduction technique, specifically UMAP (Uniform Manifold Approximation and Projection). UMAP reduces the dimensionality of the BERT embeddings, allowing for a more accessible visualization and analysis of the topics. Clustering algorithms, specifically K-means in this study, were subsequently applied to group patents into coherent topic clusters.

3.6. Fine-tuning Representations using LLMs

To further enrich the analysis, we integrated Large Language Models (LLMs) GPT (Generative Pre-trained Transformer) and BERT (Bidirectional Encoder Representations from Transformers). These models were used to embed the patent documents into dense vector representations, capturing the semantic nuances of the text. The LLMs were also employed for various tasks, including text summarization, semantic similarity analysis, and predictive modeling. These capabilities allowed for a deeper exploration of the relationships between patents and the identification of emerging trends within the wave and tidal energy sectors.

After performing topic modeling using the BERTopic library, two sets of information are obtained for each topic: a collection of keywords representing the generated topic and a series of documents that further describe it. The keywords are essentially a probabilistic vector that indicates the likelihood of each keyword's occurrence within the generated topic. The documents, on the other hand, are a selection of abstracts from patents that are classified under the specific topic.

Traditionally, this type of data would be provided to an expert in the relevant research domain, who would assign labels to the topics based on the combined set of keywords and documents. In this study, however, we utilize the capabilities of large language models (LLMs) to automate the labeling

 doi:10.20944/preprints202409.0921.v1

process. The assigned labels are subsequently validated by a domain expert to ensure their accuracy. For this purpose, we employed the GPT-4-1106-preview language model. A specific prompt, incorporating the keywords and associated documents for each topic, was crafted to generate an appropriate label.

3.7. Evaluation and Validation of Topics

Through a combination of quantitative and qualitative evaluation techniques, the efficacy of the topic modeling and LLM-based approaches was verified. The coherence and interpretability of the identified topics were assessed to ensure they provided meaningful insights into the patent data. An iterative process was employed, starting with an initial set of 15 topics, which were progressively refined and reduced to ensure that each topic represented a unique and distinct category. Ultimately, we identified 7 distinct clusters for wave energy and 7 for tidal energy. Additionally, expert opinion was sought to further validate the relevance and accuracy of the results.

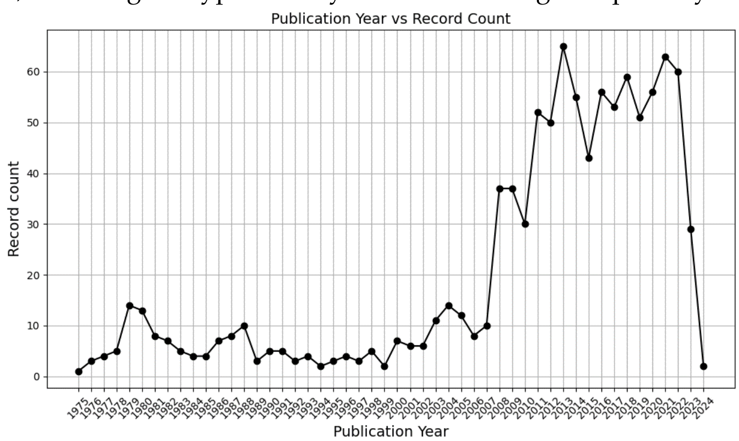
4. Results and Discussion

The results of our study begin with a descriptive analysis, offering an overview of patent publication trends, key players, and the life cycle stages of wave and tidal energy technologies. This initial analysis provides valuable insights into the growth and geographical distribution of patent. Subsequently, we applied topic modeling, which revealed distinct thematic clusters within the patent data.

4.1. Descriptive Results

4.1.1. Patent Publication Trend

Research and development in wave and tidal energy commenced in the 1970s and has consistently advanced since then. Starting in 2000, numerous large-scale prototypes for wave and tidal currents have been showcased globally [87]. Consequently, patent applications began to rise in 2000, with a sharper increase from 2006 onwards. Policies supporting renewable energy in developed nations and rising consumer demand have been the main drivers of these spikes. The number of patents peaked in 2014 for wave energy and in 2020 for tidal energy, with subsequent fluctuations. Annual statistics are illustrated in Figure 3. However, there is a noticeable sharp decline in patent publications for 2022, 2023, and 2024, which can be attributed to the lag between patent filing and publication dates, reflecting the typical delay before new filings are publicly available.



(a)

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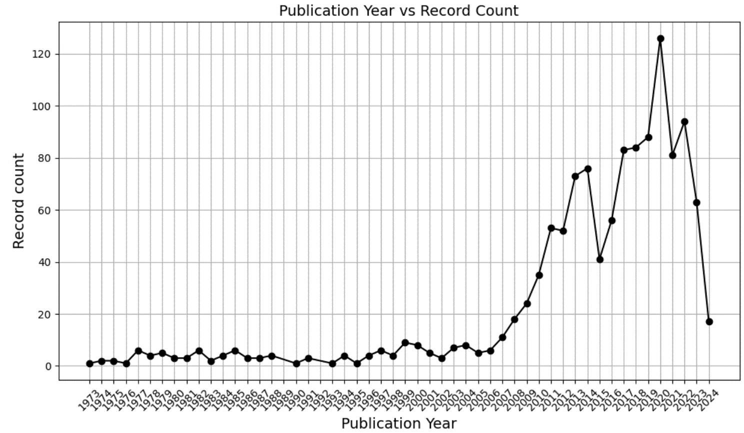


(b)

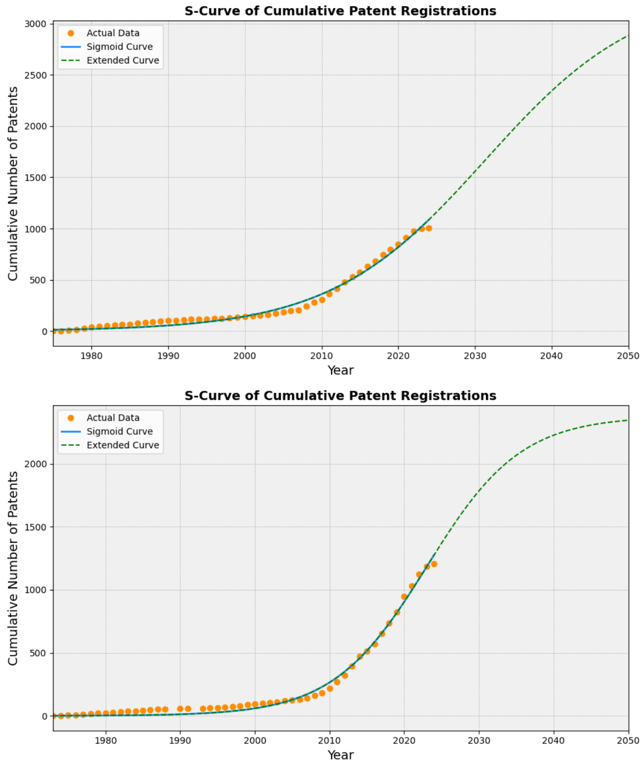
Figure 3. Total annual patent number: (a) Wave energy technology; (b) Tidal energy technology.

4.1.2. Technology Lifecycle Analysis

Technology life cycle analysis has become a widely utilized method in patent analysis that provides valuable insights into the future trajectory of technology domains. Figure 4 depicts the technology life cycle trajectory of wave and tidal energy. In our analysis we applied the logistic growth model, which was initially introduced by Richards [88] and later adapted into the Richards curve. The model is represented by the following equation:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \quad (1)$$

This model, a generalized form of the logistic function, is particularly suited for describing the growth and saturation of technologies over time. In this equation, f(x) represents the cumulative number of patents, while the parameters k, x, and x_0 are used to fit the curve to the observed data.



(a)

(b)

Figure 4. Technology S-curve: (a) Wave energy technology; (b) Tidal energy technology.

Our curve fitting analysis suggests that both wave and tidal energy technologies are currently in the middle stage of their development, a critical phase where these technologies are transitioning from early adoption and growth to a period marked by increased optimization and refinement. This stage is pivotal for the exploitation and optimization of ocean energy conversion infrastructure, as it signals that significant advancements have been made, yet there remains substantial potential for further innovation and market expansion before these technologies reach full maturity and widespread commercial deployment. The results of our curve fitting analysis, as shown in Table 1, indicate a strong correlation between the model and the observed data for both wave and tidal energy technologies. The R^2 values are 0.98 for wave energy and 0.99 for tidal energy, suggesting a very good fit. The corresponding P-values of 0.05 for wave energy and 0.01 for tidal energy confirm the statistical significance of the model. These findings reinforce the conclusion that both wave and tidal energy technologies are in a crucial middle stage, characterized by ongoing optimization efforts and considerable room for growth, which are essential for advancing the sustainable and cost-effective harnessing of ocean energy.

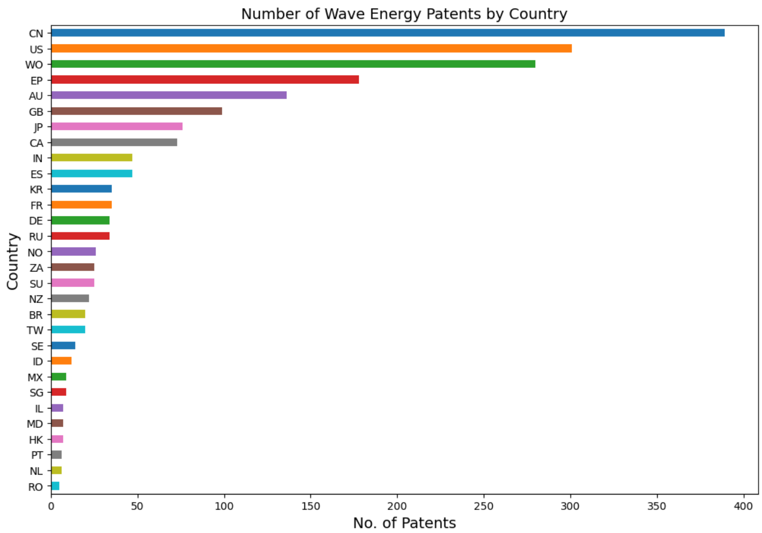
Table 1. Specific parameters for curve fitting of wave and tidal energy.

Technology	R^2	P-value
Wave Energy	0.98	0.05
Tidal Energy	0.99	0.01

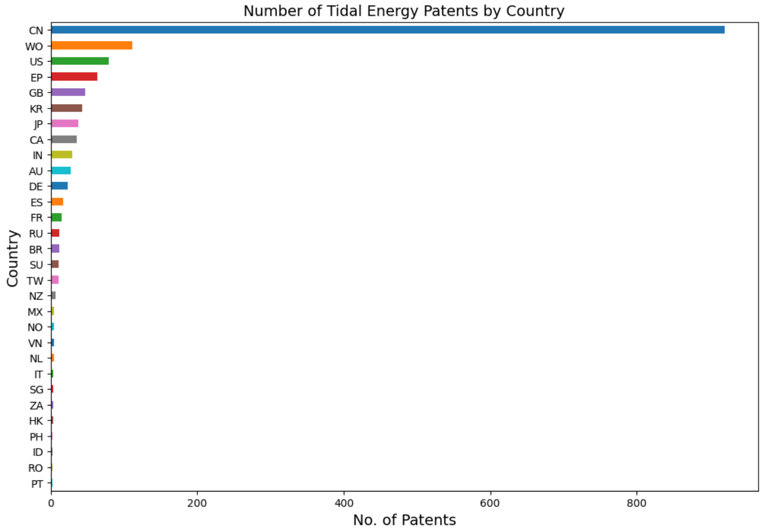
4.1.3. Patent Activity Trend by Countries

Analyzing patent activity trends by country is a critical component of analyzing wave and tidal energy technologies. It sheds light on the potential market and competitive landscape for renewable energy innovations. By examining the countries where patents have been granted or filed, researchers and industry stakeholders can gauge the market size and the level of competition in each jurisdiction. The significant research and development efforts dedicated to wave and tidal energy reflect its potential as a sustainable energy source, with many countries investing heavily in this field to achieve carbon neutrality and address climate change.

Figure 5 presents the patent activity trends by country, highlighting China's leadership with the highest number of granted patents in wave energy technology, followed by the United States. Other countries, including the Australia, United Kingdom, and Japan, are also actively engaged in patent filings, contributing to the global development of wave energy. Additionally, data on patent activity trends in tidal energy by country highlights China's leadership with the highest number of granted patents in tidal energy technology. United States follows China, indicating strong engagement in this sector. Other significant contributors include the United Kingdom, South Korea, Japan, and Canada also show notable activity respectively.



(a)



(b)

Figure 5. Number of patents by country: (a) Wave energy technology; (b) Tidal energy technology.

China's strong performance in patent filings for wave and tidal energy can be attributed to significant investments in research and development, supported by strategic government policies. The Chinese government has recognized the vast potential of ocean energy as a sustainable power source, crucial for addressing the country's growing energy demands and environmental challenges. Policies like the Renewable Energy Law and substantial funding from the National Natural Science Foundation of China (NSFC) [89] and National High Technology Research and Development Program (863 Program) [90], which have provided substantial support for research and development in this sector. Key coastal regions like Zhejiang and Fujian also offer significant potential for tidal and wave energy [91]. These efforts are part of China's broader strategy to achieve carbon neutrality and strengthen its position as a leader in renewable energy technologies [92].

Another key insight from our analysis is the comparison between the number of patents filed and the wave energy capacity for each country, as provided by Waves-Energy.co [93] is shown in Figure 6. The Wave Energy Index, a metric designed to assess the potential for countries to harness wave energy relative to their annual electricity needs, further highlights the disparities between innovation and implementation. Our findings indicate that China and the United States file significantly more patents relative to their actual wave energy capacity, suggesting a strong focus on innovation and patent filing. On the other hand, Australia demonstrates a balance between its patent filings and wave energy capacity, indicating a more direct correlation between technological innovation and implementation. In contrast, countries like Canada and Norway show fewer patent filings compared to their wave energy capacity, which may suggest that these nations are using existing technologies effectively or that their innovation activities are less focused on patentable advancements.

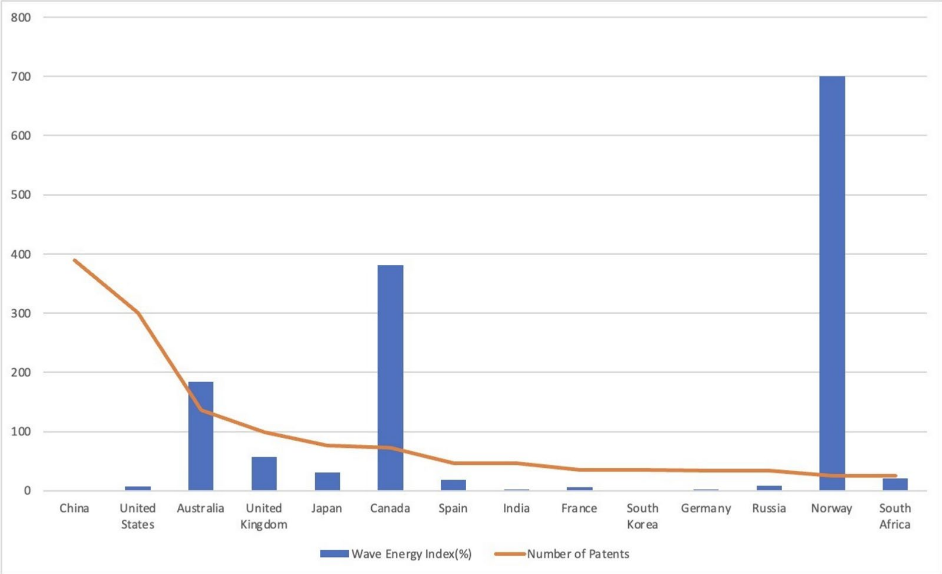
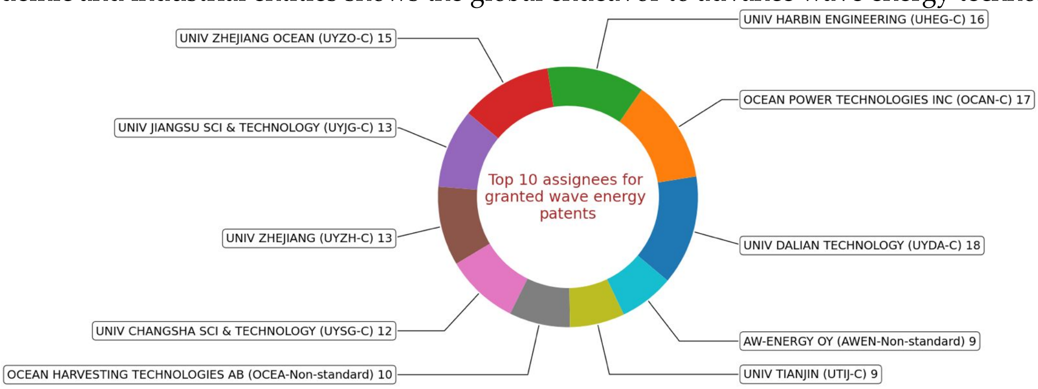


Figure 6. Wave energy index and number of patents for selected countries.

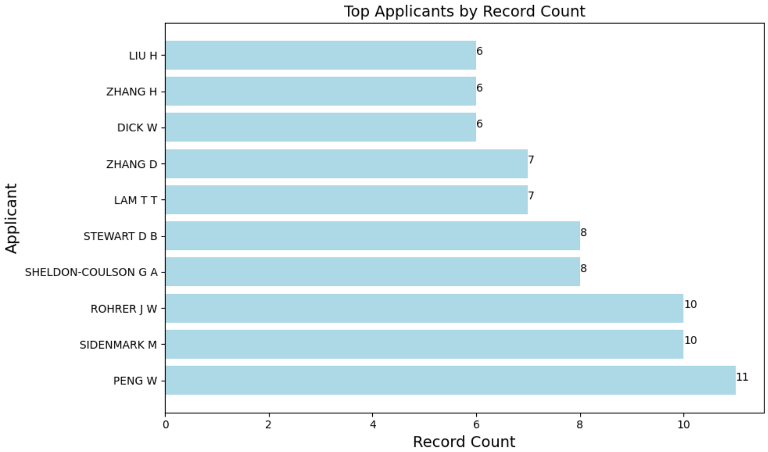
4.1.4. Patent by the Top Assignee

Identifying the foremost patent assignees and applicants is a critical component of patent analysis that offers valuable insights into the leading companies or organizations. Recognizing the leading assignees can highlight investment prospects and open up possibilities for future joint ventures or strategic alliances. This knowledge can guide stakeholders in making informed decisions about where to allocate resources and which organizations to engage with for advancing wave and tidal energy technologies.

Figure 7 displays the top ten patent assignees and applicants in the wave energy sector, reflecting the patent activity trend predominantly driven by China. Remarkably, most of the leading ten assignees in wave energy patent filings are located in China that showcase the country's substantial commitment to renewable energy research and development. Dalian University of Technology tops the list with 18 patents. Close behind are Ocean Power Technologies Inc. from the USA with 17 patents and Harbin Engineering University with 16 patents. Zhejiang Ocean University and Jiangsu University of Science and Technology also stand out with 15 and 13 patents, respectively. Additionally, Zhejiang University and Changsha University of Science and Technology contribute with 13 and 12 patents each. Ocean Harvesting Technologies AB from Sweden, Tianjin University, and AW-Energy Oy from Finland complete the list with 10 and 9 patents each. This assortment of academic and industrial entities shows the global endeavor to advance wave energy technologies.



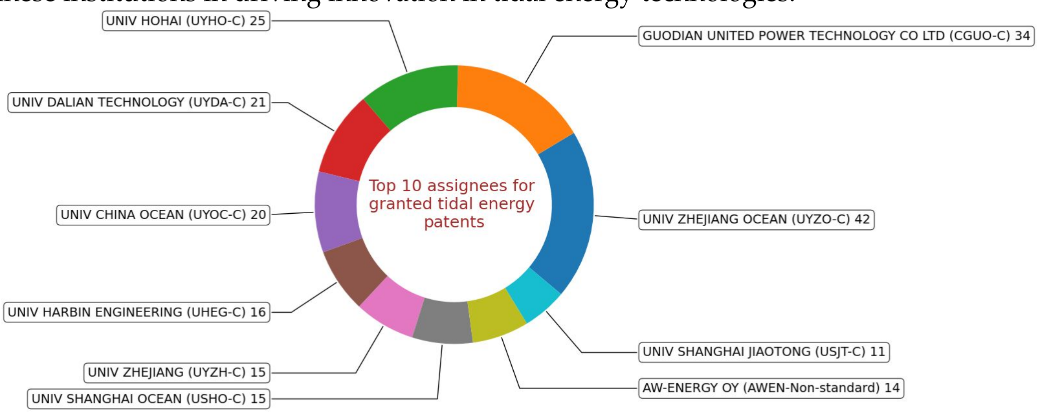
(a)



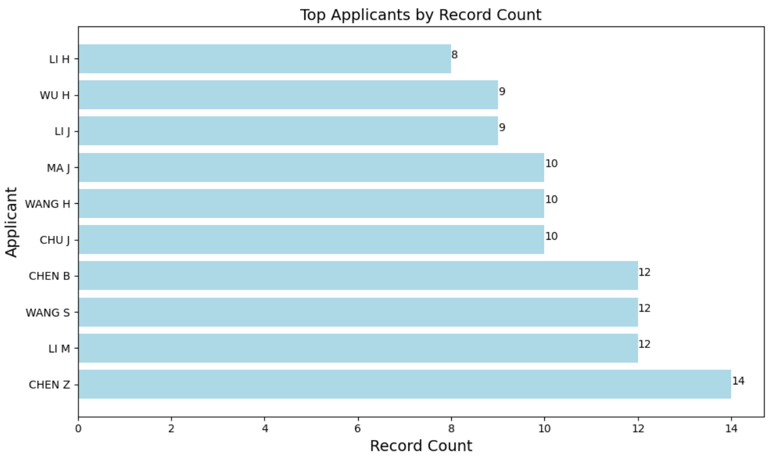
(b)

Figure 7. Wave energy patents: (a) Top assignees for granted patents; (b) Top applicants by record count.

In a similar context, the table below presents the top ten patent assignees in the tidal energy sector, with Chinese institutions dominating the landscape. University of Zhejiang Ocean leads with 42 patents, followed by Guodian United Power Technology Co Ltd with 34 patents and University of Hohai holding 25 patents. Other significant contributors include University of Dalian Technology with 21 patents and University of China Ocean with 20 patents. Additionally, University of Harbin Engineering has 16 patents, while both University of Zhejiang and University of Shanghai Ocean have 15 patents each. Internationally, AW-Energy Oy from Finland holds 14 patents, and University of Shanghai Jiaotong rounds out the list with 11 patents. This data highlights the prominence of Chinese institutions in driving innovation in tidal energy technologies.



(a)



(b)

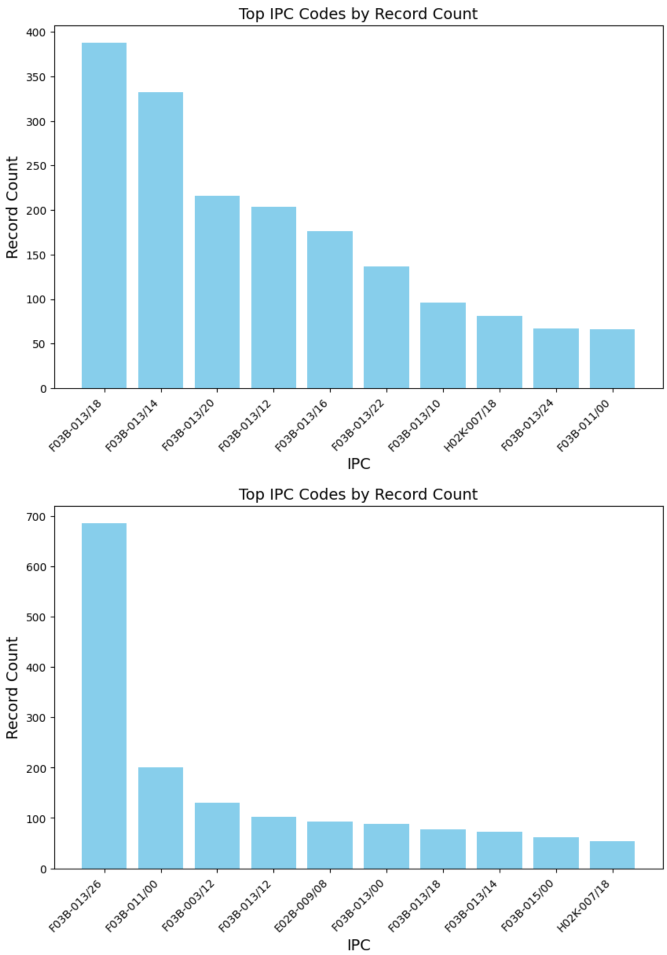
Figure 8. Tidal energy patents: (a) Top assignees for granted patents; (b) Top applicants by record count.

4.1.5. Patent by IPC Classification

Figure 9 illustrates the main International Patent Classification (IPC) codes attributed to the identified patent documents. Patents and utility models are categorized by their respective technological disciplines using a hierarchical arrangement of unique symbols in the IPC system [94]. This classification system serves as a vital tool for organizing and cataloging inventions based on their specific areas of technology that offers valuable insights into the global landscape of patent innovation.

For wave energy, identified patents are categorized under various IPC codes that correspond to different technological processes. For example, IPC codes such as F03B-013/18 and F03B-013/14 pertain to power stations utilizing wave energy, while F03B-013/22 focuses on the use of wave-induced water flow to drive hydraulic motors or turbines. Through the analysis of these classifications, companies can pinpoint relevant prior art, evaluate the uniqueness of their inventions, and gain a clearer understanding of the competitive landscape, thereby aiding in strategic decision-making for research and development.

Patents in tidal energy are categorized similarly, with IPC codes emphasizing certain innovations in technology. For instance, IPC code F03B-013/26 relates specifically to power stations using tidal energy, whereas F03B-011/00 and F03B-003/12 focus on components like blades and rotors used in tidal machinery. Broader classifications, such as E02B-009/08, cover water-power plants, including those utilizing tidal power. By examining these classifications, companies can gain insights into key technological trends, assess competition, and strategically direct their R&D efforts in the tidal energy sector.



(a)

(b)

Figure 9. Number of specific International Patent Classification (IPC): (a) Wave energy patents; (b) Tidal energy patents.

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Table 2 and Table 3 provide the definitions of the International Patent Classification (IPC) codes used for categorizing wave and tidal energy technologies, respectively. The definitions are sourced from the International Patent Classification (IPC) system by the World Intellectual Property Organization [94].

Table 2. IPC codes for identified wave energy patents.

IPC Code	Related to
F03B-013/18	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates wherein the other member is fixed, at least at one point, with respect to the sea bed or shore
F03B-013/14	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates using wave energy
F03B-013/20	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates wherein both members are movable relative to the sea bed or shore
F03B-013/12	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates characterized by using wave or tide energy
F03B-013/16	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates using the relative movement between a wave-operated member and another member
F03B-013/22	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates using the flow of water resulting from wave movements, e.g. to drive a hydraulic motors or turbine
F03B-013/10	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates submerged units incorporating electric generators or motors
H02K-007/18	Arrangements for handling mechanical energy structurally associated with dynamo-electric machines, e.g. structural association with mechanical driving motors or auxiliary dynamo-electric machines with starting devices
F03B-013/24	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates to produce a flow of air, e.g. to drive an air turbine
F03B-011/00	Parts or details not provided for in, or of interest apart from, groups F03B 1/00-F03B 9/00

Table 3. IPC codes for identified tidal energy patents.

IPC Code	Related to
F03B-013/26	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates using tide energy
F03B-011/00	Parts or details not provided for in, or of interest apart from, groups F03B 1/00-F03B 9/00

F03B-003/12	Machines or engines of reaction type; Parts or details peculiar thereto blades; blade-carrying rotors
F03B-013/12	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates characterized by using wave or tide energy
E02B-009/08	Water-power plants; Layout, construction or equipment, methods of, or apparatus for, making same tide or wave power plants
F03B-013/00	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates
F03B-013/18	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates wherein the other member is fixed, at least at one point, with respect to the sea bed or shore
F03B-013/14	Adaptations of machines or engines for special use; Combinations of machines or engines with driving or driven apparatus; Power stations or aggregates using wave energy
F03B-015/00	Controlling
H02K-007/18	Arrangements for handling mechanical energy structurally associated with dynamo-electric machines, e.g. structural association with mechanical driving motors or auxiliary dynamo-electric machines: Structural association of electric generators with mechanical driving motors, e.g. with turbine

4.2. Topic Modeling Results

4.2.1. Hierarchical Clustering

The second section of our analysis pertains to topic modeling, where the application of hierarchical clustering in conjunction with BERTopic yielded significant insights into the technological landscape of wave and tidal energy patents. By clustering the topics generated by BERTopic, we were able to identify coherent groups of patents that reflect distinct technological and innovation clusters within the field.

For wave energy, as illustrated in Figure 10, the dendrogram reveals seven clusters, each corresponding to a major area of focus within this sector. The largest cluster, comprising 182 patents, is centered on energy conversion systems, highlighting a significant concentration of patents dedicated to maximizing the efficiency and effectiveness of transforming wave energy into usable electricity. Following this, a cluster of 173 patents focuses on innovations related to water and air interactions, often associated with wave energy generation mechanisms. Another significant cluster, with 171 patents, pertains to floating structures, including buoys and other buoyant bodies crucial for wave energy systems. The next cluster includes 165 patents focused on hydraulic systems, particularly those involving cylinders and pistons, essential for energy conversion processes. Additional clusters include patents on general wave energy technologies with 126 patents, novel converters with 90 patents, and PTO (Power Take-Off) absorbers with 81 patents, which reflect the importance of these critical technologies.

For tidal energy, the hierarchical clustering revealed seven significant clusters, each reflecting a unique aspect of innovation within this domain. The largest cluster, with 243 patents, is related to tide energy conversion devices with novel mechanisms, illustrating the industry's focus on enhancing the reliability and performance of tidal energy systems. The second-largest cluster, consisting of 213 patents, is centered on innovations related to water flow and connected components, essential for tidal energy conversion. Another cluster of 208 patents focuses on mechanical components like plates and gears, which are vital for the functioning of tidal energy turbines. Additionally, 186 patents are grouped around floating platforms, indicating the importance of infrastructure in tidal energy deployment. Clusters focused on the general field of tidal energy with 152 patents and rotor and

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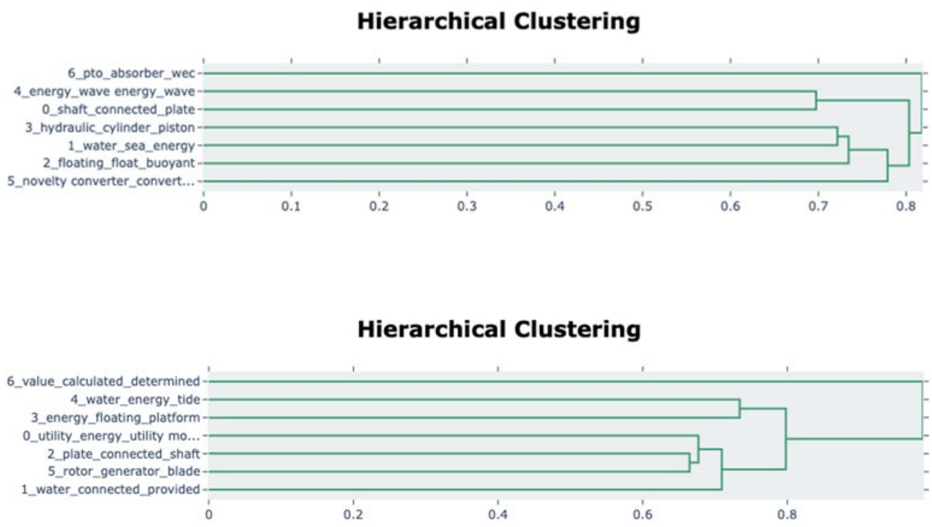
blade design with 144 patents further highlight key areas of development. The smallest cluster, with 49 patents, addresses issues related to data analysis and calculations critical for optimizing tidal energy systems.



(a)

(b)

Figure 10. Hierarchical clustering for: (a) Wave energy patents; (b) Tidal energy patents.

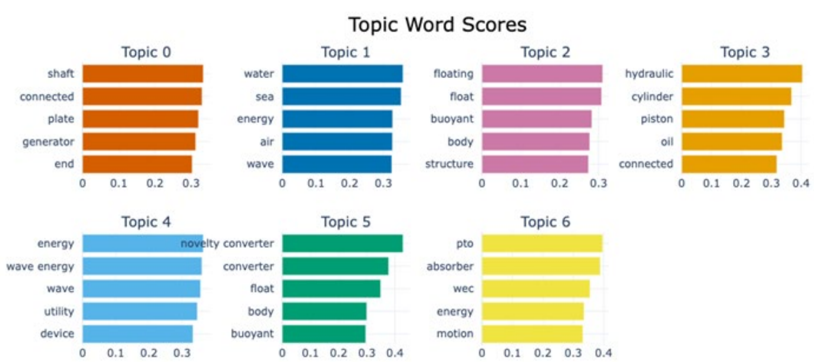
4.2.2. Topic Word Scores

Through c-TF-IDF (class-based Term Frequency-Inverse Document Frequency) scores, the BERTopic model not only distinguishes unique subjects within the patent corpus but also offers a comprehensive perspective of the most representative words for each topic. These scores quantify the importance of terms within each topic, enabling a deeper understanding of the specific concepts and technologies that dominate each cluster. The c-TF-IDF formula is presented here:

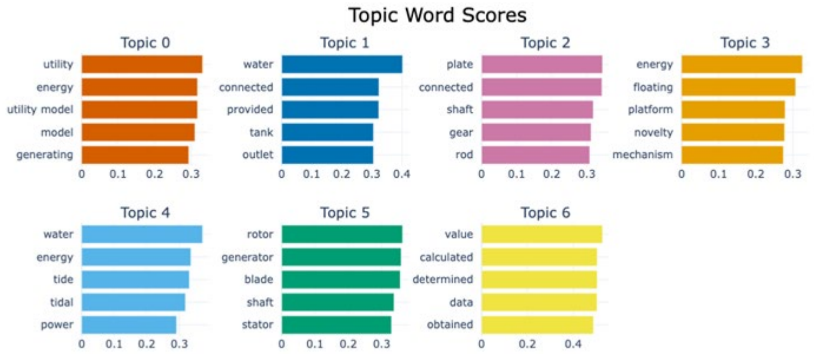
$$W_{x,c} = |tf_{x,c}| \times \log(1 + \frac{A}{f_x}) \qquad (2)$$

Where $tf_{x,c}$ is the frequency of word x in class c and f_x is the frequency of word x across all classes. A is the average number of words per class. To visualize the key terms for selected topics, bar charts of the c-TF-IDF scores were generated. These visualizations, as shown in Figure 11, allow for easy comparison of the importance of different terms both within and between topics, offering valuable insights into the thematic structure of the patent landscape.

For instance, in the topic number 2, terms such as "float," "buoyant," and "structure" exhibit high c-TF-IDF scores. These terms are crucial in understanding the primary focus of innovations within this topic, which centers on technologies designed to efficiently capture and convert wave energy into electrical power.



(a)



(**b**)

Figure 11. Topic word scores for: (a) Wave energy patents; (b) Tidal energy patents.

In the tidal energy topic, terms like "rotor"," "float," and "platform" stand out with significant c-TF-IDF scores. The significance of these terms highlights the continuous efforts to improve the efficiency and reliability of tidal energy systems, with a particular focus on optimizing turbine performance and durability in demanding marine conditions.

The visual comparison of these terms across different topics reveals the core technological areas within these sectors. For example, while both wave and tidal energy topics emphasize energy conversion, the specific technologies and challenges differ, as reflected in the distinct vocabulary and term importance captured by the c-TF-IDF scores.

While word scores provide some insight, they are often limited in their interpretability, as they only display the top words associated with each topic. This can obscure the full scope of the topic, as important nuances and additional relevant terms are not captured. To address this limitation, it is necessary to incorporate a broader range of terms and apply meaningful labels to the topics to ensure a more comprehensive understanding. In the following section we used we utilized BERTopic's GPT-based representations function to incorporate a broader range of terms and apply more meaningful labels to the topics.

4.2.3. Topic Representations

To enhance the clarity and coherence of the topics identified by BERTopic, we employed fine-tuning of topic representations using GPT-based models. This approach allowed us to refine the initial topic descriptions generated by BERTopic, ensuring that they accurately capture the nuances and specific technological aspects of each cluster. The process involved using GPT to analyze the top-ranked words and their context within each topic. By using GPT's advanced language understanding capabilities, we generated more descriptive and contextually relevant summaries for each topic. These refined representations provide a clearer and more informative view of the thematic content within each cluster.

For example, in the case of Topic 3, related to wave energy converters, the set of keywords provided was: ['hydraulic', 'cylinder', 'piston', 'oil', 'connected', 'pump', 'pressure', 'valve', 'air']. Alongside these keywords, three abstracts from relevant patents were supplied to the language model. One of these abstracts describes a "mushroom" oscillating water column wave energy conversion device. This device, belonging to the technical field of new energy utilization, comprises an air chamber, a base structure, and a turbine generating device. The air chamber is made up of a cylindrical ring body and a hemispherical ring located on the cylindrical ring body, both sharing the same radius. It features a gas hole pipeline connected with the turbine generating device, which operates under the influence of bidirectional airflow. The device is designed for 360-degree omnidirectional wave energy absorption, enhancing energy absorption rates through a stable, fixed structure, thereby improving power generation efficiency. The combined structural design also facilitates maintenance and makes the conversion device adaptable from offshore to onshore conditions. Based on the prompt provided, the language model generated the label: "Wave energy conversion devices using hydraulic systems and turbines." This description effectively captures the essence of the topic, aligning with the characteristics extracted from both the keywords and the associated documents.

The refined topic representations for wave energy are presented in Table 4. The following topics represent key areas of innovation and research within the domain of wave energy conversion. While these topics provide valuable insights into the field, they may not perfectly align with other wave energy conversion technologies due to the probabilistic nature of the topic modeling methodology used. Each topic focuses on different technological approaches to harness the power of ocean waves, reflecting the diversity and complexity of solutions being developed in this field.

Table 4. Topic representations for wave energy patents.

Topic	Count	Name	Representation
0	182	[shaft, connected, plate, generator]	Wave energy conversion devices with oscillating elements and generators.
1	173	[water, sea, energy, air]	Wave energy conversion using anchored beams, long beams, and specialized pressure-based chambers.
2	171	[floating, float, buoyant, body]	Wave energy converters with floating structures, turbines, and mooring for generating power from sea waves.
3	165	[hydraulic, cylinder, piston, oil]	Wave energy conversion devices using hydraulic systems and turbines.
4	126	[energy, wave energy, wave, utility]	Piezoelectric wave energy converters with floating bodies.
5	90	[novelty, converter, float, body]	Wave energy conversion utilizing buoyancy, ballast, and pulleys.
6	81	[PTO, absorber, WEC, energy]	Wave energy conversion using advanced control of multi-freedom PTO for optimal power extraction.

In the topics identified in wave energy, topic 0 centers on wave energy conversion technologies that employ oscillating elements combined with generators to harness energy from ocean waves. These devices, which convert wave-induced mechanical motion into electrical power, have been the focus of significant innovation in patent filings, particularly in optimizing energy capture and enhancing the durability of oscillating elements under varying wave conditions. The technologies covered in these patents are well discussed in the academic literature as well. For instance, Falcão and Henriques [95] provide a comprehensive review of oscillating water column systems and air turbines, showing key innovations similar to those found in recent patents. Their exploration of model-prototype similarity in OWC systems [96], along with Gomes et al.'s work on hydrodynamic optimization of axisymmetric floating OWCs [97], underscores the strong alignment between patented technologies and ongoing academic research. Additionally, Falcão's earlier work [98] on the control of OWC wave power plants for maximum energy production further complements these studies by offering a stochastic model to devise optimal control algorithms for maximizing power output in OWC systems equipped with Wells turbines.

Similarly, topic 1 explores wave energy conversion systems that employ anchored beams, long beams, and pressure-based chambers to extract energy from sea waves. The anchored and elongated beams act as primary energy absorbers, with the pressure-based chambers facilitating energy transfer and conversion. Innovations in this area focus on improving the stability and efficiency of these systems, ensuring they can withstand the harsh marine environment while effectively capturing the kinetic energy of waves. In the literature, studies such as those by Ghafari et al. [99] and Heo and Koo [100] have examined related technologies. Ghafari et al. [99] conducted a numerical study on the Wavestar wave energy converter with a multi-point absorber system, analyzing its performance around a floating wind turbine platform. Similarly, Heo and Koo [100] focused on the dynamic response of a Wavestar-type converter in Korean nearshore areas, investigating its effectiveness in energy capture under varying environmental conditions. Following this, topic 2 delves into wave energy converters that incorporate floating structures, turbines, and mooring systems. These technologies are designed to move with ocean waves, driving turbines to generate electricity, while mooring systems ensure the converters remain stable and effective across various sea states. The primary focus is on improving the reliability and performance of these systems, particularly under challenging offshore conditions. This area of technology has been extensively studied, with significant contributions from researchers such as Clemente et al. [101], who explored wave energy converters on multipurpose offshore platforms, and Li et al. [102], who conducted experimental studies on floating two-body wave energy converters.

Extending this discussion, topic 3 focuses on wave energy conversion devices that utilize hydraulic systems in conjunction with turbines to harness power from ocean waves. These systems typically use hydraulic pumps activated by wave motion, which then drive turbines to generate electricity. The main goal in this area is to enhance the efficiency of hydraulic energy transfer and turbine operation while ensuring the systems can withstand the continuous stresses imposed by wave action. Significant contributions to this field include research by Henderson [103], who designed and tested a hydraulic power take-off system for, as well as ongoing studies that continue to refine these technologies. In much the same way, topic 4 focuses on wave energy converters that leverage piezoelectric materials combined with floating bodies, particularly for applications near piers. These devices convert mechanical stress, induced by wave motion, into electrical energy through the piezoelectric effect. The floating bodies absorb wave energy and transfer it to the piezoelectric materials, which then generate electricity. Innovations in this area aim to maximize energy output and seamlessly integrate these systems into existing marine infrastructure, providing localized power generation. Research by Cai et al. [104], Xie et al. [105], and Yang et al. [106] has contributed significantly to advancing these technologies.

Correspondingly, topic 5 explores wave energy conversion technologies that utilize the principles of buoyancy, ballast, and pulley systems, integrated with power take-off (PTO) mechanisms. These systems typically involve floating structures that move with ocean waves, with buoyancy and ballast elements managing their motion. Pulleys and PTO systems then convert this motion into electrical energy. The focus of research in this area is on optimizing the interaction between these components to enhance energy efficiency and ensure the long-term reliability of the systems. This technology stream has been extensively studied, with significant contributions from researchers such as Falnes and Hals [107] , Korde and Ertekin [108], and Temiz et al. [109], who have explored various aspects of buoyancy, ballast, and pulley systems in wave energy conversion. Furthermore, Sjökvist et al. [110] have made important contributions by optimizing point absorber buoys, which are a key component in many wave energy systems, focusing on improving their performance and energy capture efficiency.

Ultimately, topic 6 focuses on wave energy conversion technologies that leverage advanced control strategies for multi-degree-of-freedom power take-off (PTO) systems. These systems are designed to maximize energy extraction from wave motion by dynamically adjusting their configurations in response to changing wave conditions. Innovations in this area emphasize the development of sophisticated control algorithms and PTO mechanisms that can adapt in real-time, optimizing power output and improving the overall efficiency of wave energy converters. This area of research has been extensively studied, with significant contributions from Abdelkhalik et al. [111] on wave prediction control, Ringwood et al. [112] on control technology possibilities, and Zhang et al. [113] on predictive control for wave-energy converter arrays, and Abdulkadir and Abdelkhalik [114] on optimal constrained control of wave energy converter arrays.. Other notable works include Coe [115] on practical wave energy modeling, Ahamed et al. [116] on advancements in PTO systems, and Mérigaud and Tona [117] on spectral control for non-ideal PTO systems, and Xue et al. [118] on control parameters optimization for hydraulic PTO systems in eccentric rotating wave energy converters.

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Similarly, Table 5 details the refined topic representations for tidal energy. These tables summarize the most representative topics in each domain and provide comprehensive overview of the key areas of innovation and research.

Table 5. Topic Representations for tidal energy patents.

Topic	Count	Name	Representation
0	243	[utility, energy, utility model, model]	Tide energy conversion devices with novel mechanisms for efficient power generation.
1	213	[water, connected, provided, tank]	Innovative water control devices with interconnected mechanisms for regulating flow and storage.
2	208	[plate, connected, shaft, gear]	Mechanical assemblies with rotating components for energy transmission and device operation.
3	186	[energy, floating, platform, novelty]	Tidal energy conversion using floating platforms with various mechanical and buoyancy-driven generation mechanisms.
4	152	[water, energy, tide, tidal]	Tidal energy generation with buoyant modules, pistons, and reservoirs for efficient electricity production.
5	144	[rotor, generator, blade, shaft]	Innovative turbine devices incorporating magnets, blades, and rotating shafts for energy generation.
6	49	[value, calculated, determined, data]	Optimizing tidal energy power generation through modeling and parameter analysis.

In tidal energy topics, topic 0 focuses on the development of tidal energy conversion devices that incorporate innovative mechanisms to enhance power generation efficiency. These technologies are designed to optimize energy extraction from tidal currents by employing advanced techniques, making them more effective at capturing and converting tidal energy into electricity. Significant contributions to this field include research by Khan et al. [119], who conducted a comprehensive review of hydrokinetic energy conversion systems, comparing horizontal and vertical axis turbines for river and tidal applications. In the same manner, topic 1 explores the design and implementation of advanced water control devices featuring interconnected systems to manage flow and storage in tidal energy applications. These devices are essential for optimizing energy generation and ensuring the stable operation of tidal energy systems by precisely controlling water movement and storage. Notable research in this area includes studies by Singh and Zaheeruddin[120], who investigated the enhancement of frequency regulation using virtual inertia from capacitive energy storage systems, and by Zaheeruddin and Singh [121], who explored load frequency regulation using fractional fuzzy-based PID droop controllers in tidal turbine power plants.

In a similar vein, topic 2 focuses on mechanical assemblies that incorporate rotating components critical for energy transmission and the operation of tidal energy devices. The emphasis is on improving the efficiency and reliability of these assemblies, which are vital for converting kinetic energy into mechanical and electrical energy in tidal energy systems. A significant study by Payne, Stallard, and Martinez [122] details the design and manufacture of a bed-supported tidal turbine model, highlighting advancements in blade and shaft load measurement in turbulent flow and waves, underscoring the importance of reliable mechanical assemblies in tidal energy conversion. Extending this discussion, topic 3 examines tidal energy conversion systems that utilize floating platforms equipped with a variety of mechanical and buoyancy-driven mechanisms for generating electricity. These platforms are designed to harness the power of tidal movements, offering flexibility and efficiency in energy production, especially in offshore and deep-water environments. The work of Kim et al. [123] on the development of a floating-bridge type small tidal current turbine for energy-independent islands in Korea highlights the potential of such systems in regions with limited space. Their research underscores the importance of blade design in optimizing turbine performance, particularly in small-scale installations. Additionally, Sanchez et al. [124] conducted a comparative impact assessment of floating versus bottom-fixed tidal stream turbines, revealing that while both types have similar impacts on general estuarine circulation, significant differences exist in their local effects. Further exploration by Sanchez et al. [125] into the performance of these turbines in a tidal stream project illustrates the importance of device selection, showing that floating turbines may offer advantages in certain environments due to vertical variations in flow velocity.

Topic 4 focuses on tidal energy generation technologies that employ buoyant modules, pistons, and reservoirs to produce electricity efficiently. These systems leverage the natural buoyancy of floating modules and the mechanical action of pistons to drive energy generation processes, optimizing the capture and conversion of tidal energy. Building on these concepts, topic 5 focuses on the development of advanced turbine devices that integrate magnets, blades, and rotating shafts to generate energy from tidal currents. Innovations in this area aim to enhance the design and performance of these turbines, making them more effective at capturing tidal energy and converting it into usable electrical power. A key contribution in this field is the work by McGilton et al. [126], which reviews magnetic gear technologies and their applications in marine energy, highlighting their potential to improve turbine efficiency and reliability in tidal energy systems. Additionally, Ibrahim and Legaz [127] have assessed the hydrokinetic power potential in Spanish coastal areas using a novel turbine design, the fin-ring turbine. Their study presents promising results, demonstrating the turbine's superiority in lower currents and its applicability in different marine environments.

Likewise, topic 6 focuses on optimizing tidal energy power generation by employing advanced modeling techniques and detailed parameter analysis. Researchers in this area work to understand and refine the various factors that influence the performance of tidal energy systems, aiming to maximize energy output and enhance overall efficiency. Notable contributions include Zhou et al.'s analysis of the double-elastic-constrained flapping hydrofoil for tidal current energy extraction [128], and González-Gorbeña et al.'s work on optimizing the layout of tidal energy converter arrays, considering geometric, economic, and environmental constraints [129].

4.2.5. Similarity between Topic

To further examine the relationships among the topics identified by BERTopic, we calculated the similarity between topics using cosine similarity, a well-established metric for assessing the degree of similarity between two non-zero vectors. By applying this method to the topic embeddings generated through both c-TF-IDF and other embedding techniques, we constructed a similarity matrix that quantifies how closely related different topics are within the wave and tidal energy domains. Cosine similarity is calculated using the following formula [130]:

$$\text{similarity} = \cos(\phi) = \frac{A.B}{|\text{A}|\;|B|} \quad (3)$$

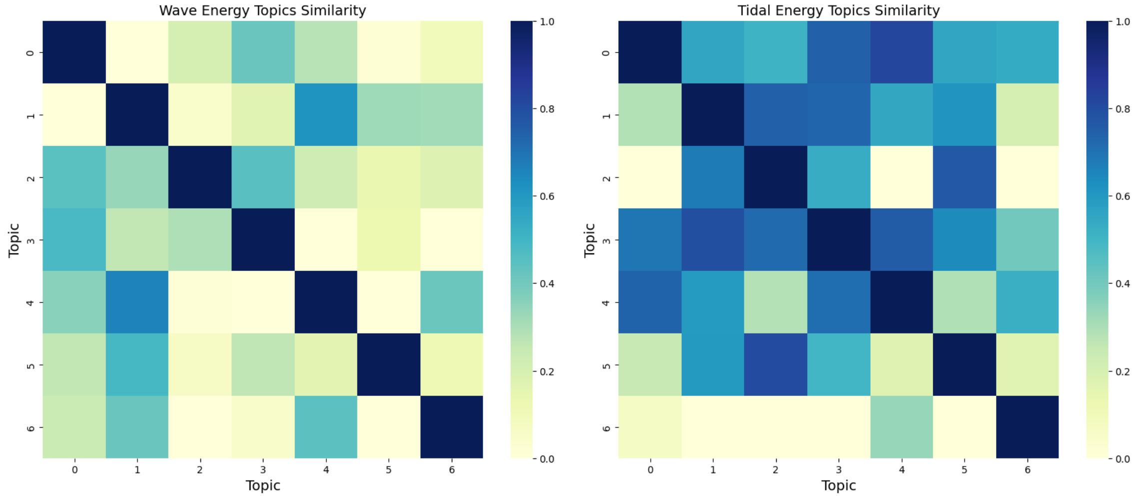
Where A and B are the topic embedding vectors, $A{\cdot}B$ represents the dot product of these vectors, and $|A|$and$|B|$ denote the magnitudes of the vectors. The cosine similarity value ranges from -1 to 1, where 1 indicates identical topics, 0 indicates orthogonality (no similarity), and -1 indicates complete dissimilarity. The resulting similarity matrix serves as a robust tool for understanding the thematic relationships between topics. It reveals clusters of topics that share significant conceptual overlaps or are closely related in their technological focus. This analysis is crucial for identifying synergies or potential redundancies in research efforts within the field.

To better interpret these relationships, we visualized the similarity matrix as a heatmap. This heatmap provides an intuitive representation of topic similarities, where darker shades indicate higher similarity scores, thereby making it easier to identify which topics are most closely related. Such visualizations are instrumental in drawing insights from complex data, facilitating a deeper understanding of the underlying patterns within the technological landscape.

The heatmap can be generated by applying the cosine similarity calculation to the topic embeddings, followed by visualization of the results in a heatmap format. This method offers an efficient and effective way to explore and interpret the relationships between topics, contributing to a more comprehensive analysis of the research and innovation trends in wave and tidal energy.

The similarity matrix is visualized in Figure 12. These heatmaps provide intuitive visual representations of the topic similarities, with darker shades indicating higher similarity scores. This makes it easier to identify which topics are most closely related, thereby facilitating the exploration of synergies, overlaps, or gaps within the respective domains.

The topics identified in wave energy patents reveal key similarities. Topic 1 and topic 4 are closely related, both focusing on wave energy conversion using floating structures, with topic 1 emphasizing anchored systems and topic 4 highlighting piezoelectric converters. Topic 0, topic 2, and topic 3 share similarities in utilizing mechanical components like shafts, floats, and hydraulic systems for energy conversion, differing mainly in their specific mechanisms. Lastly, topic 4 and topic 6 both focus on optimizing energy extraction, with topic 4 involving floating bodies and topic 6 highlighting advanced PTO control systems. In the analysis of tidal energy patents, topic 6 stands out as the least similar to the others, focusing primarily on modeling and parameter analysis for optimizing power generation, rather than specific mechanical or structural innovations. However, similarities exist among other topics.



(a) (b)

Figure 12. Similarity matrix between: (a) Wave energy topics; (b) Tidal energy topics.

4.3. Limitations and Future Directions

While this study provides valuable insights into the patent landscape and technological advancements in wave and tidal energy conversion, it is not without its limitations. One of the primary limitations is the reliance on patent data as a sole indicator of innovation. Patent filings, while indicative of technological progress, do not always equate to actual deployment or practical application of these technologies.

Furthermore, the probabilistic nature of the topic modeling methodology used in this study means that the categorization of technologies might not perfectly align with all established classifications in the field. This could result in some oversights or generalizations in how the technologies are grouped.

Another limitation is the potential lag between patent filings and their subsequent publication, which could affect the accuracy of recent trends observed in the data. The study also does not account for the quality or commercial success of the patents analyzed, which can vary significantly and influence the overall impact of the innovations.

Looking ahead, future research should consider integrating additional data sources, such as industry reports, academic publications, and deployment statistics, to provide a more holistic view of the state of these technologies. Comparative studies that examine the relationship between patent activity, scientific advancements, and real-world implementation would be particularly valuable in bridging this gap. Additionally, future work could explore the socio-economic and regulatory factors

 doi:10.20944/preprints202409.0921.v1

that influence patent activity and technology deployment, offering deeper insights into the barriers and drivers of innovation in this critical field.

By addressing these limitations and expanding the scope of analysis, future studies can contribute to a more comprehensive understanding of the innovation landscape in ocean energy conversion, ultimately supporting efforts to optimize and fully exploit this renewable energy resource.

5. Conclusions

This study has provided a comprehensive patent analysis of the technological landscape within wave and tidal energy sectors, utilizing advanced topic modeling techniques, BERTopic in our study, and further refining the results with Large Language Models (LLMs). By employing a dual approach, we conducted a descriptive analysis to explore patent publication trends, technology lifecycle stages, patent activity by country, top assignees, and IPC classifications, providing a detailed overview of the sector's growth and key players. Additionally, through the application of topic modeling, we identified seven distinct clusters for both wave energy and tidal energy. This categorization diverges in some respects from the conventional classifications found in existing literature, such as those presented for wave energy technologies [131-134], tidal energy technologies [24, 132, 135, 136], and wave-tidal conversion technologies [137]. These categories are based on expert opinions; however, we utilized a methodology driven by text data analysis. Despite the differences between these approaches, the topic-based categorization offers valuable insights that complement traditional methods, contributing to a more comprehensive understanding needed to fully exploit and optimize ocean energy conversion infrastructure. In this article, we examined these topics through a data science lens, providing a unique perspective on the innovation landscape within these sectors.

The findings from our analysis revealed significant advancements in wave energy conversion, including innovations in oscillating water columns, anchored beams, and pressure-based chambers, as well as in tidal energy systems, such as novel turbine designs and advanced control mechanisms. These technological developments are crucial for overcoming the technical challenges associated with ocean energy infrastructure, including corrosion resistance, environmental impact, and grid integration.

This study has significantly enhanced our understanding of the current state of ocean energy conversion technologies and highlighted the critical importance of ongoing research in this field. The insights gained underscore the necessity of continued innovation and strategic deployment to fully exploit the ocean's renewable energy potential and advance towards a more sustainable energy future. Future research should build on these findings by exploring the interplay between technological advancements, policy frameworks, and real-world deployment, ultimately supporting the development of resilient and efficient ocean energy infrastructures.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: Conceptualization, M.P., A.K., M.J, and M.H.R; methodology, M.P, A.K, M.J, M.H.R; software, M.P., A.K.; validation, K.R.; investigation, K.R.; data curation, A.K.; writing—original draft preparation, M.P.; writing—review and editing, M.P., A.K., M.J., K.R., and M.H.R; visualization, A.K.; supervision, M.J.; project administration, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data will be made available upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

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The following search query was designed and utilized in this study to retrieve wave energy patents, specifying topics to include (TS) or exclude (NOT TS):

TS = (("wave") AND ("attenuator" OR "ATT" OR "point absorber" OR "PA" OR "oscillating wave surge converters" OR "OWSC" OR "oscillating surge wave energy converter " OR "OSWEC" OR "oscillating water column*" OR "OWC" OR "overtopping" OR "rotating mass" OR "RM"OR "terminator*")) NOT TS=("optic*" OR "optical" OR "seismic wave*" OR "freight" OR "building" OR "wind power" OR "wind energy" OR "wind power generation" OR "wind energy generation" OR "battery energy" OR "diesel generator" OR "PV array" OR "wind photovoltaic" OR "Homer" OR "Homer software" OR "reactive power" OR "PV power" OR "PV power plant" OR "wind generator" OR "inverter wind capacity" OR "solar" OR "solar radiation" OR "MPPT" OR "maximum power point" OR "MPPT algorithm" OR "biogas" OR "biogas generator" OR "hydrogen" OR "hydrogen tank" OR "rural electrification" OR "PHEV" OR "PV wind" OR "COE" OR "photo voltaic" OR "solar PV" OR "solar photovoltaic" OR "diesel" OR "lead acid" OR "lead acid battery" OR "photovoltaic system" OR "solar photovoltaic system" OR "PV panel" OR "photovoltaic panel" OR "PV generator" OR "PV plant" OR "PV system" OR "electric vehicle" OR "hydrogen system" OR "hydrogen storage" OR "diesel fuel" OR "biomass" OR "solar field" OR "CCHP" OR "CCHP system" OR "CHP" OR "CHP system" OR "chiller" OR "cycle power plant" OR "boiler" OR "gasoline" OR "base station" OR "thermo economic" OR "combined cycle" OR "gasification" OR "gas turbine" OR "cycle efficiency" OR "organic Rankine cycle" OR "Rankine cycle" OR "combustion chamber" OR "SOFC" OR "SOFC system" OR "carbonate" OR "carbonate fuel cell" OR "heat recovery" OR "solid oxide fuel" OR "cell" OR "solid oxide" OR "fuel cell" OR "biofuel" OR "feedstock" OR "MCFC" OR "exergy" OR "exergy analysis" OR "thermodynamic" OR "thermodynamic analysis" OR "syngas" OR "combustion" "natural gas" OR "LNG" OR "cooling" OR "Compressor" OR "desalination" OR "Solar thermal" OR "bioenergy" OR "wood" OR "PV technology" OR "nuclear power" OR "nuclear energy" OR "oxygen" OR "Thermal energy" OR "signal" OR "mass flow rate" OR "recirculation" OR "heat sink" OR "heat pipe" OR "transmitter" OR "automobile" OR "quantum" OR "radio frequency" OR "IoT device" OR "wireless device" OR "UWSNs" OR "pyrolysis" OR "closed form expression" OR "wireless informant" OR "information transmission" OR "dissociation" OR "natural gas hydrate" OR "methane gas hydrate" OR "gas hydrate" OR "hydrate saturation" OR "permafrost" OR "ionic polymer" OR "ionic polymer metal")

In a similar manner, the following search query was created and applied in this study to retrieve tidal energy patents, specifying the topics to include (TS) or exclude (NOT TS):

TS = ("tid* energ*") NOT TS=("optic*" OR "optical" OR "seismic wave*" OR "freight" OR "building" OR "wind power" OR "wind energy" OR "wind power generation" OR "wind energy generation" OR "battery energy" OR "diesel generator" OR "PV array" OR "wind photovoltaic" OR "Homer" OR "Homer software" OR "reactive power" OR "PV power" OR "PV power plant" OR "wind generator" OR "inverter wind capacity" OR "solar" OR "solar radiation" OR "MPPT" OR "maximum power point" OR "MPPT algorithm" OR "biogas" OR "biogas generator" OR "hydrogen" OR "hydrogen tank" OR "rural electrification" OR "PHEV" OR "PV wind" OR "COE" OR "photo voltaic" OR "solar PV" OR "solar photovoltaic" OR "diesel" OR "lead acid" OR "lead acid battery" OR "photovoltaic system" OR "solar photovoltaic system" OR "PV panel" OR "photovoltaic panel" OR "PV generator" OR "PV plant" OR "PV system" OR "electric vehicle" OR "hydrogen system" OR "hydrogen storage" OR "diesel fuel" OR "biomass" OR "solar field" OR "CCHP" OR "CCHP system" OR "CHP" OR "CHP system" OR "chiller" OR "cycle power plant" OR "boiler" OR "gasoline" OR "base station" OR "thermo economic" OR "combined cycle" OR "gasification" OR "gas turbine" OR "cycle efficiency" OR "organic Rankine cycle" OR "Rankine cycle" OR "combustion chamber" OR "SOFC" OR "SOFC system" OR "carbonate" OR "carbonate fuel cell" OR "heat recovery" OR "solid oxide fuel" OR "cell" OR "solid oxide" OR "fuel cell" OR "biofuel" OR "feedstock" OR "MCFC" OR "exergy" OR "exergy analysis" OR "thermodynamic" OR "thermodynamic analysis" OR "syngas" OR "combustion" "natural gas" OR "LNG" OR "cooling" OR "Compressor" OR "desalination" OR "Solar thermal" OR "bioenergy" OR "wood" OR "PV technology" OR "nuclear power" OR "nuclear energy" OR "oxygen" OR "Thermal energy" OR "signal" OR "mass flow rate" OR "recirculation" OR "heat sink" OR "heat pipe" OR "transmitter" OR "automobile" OR "quantum" OR "radio frequency" OR "IoT device" OR "wireless device" OR "UWSNs" OR "pyrolysis" OR "closed form expression" OR "wireless informant" OR "information transmission" OR "dissociation" OR "natural gas hydrate" OR "methane gas hydrate" OR "gas hydrate" OR "hydrate saturation" OR "permafrost" OR "ionic polymer" OR "ionic polymer metal")

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