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Review

State-of-the-Art in the Use of Renewable Energy Sources on the Example of Wind, Wave Energy, Tidal Energy, and Energy Harvesting: A Review from 2015 to 2024

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Abstract: Today, there is a marked increase in interest in the share of renewable energy sources in the energy mix, which benefits the environment. This also applies to the energy of sea (wave) current, as, without a doubt, the offshore area is becoming one of the leading areas of renewable energy, which translates into changes in energy production. This can be exemplified by the latest research in the context of theory, design, modeling, as well as application, control, and monitoring of wave turbines to enhance their performance. This article reviews the research in this context, systematizes information, identifies literature gaps, and presents future directions in this area. For this purpose, 3240 English-language publications from 2015 to 2024 were identified in the Scopus database. The data are analyzed according to the selected research domains. Some of them are review or conceptual in nature, while others are empirical in nature (experimental attempts and case studies). From this point of view, it becomes possible not only to systematize the state-of-the-art but also to identify future research prospects.

Keywords: energy safety; energy harvesting; wind energy; wave energy; ocean energy; tidal energy; offshore and floating wind turbines; wave energy converters; energy storage systems; energy efficiency; assessment and analyses

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1. Introduction

In recent years, the need to combat climate change and ensure energy security on a global scale in the broadest sense has been noted. As a result, the efforts of many research centers are directed at increasing interest in the use of renewable energy sources, including the design and implementation of various types of ever newer and more efficient solutions. In this context, on a global scale, further changes in the structure of electricity produced can be expected as a result of the rapid increase in the amount of electricity generated from renewable sources relative to that generated by conventional sources, influenced, among other things, by ongoing government programs, including subsidies for investment in renewable energy technologies for the public sector [1–5]. In this regard, the wind and wave energy capture and conversion sector and the use of offshore and floating wind turbines, among others, play an important role, making it possible to transfer many investments from terrestrial areas to aquatic areas, which is the subject of various studies conducted in many academic and scientific centers around the world [6–10]. Certainly, a factor in favor of this is the stability of the energy supply, which becomes possible through the predictability of tidal, ocean, and wind energy [11]. Benefits in favor of the use of renewable sources are the inexhaustibility of the energy produced with them as well as their environmentally friendly nature (it is clean energy using wave and tidal/ocean energy and wind to produce electricity). Therefore, it is worth noting that offshore wave energy and tidal energy are noted for their positive environmental and human impact. Undoubted benefits arise, among other things, from the minimization of the CO_2 footprint as a result of not burning traditional fuels, such as coal, oil, and gas. Furthermore, the sector can serve as a complementary (backup) area to ensure energy safety in certain regions in the event of undesirable events, including natural disasters on land. In addition, the use of solutions installed on the seas or oceans has a positive impact on improving the aesthetics of terrestrial landscapes—free of wind turbines.

In practice, regardless of the energy source used (wind or wave), the challenge is to find a suitable location to ensure that the turbines function according to the characteristics of the wind or wave (maximum power point), perform the required expertise, and then perform the designs and implementation of technical solutions taking into account the applicable legal standards. Not without significance are the capacity of the grid and its continuous, increasingly intelligent monitoring, both of which translate into efficient distribution of power in the grid. Unsurprisingly, due to the location of the equipment and the benefits of using the marine or ocean area, it is becoming one of the key areas of renewable energy production, which, in turn, is reflected in the observed trends of change in the electricity generation market.

This review paper aims to provide a comprehensive review of research on the state-of-the-art in the use of renewable energy sources based on offshore wave energy and tidal energy and to identify possible research gaps and future research directions. In particular, this article focuses on the state-of-the-art in the use of renewable energy sources using the example of offshore wave energy and tidal energy based on publications from the last decade, i.e., from 2015 to 2024. Additionally, due to the review topic of this article, an analysis of optimal control and wave energy converters was performed as well as a review of the latest developments and scientific achievements in theory and practice, including the design, modeling, and practical use of offshore and floating wind turbines (in this regard, publications on control and monitoring of the operating condition, including, among others, energy storage systems, were analyzed in order to increase the efficiency of their operation). There were a total of 3240 results indexed in the Scopus database covering the last 10 years. It should be noted that there has been a significant increase in the number of publications during this period, which indicates the interest of researchers in this topic.

2. Materials and Methods

2.1. The Categories Used in This Study

To identify articles from the Scopus database on specific types of energy, an approach was used that will be described further, including the elements of system analysis. The selection of relevant categories (domains) was preceded by an extensive search by combining some specific search words into the title, abstract, and keywords of the publication according to the following scheme:

TITLE-ABS-KEY (((offshore AND wave AND energy) OR (tidal AND energy))AND ((energy AND converter) OR (wave AND turbine))) AND PUBYEAR > 2014 AND PUBYEAR < 2025

As previously written, this resulted in 3240 records, whose publication data were imported from the Scopus database into a CSV (Comma-Separated Values) file and, additionally, into a text file. Consequently, the results can be viewed in terms of the information contained therein. This file has the following columns: "Authors", "Author full names", "Author(s) ID", "Title", "Year", "Source title", "Cited by", "DOI", "Link", "Abstract", "Author Keywords", "Index Keywords", "Document Type", "Publication Stage", "Open Access". To take into account the directions of interest of contemporary researchers, it was decided to select only those documents with a citation count of at least seven. The publications on energy efficiency and innovation, which translate into the development of technologies, were analyzed. In turn, those publications that were directly related to economics (economic analysis) were excluded from the analyses. As a result, 105 results were obtained and further reviewed. Each publication was reviewed for belonging to different categories. Documents that did not meet the specified criteria were rejected. Sometimes, it was difficult to assign a particular publication to a particular group of categories (it was necessary to read the entire article), or the publication belonged, by virtue of the subject matter undertaken, to several categories, which can be seen in the summary tables presented later in this manuscript. This is because, for example, information on the research methodology used did not always appear in the data analyzed from the source file. In turn, some of the documents could be assigned to multiple categories, as the topics addressed in them involved several categories. The data analysis process is illustrated in Figure 1.

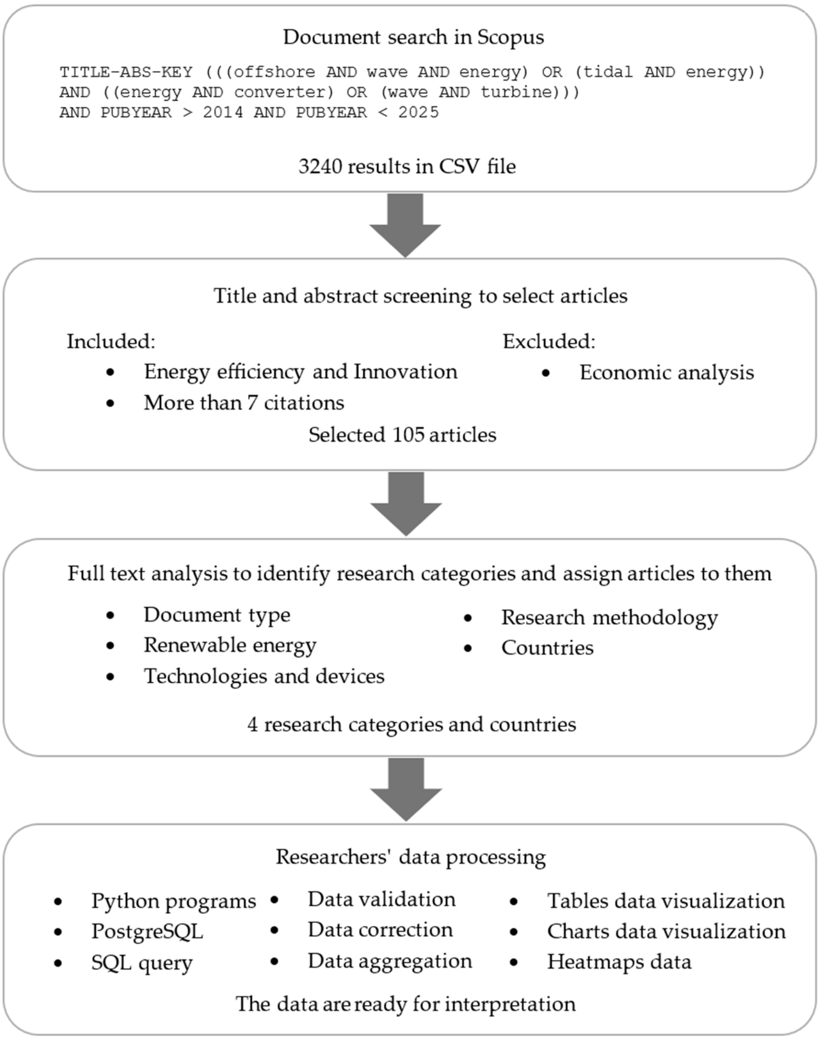

Figure 1. Data acquisition and preparation workflow.

All 105 results were analyzed for assignment to a specific document type (publication), subject category, research methodology, and country. This made it possible to show the directions and prospects of technology development with innovation and energy efficiency, taking into account the most cited publications. Partial data to identify the publication (its title, keywords, number of citations, and identifier) were recorded using the open-source relational database management system PostgreSQL (Postgre Structured Query Language). This paper includes tabular summaries to facilitate the document analysis process. An added value is the quantitative presentation of frequencies as well as cross-tables and thematic analysis of publications for each of the separated fields. The interrelationships of the systems are included in Figure 2.

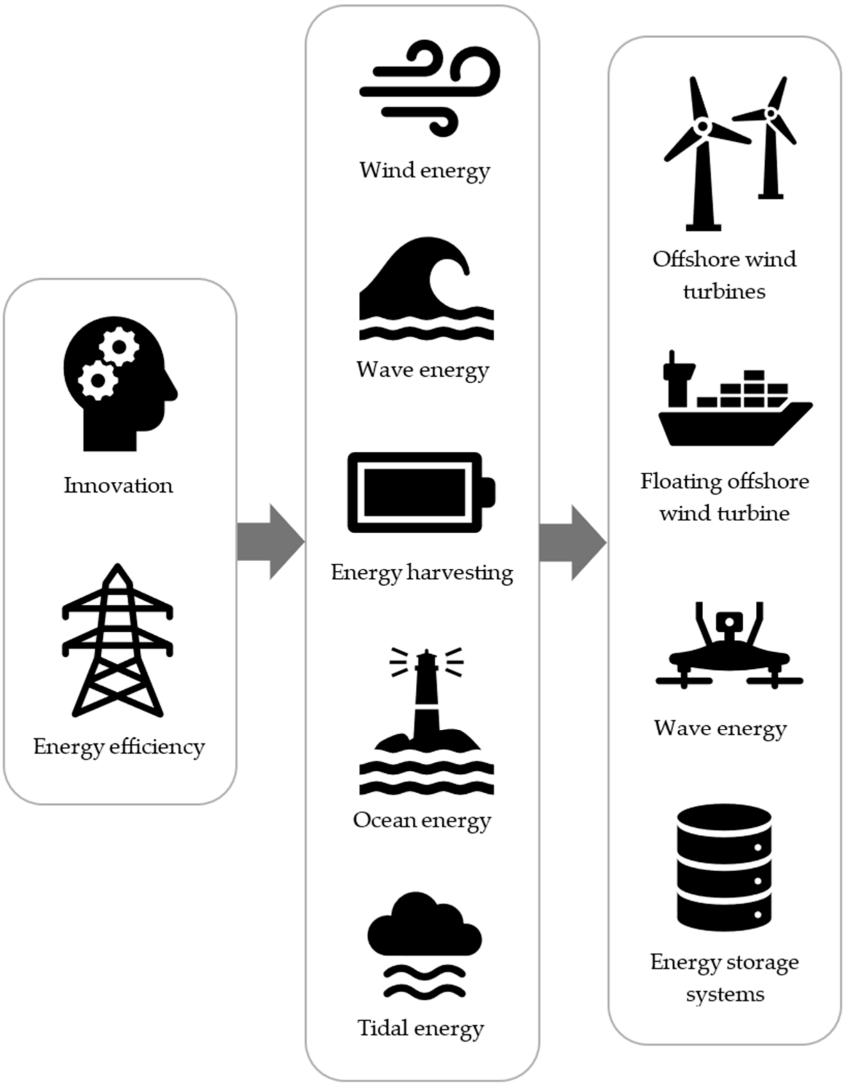

Figure 2. The interconnectedness of the systems.

In practice, the expectations of contemporary science are focused on energy efficiency and innovations, which translates into a growing interest in renewable energy sources, including wind, wave, ocean, tidal, and energy harvesting. This contributes to the development of technologies and equipment, including offshore wind turbines, floating offshore wind turbines, wave energy converters, and energy storage systems. The analysis carried out made it possible to assign publications to specific categories. The renewable energy category in this study does not contain strictly separate categories but should be viewed more as broader keywords. This includes the technologies and devices category. Within this group, the categories are not strictly separate. Offshore wind turbines can encompass both floating offshore wind turbines and fixed offshore wind turbines. Therefore, the authors included the broader category of offshore wind turbines and, within it, distinguished floating offshore wind turbines. This approach reflects the reality that many articles discuss both types within the same study. As can be seen in the table later in this article, the summed numbers in these categories exceed the total number of articles, indicating the overlap and integration of these subdomains in the literature. The results obtained were visualized using bar charts.

It should be noted that, for the purpose of this article, a classification was distinguished in which documents were assigned to one of three types of publications (document type). The first was conference paper, the second was journal article (paper), and the third and final was a subcategory other that included all other publications. In practice, this type included books or chapters in books, conference reviews, as well as reviews of scientific works, letters, editorials, erratas, published notes, short surveys, and documents containing various data from articles (data papers).

Subsequently, all articles found in the Scopus database were analyzed for division into two main broad domains (i.e., main categories) related to (1) renewable energy as well as (2) technologies and devices. Within the first domain, i.e., renewable energy, five subdomains were specified, understood as areas (subcategories): wind energy, wave energy, energy harvesting, ocean energy, and tidal energy. The work that belonged to the renewable energy domain concerned, in particular, (1) wind energy, including offshore wind turbines for its generation and design work; (2) wave energy, including conversion of wave energy into electricity, performance analyses, optimization and improvement of technical solutions, and cooperation of energy systems with other energy generation and distribution systems; (3) energy harvesting from waves and wind and improvement of efficiency of applied energy harvesting techniques; (4) ocean energy, including analyses of the application of various technologies for the use of ocean energy, among others, e.g., ocean thermal energy conversion; and (5) tidal energy, including extensive research on tidal turbines, their efficiency, as well as their environmental impact. In practice, the ocean energy category includes both wave energy and tidal energy. Often, articles categorized under ocean energy discuss aspects of both wave energy and tidal energy.

Within the second domain, i.e., technologies and devices, four areas of research interest were specified, understood as subdomains, in terms of which state-of-the-art was analyzed: offshore wind turbines, floating offshore wind turbines, wave energy converters, and energy storage systems. The documents that belonged to the technologies and devices domain dealt specifically with (1) offshore wind turbines, including designs, technical implementations, and their optimization; (2) floating offshore wind turbines, including refinement of applied solutions and integration of energy systems with other power generation and distribution systems; (3) wave energy converters, in particular analyses of the performance of different types of converters and research aimed at improving their efficiency; and (4) energy storage systems—this subcategory covered aspects of energy storage, including issues of compatibility of renewable energy systems.

In addition, in the analysis of documents from the Scopus database, attention was paid to the research methodology used. In this regard, depending on the research method applied, each publication was assigned to the appropriate subcategory: (1) experimental (laboratory, field); (2) literature analysis, including reviews of the literature and legal acts, semiotic analysis of books, chapters in books, papers, etc.; (3) case study (observation, field reports); and (4) conceptual (research aimed at developing new concepts or theories). In doing so, it should be noted that, depending on the subject matter covered and the research methods applied, each document was analyzed for belonging to more than one category and subcategory. In practice, this means that a document can be classified in more than one research domain. Similarly, if more than one research method was applied to a given document, several research methods were assigned to it, as exemplified by the summaries presented in the Section 3.

2.2. State-of-the-Art: A Review from 2015 to 2024

As previously mentioned, the presented review is primarily devoted to renewable energy as well as technologies and devices as the main domains (i.e., main categories). Within these domains, five and four subdomains were specified, respectively. In this section, all 105 articles from the Scopus database that meet the criteria described in the previous section are analyzed in terms of their covered topics. However, since many of these articles address multiple issues simultaneously (categories are not mutually exclusive), to avoid redundancy and unnecessary manuscript lengthening due to repeated references to the same articles analyzing different subcategories, each article is qualitatively analyzed in this section in relation to its alignment with the overall topic of this paper. Comprehensive summaries in the form of tables illustrating the quantitative summary of publications in 2015–2019 and 2020–2024 across all categories, the number of publications in 2015–2019 and 2020–2024 in different countries, and publications on renewable energy across other subcategories are presented in the Results section. Additionally, this section will include figures depicting the number of publications in 2015–2019 and 2020–2024 by document type; the number of publications in 2015–2019 and 2020–2024 within the first thematic category, i.e., renewable energy, divided into subcategories; the number of publications in 2015–2019 and 2020–2024 within the second thematic category, i.e., technologies and devices, divided into subcategories; the number of publications in 2015–2019 and 2020–2024 within the research methodology category, divided into subcategories; and the number of publications in 2015–2019 and 2020–2024 by country. This approach ensures that the articles undergo both qualitative and quantitative analysis. Additionally, a synthetic discussion and a critical analysis of the state-of-the-art research will complement the review. This aims to enhance the depth of the manuscript and provide a more comprehensive understanding of the current advancements and challenges in the field, which will be included in the next subsection.

Analyzing the state-of-the-art, an important and desirable issue related to the generation of renewable energy in the area of seas and oceans is to maximize its generation while reducing the movement of the platform on the water. Very good results are achieved by using different types of renewable energy systems: integrated floating wind, wave, and tidal energy systems [11,12]. Thanks to such synergy, it is possible to achieve a reduction in the tilt movements of the turbine, which translates into an increase in the amount of energy extracted. An undoubted advantage is the low failure rate of technical solutions. An example of the interaction of multiple renewable energy systems is the wind–wave hybrid system [12–15]. In practice, the reduction in unwanted oscillations in floating wind turbines is the subject of numerous studies [16–21]. The combination of wind energy and wave energy is presented in [22]. In turn, future trends and prospects for technology development are described, among others, in [19]. Many researchers have highlighted the problematic issue of reducing the efficiency of wind energy systems as a result of strong wind and wave power as well as the optimization of techniques to harness wind and wave power, for example, the optimization of wind turbines using aerodynamic thrust as well as mechanisms to control the position of the turbine to mitigate the wake effect, which can help improve the efficiency of the equipment, as described in [23–25]. In turn, the paper [26] presents an analytical model for analyzing the dynamic response of a combined wind turbine–damper system using the Simulink/Matlab environment.

In practice, wind speeds at sea are generally higher than on land and more uniform. A useful functionality of wind turbines is the ability to supply electricity to coastal areas as well as the lack of negative impact on the landscape. In addition to the advantages of their use, there are also disadvantages, including extreme loads during operation, which have a significant impact on the safety of system operation. In practice, all wind, wave, and seismic loads negatively affect the operation of offshore wind turbines, resulting in their energy efficiency as well as an increased risk of fatigue damage [27,28]. A linear model of a wind turbine controller to dampen rotor speed fluctuations caused by wave forcing is described in a paper on offshore wind and wave energy conversion [29]. The advantage of such a solution is to ensure a stable power supply to consumers in the coastal zone or on-island areas. Article [30] proposes a solution to the so-called average conditional exceedance rate method to minimize potential mechanical damage to the wind turbine. According to the concept presented in the article [31], the introduction of additional wave energy converters can increase energy production. As the authors write, much more energy can be obtained in this way than from a single floating wind turbine. The advantages of such a combination are less susceptibility to harmful weather conditions, lower costs, easier installation, and independent water depth inverter–turbine connections [32]. In general, wind and wave energy conversion is the subject of many works that describe generator optimization algorithms, such as [33–35]. Simultaneous generation of electricity from wind and wave energy can be carried out using a dedicated wave energy converter based on an oscillating column of water, which can affect sustainable energy production [36]. Some works, such as [37], describe an integrated energy conversion system through the use of a linear-rotating permanent magnet generator with a double stator. A promising device that, through the use of moored aerial systems, allows for one to harvest energy from wind blowing at heights inaccessible to traditional wind turbines is the design described in [38].

One solution to increase the use of wave energy as well as other renewable energy sources is to integrate an offshore wind turbine and a wave energy converter to produce potential energy [39]. The results presented in this work provide useful information in terms of optimizing integrated offshore wind–wave energy systems. The added value is the quantification of the benefits of optimized technical solutions. Since offshore wind turbines are systems with complex and highly nonlinear dynamics that are subjected to continuous loads, their control is an issue [17,40]. Today, smart control techniques are popular. To use renewable energy in the most optimal way, hybrid DC/AC microgrids (MG) are being modeled and designed for the power sector, which helps reduce the number of energy conversions [41]. The use of fuzzy logic is helping to improve the efficiency of energy harvesting [42–45]. Some of the work deals with the design of integrated wind–wave power generation platforms using numerical simulations. For example, the work [46] analyzed the effects of various factors on the hydrodynamic characteristics as well as the efficiency of wave energy conversion for an integrated energy platform. In the work [47], a torque compensation control strategy is included that takes into account the mitigation of large fluctuations in output power (due to the increase in response speed) as well as the use of a fuzzy inference system and optimization of the turbine power factor curve. On the other hand, an order reduction methodology for efficient estimation of the steady-state response of an offshore wind turbine is described in [48]. Control schemes to increase the efficiency of energy harvesting and the results of tests carried out in various scenarios can be found in [49,50]. Some works deal with the upgrading of available solutions for the construction of small wind turbines that can be applied locally with an energy storage system [51]. It turns out that offshore energy can make a significant contribution to the development of energy production and increase the reliability of mining complexes [52]. Structural works include procedures for determining the efficiency of pile driving for wind turbine foundations [53]. New trends and development prospects for renewable energy-powered desalination systems are included in [54,55].

In many publications, the authors highlight the need for alternative energy sources due to the worsening problem of global warming and the energy crisis [56,57]. The rapid consumption of conventional energy sources is also a factor in favor of this [58]. The energy generated from renewable resources (including wind and tidal power) is environmentally clean, which results in lower carbon emissions [59]. This is an issue of particular concern in Gulf countries, which are on the list of the world's largest carbon emitters [60]. Ultimately, the environmental impact can be further reduced by using technological improvements as well as increasing the efficiency and reliability of the clean energy solutions employed [61,62]. In practice, the subject of interest for contemporary researchers is the energy ecosystem in the context of specific applications [63]. As is well known, hydrogen is the cleanest propellant, whose combustion produces water. Hydrogen used in a fuel cell is characterized by high combustion efficiency, which translates into a lack of vibration and quiet operation of equipment. Researchers point out that hydrogen can be produced from solar energy, wind energy, coastal ocean energy, and bioenergy through chemical technology and water electrolysis using renewable energy sources [63,64].

In the case of wave energy, contemporary work includes oscillating columns (single chamber and multichamber), taking into account their advantages, service life, and performance (computer modeling is often used for this) [65], including the hydrodynamic characteristics of oscillating water column devices [66], multifunctional platforms [67], increasing energy production while reducing platform movements by combining various renewable energy systems [12], as well as energy harvesting system optimization techniques [68]. In recent years, modular solutions have become increasingly popular [60].

It should be noted that offshore renewable energy grids are currently the subject of much research [69,70]. Some works focus on articulated solutions [71], while others are conceptual and focus on optimization in terms of increasing the efficiency of energy harvesting [72–76], which is possible, among others, by negating the reactance of the system impedance. Engineering analyses often use numerical methods and employ Bayes' theorem (Bayesian optimization) [77]. Some designs are based on the use of triboelectric nanogenerators, which make it possible to acquire low-frequency and microamplitude wave energy, which is very difficult with traditional electromagnetic generators (the reason being the random and low-frequency nature of ocean waves) [78,79]. Many articles describe the latest developments in wave energy converter control [80–89]. In practice, the process of converting a renewable wave energy source into electrical energy plays an important role, which is reflected in the power capture performance of oscillating wave energy converters [90].

Undoubtedly, tidal energy is one of the potential sources of clean energy in both marine and ocean energy systems [91]. Contemporary developments related to ocean/tidal energy focus, among others, on the design and testing of ocean current turbines [92–95] as well as improving their operation [96]. Some of the work is simulation-based, such as [88,97]. The subject of research is also the analysis of future trends in the development of tidal current energy converters [98–100] or energy management systems [101]. The work related to tidal energy very often deals with hybrid solutions [102,103]. To automate and speed up the design process, a paper [104] proposes custom power converters based on design specifications, including solutions to control nonlinear loads (artificial intelligence can be useful [105]). On the other hand, work related to energy harvesting includes horizontal hydrodynamic power generation [106], design and development of horizontal marine current turbines [107], wave energy conversion [108,109], as well as optimization techniques [68,110] and integration of hybrid energy sources [63]. It should be noted that tidal and wave energy harvesting structures are currently the most advanced channels for ocean energy generation, with ocean energy devices in the early stages of development [111]. More work is expected in evaluations of applied technologies, the use of renewable energy, and the optimization of energy converters, including the application of artificial intelligence [112–116].

In conclusion, it is possible to see great potential and interest among researchers in the subject of renewable energy, with a particular focus on ocean energy and wave technologies, while at the same time, there is a need to continue research on energy storage and other less explored technologies used in the sector of renewable energy generated in the seas or oceans.

In the Section 3, quantitative summaries of the number of publications that meet the criteria are presented and described, allowing for us to see the prospective nature of the renewable energy sources analyzed, including harvesting as well as the directions of development of technologies and devices involving offshore wind turbines, floating offshore wind turbines, wave energy converters, and energy storage systems. In turn, the next subsection provides a technical discussion and critical analysis of the research on the state-of-the-art.

2.3. Technical Discussion and Critical Analysis

The analysis of the state-of-the-art in renewable energy technologies reveals several key trends and challenges. One significant trend is the increasing integration of multiple renewable energy systems, such as combined wind–wave hybrid systems, which aim to maximize energy generation while minimizing platform movements. This synergy not only enhances energy extraction but also reduces the failure rates of technical solutions. However, the optimization of these integrated systems remains a critical challenge, particularly in terms of mitigating the wake effect and improving the efficiency of energy converters [7,12,37,67].

Another notable trend is the development of advanced control strategies for offshore wind turbines and wave energy converters. Techniques such as aerodynamic thrust optimization and torque compensation control are being explored to enhance the stability and efficiency of these systems. Despite these advancements, the implementation of such control strategies in real-world scenarios is still in its nascent stages, requiring further research and validation [9,19,47,68,101].

The review also highlights the growing interest in modular solutions and the use of triboelectric nanogenerators for low-frequency wave energy harvesting. These innovations offer promising avenues for improving the efficiency and reliability of renewable energy systems. However, the scalability and long-term performance of these technologies need to be thoroughly investigated to ensure their viability for large-scale deployment [6,18,38,78,108].

In terms of research methodology, the predominance of conceptual and experimental approaches indicates that many solutions are still in the early stages of development. This underscores the need for more comprehensive case studies and literature analyses to evaluate the practical implementation and long-term impacts of these technologies. Additionally, the relatively low number of publications on energy storage systems suggests a critical gap in the research, highlighting the need for further exploration of efficient energy storage solutions to complement renewable energy generation [5,21,45,70,102].

Overall, while significant progress has been made in the field of renewable energy, several challenges and research gaps remain. Addressing these issues will require continued innovation, interdisciplinary collaboration, and substantial investment in research and development [1,4,40,71,111].

3. Results

Table 1 provides a summary covering the years of publication divided into two groups, 2015–2019 and 2020–2024, and the total number of publications for the given period. From a statistical point of view, when the *p*-values are significantly lower than 0.05, the null hypothesis can be rejected, which means that there are statistically significant differences between the distribution of the categories analyzed in the years 2015–2019 and 2020–2025, while otherwise, when the *p*-values are significantly higher than the assumed significance level, there is no basis to reject the null hypothesis, which means that no statistically significant differences are detected.

Table 1. Quantitative summary of publications in 2015–2019 and 2020–2024 in all categories.

Name	2015–2019	2020–2024	All Years	Share [%]	Chi-Square
Total	43	62	105	100.0	χ^2
Document type					
Conference paper	14	7	21	20.0	
Journal article	28	50	78	74.29	$\chi^2 = 8.03$ (df = 2, $p = 0.02$)
Other [a]	1	5	6	5.71	
Renewable energy [b]					
Wind energy	17	35	52	49.52	
Wave energy	30	36	66	62.86	
Energy harvesting	33	37	70	66.67	$\chi^2 = 3.43$ (df = 4, $p = 0.49$)
Ocean energy	42	48	90	85.71	
Tidal energy	17	19	36	34.29	
Technologies and devices [b]					
Offshore wind turbines	15	30	45	42.86	
Floating offshore wind turbines	9	24	33	31.43	$\chi^2 = 4.95$ (df = 3, $p = 0.18$)
Wave energy converters	28	30	58	55.24	
Energy storage systems	5	11	16	15.24	
Research methodology [c]					
Experiment	11	15	26	24.76	
Literature analysis	4	5	9	8.57	$\chi^2 = 0.49$ (df = 3, $p = 0.92$)
Case study	1	3	4	3.81	
Conceptual	27	39	66	62.86	

[a] Other document types are book, book chapter, review and conference review, letter, short survey, data paper, editorial, erratum, and note. [b] Each document analyzed can be classified into more than one research domain, such as renewable energy and technologies and devices, as well as subcategories (depending on its subject matter). [c] More than one research method can be applied in each analyzed document.

In Figure 3, based on the summary table, there are bar charts showing the number of documents of a certain type that had been published in two 5-year intervals (2015–2019 and 2020–2024), which is a total of ten years.

Based on Figure 3, it can be seen that the largest number of documents among the analyzed topics are scientific articles published in scientific journals as well as conference papers. Few publications in the field of renewable energy sources as well as technologies and devices accounted for the remaining publications, including books and chapters in books. It is worth noting that this trend is noticeable regardless of the analyzed time period of 5 years. In the period 2020–2024, there is an increased interest in the topic of offshore wave energy and tidal energy, which is exemplified primarily by the number of articles published in scientific journals. In 2020–2024, 50 papers were published versus 28 published papers in 2015–2019, which means almost a doubling of the number of publications over the last 5 years (an increase of 22 papers).

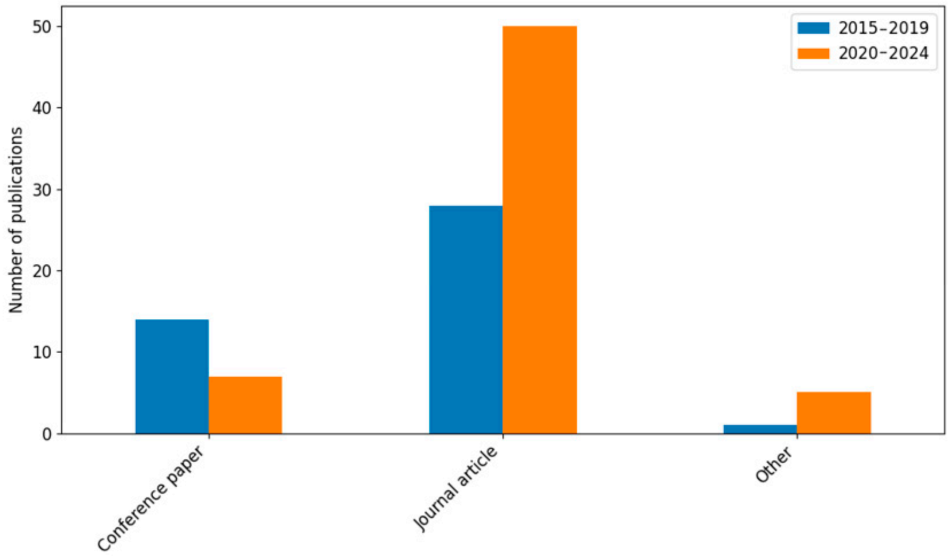

Figure 3. Number of publications in 2015–2019 and 2020–2024 in document type category.

The increased interest in the topic, especially considering the last five years, is also confirmed by the statistics in the form of bar charts in Figures 4 and 5, showing the number of publications in 2015–2019 and 2020–2024 that belong to the main thematic categories, i.e., renewable energy, as well as technologies and devices. In practice, it provides a quantitative analysis of frequency as well as a qualitative thematic analysis of publications in each of the identified fields by separate subcategories.

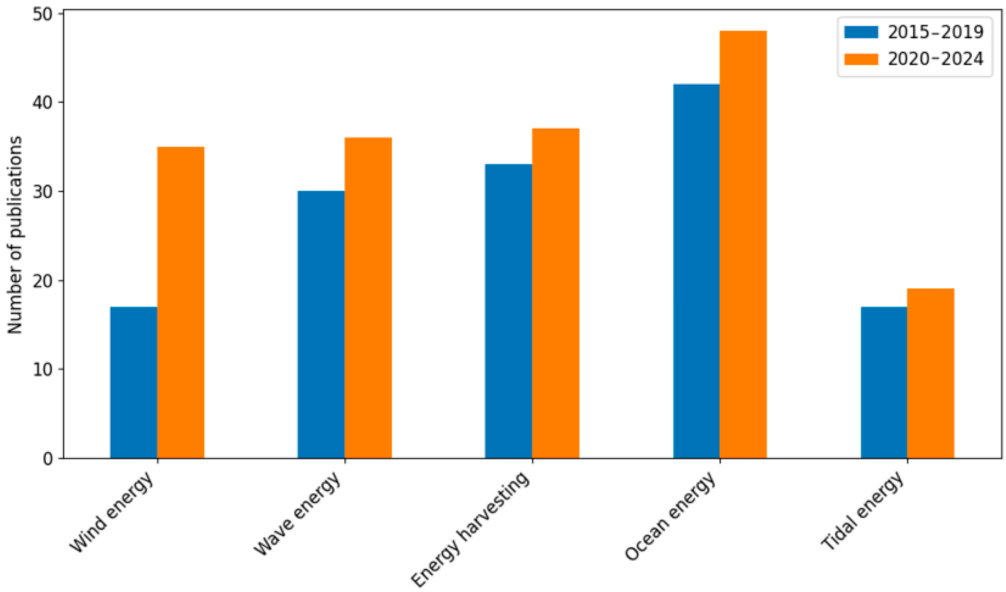

Figure 4. Number of publications in 2015–2019 and 2020–2024 that belong to the first thematic category, i.e., renewable energy, divided into subcategories.

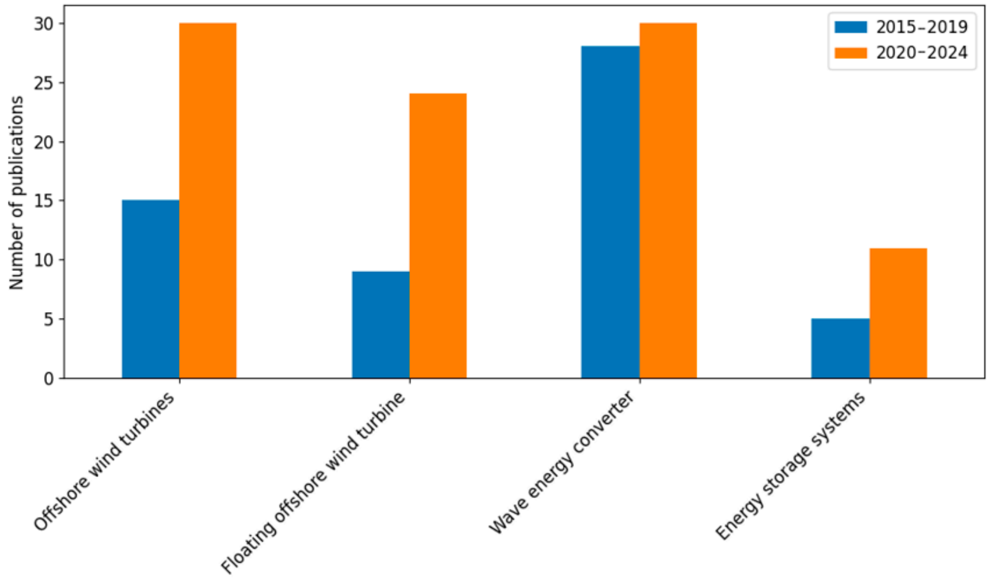

Figure 5. Number of publications in 2015–2019 and 2020–2024 that belong to the second thematic category, i.e., technologies and devices, divided into subcategories.

Although a clear increase in the number of publications in the renewable energy category can be seen over the last five years, the trend in the number of publications in each subcategory regardless of the time frame analyzed is similar. As Figure 4 shows, the topic most frequently covered within the renewable energy category was ocean energy (more than 48 publications in the last 5 years). Wind energy, wave energy, and energy harvesting were also topics of interest for researchers (more than 30 publications in each of these subcategories in the last 5 years). The topic that was the least frequently covered was tidal energy (there were less than 19 publications within this category in the analyzed time frame). However, regardless of the analyzed subcategory, one can observe an increase in the number of publications compared to 2015–2019 that ranges from 2 (tidal energy) to 18 (wind energy).

The results obtained for the technologies and devices category seem interesting against this background. As Figure 5 shows, offshore wind turbines and wave energy conversion were the most common topics within this category (a total of 60 publications in the last 5 years and 43 publications in 2015–2019). Floating offshore wind turbines have been the subject of 33 scientific papers in the last decade, while energy storage systems have been the subject of 16. Relating data from the last 5 years to the 2015–2019 period, a significant increase in the number of publications in each of the analyzed subcategories is noticeable. There was an increase in the number of publications on offshore wind turbines by 100% compared to the previous time period and floating offshore wind turbines by more than 260%, while the energy storage systems subcategory noted a 220% increase in the number of publications compared to 2015–2019. In practice, this makes it possible to observe a significant increase in researchers' interest in this topic. It should be noted that the most popular topic in this category was invariably wave energy conversion in 2015–2019, and the trend in the number of publications in each subcategory regardless of the analyzed time frame is similar. This may indicate the intensive development of technologies and devices for wind and wave energy conversion and the use of offshore and floating offshore wind turbines.

In Figure 6, bar charts show the number of publications in 2015–2019 and 2020–2024 that belong to the research methodology category, divided into four subcategories. Each time, depending on the research methodology used, the publications were assigned to at least one subcategory, experiment, literature analysis, case study, or conceptual, because more than one research method can be applied in each analyzed document (this applies when several research methods were used in a given document).

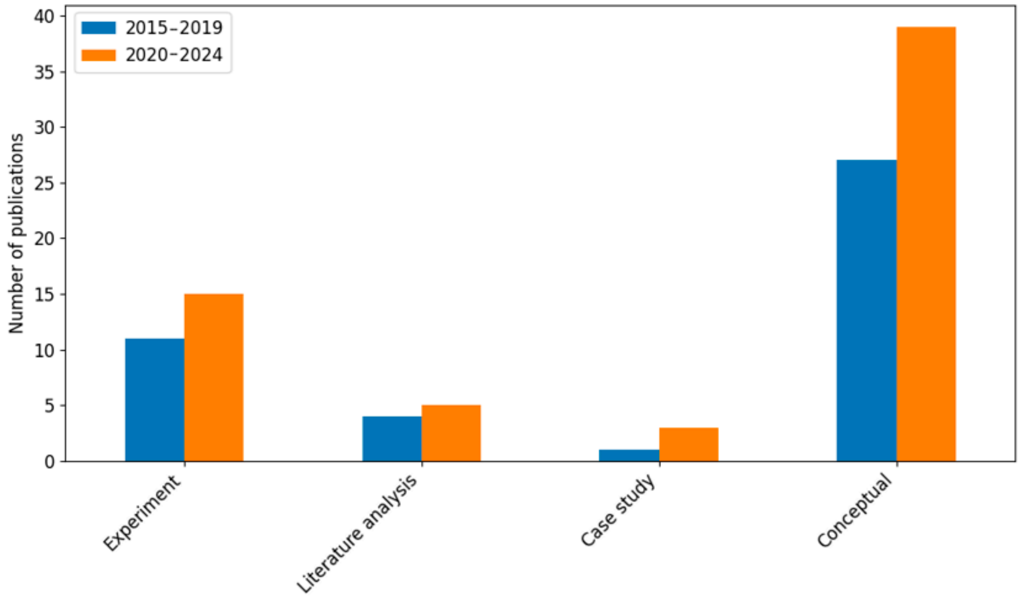

Figure 6. Number of publications in 2015–2019 and 2020–2024 that belong to the research methodology category, divided into subcategories.

The category containing conceptual works included all publications that conducted simulation studies (mainly in Matlab), publications involving mathematical modeling and using artificial intelligence to simulate physical phenomena. Based on the analysis of the results, it can be concluded that the most common methods used were conceptual and experimental as well as literature analysis. The smallest group of publications were those that used the case study method, which can be explained by the subject matter of the publication and the approach used to study reality.

The results, taking into account the countries of publication, look interesting against this background (see Table 2). It turns out that, in total, China had the highest number of publications between 2015 and 2024, namely 39 publications (more than twice as many as India, which ranked second, with 14 publications). Furthermore, a significant number of publications were recorded in Spain and the United Kingdom (13 publications each) as well as in the United States (10 publications). In the remaining countries, there was little interest in the analyzed topics, as evidenced by the number of papers published (fewer than 10 throughout the analyzed period). In practice, if an article has multiple authors affiliated with different countries, each of these countries is assigned to the article.

Table 2. Number of publications in 2015–2019 and 2020–2024 in countries.

Country	2015–2019	2020–2024	All Years	Share [%]	Chi-Square
All countries	43	62	105	100.0	χ^2
China	12	27	39	37.14	$\chi^2 = 12.99$ (df = 8, $p = 0.112$)
India	4	10	14	13.33	
Spain	6	7	13	12.38	
United Kingdom	9	4	13	12.38	
United States	4	6	10	9.52	
Italy	4	2	6	5.71	
Norway	0	5	5	4.76	
Portugal	3	2	5	4.76	
Other	8	13	21	20.00	

Figure 7, for illustrative purposes, includes bar charts showing publications in countries.

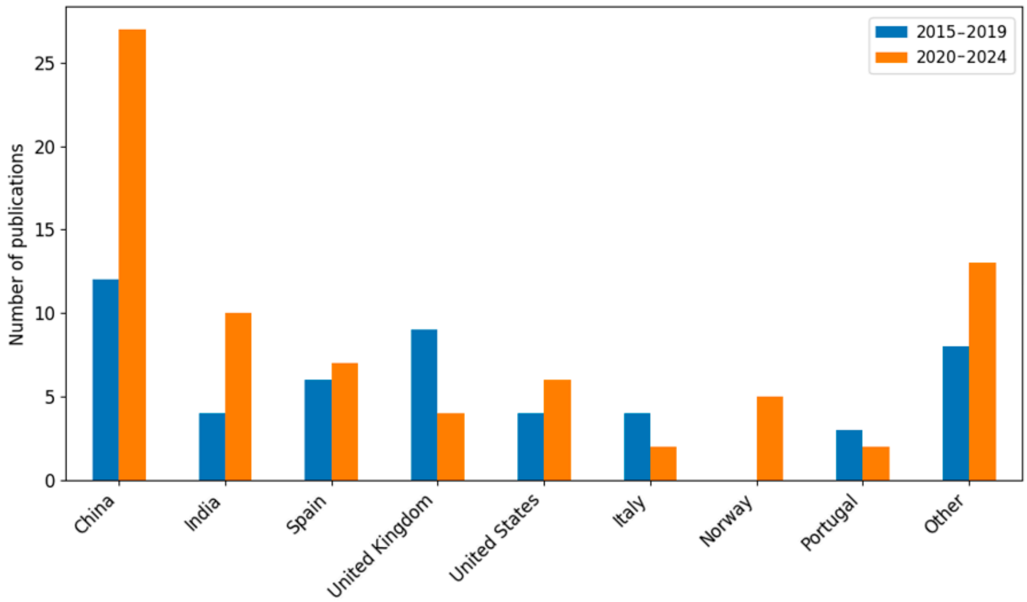

Figure 7. Number of publications in 2015–2019 and 2020–2024 divided into countries.

It should be noticed that the other category includes the following countries: France (4), Egypt (4), Australia (4), South Korea (3), The Netherlands (3), Brazil (3), Sweden (2), Ireland (2), Iran (2), Germany (2), Canada (2), Algeria (2), Singapore (1), Saudi Arabia (1), Russian Federation (1), Romania (1), Poland (1), Malaysia (1), Lebanon (1), Indonesia (1), Hong Kong (1), Greece (1), Denmark (1), and Bangladesh (1). For ease of reference, the number of publications in these countries is indicated in parentheses.

An analysis of the data in Table 2 and Figure 7 reveals some regularities. Between 2015 and 2024, a total of 105 publications were published in all countries, the majority of which were in 2020–2024 (60% of the total texts), which indicates a growing interest in the topic at that time, resulting in increased scientific activity. In practice, for 2015–2019, there were 43 publications, while for 2020–2024, the total number of publications increased to 62. As the analysis shows, there are no statistically significant differences in the number of publications between 2015 and 2019 and 2020 and 2024. The greatest interest in the topic in the last decade, regardless of the interval analyzed, was in China (a total of

39 publications, accounting for 37% of the total), which may be influenced by the country's geographic location and the advancement of authors from this country in this type of technology. As previously indicated, India ranked second, with 14 publications, accounting for just under 13% of the total. Spain and the United Kingdom shared third place (ex aequo), each with 13 publications. Notably, in both China and India, there has been a significant increase in the number of publications over the past five years. Specifically, China recorded a 225% increase, resulting in a final share of just over 37% of all publications, while India experienced a 250% increase, corresponding to a 13% share of all publications. Spain and the United Kingdom (each accounting for more than 12% of the total number of publications) also stand out positively in ongoing research. A broader analysis reveals that research is particularly concentrated in four countries—China, India, Spain, and the United Kingdom—as the work conducted there represents approximately 75% of all publications, confirming the strong interest in this research area within these countries.

Interestingly, against this background, the results summarized in Table 3 are related to publications by renewable energy in other thematic subcategories.

Table 3. Publications by renewable energy in other subcategories.

Name	Wind Energy	Wave Energy	Energy Harvesting	Ocean Energy	Tidal Energy	Total	Chi-Square
Total	52	66	70	90	36	105	χ^2
Technologies and devices							
Offshore wind turbines	45	31	31	39	5	45	$\chi^2 = 41.39$ (df = 12, $p = 4.22 * 10^{-5}$)
Floating offshore wind turbine	30	20	22	29	5	33	
Wave energy converter	25	58	57	57	12	58	
Energy storage systems	6	8	9	11	9	16	
Research methodology							
Experiment	9	15	21	23	9	26	$\chi^2 = 7.76$ (df = 12, $p = 0.8$)
Literature analysis	6	4	4	7	6	9	
Case study	3	4	3	4	1	4	
Conceptual	34	43	42	56	20	66	

As can be seen in Table 3, publications related to the main category of renewable energy were assigned to various subcategories (subdomains) related to wind energy, wave energy, energy harvesting, ocean energy, and tidal energy and then analyzed according to the areas of the second main category, that is, technologies and devices. This approach made possible a multifaceted analysis of publications from the Scopus database in terms of their affiliation with the subcategories of the two main areas. Furthermore, Table 3 provides a breakdown by the research methodology used, which is an added value.

Considering the first category, as can be seen from the summaries in Tables 1 and 3, the largest number of publications was devoted to ocean energy (90 publications), with slightly fewer devoted to energy harvesting (70 publications) and wave energy and wind energy (66 and 52 publications, respectively), suggesting the greatest interest among researchers in this issue. The smallest number of publications (36 publications) was recorded for tidal energy, which may indicate the need to develop this technology compared to other areas. For the second of the main categories, that is, technologies and devices, the highest number of publications was related to wave energy converters (58 publications). Offshore and floating wind turbines were slightly less popular among researchers (45 and 33 publications on this topic, respectively), allowing for us to see the high intensity of research conducted on these technologies. The least interest was recorded for energy storage systems (a total of 16 publications), indicating the relatively low popularity of solutions and analyses presented by researchers in this field. Consequently, more work is expected to be performed to develop renewable energy sources by providing efficient storage of energy from the seas and oceans. It should be noted that publications on energy storage systems are much less numerous in each of the subcategories of renewable energy, with the highest number recorded for the area of ocean energy (11 publications). The other subcategories of renewable energy sources had fewer than 10 publications (tidal energy—nine documents, wave energy—eight documents, and wind energy—six documents). In turn, nine publications were recorded for energy harvesting. On the basis of this, it can be concluded that energy storage systems are the subject of few scientific studies in relation to renewable energy, which suggests the need for continued future research in this area. The fact that subcategories are not mutually exclusive is evident, for example, in Figure 8, including publications by renewable energy in technologies and devices category. A heatmap is presented below.

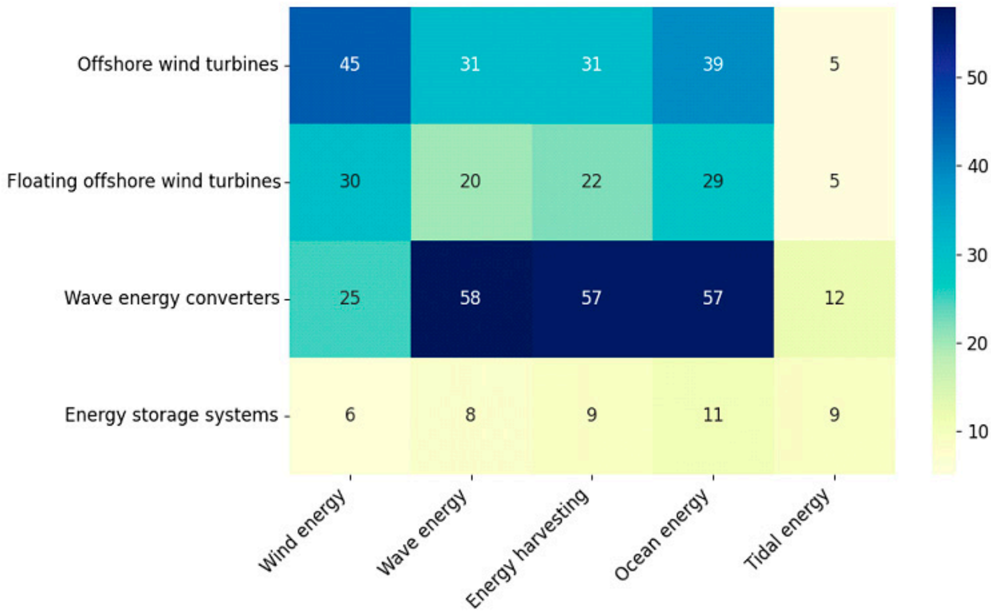

Figure 8. Publications by renewable energy in technologies and devices category.

Based on the data presented in Table 3 and Figure 8, it can be seen that a significant number of publications on wave energy converters were recorded for various subcategories of energy sources, particularly wave energy (58 publications) and ocean energy (57 publications). In addition, a large number of publications, i.e., 57, are works related to energy harvesting. This analysis leads to the conclusion that this technology is well developed and is being researched worldwide. In the case of offshore wind turbines, 45 publications were recorded in the wind energy subcategory, making it the main subject of research in this field. In contrast, slightly fewer publications were recorded for floating offshore wind turbines and wave energy converters—30 and 25 documents, respectively. It should be noted that a significant number of publications on offshore wind turbines were also recorded for the subcategories ocean energy (39 documents) and wave energy (31 documents). In addition, 31 papers are energy harvesting-related works. Relatively few publications were devoted to tidal energy (the least studied area), as exemplified by the smallest number of publications in this area (36 papers in total). Within this area, the least studied topics were offshore wind turbines and floating offshore wind turbines (five publications each), suggesting that these technologies are rarely the subject of new scientific papers. This may be due to the need for further development of the technology to increase its practical use. In practice, the predominance of wave energy converters in the ocean energy category, as shown in Figure 8, reflects the common practice of integrating multiple renewable energy sources within a single study.

Taking into account the research methodology (Table 3), the most frequently used research methods were conceptual (66 publications) and experimental (26 publications), which indicates the dominance of theoretical research and models in the field of renewable energy as well as their experimental nature. Since the research methodology based on literature analysis and case studies concerns a small number of documents (nine and four publications, respectively), it can be observed that relatively few publications represent the state-of-the-art, so there was a need to fill the literature gap in this area. A summary heatmap is presented in Figure 9.

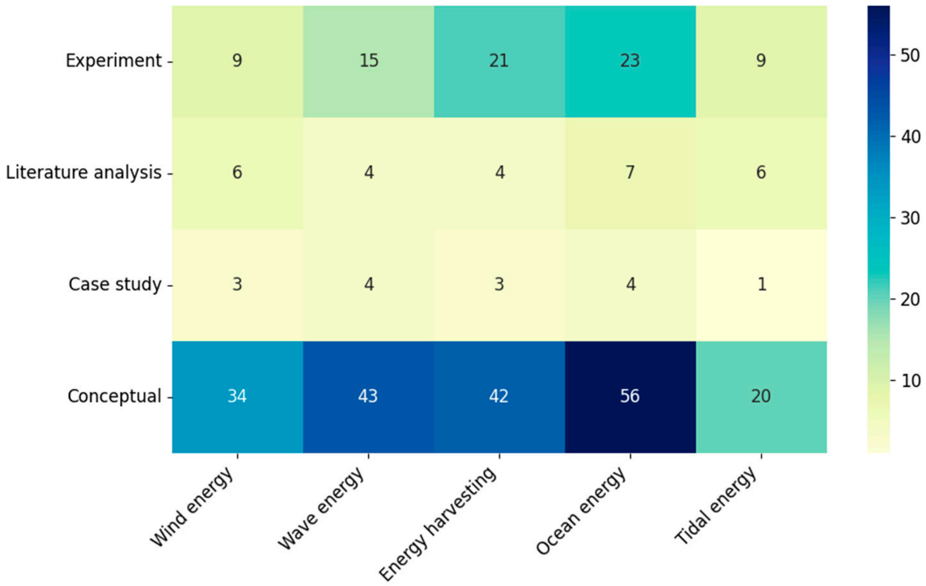

Figure 9. Publications by renewable energy in research methodology category.

Based on the heatmap in Figure 9, regarding the applied research methodology for the subcategories related to renewable energy analyzed, it can be seen that, of all the research methods for each of the subcategories of renewable energy, the conceptual approach dominates (for ocean energy—56 documents, for wave energy—43 documents, for energy harvesting—42 documents, while for wind energy—34 documents). The type of research methodology used makes it possible to note that the vast majority of documents are related to analysis and investigation of technological concepts. Also, in the case of experimental research, a similar relationship was observed (the largest group of publications were those on ocean energy—23 documents; slightly fewer publications were on energy harvesting—21 documents and wave energy—15 documents, while nine documents each were classified as wind energy and tidal energy). On the basis of this, it can be concluded that the experimental approach is often used. In turn, literature analysis and case studies have an insignificant share in scientific work, exemplified by the small number of published papers. In response to this, it was decided to conduct a comprehensive review of the state-of-the-art in the subject areas analyzed. As for case studies, the smallest number of publications was recorded in the areas of wind energy, energy harvesting, and tidal energy, suggesting that practical analyses of implemented projects are mostly in an early stage. It should be noted that only one publication was noted in the area of tidal energy. This means that tidal energy is the least studied area of all subcategories of renewable energy analyzed. Therefore, further scientific work, research projects, and investments in this area can be expected. In turn, ocean energy and wave energy are the most researched (state-of-the-art), which suggests their significant role in the renewable energy sector. Furthermore, energy harvesting and wind energy are the focus of contemporary researchers, with theoretical approaches dominating.

4. Unsolved Problems

Undoubtedly, interconnected economic, political, and market systems that emphasize energy efficiency and innovation are driving technological development, and this is also true for the renewable energy sector. This impact is immense. Consequently, in the last decade, there has been an increase in interest in work on the acquisition and use of renewable energy, including wind, wave, ocean, and tidal, and its harvesting. This, in turn, contributes to the development of technologies and equipment, including offshore wind turbines, floating offshore wind turbines, wave energy converters, and energy storage systems. This process is positively influenced by government subsidies and programs that provide incentives for the development of offshore and ocean wind farms, which is especially important for countries with access to seas or oceans. This is reflected in the significant activity of researchers from China, India, Spain, and the United Kingdom in the field of renewable energy sources. In practice, a considerable amount of work has been published in China and India, especially over the past five years. Technological developments are also influenced by advances in materials science (depending on the materials used, corrosion of components can be a concern) and electrical engineering, resulting in the construction of increasingly efficient and reliable energy converters. Technological developments are expected to continue to drive the change in the renewable energy market, positively impacting sustainability as well as the increasingly green future of the energy sector.

In the future, it will become possible to expand the research to include other major categories, such as environmental impact. Although this article, due to its finite volume and subject matter, omits economic, policy, and market analyses, among others, these issues are also relevant to the direction of technology development. It becomes possible to analyze works that include economic analysis, including the balance sheets of profits and losses resulting from the implementation of specific renewable energy systems, with particular attention to their environmental impact. An interesting area of research would be to focus scientific efforts on life cycle assessment so that the articles analyzed would address life cycle assessment of contemporary technologies for the renewable energy sector, noting that these are relatively new technologies, which translates into a limited number of available studies. A separate (and also not very numerous) group of publications is policy analyses, which include papers that deal with legislation and regulations applicable to the renewable energy sector, as well as market analyses, which deal with market research in the broadest sense, which is of particular interest in the context of forecasts for the development of technologies that use renewable energy sources. On this basis, analogous to the method presented, it will become possible to make compilations and heatmaps that will supplement the analysis of the state-of-the-art.

The renewable energy sector is poised for significant advancements and transformations in the coming years. Several key trends are expected to shape the future of this industry:

1. Integration of Multiple Renewable Energy Systems: The trend toward integrating various renewable energy systems, such as wind–wave hybrid systems, is expected to continue. This integration aims to maximize energy generation while minimizing platform movements, thereby enhancing overall efficiency and reliability [117].

2. Advanced Control Strategies: It is essential to develop advanced control strategies for offshore wind turbines and wave energy converters. Techniques such as aerodynamic thrust optimization and torque compensation control are being studied to improve stability and efficiency [118]. However, real-world implementation of these strategies will require further research and validation.
3. Modular and Scalable Solutions: Modular solutions and the use of triboelectric nanogenerators for low-frequency wave energy harvesting are gaining popularity. These innovations offer promising avenues for improving the efficiency and reliability of renewable energy systems [117]. The scalability and long-term performance of these technologies will be critical to large-scale deployment.
4. Energy Storage Systems: The relatively low number of publications on energy storage systems highlights a critical gap in the research. Efficient energy storage solutions are essential to complement renewable energy generation and ensure a stable energy supply [119]. Future research will likely focus on developing and optimizing these systems.
5. Policy and Market Dynamics: Government policies and market dynamics will continue to play a crucial role in the advancement of renewable energy technologies. Subsidies, incentives, and regulatory frameworks will drive innovation and investment in this sector [119]. Additionally, the growing demand for clean energy will push the industry towards more sustainable and efficient solutions.
6. Technological Innovations: Emerging technologies, such as artificial intelligence, blockchain, and advanced materials, will revolutionize the renewable energy sector. These innovations will enhance the efficiency, reliability, and integration of renewable energy systems [120].
7. Global Collaboration and Investment: International collaboration and investment will be crucial for the advancement of renewable energy technologies. Countries with significant renewable energy potential, such as China and the United States, are expected to lead the way in research, development, and deployment [121].

Overall, the future of renewable energy looks promising, with continuous advancements and innovations driving the industry towards a more sustainable and efficient energy landscape.

5. Conclusions

The implementation of smart solutions and remote monitoring significantly impacts efficient energy distribution. These systems optimize operations and maintain a constant energy supply, even under adverse conditions. Key issues include their integration with other energy sources to create hybrid power parks capable of operating during natural disasters. Satellite communications can then be used for data transmission from remote and difficult-to-reach locations [122–126], whose reception depends on a number of factors [127–135]. In practice, the spectrum of service integration and applied solutions based on conditions, including the occurrence of various emergencies, translates into a change in the way a given risk is identified, assessed, and controlled [136–146].

Public and private sector investments are driving many projects in seas and oceans. Over the last decade, numerous studies have focused on improving energy efficiency in the renewable energy sector. Research on new technologies and innovative solutions suggests many will be practically implemented in the future. Additionally, studies on the reliability of current power transmission lines are prevalent [147–150].

Ocean and wave energy research is prominent, highlighting their potential in the energy sector. Wave energy converters and offshore wind turbines are key research areas, while tidal energy and energy storage systems are less frequently studied, indicating a need for further development.

Conceptual and experimental methods dominate research, suggesting many solutions are in early testing stages. The limited number of literature analyses and case studies indicates a need for more in-depth evaluations of implemented solutions.

Renewable energy plays a transformative role in the global energy transition, promising a sustainable future. However, implementing innovative solutions requires costly research, public awareness, and extensive cooperation across political, economic, and social fields. While renewable energy sources in seas and oceans have a minimal carbon footprint, concerns about their impact on marine ecosystems persist. Efforts are being made to minimize this interference.

Key conclusions:

1. The location of systems in seas poses logistical and operational challenges. Implementing innovative technologies requires significant investment and cooperation.
2. Recent years have seen numerous studies on offshore wind turbines, wave energy, and energy harvesting, indicating their application potential. Tidal energy and energy storage systems, despite their potential, are less frequently researched.
3. Renewable energy in seas and oceans offers a minimal carbon footprint but raises concerns about ecosystem impact. Integrating different energy sources can create hybrid power parks that withstand extreme conditions, enhancing energy supply stability.

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