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Energy Transition and Sustainability in the United Kingdom: A Systematic Review under the PRISMA Guidelines

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ABSTRACT

In the energy transition, environmental sustainability has led to the development of new renewable energies, such as tidal energy, which generates continuous and predictable electricity from ocean tides. This study conducts a Systematic Literature Review (SLR) according to the PRISMA 2020 method, focusing on the implementation and technological development of tidal energy. A quantitative approach was used to analyze 37 studies from 2020 to 2024 in Scopus. The results show the use of key tools such as the 0-D model, TPXO9, and the acoustic doppler current profiler (ADCP) to optimize this renewable source. The TPXO9 model stands out for its accuracy in predicting tides, assisting in infrastructure planning and energy efficiency. The United Kingdom leads the development of tidal energy, promoting innovative research and projects. The review highlights the importance of this renewable energy in reducing dependence on fossil fuels and carbon emissions, serving as a basis for future research and the advancement of the energy transition towards green production and environmental sustainability.

Keywords: Tidal Energy, Sustainability, Green Production, Renewable Energy, Optimization
JEL Classifications: Q42, Q48, Q55, Q57

1. INTRODUCTION

Currently, the need to increase environmental sustainability and green production is leading to further research into the transition to renewable energy sources, with the aim of tackling climate change, reducing dependence on fossil fuels, and minimizing carbon emissions. In this context, the energy potential of the oceans has led to the study and research of tidal energy, due to its predictability and constant generation capacity (Neill et al., 2021). However, its implementation presents technological, economic, and environmental challenges, which are still in the research stage for future development.

Internationally, advances in offshore renewable technologies have contributed to the growth of energy sources such as tidal, offshore wind, and wave power (Smith et al., 2023). There are projects focused on the economic viability of tidal energy, such as Enabling Future Arrays in Tidal (EnFAIT), funded by the European Union, with the aim of optimizing production through interconnected turbine arrays (Jump et al., 2020).

Likewise, additive manufacturing is considered an efficient solution for the design of tidal turbine structural components due to its production flexibility (González-Montijo et al., 2023). And to achieve commercial viability, it is essential to develop advanced control strategies and permanent energy electronic power converters (Darwish and Aggidis, 2022).

The large-scale implementation of tidal energy has a significant impact on the environment. These impacts can be classified as atmospheric, hydrodynamic, and ecological. For example, sea level rise alters tidal patterns and changes the availability of this resource in certain regions; the variability of renewable sources presents challenges in the stability of energy supply; underwater noise pollution affects marine biodiversity, etc. In view of this, it is necessary to implement highly accurate predictive models, develop efficient energy storage technologies, and conduct baseline studies prior to the installation of these energy sources (Khojasteh et al., 2022; Maghrabie et al., 2023; Ouro et al., 2024).

Despite the challenges, marine testing research is a fundamental process for improving the design and control of these systems, providing efficient integration of renewable energy systems (Apsley et al., 2023). In summary, this article analyzes the challenges and opportunities presented by tidal energy, highlighting its impact on sustainability and green energy production, which will depend on investments in infrastructure, adequate regulations, and collaboration between the public and private sectors to reach its full potential.

Given this scenario, it was essential to conduct a Systematic Literature Review (SLR) following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for a more accurate understanding of how tidal energy is related to environmental sustainability and green production. This ensures a detailed evaluation of relevant studies related to the research topic published in the last 5 years (2020-2024). Based on this review, the following key research questions are suggested:

How has tidal energy impacted environmental sustainability and green production to conduct systematic review? What factors have enabled the United Kingdom to excel in the development of tidal energy? What prediction tools are most commonly used to determine the efficiency of tidal energy in certain areas?

2. METHODOLOGY

The growing availability of information in various areas of knowledge has driven the need for tools that facilitate its organization and evaluation in a structured manner. In this regard, systematic reviews have established themselves as a key methodology for integrating the findings of multiple primary studies through well-defined criteria, allowing for a comprehensive evaluation of the available evidence on the subject (Beltrán and Óscar, 2005; Freeman et al., 2006).

In this context, the research was carried out using a quantitative approach, with the aim of conducting an in-depth and detailed analysis of the existing literature on the subject of study, following the guidelines established by the PRISMA methodology. These guidelines are essential to ensure that the data analysis is consistent and of high quality (Urrutia and Bonfill, 2014). By applying the PRISMA guidelines, systematic reviews allow for a thorough and rigorous analysis of the studies available on a particular topic. This approach ensures that the selection of studies is both objective and critical, facilitating their proper evaluation and accurate summary of findings. By following a transparent protocol, potential biases are minimized, and the validity of conclusions is reinforced, making systematic reviews an essential tool for informed decision-making (Moreno et al., 2018; García-Perdomo, 2015).

In addition, systematic reviews play a key role in defining a future research agenda by resolving key questions and clarifying areas of uncertainty. In this way, they become an invaluable resource for consolidating existing knowledge and guiding future research, directing researchers toward relevant questions and areas that still require further exploration (Chrcanovic, 2019).

2.1. Search Procedure

In order to find documents on tidal energy and its relationship with sustainability and the optimization of resources and processes, an SLR was conducted in the Scopus database. The purpose of this search was to consolidate information, identify previous research on the topic of interest, and locate documents that provide relevant knowledge. The search strategy was carefully developed, using words directly related to tidal energy and sustainability for green production, applying titles, abstracts, and keywords from the articles, as shown in Figure 1.

After searching the database, 2,393 documents related to tidal energy and sustainability were found. In addition, the criteria listed in Table 1 were used to select the articles used in the RSL.

2.2. PRISMA Approach

For step 1, documents based solely on abstract review were eliminated, reducing the total to 2,375 studies. Finally, in step 2, articles were discarded according to the criteria set out in Table 1, leaving a total of 37 studies, as shown in Figure 2.

Next, Table 2 presents the Scopus database along with the final search string used. This is done in order to make it easier for other researchers to easily find information related to the topic under investigation.

Figure 1: Search string

Article title, Abstract, Keywords for Searching: ("Tidal energy" OR "Tidal power") AND ("sustainability" OR "green energy" OR "renewable energy")

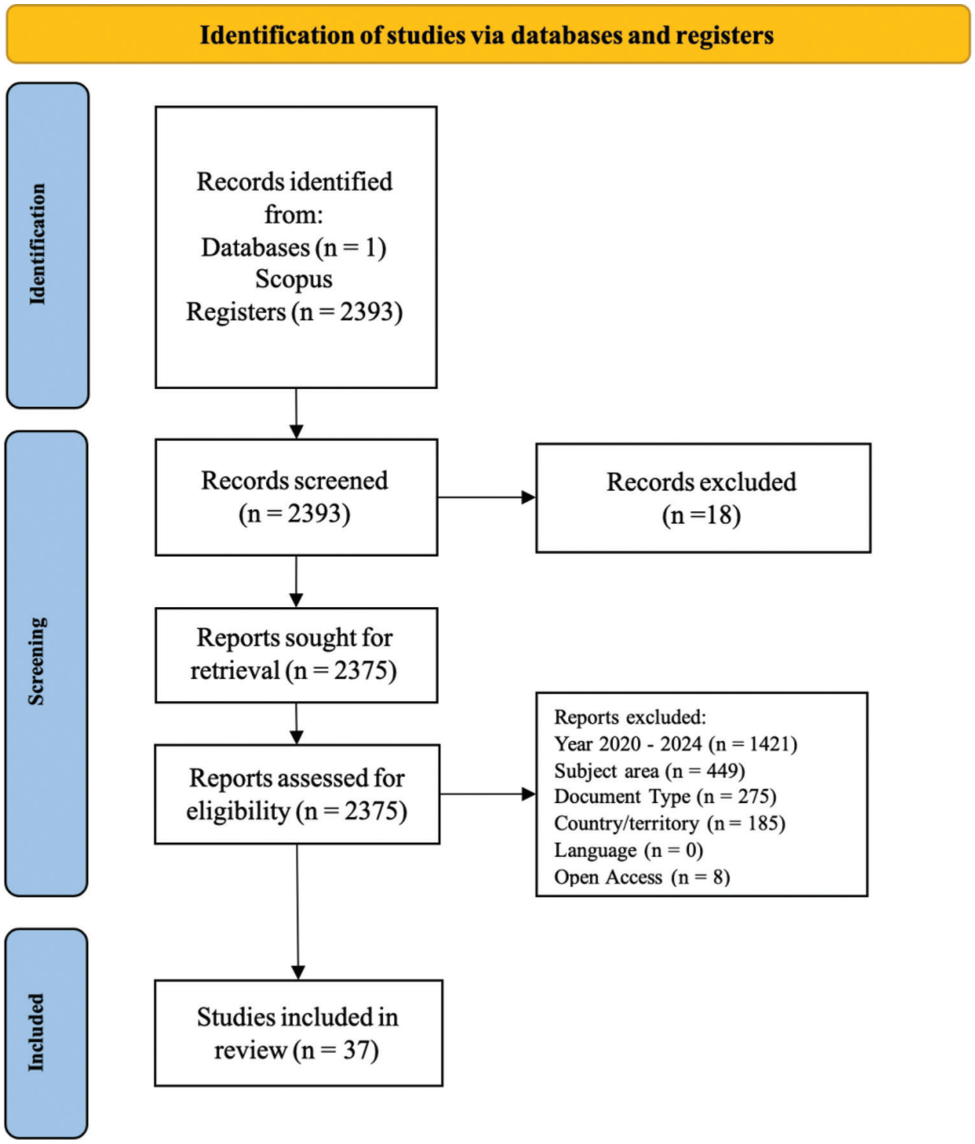
Table 1: Inclusion and exclusion rules and their respective explanations

C1	They must be published between 2020 and 2024.
C2	The area of interest is Energy.
C3	The document included must be an article.
C4	The documents must focus solely on the United Kingdom.
C5	The document must be written in English.
C6	The document must be in the "Open Access" category.

Table 2: Final search string

Database	Final search
Scopus	(TITLE-ABS-KEY ("Tidal energy" OR "Tidal power") AND TITLE-ABS-KEY ("sustainability" OR "green energy" OR "renewable energy")) AND PUBYEAR>2019 AND PUBYEAR<2025 AND (LIMIT-TO (SUBJAREA, "ENER")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (AFFILCOUNTRY, "United Kingdom")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (OA, "all"))

Figure 2: Process diagram according to PRISMA



3. RESULTS

3.1. Bibliometric Discoveries

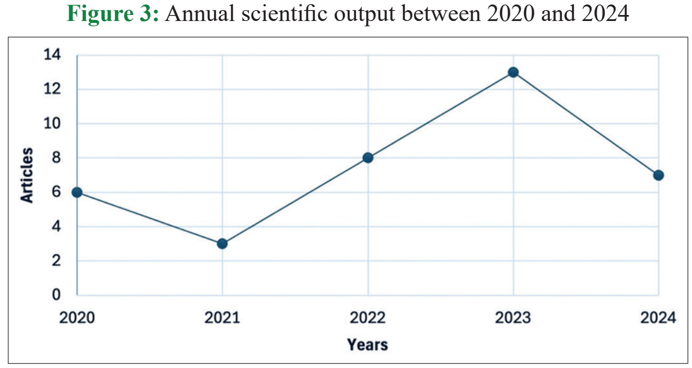
First, Figure 3 shows annual production over the last 5 years. In this regard, the year with the highest scientific output was 2023, accounting for 35% of the total with 13 articles published, followed by 2022, accounting for 22% of the total with eight articles published.

Figure 4 shows the countries most relevant to the study, with the darker colors indicating the highest levels of participation. In this case, given that the country of interest is the United Kingdom, this can be seen by its darker color, which covers 81% of the total.

In the case of sources most relevant to the study, Figure 5 shows that the most prominent journal was Renewable Energy, with 26% of the total and eight articles, followed by Energies, covering 23% of the total with seven articles.

Figure 6 shows the words that have been most frequently used by the authors included in the study. The most relevant words are shown in larger font. On the one hand, we have "renewable energy" with a frequency of 9. This is followed by "tidal energy" and "tidal stream energy" with a frequency of 4. On the other hand, among those that appeared least frequently are "climate change" and "circular economy" with a frequency of 1.

Figure 3: Annual scientific output between 2020 and 2024



In relation to Figure 7, it shows us the number of countries with corresponding authors and their participation in scientific publications. These are divided into two sectors: Single Country Publications (SCP, in blue) and Multi-Country Publications (MCP, in red). For this research, the United Kingdom stands out due to the criteria mentioned above. Despite this, we can interpret that SCP stands out over MCP, obtaining an MCP% of 25.8.

Figure 8 shows us a thematic map, which classifies various research topics according to their centrality and density. This type of graph is crucial to our study, as it provides a clear overview of the topics that are declining or consolidating in the field of analysis.

Figure 4: Country scientific production

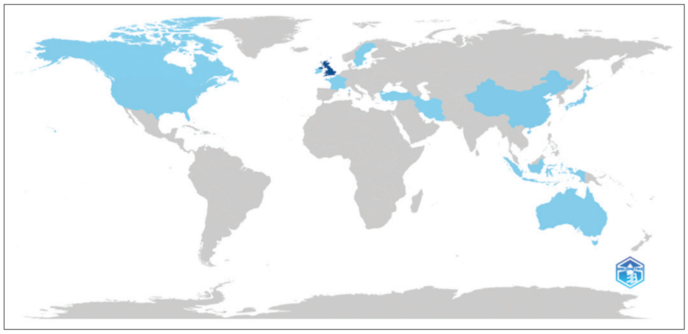


Figure 5: Most relevant journals for the study

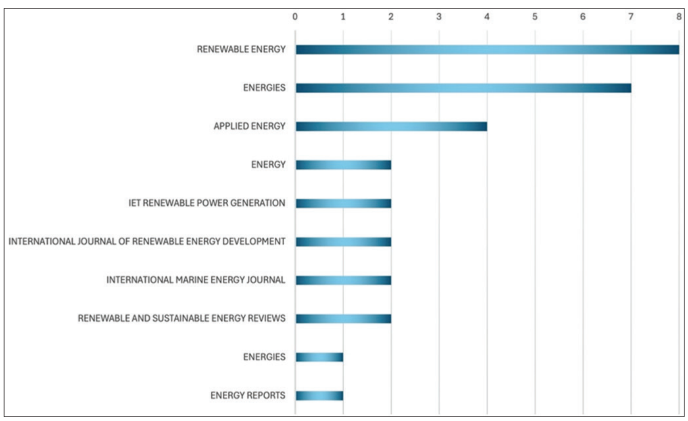


Figure 9 below shows three fields, which facilitate the interrelation between three variables. The left column contains the "DE"s, which are the keywords most highlighted by the authors, similar to Figure 6. In the middle are the relationships with the authors "AU," which highlight Neill sp, Angeloudis a, Pennok s, and Driscoll h. It is also important to highlight the relationship between the authors and the journals where their research has been published in the right-hand column "SO."

Figure 10 shows a neural network map related to keywords, with the most prominent being the term "tidal energy," which first appeared in 2022. This connects with words such as "alternative energy," "renewable energies," and "tidal power plants," ensuring a commitment to sustainability and a viable alternative for clean and renewable production. Likewise, "solar power" and "wind power" indicate its relationship with other environmentally friendly energy generation alternatives.

3.2. Content Discoveries

In this systematic review, five key purposes for the use of specialized tools are identified: Assessing the energy potential of marine resources, modeling tidal flows and their impact on infrastructure, optimizing energy generation and distribution, forecasting the long-term viability of projects, and simulating various operational scenarios to improve the efficiency and sustainability of systems. These approaches are essential for the advancement and successful implementation of this renewable energy source.

From an assessment perspective, tools such as Pentland Firth and Orkney Waters (PFOW), MATLAB, STAR CCM+, and Acoustic doppler current profiler (ADCP) allow for the analysis of particle displacement using flow vectors with high accuracy, even at high speeds. This facilitates the study of hydrodynamic coefficients such as vertical force, horizontal force, and pitching moment, as well as turbulence intensity (TI) and turbulent kinetic energy (TKE), which are fundamental data for the design and positioning of energy extraction devices (McIlvenny et al., 2023; Mo et al., 2024; Neill et al., 2023). In addition, life cycle assessment (LCA)

Figure 6: Display of most relevant keywords

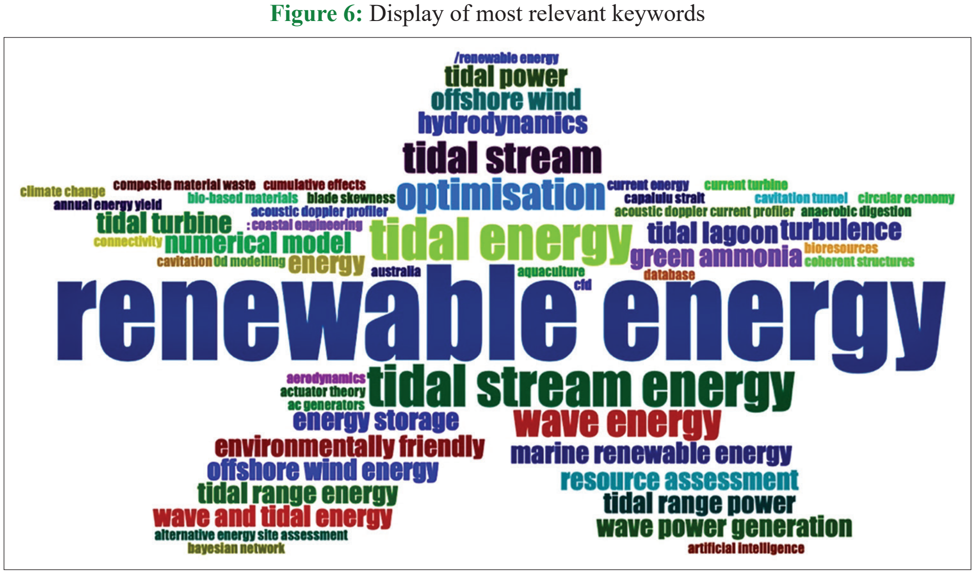


Figure 7: Distribution of scientific publications by country

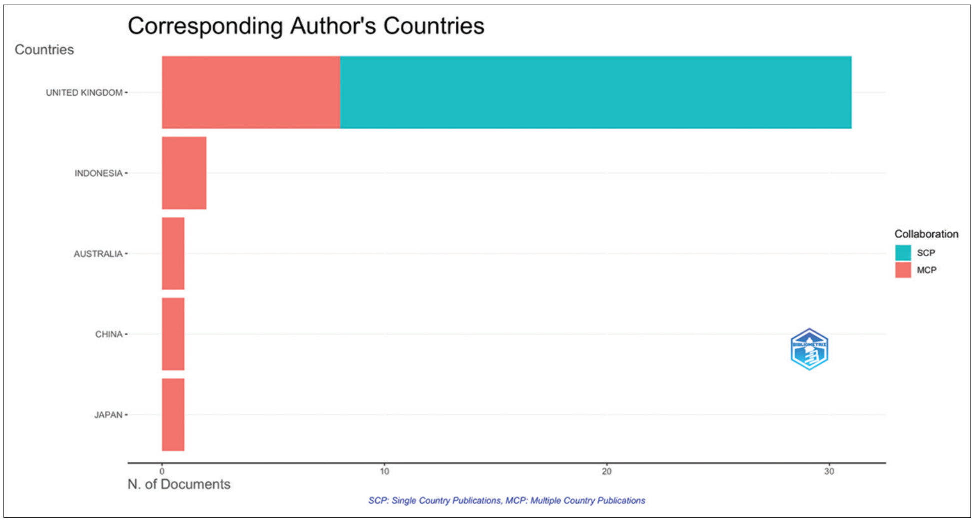


Figure 8: Strategic diagram of research theme

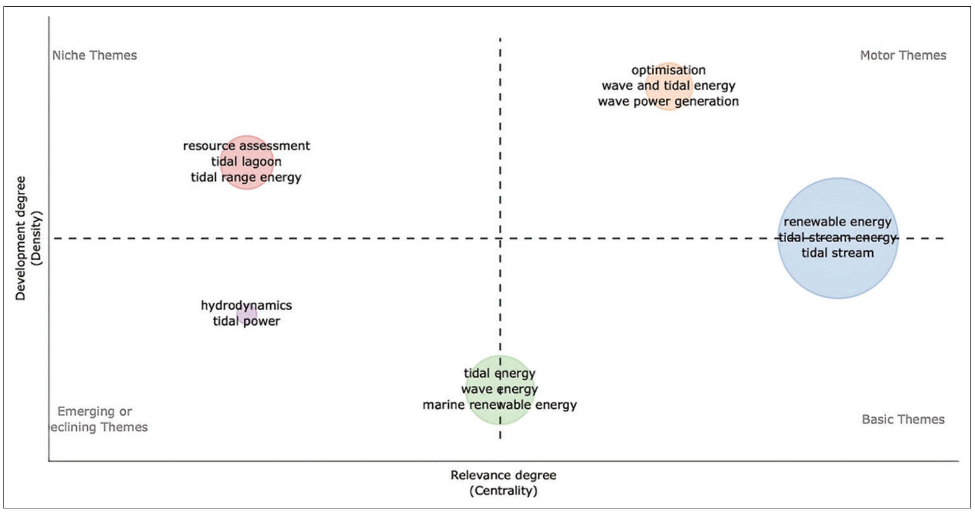
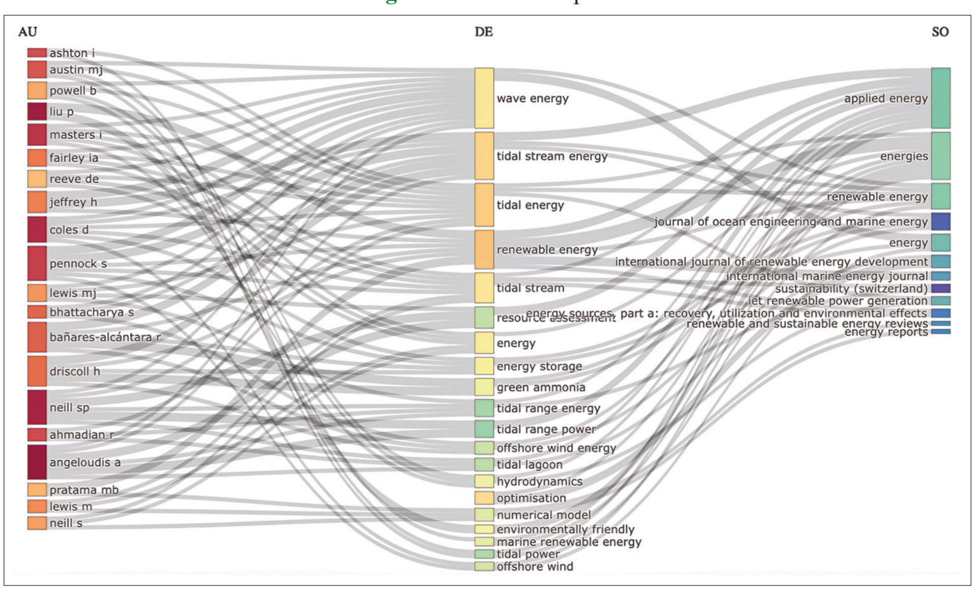
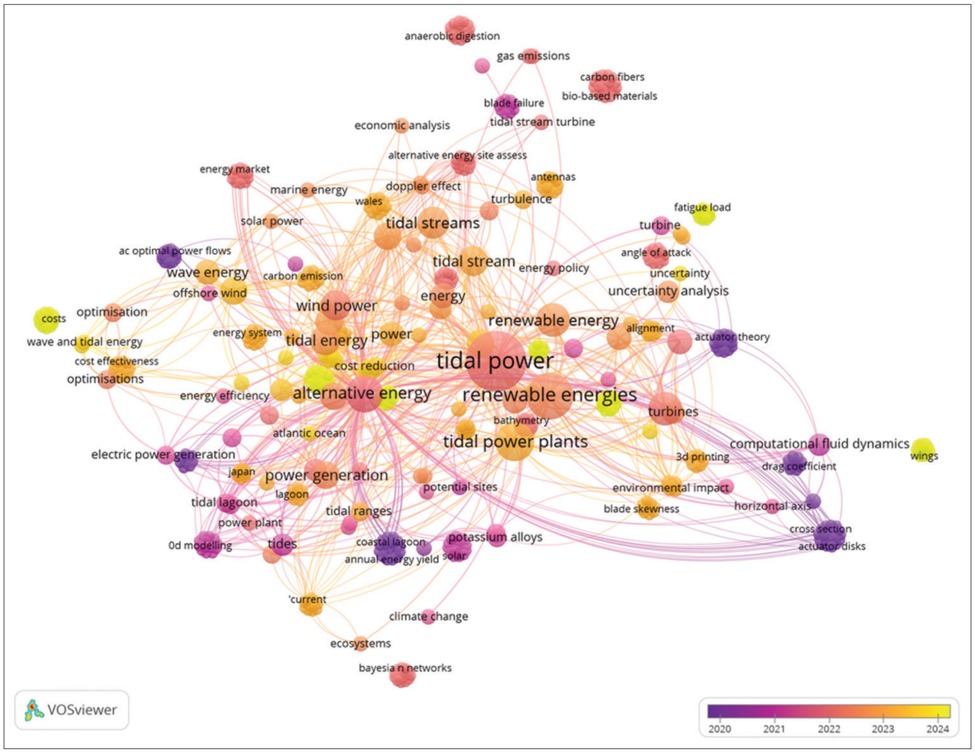


Figure 9: Three field plot



is used to evaluate environmental impacts throughout all stages of the product life cycle, highlighting that anaerobic digestion offers superior environmental benefits over other waste disposal methods (Reynolds et al., 2022; Walker and Thies, 2022).

Figure 10: Thematic network visualization of keywords



On the other hand, tools such as TPXO9, ADCP, and SolidWorks are integrated into tidal turbine modeling, combining tidal data, flow measurements, and 3D design (Khanjanpour and Javadi, 2020; Lucas et al., 2022; Martí Barclay et al., 2023; Neill et al., 2021). Delft3D-4 is used to model tidal flow (Kurniawan et al., 2024), while Horizontal Axis Tidal Turbine (HATT) allows the hydrodynamic effects of turbine rotors with different inclinations to be analyzed, evaluating how blade design impacts energy efficiency, noise, and vibration, thus contributing to the design of more efficient and environmentally friendly turbines (Xu et al., 2023; Zhang et al., 2023). In addition, the use of multibeam echosounder Surveys (MBES) provides detailed maps of the seabed to identify suitable areas for testing devices, ensuring compatibility with marine energy technologies (Neill et al., 2023; Driscoll et al., 2023).

In terms of energy system optimization, advanced tools such as the grey wolf optimizer (GWO) and neural networks are used to accurately predict significant wave height and optimize tidal turbine performance (Dokur et al., 2024; Edmunds et al., 2020; Erriah et al., 2024; Pisetta et al., 2022). In addition, acceleration analysis using Pearson's coefficient and phasing, which is a key strategy in tidal systems for green ammonia production, allows for the stabilization of the energy generated and reduces costs, thereby optimizing its use (Driscoll et al., 2023; Driscoll et al., 2024; Pennock et al., 2022). Tools such as response surface methodology (RSM), Generalized Actuator Disk CFD (GAD-CFD), and Morphing Blade Model allow turbines to be simulated taking into account complex aerodynamic effects, improving the design of propellers and adaptive turbines to optimize efficiency and reduce wear (Jafari et al., 2023). These advances not only promote energy sustainability but also optimize tidal energy management (Sun et al., 2020; Xue et al., 2020; Pennock et al., 2023).

In terms of marine phenomenon forecasting, specialized tools such as the particle tracking model (PTM), power weighted rotor average (PWRA), and T-TIDE software are used. The PTM simulates and estimates the dispersion of Mytilus edulis larvae at various sites, providing crucial information for aquatic ecosystem management (Demmer et al., 2022). The PWRA analyzes ocean flow direction using a weighted energy average, providing key data for understanding hydrodynamic patterns (Evans et al., 2023). T-TIDE, for its part, generates accurate predictions of tidal level time series, optimizing resource use and reducing computational costs (Mejia-Olivares et al., 2020).

Tools such as Delft3D, PFOW and Firth of Clyde (FOC), FFT, and WEM were also used to simulate tidal flows in 1D, 2D, and 3D models. These tools made it possible to model tidal current velocities based on historical and temporal data, facilitating the assessment of tidal power and its distribution in different areas. The results obtained were fundamental for analyzing various energy scenarios and, in this way, reducing the costs associated with green ammonia production (Driscoll et al., 2024). In addition, the scales and periodicity of coherent structures in the flow were identified, providing valuable information for the optimization of energy models and the design of more efficient solutions (Ajiwibowo and Pratama, 2022; Lucas et al., 2022). The finite element method (FEM) and energy system model for remote communities (EnerSyM-RC) were also used to evaluate the structural stability of wind turbines and simulate 31 scenarios of hybrid systems with solar, wind, and tidal energy. These models, considering a full year, facilitated the analysis of a synergistic hybrid system for harvesting renewable marine energy (Cui et al., 2024; Garcia-Novo et al., 2023).

Similarly, Table 3 shows the 0-D model tool, which made it possible to simulate changes in water elevation within dam areas, optimizing the configuration of tidal power plants and evaluating various operating scenarios (Martí Barclay et al., 2023). This tool also facilitated the simulation of operational strategies for tidal range power plants, allowing the technical energy performance of the selected sites to be evaluated (Mejia-Olivares et al., 2020). In addition, it contributed to a simplified representation of the relationship between hydraulics and power generation in tidal range power systems (TRPS), offering fast and computationally efficient simulations that capture the key characteristics of tidal range system operation (Zhang et al., 2023).

In this regard, several key issues have been identified regarding the impact of tidal energy on sustainability and green production, as presented in Table 4. To analyze these aspects, a systematic review of the literature will be conducted.

First, 14 studies on energy efficiency in sustainability were compiled. One of the most relevant cases is that of the Isle of Wight, where the gross annual demand of 1.1 TWh requires a combination of solar photovoltaic (150 MW), offshore wind (150 MW), and tidal currents (120 MW) energy. This model has proven beneficial in reducing net energy shortages and surpluses (Coles et al., 2023). In addition, strategies have been proposed to optimize energy performance with limited resources, reducing dependence on fossil fuels. These measures allow for more efficient integration of renewable sources, such as propellers used in low-speed vessels (Erriah et al., 2024). Furthermore, proper turbine design has been shown to reduce annual energy production losses during low tide cycles by up to 11%, highlighting the importance of adapting technology to site characteristics (Evans et al., 2023).

Table 3: Tools compiled in the systematic review on tidal energy and sustainability

Tools	No. of studies
Co Pearson	3
0-D model	3
TPXO9	3
Acoustic doppler current profiler (ADCP)	2
Energy system model for remote communities (EnerSyM-RC)	2
Pentland firth and orkney waters (PFOW)	2
STAR CCM+	1
SolidWorks	1
Delft3D-4	1
Other tools	40
Total	58

Table 4: Effects and aspects compiled in the systematic review on tidal energy and sustainability

Effects and aspects found	No. of studies
Sustainability	22
Energy efficiency	14
Technology improvement	3
Circular economy	1
Sustainable design	4
Green production	14
Cost reduction	7
Optimization	7
Performance	6
Improved prediction	6
Total	42

Tidal energy is key to reducing energy deficits and improving storage in island systems, standing out for its stability in the face of seasonal variations and its impact on remote communities, thus facilitating access to renewable energy in remote communities (Garcia-Novo et al., 2023). On the other hand, the optimization of turbines through CFD analysis has increased efficiency by 5% and reduced friction losses, favoring more sustainable technologies (Khanjanpour and Javadi, 2020). Likewise, efficiency has been increased by 5%, which represents a significant advance in renewable systems. Reducing non-generation times to <20% improves supply stability, a key factor in long-term projects. In addition, achieving 40-50% energy conversion has allowed projects in Patagonia to compete with internationally renowned locations, boosting economic development and strengthening the region's position in the energy market (Martí Barclay et al., 2023).

In terms of technological improvement, two-way generation with pumping optimizes technical performance, although it requires additional energy, which implies a balance between production and consumption of resources (Mejia-Olivares et al., 2020). On the other hand, the Wing-in-Ground (WIG) effect has been shown to increase the efficiency of oscillating hydrofoils by 16.34%, thanks to the reduction of pressure on their underside and the optimization of force synchronization. However, its effectiveness depends on the distance to the plane of symmetry (Mo et al., 2024). In Western Australia, the combination of two complementary locations has reduced variability in tidal power generation, improving supply stability (Neill et al., 2021). Similarly, the use of predictable currents at strategic sites, such as Bristol, has been shown to enable more stable and efficient energy production, complementing other renewable sources (Newbold et al., 2021).

Another significant advance has been the optimization of morphed blades in tidal turbines, which reduce energy variability by more than 99% (Pisetta et al., 2022). Likewise, the impact of bias on rotor blades has been studied, and experimental data has made it possible to improve turbine design and increase their energy efficiency (Xu et al., 2023). A model based on genetic algorithms (GA) has managed to increase electricity generation in tidal energy systems (TRS) by more than 16% compared to fixed operation models (Xue et al., 2020).

Secondly, three studies have addressed technological improvements in sustainability. According to Neill et al. (2023), the META project has optimized designs adapted to complex local conditions, promoting more efficient renewable sources aligned with energy sustainability and carbon emission reduction goals. Similarly, Pitsikoulis et al. (2023) highlight the direct relationship between tidal turbine design and its impact on sustainability. It has been shown that, in the absence of bias, turbines achieve greater energy efficiency. In addition, Vandercruyssen et al. (2023) show an increase in generation efficiency through improvements in turbines and pumping systems, allowing them to adapt to sea level rise.

In terms of the circular economy, one study has explored how to close the waste cycle by converting waste into energy and useful by-products, such as fertilizers. This strategy minimizes waste, reduces pollution, and promotes sustainable agricultural practices (Reynolds et al., 2022).

Fourth, four studies have addressed sustainable design in tidal energy. One of the key aspects is the strategic selection of locations to minimize the impact on marine wildlife, which improves the social acceptance of projects (Lucas et al., 2022). Likewise, the combination of wind, solar, and tidal energy has proven to be an effective strategy for improving the stability of the electrical system, reducing carbon emissions (Pennock et al., 2022). In addition, the implementation of active control schemes has optimized the capacity of the electricity grid, allowing for better integration of renewable energies (Sun et al., 2020). Finally, reducing the environmental impact of turbine manufacturing through the use of recyclable or biological materials contributes to a greener industry (Walker and Thies, 2022).

As a fifth point, seven studies on cost reduction in green production were taken into account. Cui et al. (2024) implemented a hybrid system that increased the natural frequency of the wind farm by 6%, demonstrating its structural viability, achieving better energy production by lowering levelized energy costs, and promoting renewable marine energy. On the other hand, Driscoll et al. (2023) use advanced simulations to demonstrate how combining these sources can reduce operating costs in hybrid projects. A significant reduction in the cost of green ammonia production was also demonstrated, proving its industrial viability. The incorporation of anticorrelated sites such as Graemsay in Orkney resulted in a direct decrease of up to 12% in production costs (Driscoll et al., 2024).

The ease of implementing advanced technologies at lower cost has enabled more accessible and accurate monitoring of energy resources in marine environments. This optimizes the cost-benefit ratio and supports informed decision-making for the development of tidal energy projects (Lucas et al., 2022). In this context, the use of drones (UAVs) and videography, replacing traditional instruments such as ship-mounted ADCPs, has proven to be an efficient alternative, significantly reducing operating costs and minimizing the physical risks associated with the installation and recovery of equipment in marine environments (McIlvenny et al., 2023). In addition, these innovations have contributed to reducing dependence on fossil fuels, resulting in a substantial reduction in carbon emissions and reinforcing the commitment to environmental sustainability (Pennock et al., 2023). Finally, the coordination of multiple tidal range schemes within the electrical system has made it possible to reduce operating costs, especially in terms of fuel consumption, through dynamic adjustment of energy production based on demand and available supply (Zhang et al., 2023).

Sixth, seven studies highlight optimization in green production, emphasizing the impact of tidal energy on various sustainable processes. It has been observed that the dispersion of larvae varies in direction and distance depending on the six release sites, due to fluctuations in tidal currents, which can exceed 2 m/s in different regions. This finding underscores the importance of understanding ocean dynamics to minimize ecological impacts and optimize the use of marine resources (Demmer et al., 2022). In addition, the integration of tidal and wind energy improves energy predictability and significantly reduces costs in green ammonia production. Optimizing the design and operation of these hybrid systems also reduces their environmental impact, promoting industrial sustainability (Driscoll et al., 2023). A crucial advance in this area is the 96% reduction in hydrogen storage, eliminating the need for fuel cells thanks to the combination of renewable sources (Driscoll et al., 2023). Similarly, in Driscoll et al. (2024), green ammonia production has been optimized using out-of-phase tidal sites. In the Irish Sea, the use of the 100 locations with the highest energy and phase differences reduced the LCOA by 8%, consolidating the potential of these systems in the transition to a sustainable economy.

On the other hand, technological advances have optimized the electromagnetic and thermal performance of linear vernier machines, achieving improvements in force density and efficiency. In particular, configurations such as the 20/21 model have been shown to achieve higher force density, demonstrating their potential in renewable energy applications (Jafari et al., 2023). Likewise, sensitivity analysis to change showed a 90% variation in tidal turbine load fluctuations, allowing areas for improvement to be identified and adapted to various environmental conditions (Naberezhnykh et al., 2024). Finally, the 36% reduction in operational failures with more hours of use demonstrates progressive learning, which optimizes design, improves system reliability, and reduces costs, increasing the useful life of tidal technologies (Walker and Thies, 2021).

Finally, six studies were compiled on improving the prediction of marine renewable energy technology performance. The identification of the optimal site for implementation determined that the Lepar Strait is the most suitable location for installing a Gorlov helical turbine (GHT), due to its shallow waters, an average speed of 0.5 m/s, and an energy flow reaching 1.5 m/s, which improves the project's viability (Ajiwibowo and Pratama, 2022). On the other hand, the development of more efficient computational models has made it possible to optimize the operation and design of marine turbines. A HATT turbine model, with 98% accuracy, allows for more reliable prediction of the coupled behavior of floating turbines, facilitating their integration into marine energy projects (Brown et al., 2020). Similarly, a prediction tool has achieved 85% accuracy in assessing hazards associated with large-scale marine renewable energy projects (MRED). Although these activities increase ecosystem risk by 12%, the model could reduce these impacts by 5%, balancing energy expansion with marine habitat conservation (Declerck et al., 2022).

In terms of wave height prediction accuracy, an integrated model has been developed with an unprecedented accuracy of 98.5%, validating its applicability in the renewable energy sector (Dokur et al., 2024). In addition, advanced simulation of turbine performance in wind and tidal environments has improved the estimation of power characteristics and turbulence distributions, minimizing environmental impacts by more accurately modeling the turbulence and wakes generated (Edmunds et al., 2020). Finally, the correct identification of renewable energy sources not only optimizes generation but also reduces dependence on fossil fuels, contributing to a long-term decrease in greenhouse gas emissions (Kurniawan et al., 2024).

4. DISCUSSION

The advancement of tidal energy is determined not only by technological maturity, but also by its economic viability and public policy support. Tools such as the 0-D model, TPXO9, and ADCP reduce technical and financial uncertainties by optimizing the prediction of energy yields and operating costs (Khanjanpour and Javadi, 2020; Martí Barclay et al., 2023). This accuracy contributes to lowering the Levelized Cost Of Energy (LCOE), favoring the competitiveness of tidal power over other renewables and facilitating its insertion into electricity markets.

From a policy perspective, experiences such as EnFAIT in the United Kingdom show how the combination of economic incentives, rigorous environmental assessments, and public-private partnership schemes can reduce investment risks and align environmental sustainability with energy security (Jump et al., 2020; Demmer et al., 2022). These mechanisms are essential for generating regulatory certainty and attracting capital to a sector that requires significant initial investment.

Technological innovation reinforces these dynamics by increasing the efficiency of hydrodynamic simulations and operational optimization through CFD, GWO, and other advanced models. These advances have significantly reduced energy variability and computational and operational costs (Pisetta et al., 2022; Driscoll et al., 2024), strengthening both the reliability of supply and the justification for energy diversification policies. In turn, lower emissions and reduced dependence on fossil fuels generate positive externalities that support the allocation of tax incentives and public funds to the sector (Pennock et al., 2023).

Taken together, the evidence suggests that tidal energy should be understood as a strategic component of energy policy. Reducing the LCOE, designing stable regulatory frameworks, and promoting innovation are pillars for consolidating its competitiveness. In the future, advancing standardization, tax incentives, and international cooperation will be key to positioning it as an economically viable and environmentally sustainable alternative in the global energy transition.

5. CONCLUSION

Tidal energy has made significant progress in its integration into a sustainable model, standing out for its ability to provide electricity continuously and predictably. This allows for optimized use, reduced waste, and maximized performance of installed systems. In addition, it has growing economic viability and competitiveness, because it has driven its adoption on a larger scale as a renewable source.

The United Kingdom has also positioned itself as a leader in the development of tidal energy, promoting research and innovative projects for its long-term implementation. As an advanced nation, it has the infrastructure, knowledge, and resources necessary to optimize this technology, increasing its chances of success. Through various investments and tests, the country has explored its potential in the energy transition, consolidating its strategic role in the search for solutions.

On the other hand, key tools such as Co-Pearson, TPXO9, and the 0-D model are used for the study and optimization of this energy source. These technologies have been key to understanding how to increase the potential of tidal energy within a sustainable production model that controls carbon emissions and dependence on fossil fuels. In particular, the TPXO9 model has made it possible to predict tidal behavior with great accuracy, facilitating adequate infrastructure planning and efficient use of resources. It has established itself not only as a clean and renewable alternative but also opens up new opportunities for an energy future.

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