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A COMPREHENSIVE ANALYSIS OF HYDROGEN AS A PROPULSION SOURCE IN THE SHIPPING SECTOR

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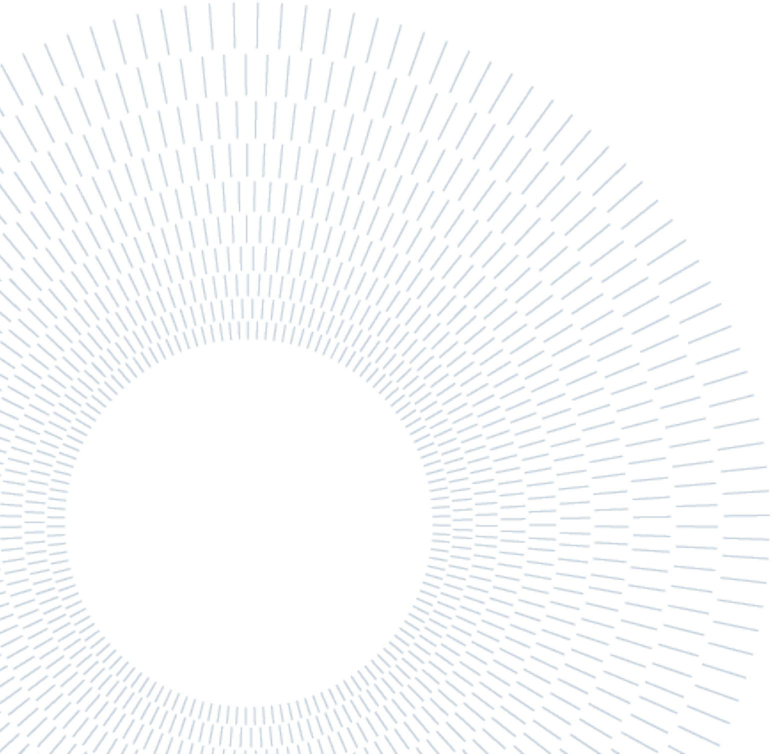

ABSTRACT

The transition to sustainable propulsion sources in the shipbuilding sector is vital to achieving decarbonisation goals. In this context, hydrogen has emerged as a promising alternative with the potential to significantly reduce emissions and improve air quality. This thesis presents a comprehensive analysis of hydrogen as a propulsion source in the maritime sector, incorporating a thorough literature review, a bibliometric analysis to identify trends and research gaps, and a detailed case study of a hydrogen application project on ships. By examining the current state of knowledge, identifying research trends, and providing real-world insights, this research offers a holistic understanding of the capabilities and implications of hydrogen adoption in sustainable shipping practices. The findings highlight the environmental benefits of hydrogen, including its zero greenhouse gas emissions and its potential to mitigate air pollution and associated health risks. This research aims to empower stakeholders to assess the feasibility and evaluate the profound implications of hydrogen adoption in the shipping sector, to accelerate progress towards sustainable and environmentally friendly practices.

Key-words: Sustainable propulsion sources, Decarbonisation goals, Hydrogen, Transition, Shipbuilding sector, Literature review, Bibliometric analysis, Case study.

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1 INTRODUCTION

Throughout history, fuels have played a pivotal role in advancing civilisation. From the discovery of fire to the invention of fossil fuels and renewable energy sources, humanity has relied on energy sources to power its progress. Fuels have been an essential part of human development. [1]

However, in the modern era, the world faces a pressing challenge: climate change. It is caused by the steady increase in the average temperature of Earth's atmosphere and oceans, primarily due to the accumulation of greenhouse gases, such as carbon dioxide (CO2). The combustion of fossil fuels, including oil, coal, and natural gas, is the primary source of these emissions.

In response to this global crisis, the European Union (EU) has set an ambitious goal of achieving zero net emissions of CO2 by 2050. This means reducing emissions and finding ways to actively remove carbon dioxide from the atmosphere, ensuring a healthier and more sustainable planet. To achieve this goal, the EU promotes the development of clean energy sources and technologies, such as renewable energy and energy storage. Additionally, the EU is investing in research, innovation, and more efficient emissions-reduction measures, such as emissions trading. [2]

Hydrogen fuel is a potential solution to help achieve this net-zero emissions target. Hydrogen is an abundant, clean-burning, and renewable resource that produces no emissions when burned. It can generate electricity, power vehicles, and provide heat and other forms of energy. Furthermore, hydrogen can serve as a means of storing excess energy from renewable sources, such as solar or wind, when these renewable sources are not actively generating power.

Recognising the potential of hydrogen as a crucial element in the future energy landscape, the European Commission has devised a comprehensive strategy for developing a hydrogen economy. This strategy encompasses plans for hydrogen production, transport, and storage. The Commission is also committed to investing in research and innovation to advance the technology further and reduce costs associated with hydrogen implementation. [3]

Hydrogen fuel is increasingly being adopted as a sustainable, clean energy source in transportation. Its versatility enables its use in various modes of transportation, including cars, buses, aeroplanes, and ships.

With its significant role in global trade, transportation, and leisure activities, the maritime sector faces a particular challenge. The heavy reliance on fossil fuels for propulsion in boats and ships contributes substantially to greenhouse gas emissions, exacerbating climate change. To address this urgent issue, the application of hydrogen as a clean energy source for marine propulsion has emerged as a promising solution.

This thesis aims to investigate the potential of hydrogen fuel as a sustainable and clean energy source in the maritime sector, particularly in ship propulsion. The project will conduct a case study to explore the technical feasibility, economic viability, and environmental benefits of using hydrogen for ship propulsion. The case study will examine the challenges faced and lessons learned during the implementation of hydrogen technology in the maritime sector. The study aims to provide practical insights into the potential of hydrogen as a sustainable and efficient power source for the maritime industry.

In addition to the case study, a bibliometric analysis will provide a comprehensive overview of the current knowledge of hydrogen application in marine propulsion. Analysing existing literature and research on the applications of hydrogen in marine propulsion, the study aims to offer valuable insights into the existing literature, scientific advancements, and related technological developments.

Overall, this project aims to contribute to the ongoing research and development in utilising hydrogen and fuel cells for sustainable and efficient power generation in the maritime industry. The findings of this project will provide valuable insights for policymakers, industry stakeholders, and researchers seeking to advance clean and sustainable propulsion systems in the maritime industry.

2 LITERATURE REVIEW

2.1 HYDROGEN

Climate change poses a significant global challenge, with rising temperatures linked to human-induced greenhouse gas emissions from fossil fuel combustion. To mitigate this issue, renewable energy sources have become a clean and abundant alternative to fossil fuels. The Paris Agreement sets the objective of limiting global warming to below 2 degrees Celsius, necessitating a substantial expansion of renewable energy.

Hydrogen has emerged as a promising alternative energy source in recent years, offering a means to reduce carbon emissions and transition to a low-carbon economy. Its potential to replace fossil fuels in transport, industry, and heating sectors makes it a key element in addressing climate change. Recognising this potential, the European Union has integrated hydrogen into its long-term emission reduction strategy, as outlined in the "EU Hydrogen Strategy." This strategy highlights the deployment of hydrogen technologies, scaling-up of production, and penetration into new sectors. [4]

As a chemical element abundantly available on Earth, hydrogen has diverse applications and is a highly efficient energy source. It can be produced through various methods, including steam methane reforming, electrolysis, and biomass gasification. Hydrogen can generate electricity in fuel cells, emitting only water vapour as a by product when used as a fuel. This characteristic positions hydrogen as a zero-emission energy carrier with the capacity to significantly reduce greenhouse gas emissions.

Hydrogen offers several advantages as a propulsion source, including its high energy density, enabling the storage of large amounts of energy per unit of weight. Furthermore, hydrogen can be produced from renewable energy sources, facilitating the utilisation of clean and sustainable "green hydrogen". [5]

Nevertheless, challenges still need to be solved in the adoption of hydrogen. Production, storage, and infrastructure require careful planning and investment. Due to its highly volatile nature, hydrogen necessitates appropriate handling and safety measures. Additionally, the costs associated with hydrogen production and fuel cell technologies may impede broad implementation, although ongoing advancements and economies of scale are expected to drive cost reductions.

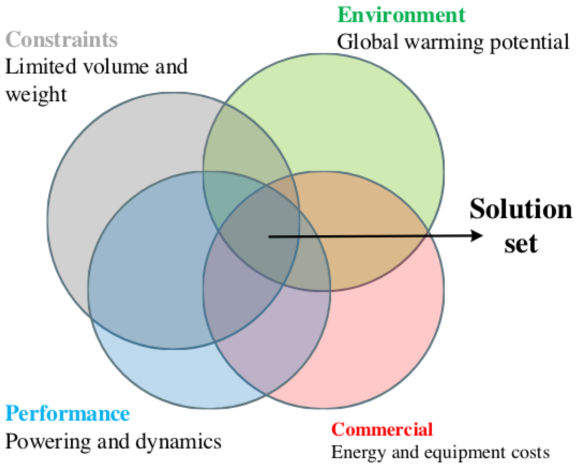


FIGURE 1 The complexity of alternative propulsion system design

SOURCE: [6]

2.1.1 HYDROGEN PRODUCTION

Hydrogen production is a crucial aspect of the global energy transition, with the potential to play a significant role in decarbonising challenging sectors such as heavy transport, industry, and heating. Various methods of hydrogen production exist, each with its characteristics and implications.

The most common method for hydrogen production is Steam Methane Reforming (SMR), which involves reacting methane (natural gas) with high-temperature steam. This process generates hydrogen and carbon monoxide, with the carbon monoxide further reacting to produce additional hydrogen through the water-gas shift reaction. SMR is widely used in industrial applications.

Electrolysis is another method used for hydrogen production. It involves splitting water into hydrogen and oxygen using an electric current. Electrolysis can be categorised into two types: alkaline electrolysis (AE), which uses an alkaline solution as an electrolyte, and proton exchange membrane electrolysis (PEM), which uses a solid polymer membrane.

Thermochemical processes are another avenue for hydrogen production. These processes utilise high temperatures and chemical reactions to produce hydrogen. One example is the sulfur-iodine cycle, which involves multiple chemical reactions to separate hydrogen from water molecules. Thermochemical processes are still in the research and development stage.

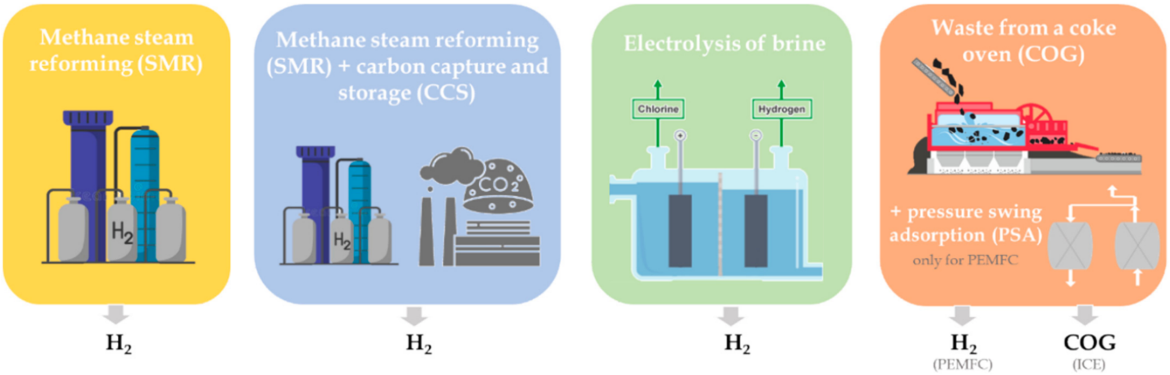


FIGURE 2 Some hydrogen sources

SOURCE: [5]

It is important to note that producing hydrogen using fossil fuels, known as grey hydrogen, can result in significant greenhouse gas emissions. Addressing this issue, low-carbon hydrogen has emerged as a solution to achieve climate goals. Low-carbon hydrogen comes in three types:

- Green hydrogen is produced using renewable electricity through electrolysis, where water is split into hydrogen and oxygen. This method relies on renewable energy sources such as solar and wind power, making it a sustainable and clean alternative to traditional hydrogen production. Green hydrogen does not produce carbon emissions during production, making it a pure form of hydrogen.
- Blue hydrogen is produced using natural gas, a fossil fuel, but incorporates carbon capture and storage (CCS) technology. This process captures carbon emissions from natural gas and stores them underground, reducing the carbon footprint of hydrogen production. While blue hydrogen is not as clean as green hydrogen, it still significantly reduces carbon emissions from difficult-to-electrify sectors.
- Turquoise hydrogen utilises natural gas with carbon capture and utilisation (CCU) technology. This process captures carbon emissions from natural gas and repurposes them for other valuable products. Although turquoise hydrogen is a low-carbon alternative, some emissions may not be captured and stored, making it less clean than blue hydrogen.

While green hydrogen is a promising long-term solution aligned with sustainability and renewable energy goals, blue hydrogen and other hydrogen production methods play a crucial role in transitioning to a low-carbon economy. They offer a bridge between traditional fossil fuel-based systems and a more sustainable energy future. Green hydrogen stands out due to its renewable energy integration, carbon neutrality, the potential for sector integration, policy support and investments, and growing public interest in addressing climate change.

2.1.2 HYDROGEN BENEFITS

Hydrogen as a propulsion source offers numerous benefits that can contribute to a sustainable and decarbonised future. These advantages span environmental, economic, and technological aspects, making hydrogen an attractive option for various sectors. The key benefits of hydrogen as a propulsion source are discussed below:

- Clean and Sustainable: Hydrogen is a pure energy carrier that produces no direct emissions of greenhouse gases or pollutants when used in fuel cells or hydrogen combustion engines. It offers a sustainable alternative to conventional fossil fuels, mainly when produced from renewable energy sources. The production of hydrogen using renewable energy (green hydrogen) ensures a minimal carbon footprint, aligning with global efforts to mitigate climate change.
- Environmental Impact: Hydrogen can be crucial in decarbonising various sectors, particularly transportation. When used in fuel cells, hydrogen produces no direct emissions, helping to reduce greenhouse gas emissions and improve air quality. Furthermore, hydrogen becomes a carbon-free fuel option when created using renewable energy sources, significantly reducing its environmental impact.
- Versatile Applications: Hydrogen exhibits versatility in its applications across various sectors, including transportation, industry, and power generation. It can potentially replace fossil fuels in many applications, including powering vehicles, providing heat for residential and commercial use, and serving as a feedstock for producing chemicals. This versatility makes hydrogen a promising candidate for decarbonising multiple sectors simultaneously.
- High Energy Density: One of the significant advantages of hydrogen is its high energy density per unit weight. This characteristic makes hydrogen well-suited for applications that require long-range or high-power outputs. It provides a viable alternative to conventional fossil fuels. This high energy density contributes to the practicality and efficiency of hydrogen as a propulsion source.
- Circular Economy Potential: Hydrogen can be produced from renewable or waste sources, such as biomass or organic waste, enabling a circular economy approach. Hydrogen production can help reduce waste and maximise resource efficiency by utilising waste streams or excess renewable energy. This circular economy potential of hydrogen further supports the transition to a sustainable and resource-efficient society.

- Technological Advancements: The development and adoption of hydrogen technologies drive innovation, research, and technological advancements. This includes advances in fuel cell technology, electrolysis, storage methods, and infrastructure. The progress in hydrogen-related technologies can have broader applications beyond propulsion, leading to advancements in renewable energy integration, energy storage, and industrial processes. The continuous development and improvement of hydrogen technologies foster the overall progress of sustainable energy solutions.

2.1.3 HYDROGEN RISKS AND LIMITATIONS

Having explored the numerous benefits of hydrogen as a propulsion source in the section before, it is crucial to take a comprehensive view of the topic by examining the associated risks and limitations. While hydrogen offers significant potential for decarbonising various sectors and achieving sustainable energy systems, it is essential to acknowledge and address the challenges of its adoption. Utilising low-carbon hydrogen presents several challenges and risks that must be carefully considered to enable its widespread adoption. These include limitations in infrastructure, safety risks, material considerations, storage and transportation challenges, energy efficiency concerns, cost implications, and carbon footprint considerations. By examining these risks, limitations, and considerations, we can comprehensively understand hydrogen's practicality, safety, and efficiency as a sustainable solution for transportation and other industries.

- Infrastructure Development: One of the significant challenges associated with adopting hydrogen as a propulsion source is developing an extensive infrastructure network for its production, storage, distribution, and refuelling. Unlike fossil fuel infrastructure, establishing a hydrogen infrastructure requires substantial investment, time, and planning.
- Storage and Transportation Challenges: Hydrogen's low energy density poses significant challenges for its storage and transportation. Due to this limitation, high-pressure or cryogenic storage methods are often required, which can be complex, expensive, and require additional safety measures. The highly flammable nature of hydrogen also requires specialised handling and transportation protocols to ensure safety. [7]
- Cost Implications: Currently, hydrogen production, particularly green hydrogen derived from renewable sources, can be more expensive than traditional fuels. The cost of technologies such as electrolysers, renewable energy sources, and infrastructure deployment contribute to the overall expense. However, as technology advances and economies of scale are achieved, the cost competitiveness of hydrogen is expected to improve over time, making it more economically viable as a propulsion source.

- Safety Risks: Hydrogen possesses unique safety considerations compared to conventional fuels. Its high flammability makes it potentially dangerous when mixed with air, posing fire and explosion risks. Moreover, hydrogen gas is odourless and colourless, making leak detection challenging. However, continuous advancements in safety measures, codes, and standards and the development of dedicated detectors and leak detection systems are improving safety protocols to mitigate these risks.
- Material Considerations: During the design phase of hydrogen systems, the risk of embrittlement and hydrogen-assisted cracking must be carefully considered. These phenomena can compromise the structural integrity and safety of hydrogen systems. The selection of appropriate materials capable of handling the anticipated loads and considering operating conditions like pressure, temperature, and mechanical loading becomes crucial. It's important to note that high-yield strength steel is particularly vulnerable to hydrogen-related damage, necessitating special attention in its use.
- Energy Efficiency: The overall energy efficiency of hydrogen as a propulsion source can be a limitation. Energy losses occur at various stages, including production, storage, and conversion. The efficiency of hydrogen fuel cells or combustion engines can also be lower compared to other propulsion technologies. Improving efficiency throughout the hydrogen value chain is an ongoing research and development focus, aiming to maximise energy output and minimise losses.
- Carbon Footprint: The carbon footprint of hydrogen production depends on the method used. Green hydrogen, produced through processes such as electrolysis powered by renewable energy sources, has no direct carbon emissions during use. However, certain production methods, such as steam methane reforming without carbon capture, can result in significant carbon emissions. To maximise the environmental benefits of hydrogen as a propulsion source, it is crucial to prioritise the adoption of low-carbon or carbon-neutral hydrogen production methods.

While there are risks and limitations associated with hydrogen as a propulsion source, significant progress is being made to address them through research, technology development, and policy support. Ongoing investments in innovation, infrastructure development, safety measures, efficiency improvements, cost reduction, and the adoption of low-carbon production methods are essential to fully harness the potential of hydrogen as a sustainable propulsion solution. [8]

2.2 POTENTIAL IMPLICATIONS OF HYDROGEN IN THE SHIPPING SECTOR

The shipping sector plays a vital role in global trade and commerce but also accounts for a significant share of greenhouse gas emissions and air pollution. According to the Fourth GHG Study by the International Maritime Organization (IMO), international shipping emissions reached 1056 million tons of CO2 equivalent in 2018, accounting for approximately 2.89% of annual GHG emissions. Without action, these emissions are projected to increase significantly, making decarbonisation a top priority for shipping organisations. In response, measures such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) have been implemented to promote more energy-efficient engines and reduce the carbon footprint.

The decarbonisation of marine fuels is key to meet the GHG reduction. However, some measures are being developed to implement promising alternatives to conventional fuels, promoting the transition to green transport. In this sense, the Hydrogen Strategy for a climate-neutral Europe of the European Commission establishes strategies based on regulations, investment, research, and innovation to promote decarbonisation in industry, transport, and energy generation in Europe, using H2 as energy vector. Hydrogen is becoming an essential source of energy, and scientists around the world are involved in making this compound commercially available because of its environmentally friendly nature.

In addition, its high mass-energy density, 120 MJ/kg (allowing for longer voyages without frequent refuelling), environmentally friendly combustion, and potential for production from renewable sources make it a viable option for the shipping industry. This characteristic makes hydrogen an attractive option for reducing greenhouse gas emissions and improving air quality in coastal regions and densely populated areas. However, the great importance of the energy system resides in its clean combustion, which, unlike other conventional fuels, only produces pure water and heat.

Unfortunately, the implementation of the hydrogen economy is not immediate, and although significant progress is currently being made, it is necessary to deal with technological, economic, and social barriers. The key issues that necessitate examination are hydrogen storage, transportation, and safety to enable the usability of hydrogen, especially storage in maritime applications. [9]

Among hydrogen-based propulsion technologies, hydrogen fuel cells (specifically PEMFCs) are considered a green power source for the 21st century. PEMFCs offer high electrical efficiency, low pollutant emissions, ease of installation, and rapid start-up. Several international projects, such as Nemo H2, Hydrogenesis, FreeCO2ast, and Zemship, have successfully integrated vessel fuel cell systems, demonstrating the feasibility of zero-emission hydrogen-powered ships.

Also, hydrogen internal combustion engines (ICEs) present an alternative to fuel cells. These engines can be adapted to run on hydrogen by making modifications such as substituting fossil fuel injectors with hydrogen injectors and incorporating a nitrogen purge and hydrogen accumulator. H2 ICEs offer advantages such as running with less pure hydrogen and utilising existing manufacturing infrastructure developed for petroleum-fueled engines. However, the environmental performance of hydrogen production depends on primary sources and specific production processes.

To facilitate the integration of hydrogen into the shipping sector, collaboration between industry stakeholders and regulatory bodies is vital. Developing international standards, guidelines, and regulations can ensure safety, promote interoperability, and address potential barriers to using hydrogen as a marine fuel. Governments, shipping companies, and research institutions must work together to establish a supportive regulatory framework that encourages hydrogen infrastructure investment and promotes the use of hydrogen-powered vessels.

Also, demonstration projects are pivotal in showcasing hydrogen's feasibility and viability in shipping. Several pilot projects involve deploying hydrogen-powered vessels in different maritime contexts. These projects provide valuable insights into the practical challenges and performance of hydrogen-fueled ships, helping to pave the way for broader implementation. Looking ahead, continued research, innovation, and collaboration will be necessary to overcome remaining obstacles and fully unlock the potential of hydrogen as a sustainable fuel in the shipping sector. [5]

Hydrogen holds great promise as a sustainable fuel in the shipping sector. When harnessed through fuel cell technologies, its clean and efficient characteristics offer a pathway to achieve zero-emission maritime transportation. Overcoming challenges related to storage, infrastructure, and regulations will be crucial to realising the full potential of hydrogen in the industry. By fostering collaboration, supporting demonstration projects, and advancing technological advancements, the shipping sector can transition to a greener, more sustainable future powered by hydrogen.

3 BIBLIOMETRIC ANALYSIS

3.1 MATERIALS AND METHODS

3.1.1 DATA COLLECTION

The selection discusses a research analysis conducted on May 17th to identify articles on hydrogen as a sustainable fuel for propulsion in the shipping sector. It was defined a set of search terms such as "hydrogen," "ship," "propulsion," "fuel," and "climate change" to identify relevant articles. It limited the publication date range to articles published between 1998 and 2023. The Web of Science identified 72 articles, which were analysed using bibliometric software to identify key trends, themes, and authorship patterns. The final research terms, after applying exclusion criteria, were:

"Climate change" and "Hydrogen" and "European commission" (Topic) or fuel and "Hydrogen" and production and storage and propulsion (Topic) or fuel and "Hydrogen" and propulsion and "ship" (Topic) or Hydrogen and"ship" and sea and coast and maritime (Topic) and Article (Document Types) and Archaeology or History or International Relations or Biodiversity Conservation or Geography Physical or Imaging Science Photographic Technology or Remote Sensing or Anthropology (Exclude – Web of Science Categories) and Humanities Multidisciplinary or Instruments Instrumentation or Telecommunications (Exclude – Web of Science Categories) and Computer Science Software Engineering (Exclude – Web of Science Categories) and Computer Science Interdisciplinary Applications (Exclude – Web of Science Categories) and Oceanography or Metallurgy Metallurgical Engineering or Ecology (Exclude – Web of Science Categories) and Engineering Multidisciplinary or Mathematics Interdisciplinary Applications or Multidisciplinary Sciences or Nanoscience Nanotechnology (Exclude – Web of Science Categories) and Physics Fluids Plasmas (Exclude – Web of Science Categories) and Engineering Aerospace (Exclude – Web of Science Categories).

3.1.2 BIBLIOMETRIC ANALYSIS

The following statistical programs were employed along with their corresponding analyses:

- **HistCite software** (version 2010.12.6; HistCite Software LLC, New York, NY, USA) (54): This software was utilised to calculate fundamental bibliometric indices, including the number of articles per year, per author, per country, per institution, and per journal. The results were presented in a comprehensive and detailed manner, accompanied by quality indicators such as the total global score (TGCS) and the local global score (TLCS). TGCS represents the total number of citations received by the analysed articles. In contrast, TLCS represents the number of citations received in the Web of Science (WoS) solely by the articles selected for the specific analysis carried out.

- **VOSviewer software**: This software facilitated the analysis of bibliographic and thematic linkages. It enabled the identification of significant articles through bibliographic linkage analysis. Notably, VOSviewer is advantageous for visualising bibliometric networks, as it generates clusters that illustrate the similarity between two or more articles based on the number of shared references. This program is unaffected by the timing of its usage, making it suitable for systematic literature reviews.
- **R software**: Bibliometric analysis was conducted using this package. It facilitated the identification of co-authorships, collaborations between countries, common keywords, and thematic analysis. Furthermore, it provided various types of graphical representations, such as networks, three-field plots, word clouds, tree maps, historiography, strategic diagrams, evolution maps, and world maps.

In conclusion, various statistical programs were employed to conduct thorough bibliometric analyses. The HistCite software package was utilised for calculating basic bibliometric indices and presenting the results with quality indicators. The VOSviewer software package aided in analysing bibliographic and thematic linkages, providing valuable insights into article relationships. The R software package was instrumental in performing comprehensive bibliometric analysis, including the identification of co-authorships, collaborations, common keywords, and thematic trends. These programs offered a variety of graphical representations, enabling the visualisation of networks, trends, and geographical distributions. Together, these statistical programs enhanced the understanding of the analysed literature and provided valuable insights.

3.2 RESULTS

Table 1 provides a summary of the results obtained from the review of documents in the WoS database. A total of 72 articles, distributed across 37 journals, were identified. These articles were authored by 291 individuals. On average, each document received 21.16 citations. The search also revealed the presence of 198 keywords and 326 author's keywords. The average number of authors per paper was around 1, with an international collaboration rate of 22.22%.

MAIN INFORMATION ABOUT DATA	
Timespan	1998:2023
Sources (Journals, Books, etc)	37
Documents	81
Annual Growth Rate %	8.67
Document Average Age	4.96
Average citations per doc	21.16
References	3242
DOCUMENT CONTENTS	
Keywords Plus (ID)	198
Author's Keywords (DE)	326
AUTHORS	
Authors	291
Authors of single-authored docs	5
AUTHORS COLLABORATION	
Single-authored docs	5
Co-Authors per Doc	3.96
International co-authorships %	22.22
DOCUMENT TYPES	
Article	72
Article; Book chapter	1
Article; Early access	4
Article; Proceedings paper	4

TABLE 1 Main information

SOURCE: Bibliometrix

3.2.1 BASICS INDICATORS

The first section of the results provides fundamental indicators, offering information on the yearly distribution of papers and citations and the number of papers and citations per author, institution, and country. The list includes journals that have published at least one article, along with the corresponding figures for publications, citations, and impact factor.

3.2.1.1 Years

A total of 77 articles were published between 1998 and 2023. The yearly distribution of publications varied from one to 20, with an average of 4.05 and a standard deviation of 4.97 (n = 77; range = 1-20; mean = 4.05; SD = 4.97). The first article was published in 1998, with only one publication (n = 1). In subsequent years, the number of publications remained relatively steady, with slight increases in 2010 (n = 3) and 2014 (n = 3), until 2016 when there was a gradual rise, reaching seven publications in 2020. Since 2020, there has been a significant increase in the number of articles, with a peak of 20 publications.

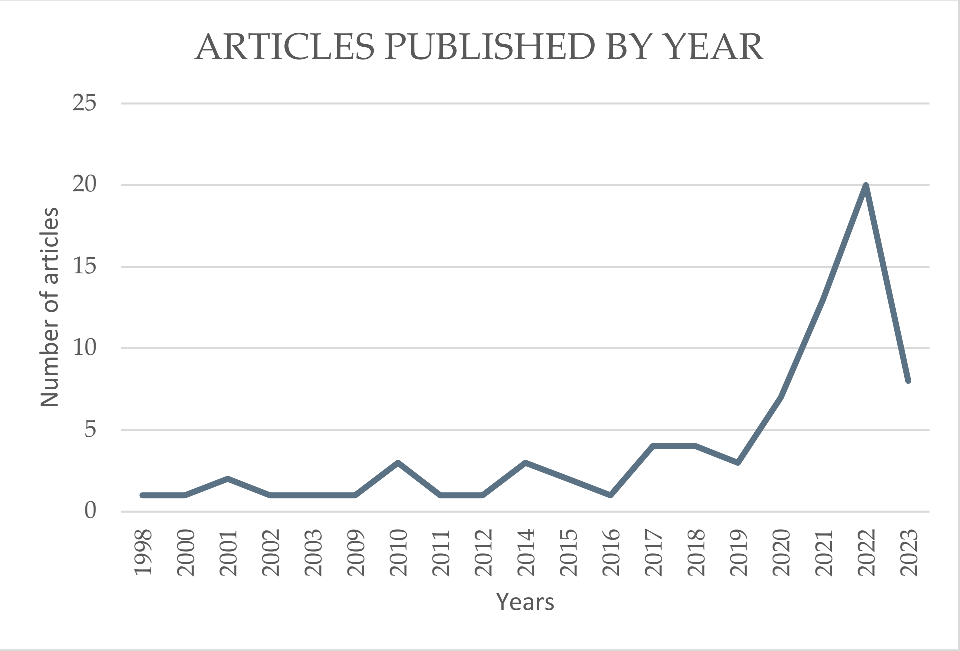


FIGURE 3 Articles published by year.

SOURCE: Histcite

The various fluctuations observed may be attributed to several factors. In 2011, the European Commission released a roadmap outlining the transition towards a competitive low-carbon economy by 2050. In 2014, the EU established a target to reduce greenhouse gas emissions within the EU by a minimum of 40% by 2030 (compared to 1990 levels), in conjunction with other energy objectives: achieving a minimum of 27% renewable energy share and improving energy efficiency by at least 27% (with a possibility of revising this target to 30% by 2020). Furthermore, the implementation of the legislation occurred between 2016 and 2017. [2]

Furthermore, the annual growth rate percentage is 8,67%, as we can see on Table 1.

3.2.1.2 Authors

A total of 291 researchers have contributed to the publication of at least one article on the topic of *"Hydrogen as a propulsion source in the shipping sector*". The number of publications varied from one to four, with an average of 1.1 and a standard deviation of 0.4 (range = 1-4; Mean = 1.1; SD = 0.4). Notably, Dall'Armi C, Taccani R, Pilidis P, and Sampath S emerged as the researchers with the most publications on this subject, each having four papers. Additionally, Brynolf S and Ahn J demonstrated significant contributions with three papers each, as illustrated in Table 2.

Author	Recs	TGCS
Dall'Armi C	4	53
Taccani R	4	53
Pilidis P	4	18
Sampath S	4	18
Brynolf S	3	57
Ahn J	3	54

TABLE 2 Authors with the most publications

SOURCE: Histcite

Brown LF had the most overall citations with 516, followed by Turnock SR with 150, Charpentier JF, Han JG and Tang TH with 103 and lastly Bassam AM, Phillips AB and Wilson PA with 102, as shown Table 3.

AUTHOR	Recs	TGCS
Brown LF	1	516
Turnock SR	2	150
Charpentier JF	1	103
Han JG	1	103
Tang TH	1	103
Bassam AM	1	102
Phillips AB	1	102
Wilson PA	1	102

TABLE 3 Authors with most Total Global Citations Score

SOURCE: Histcite

These authors work in different research fields. The most common is “Eenergy fuels” with 58 authors, followed by “Chemistry Physical” and “Electrochemistry” with 35 and 33 authors each one. The results are shown in Figure 4.

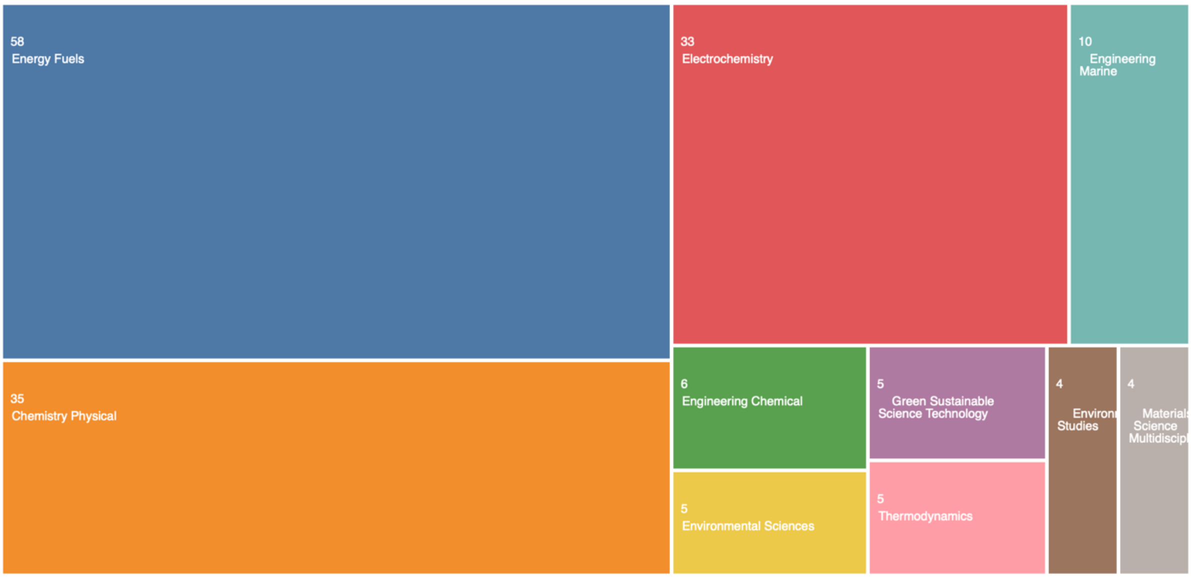
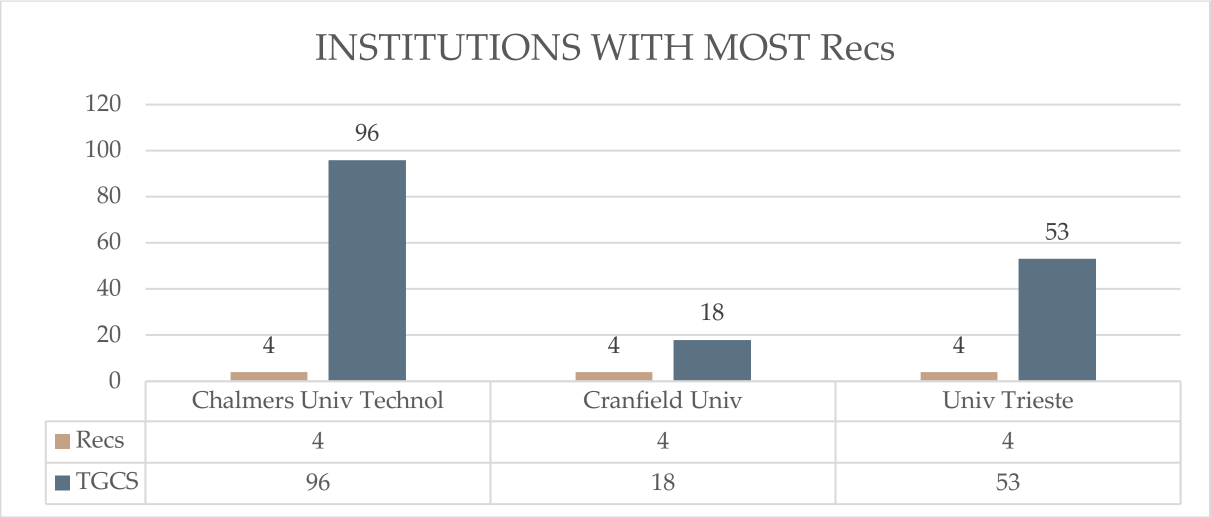


FIGURE 4 Publications per research field

SOURCE: Web of Science

3.2.1.3 Institutions

A total of 130 institutions have published articles. The number of publications varies from one to four, with an average of 1.16 and a standard deviation of 0.53 (range = 1-4; Mean = 1.16; SD = 0.53). Among these institutions, three of them have four articles, twelve have two articles, and the remaining institutions have one article each. Figure 5 illustrates this distribution, where a threshold of four publications (≥4) has been set. Chalmers University of Technology, Cranfield University, and the University of Trieste are the top universities with four published papers each.



	Chalmers Univ Technol	Cranfield Univ	Univ Trieste
Recs	4	4	4
TGCS	96	18	53

FIGURE 5 Institutions with most Recs

SOURCE: Histcite

Nonetheless, the total number of global citations amounts to 3,154, ranging from 0 to 516. The average number of citations is 24.26, with a standard deviation of 52.84 (range = 0-516; mean = 24.26; SD = 52.84). Using a threshold of 96 citations (≥ 94), it is evident that the University of California Los Alamos National Laboratory holds the highest number of global citations, totalling 516. Following closely is the University of Southampton with 150 citations, and the French Naval Academy and Shanghai Maritime University with 103 citations each. Additionally, NERC and Port Said University received 102 citations, while Chalmers University of Technology obtained a notable number of global citations, as depicted in Figure 6.

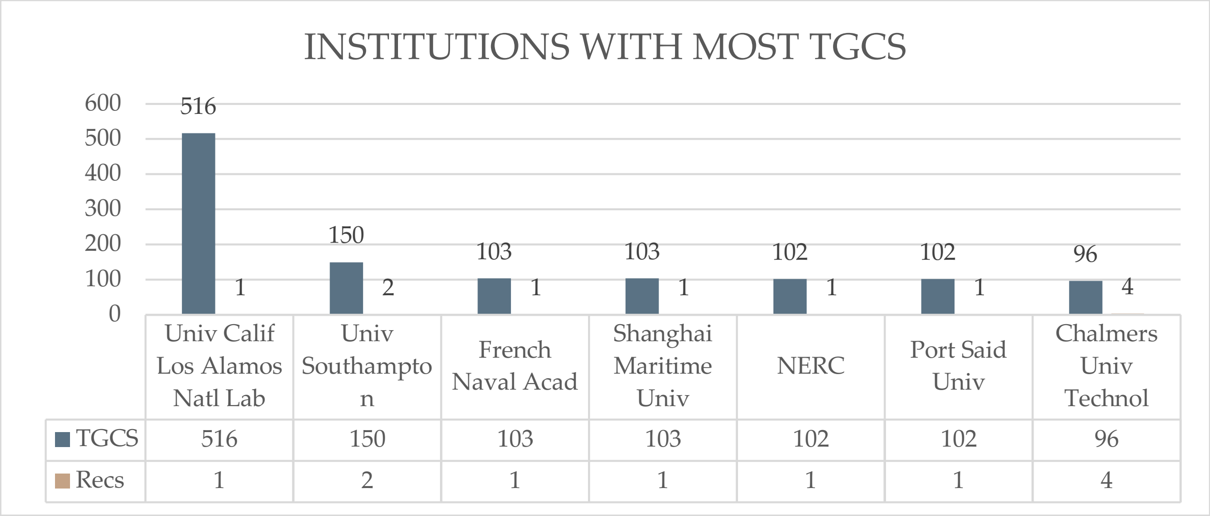


FIGURE 6 Institutions with most TGCS

SOURCE: Histcite

3.2.1.4 Countries

A total of 29 countries are represented in the publications of this Research Topic, with a cumulative count of 101 articles. The number of publications per country varies from one to 15, with an average of 3.48 and a standard deviation of 3.39 (N = 56; range = 1-15; mean = 3.48; SD = 3.39). By setting the threshold at two articles (≥4), the United Kingdom emerges as the country with the highest number of publications, totalling 15. Italy closely follows with 13 publications, while Spain contributed seven publications. People's Republic of China and South Korea each have six publications, Sweden has five, and Canada and Singapore each have four. These details are presented in Figure 7 below.

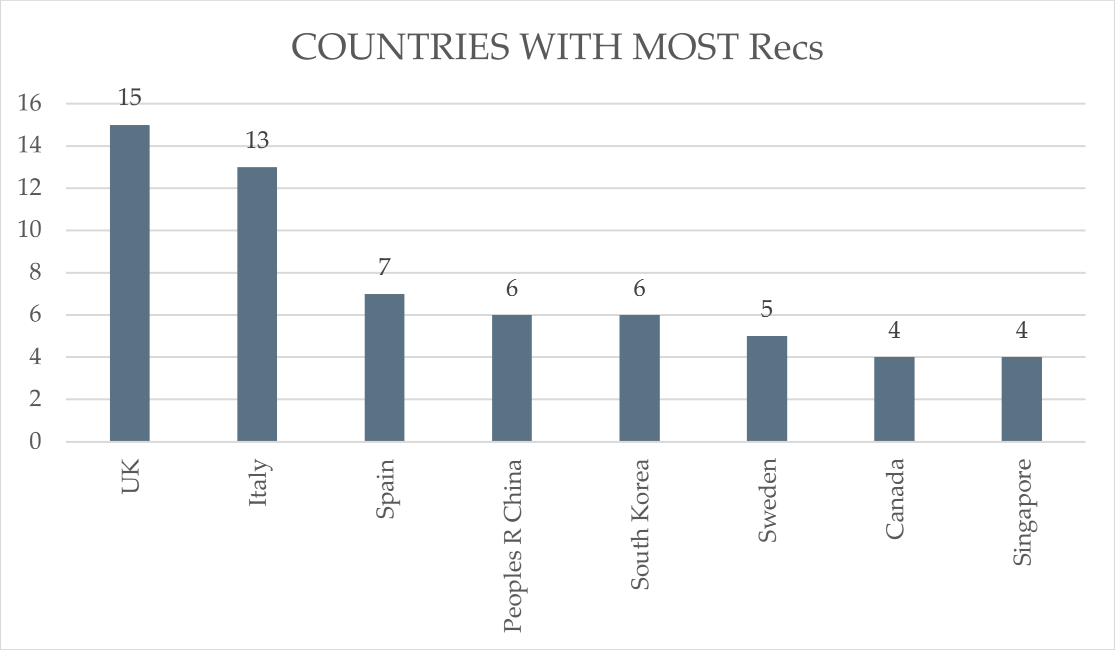
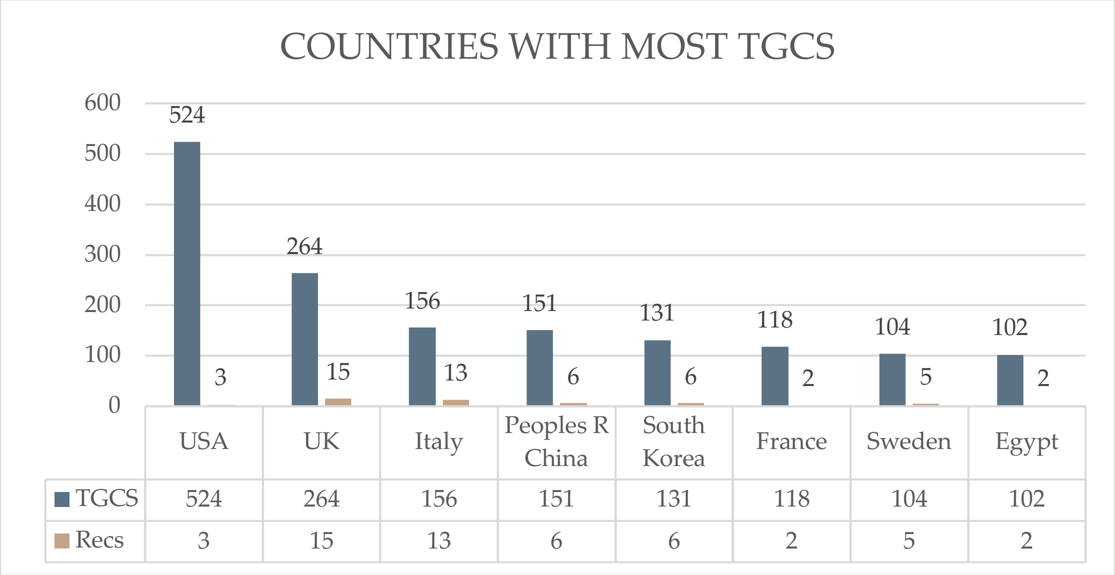


FIGURE 7 Countries with most Recs

SOURCE: Histcite

The citation count spans from zero to 524, with an average of 71.07 and a standard deviation of 108.71 (range = 0-524; Mean = 71.07; SD = 108.71). The countries that have garnered the highest number of citations in the WoS database, surpassing the threshold of 102 articles, are as follows: USA (n = 524), UK (n = 264), Italy (n = 156), People's Republic of China (n = 151), South Korea (n = 131), France (n = 118), Sweden (n = 104), and Egypt (n = 102) (refer to Figure 8).



	USA	UK	Italy	Peoples R China	South Korea	France	Sweden	Egypt
■ TGCS	524	264	156	151	131	118	104	102
■ Recs	3	15	13	6	6	2	5	2

FIGURE 8 Countries with most TGCS

SOURCE: Histcite

3.2.1.5 Journals

A sum of 81 journals have contributed to the publication of at least one article on this subject. By setting the threshold at three or more publications (n≥3), we can extract the corresponding details, which are presented in Table 4. The journals with the most articles published are *International Journal Of Hydrogen Energy (n=32), Energies (n=5), Energy Conservation and Management (n=4) and Applied Energy (n=3)*

JOURNAL	Recs
International journal of hydrogen energy	32
Energies	5
Energy conversion and management	4
Applied energy	3

TABLE 4 Journals with most publications (Recs ≥ 3)

SOURCE: Histcite

The articles published by each journal are linked to the total global citations they have received. Table 5, provided below, displays the journals ranked in descending order based on their total global citations, with a threshold set at TGCS = 28. The overall order of relevance remains largely unchanged, except for the introduction of *Journal of Power Sources and Renewable & Sustainble Energy Reviews* in the position three, four and five between Energies and *Energy Conservation and Management.*

JOURNAL	Recs	TGCS
International journal of hydrogen energy	32	1233
Energies	**5**	**140**
Journal of power sources	1	65
Renewable & sustainable energy reviews	**1**	**49**
Energy	1	42
Energy conversion and management	**4**	**33**
Applied energy	3	28

TABLE 5 Journals with most TGCS

SOURCE: Histcite

3.2.2 CO-CITATION ANALYSIS

In this section, the co-citation analysis is presented. Initially, the co-authorship network is depicted, followed by the networks showcasing cross-country collaborations. All of these findings are visually presented in the maps below.

3.2.2.1 Co-authorship

Among the 291 authors, only collaborations between authors who have co-authored one or more articles together are included in the presentation. The focus is on 11 co-authorship networks involving 33 researchers who have jointly published articles on this topic. These networks consist of one network with five collaborators, three networks with four collaborators, two networks with three collaborators, and five networks with two collaborators. Figure 9 illustrates these diverse collaborative networks.

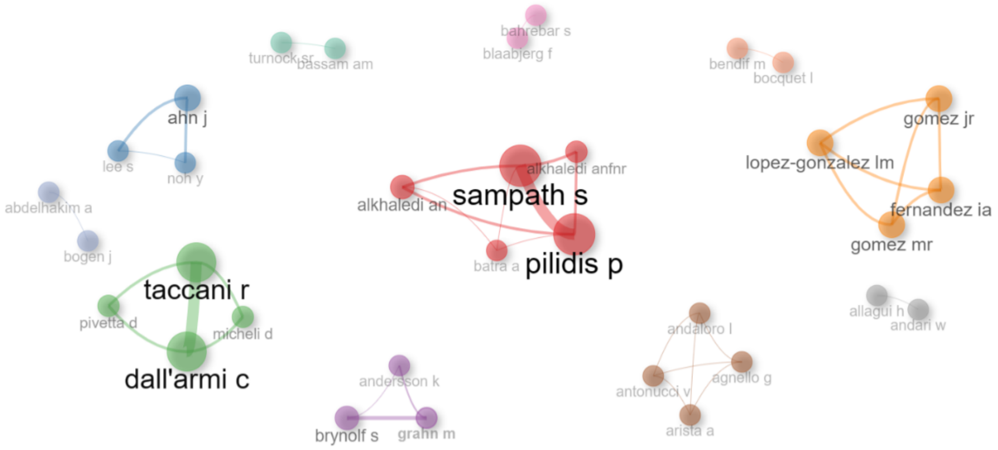


FIGURE 9 Co-authorship networks

SOURCE: Bibliometrix

3.2.2.2 Collaborations between countries

As shown in Figure 10, RU is the most collaborative country in terms of cross-country collaboration. There are also strong collaboration networks with China, Malaysia, USA, Canada and in general Europe.

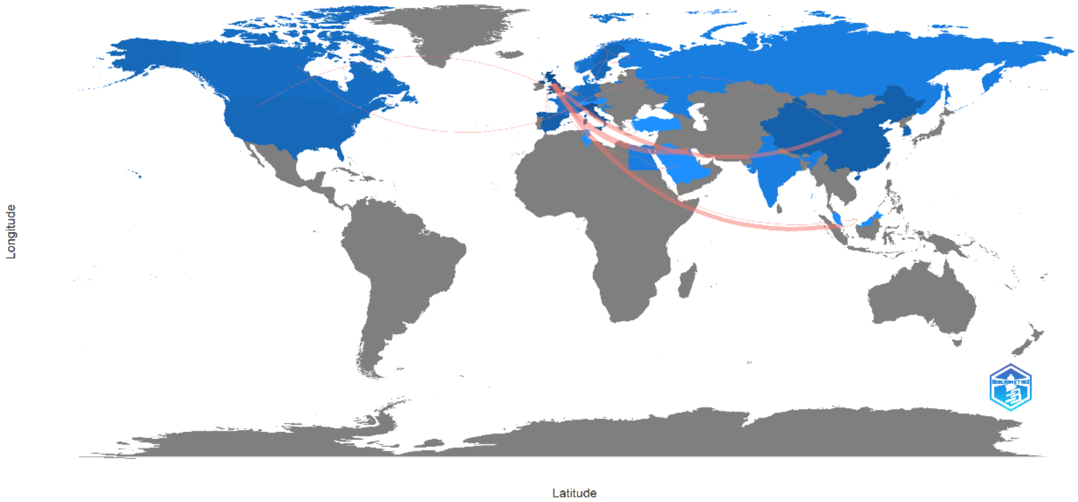


FIGURE 10 Country collaboration world map

SOURCE: Bibliometrix

3.2.3 THEMATIC ANALYSIS

In this section, the results of the thematic analysis are presented. Initially, the bibliographic coupling analyses are showcased, both in terms of documents and words. Subsequently, a strategic diagram illustrating the different themes is provided. All of these findings are visually represented through maps.

3.2.3.1 Bibliographic coupling for documents

A cut-off point of at least two citations per document (≥10) was established in the bibliographic coupling for documents. Subsequently, only those that were connected were selected, leaving the final analysis with 25 documents, which were distributed in six different clusters (one color per cluster). The size of the letter is proportional to the number of citations and to the frequency of connections between them. These clusters are shown in Figure 11.

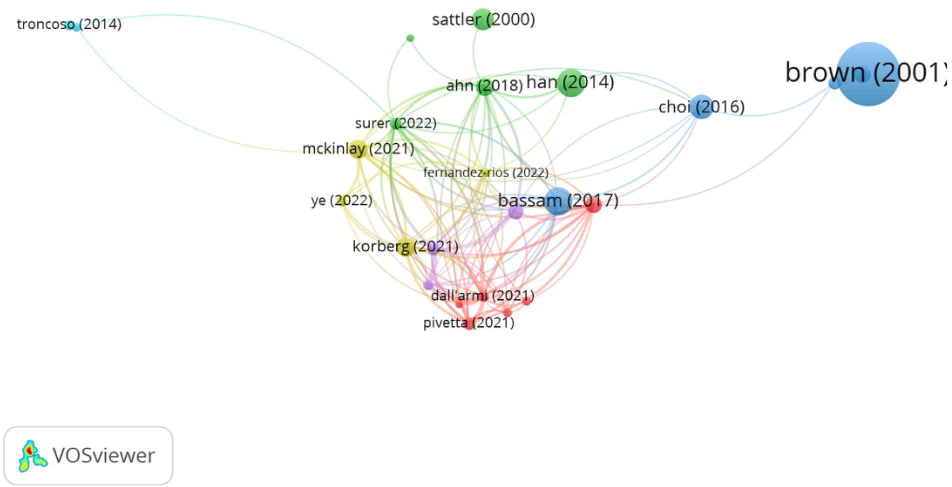


FIGURE 11 Bibliographic coupling analysis for documents (≥2 citations of publications).

SOURCE: VOSviewer

A thematic review of each cluster with the number of papers, citations and most prominent authors is provided below.

3.2.3.1.1 Cluster 1

In this case, I have gathered information from six articles focusing on innovative ship design, alternative fuels, and power generation systems in the maritime industry.

In the article "*High energy density storage of gaseous marine fuels: An innovative concept and its application to a hydrogen powered ferry*" the shipping sector is currently facing stricter limitations on pollutant and greenhouse gas emissions, prompting the need for innovative ship design, fuel choice, and power generation system. In this context, natural gas and hydrogen-based propulsion systems have emerged as promising alternatives for the medium and long term. Hydrogen, in particular, offers the advantage of zero total well-to-propeller emissions, making it an attractive option.

However, hydrogen's low volumetric energy density poses challenges to its widespread adoption. To overcome this, research has focused on exploring storage solutions for compressed hydrogen, as well as advancements in fuel cells for the efficient conversion of hydrogen into electricity. Fuel cells, such as polymer electrolyte membrane fuel cells (PEMFC), are highly efficient and environmentally friendly devices that can be integrated into hybrid power systems used in ship propulsion applications.

The International Maritime Organization (IMO) has imposed stricter limitations on nitrogen oxides (NOx) and sulfur oxides (SOx), necessitating innovative ship design and power generation systems to comply with these regulations. Hydrogen, when used to power fuel cells, is gaining recognition as an alternative fuel for achieving zero local emissions. In contrast, liquefied natural gas (LNG) is already being implemented as a marine fuel, particularly in Emission Controlled Areas (ECAs).

Storage of gaseous fuels, including hydrogen and natural gas, remains a crucial area of focus. The European project GASVESSEL® has developed an innovative solution for storing gaseous fuels with higher energy density than conventional containment system. This storage solution is particularly relevant for compressed hydrogen used in hybrid power systems. [10]

The *"Comparison of different plant layouts and fuel storage solutions for fuel cells utilisation on a small ferry"* article emphasises the importance of low-temperature polymer electrolyte membrane fuel cells (LT-PEMFC) fueled by hydrogen for achieving zero local emissions propulsion. However, the low volumetric density of pure hydrogen storage systems poses challenges for utilising LT-PEMFC in long-distance shipping. Researchers are exploring high-density hydrogen storage systems and refill processes to enable the use of fuel cells in long-distance operations. [11]

For the article *"Hybrid fuel cell and battery propulsion system modelling and multi-objective optimisation for a coastal ferry"*, hybrid propulsion systems, combining fuel cells and batteries, are being considered for coastal ships operating on short routes. These hybrid systems can significantly reduce greenhouse gas emissions. However, challenges related to hydrogen production costs and fuel cell degradation must be addressed for optimal performance. [6]

Talking about adopting fuel cell systems, in the article *"Multi-objective optimisation of hybrid PEMFC/Liion battery propulsion systems for small and medium size ferries"* particularly PEMFC, presents several challenges for maritime applications. High-purity hydrogen and onboard storage and safety concerns hinder the widespread implementation of such systems. Rapid load variations during fuel cell operation and the relatively high cost of fuel cells compared to traditional internal combustion engines make hybridisation with energy storage systems favourable. [12]

To develop zero-carbon marine fuel production and fueling systems, a study evaluates the technical and economic aspects of utilising a floating photovoltaic system for electricity production and hydrogen-driven propulsion systems. The aim of the article *"Techno-economic analysis of green hydrogen ferries with a floating photovoltaic based marine fueling station"* is to provide insights into sustainable and efficient propulsion systems for short-distance ferries. [13]

In conclusion, the shipping sector is undergoing significant changes to meet stricter emissions regulations. The adoption of alternative fuels, such as hydrogen and other renewable energy sources.

3.2.3.1.2 Cluster 2

These articles highlight the benefits of using alternative propulsion systems, particularly in reducing emissions and increasing efficiency.

One of the articles, *"An Energy Management System of a Fuel Cell/Battery Hybrid Boat"* discusses using a hybrid fuel cell-battery system for a low-power boat. The article emphasises the high efficiency and low emissions of fuel cells, making them an attractive option for powering ships. The hybrid system comprises a proton exchange membrane fuel cell (PEMFC) and a lithium-ion battery bank. The boat has been developed by the Zero Emission Ships (Zemships) project, funded by the European Union. The project aimed to provide technical solutions that are suitable for surface vessels.

The article highlights the advantages of using fuel cells as power sources in hybrid energy systems. Fuel cells have high efficiency and low emissions, making them an attractive option for powering ships. The article also discusses the different types of fuel cells, including PEMFC, alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and direct methanol fuel cells (DMFC). The low-temperature FCs, with an operating temperature range of 50–250 °C, include PEMFC, AFC, and PAFC. MCFC and SOFC operate in a high-temperature range of 650–1000 °C. [14]

Another article, *"A hydrogen fuelled LH2 tanker ship design"* focuses on the use of liquid hydrogen as a fuel for a tanker ship. The article highlights the advantages of liquid hydrogen, including the smaller volume and storage requirements compared to compressed hydrogen gas. The article discusses the Neom project, which is expected to commission the largest green hydrogen project by creating 650 tons of hydrogen each day. The hydrogen will be transported to other countries via seaborne using liquefied hydrogen carrier ships.

The article discusses the technical details of the LH2 tanker ship, which is 370 m long, 75 m wide, and draws 10.012 m under the fully loaded condition. The fully loaded displacement tonnage is 230,000 tonnes to transport 20,000 tonnes of hydrogen. Its power system is a combined-cycle gas turbine of roughly 50 MW. The size and displacement of the ship depend largely on its required capacity to transport liquefied hydrogen at 0.5 MPa. [9]

The third article, *"Molten carbonate fuel cell (MCFC)-based hybrid propulsion systems for a liquefied hydrogen tanker"* discusses the potential of fuel cells for use in marine transportation. The article specifically highlights the potential of MCFC technology, which is currently used in large-scale power plants and ship propulsion systems. The article discusses the use of MCFC-based hybrid propulsion systems for a liquefied hydrogen tanker. The article emphasizes the need for alternative propulsion systems in the shipping industry, particularly as greenhouse gases continue to cause sea-level increases and temperature increases in the atmosphere and oceans.

The article discusses the potential of hydrogen as a clean fuel for fuel cells. The technology of fuel cells is innovative and shows promise for use in next-generation power systems that emit few pollutants. High-temperature fuel cells are classified into two types: MCFC (molten carbonate fuel cell) and SOFC (solid oxide fuel cell). The practical application of MCFCs has been demonstrated for large-scale power plants and ship propulsion systems. MCFC technology is more mature than SOFC technology and is responsible for much of the power generated in South Korea, the United States, Europe, and Japan. [15]

The fourth article, "*Fuel cells going on-board*" provides an overview of the use of fuel cells for ship propulsion systems. The article discusses the different types of fuel cells and their potential applications in different types of ships. In the case of surface ships, for logistic reasons, the most acceptable fuel is diesel, except for special-purpose tankers carrying hydrogen or other gas with a high hydrogen content as cargo. Fuel cells using hydrogen and oxygen in a dead-end configuration have proved suitable.

The article emphasises the importance of finding alternative propulsion systems for ships that are both cost-effective and reliable. The article discusses the different stages of introducing new components or systems to the market, including "idealistic" projects, R&D projects, pilot and demonstration projects, and attempts at commercialisation. The use of fuel cells onboard merchant ships has not yet progressed beyond the stage of feasibility studies and demonstration. [16]

The articles highlight the importance of finding alternative propulsion systems for ships that are both cost-effective and reliable. Fuel cells have been identified as a promising alternative propulsion system due to their high efficiency and low emissions. They also discuss the potential of alternative fuels, such as liquid hydrogen, for powering ships. While the use of alternative propulsion systems in the shipping industry is still in the early stages, the articles suggest significant potential for these systems to be widely adopted in the future.

3.2.3.1.3 Cluster 3

In this cluster of articles, there is a common focus on exploring the potential of hydrogen as a propulsion system in various transportation sectors. The studies analyse hydrogen's advantages, challenges, and integration with other power sources, such as fuel cells and batteries, to create hybrid systems.

The article titled "*A comparative study of fuels for on-board hydrogen production for fuel-cell-powered automobiles*" compares various primary fuels as potential hydrogen sources for fuel cells in automobiles. Methanol, gasoline, diesel fuel, and other options are evaluated, considering their availability, cost, and characteristics. Although methanol appears to be the preferred fuel, substitute options are also considered to ensure an uninterrupted supply. [17]

In the article *“Cost-effective energy carriers for transport – The role of the energy supply system in a carbon-constrained world”* focuses on the role of the energy supply system in a carbon-constrained world and its influence on the cost-effectiveness of fuels and propulsion technologies in the transportation sector. It examines three alternatives: hydrogen, electricity, and biofuels/synthetic fuels derived from coal. The findings indicate that cost-effective choices depend on the dominant energy supply, such as solar, nuclear, or coal, with carbon capture and storage. [18]

The paper *“Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boats”* highlights the development and demonstration of a PEM fuel-cell-battery hybrid system for a tourist boat. This hybrid system integrates PEM fuel cells with Li-ion batteries to power the boat's propulsion system and auxiliary equipment. The article underscores the successes achieved, including power output and energy capacity, while acknowledging the challenges related to boat design and manufacturing costs. [19]

The *“Development of A Multi-Scheme Energy Management Strategy For A Hybrid Fuel Cell Driven Passenger Ship”* expands the discussion to the shipping industry, emphasising the need to minimise environmental impacts and enhance energy efficiency. It suggests incorporating fuel cells, particularly PEMFC, as the primary power source in hybrid propulsion systems for ships. Integrating fuel cells with batteries necessitates the development of an energy management strategy to optimise power allocation, affecting system dynamics, fuel consumption, and efficiency. [20]

Finally, the last article, *“Study and design of a hybrid electric vehicle (Lithium Batteries-PEM FC)”*, explores the design of a hybrid electric vehicle (HEV) that combines lithium batteries and a polymeric fuel cell system. This design aims to increase the vehicle's range of autonomy. Although not directly related to boats or ships, it aligns with the cluster's theme by examining the integration of fuel cells with other power sources in the transportation sector. [21]

Collectively, these articles contribute to our understanding of hydrogen as a propulsion option, either independently or in hybrid systems, across various transportation sectors. They highlight the advantages, challenges, and potential applications of hydrogen fuel cells while emphasising factors such as cost-effectiveness, energy efficiency, environmental impact, and power allocation strategies.

3.2.3.1.4 Cluster 4

The articles revolve around the environmental sustainability of alternative marine propulsion technologies, particularly focusing on hydrogen, ammonia, and methanol as potential fuels for decarbonising the shipping industry. These fuels are considered promising options for reducing greenhouse gas emissions and achieving zero-emission shipping.

"Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach" emphasises that shipping is a significant source of pollution globally. It highlights the potential of hydrogen as an energy carrier for energy transition and decarbonisation in maritime transport. It compares two hydrogen-based technologies, H2 Polymeric Electrolytic Membrane Fuel Cell (PEMFC) and H2 Internal Combustion Engine (ICE), with traditional diesel ICE. The results of the life cycle assessment (LCA) indicate that both H2-based technologies have the potential to be future substitutes for diesel, with the H2 ICE demonstrating superior environmental performance. [5]

The second article, *"Route to zero emission shipping: hydrogen, ammonia or methanol?"*, expands the discussion to include three potential zero-emission propulsion solutions: hydrogen, ammonia, and methanol. It addresses the challenges of integrating these fuels into ships, such as production and supply emissions. Hydrogen is considered a viable zero-emission solution, but issues related to NOx pollutants and storage requirements are highlighted. Ammonia and methanol are also explored as alternative fuels, with considerations given to their emissions, toxicity, and storage needs. [22]

The article titled *"System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping"* provides a system-level comparison of ammonia, compressed hydrogen (GH2), and liquid hydrogen (LH2) as fuels for polymer electrolyte fuel cell-powered shipping. It examines fuel cell systems, including GH2 PEMFC, LH2 PEMFC, and LNH3 PEMFC, which are powered by proton exchange membrane fuel cells. The study evaluates the efficiency, environmental impacts, and cost considerations of these systems. It also emphasises the importance of integrating battery systems to assist fuel cell stacks and meet power demands. [23]

The last one, *"Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships"*, focuses on the techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. It analyses various fuels, including methanol, dimethyl ether (DME), and ammonia, as alternatives to traditional options. Both battery electric (BE) and fuel cell (FC) technologies are considered potential replacements for internal combustion engines (ICE) in ships. The study examines the costs associated with different fuel options. It highlights the importance of considering factors such as total cost of ownership, ship types, utilisation rates, and future fuel costs when selecting propulsion systems. [24]

When considering all this information together, it is evident that hydrogen, ammonia, and methanol have shown potential as alternative fuels for reducing greenhouse gas emissions in the shipping industry. These fuels offer different advantages and challenges, including varying environmental impacts, storage requirements, toxicity concerns, and costs. The articles highlight the need for further research, technological advancements, and collaboration among stakeholders to overcome these challenges and drive the transition towards sustainable marine propulsion technologies.

3.2.3.1.5 Cluster 5

In a research paper titled *"Application of fuel cells with zero-carbon fuels in short-sea shipping"*, the viability of different fuel cell types in ship power systems is explored, specifically focusing on hydrogen and ammonia as zero-carbon fuels. The study reveals that fuel cell systems utilising grey hydrogen and grey ammonia are not environmentally friendly. However, systems that use blue and green versions of these fuels exhibit a lower environmental impact than diesel-powered ships. When green ammonia is used, CO2-eq emissions can be reduced by up to 84%.

The study also addresses the profitability aspect of these systems. It concludes that diesel-powered ships currently have the lowest total costs. The second most cost-effective option is a fuel cell system using blue ammonia, although costs can range from 27% to 43% higher than diesel-powered ships, depending on the type of fuel cell used. This cost difference is influenced by significant investment costs and equipment replacement expenses associated with fuel cell power systems. [25]

Another research paper, *"BoP incidence on a 240 kW PEMFC system in a ship-like environment"*, focuses on calculating characteristic curves for fuel cell modules. The study utilises experimental and theoretical data to optimise fuel cell system performance. The research highlights the need for decisive action in reducing greenhouse gas (GHG) emissions and addresses the importance of maritime transportation in this regard. The study also emphasises the significance of the International Maritime Organization's (IMO) quantitative GHG reduction strategy for international shipping. [26]

The study *"Thermodynamic analysis and assessment of an integrated hydrogen fuel cell system for ships"* discusses the increasing global energy demands and environmental impact of diesel generators in marine transportation. The research advocates for alternative power generation solutions to achieve sustainable transportation, particularly emphasising hydrogen fuel cells. The study conducts a comprehensive analysis to evaluate the proposed system's performance and determine its components' exergy efficiency. The results indicate that the solid oxide fuel cell (SOFC) exhibits the highest efficiency, followed by the pump and mixing chamber.

The integrated multigeneration system presented in this research combines various renewable energy sources to power long-distance shipping. The ship can be supplied with electricity and potable water by integrating a liquefied hydrogen-fueled SOFC system with a steam-producing cycle. The study also introduces heat recovery systems that drive the ship's thrust and refrigeration cycle. Using renewable power sources, such as solar or wind, ensures the sustainability of the produced hydrogen. The proposed system demonstrates overall energy and exergy efficiency values of 41.53% and 37.13%, respectively, and suggests increasing the combustor efficiency and investigating SOFC-based energy systems for even higher efficiencies. [27]

These articles collectively highlight the potential of fuel cell technology, particularly when powered by green hydrogen or green ammonia, in mitigating environmental impacts and achieving sustainable transportation in the maritime sector. They address the challenges associated with GHG emissions, cost-effectiveness, system optimisation, and the need for alternative power generation solutions to decarbonise the shipping industry.

3.2.3.1.6 Cluster 6

While the articles may not directly align with the thesis topic, I can still discuss their main topic briefly. The main topic of the articles revolves around the application of fuel cells, specifically proton exchange membrane fuel cells (PEMFC), in unmanned aerial vehicles (UAVs). The use of fuel cells in UAVs offers the potential for extended endurance and improved mission capabilities. The articles explore the combination of fuel cells with other power sources, such as batteries, in hybrid propulsion systems to enhance the UAV's performance. They also highlight the advantages of PEMFC, including their lower operating temperature and compactness, which make them suitable for mini-UAVs. Additionally, one of the articles introduces a novel hydrogen-powered UAV called the NederDrone, which utilises a PEM fuel cell and pressurised hydrogen storage. While these topics may not directly align with the thesis, they showcase the ongoing research and development in utilising fuel cells for sustainable and efficient power generation in unmanned aerial vehicles. [28] [29]

3.2.3.2 Strategic thematic analysis

Finally, the strategic diagram of the thematic area is analyzed in Figure 12 below. The photo is divided into four quadrants. The upper right quadrant contains driving themes, such as "system," "fuel-cell," "hydrogen," "emissions," "transport," "natural-gas," "systems," "alternative fuels," and "hydrogen fuel." These themes are relevant and well-developed within the research field. In the upper left quadrant, there are niche or specialized themes, including "gas-turbine," "multiobjective optimisation," and "power plants." These themes are relevant but underdeveloped, suggesting a need for further research in these areas, particularly in statistical aspects. The lower left quadrant consists of underdeveloped themes representing emerging or disappearing topics. One example you mentioned is "hydrogen application," which is identified as an emerging theme with significant potential for development. Finally, the lower right quadrant focuses on themes related to "ammonia," "behaviour," and "temperature."

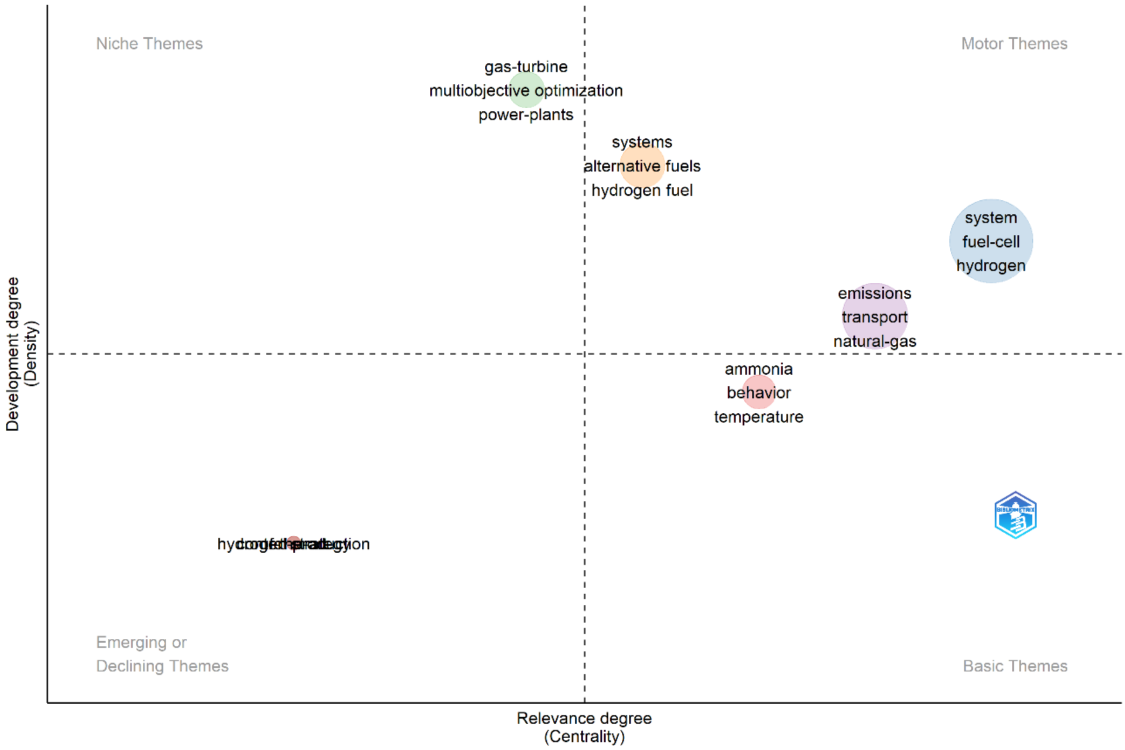


FIGURE 12 Strategic diagram

SOURCE: Bibliometrix

The analysed strategic diagram of the thematic area suggests that hydrogen is a relevant and well-developed theme within the research field. As a potential solution to help achieve net-zero emissions, hydrogen offers numerous benefits that can contribute to a sustainable and decarbonised future. Hydrogen's versatility in its applications across various sectors, its high energy density, and its clean and renewable nature make it an attractive option for propulsion, energy storage, and power generation.

3.2.4 ANALYSIS OF THE MAIN THEMATIC RESULTS

The articles reviewed discuss emerging trends in the maritime sector about stricter emission regulations and growing environmental concerns, with a focus on sustainable solutions. The main themes that follow are discussed below:

- Hydrogen as an Alternative Fuel: Hydrogen emerges as a promising alternative fuel for the medium and long term in the maritime industry. It offers the advantage of zero total well-to-propeller emissions, making it an attractive option. However, challenges related to hydrogen's low volumetric energy density, storage, transportation, and safety must be addressed. The articles highlight ongoing research into storage solutions for compressed hydrogen and advancements in fuel cells for the efficient conversion of hydrogen into electricity.
- Fuel Cells in Maritime Applications: Fuel cells, particularly polymer electrolyte membrane fuel cells (PEMFC), are highlighted as highly efficient and environmentally friendly devices that can be integrated into hybrid power systems for ship propulsion. They offer the potential for zero local emissions and align with stricter emissions limitations. Integrating fuel cells with other power sources, such as batteries, is explored to enhance energy efficiency and reliability.
- Hybrid Propulsion Systems: Hybrid propulsion systems, combining fuel cells and batteries, are considered for coastal ships operating on short routes. These systems have the potential to reduce greenhouse gas emissions significantly. However, challenges related to hydrogen production costs and fuel cell degradation must be addressed for optimal performance. Energy management strategies and power allocation optimisation play a crucial role in achieving efficiency in hybrid systems.
- Renewable Energy Integration: The articles emphasise the integration of renewable energy sources into maritime propulsion systems. Using floating photovoltaic systems for electricity production and hydrogen-driven propulsion systems is explored for short-distance ferries. This highlights the importance of sustainable and efficient propulsion systems in reducing the reliance on fossil fuels and achieving zero-carbon marine fuel production and fueling systems.
- Stricter Emissions Regulations and Environmental Concerns: One of the central themes in the articles is the increasing focus on stricter limitations on pollutant and greenhouse gas emissions in the shipping sector. Organisations like the International Maritime Organization (IMO) have imposed regulations to reduce nitrogen oxides (NOx) and sulfur oxides (SOx) emissions. This emphasis on environmental concerns

and the need for sustainable solutions drives the exploration of innovative ship design, fuel choice, and power generation systems.

- Storage Solutions for Gaseous Fuels: The storage of gaseous fuels, including hydrogen and natural gas, is a crucial area of focus. Innovations in storage systems, such as the GASVESSEL® project, aim to develop solutions with higher energy density than conventional containment systems. Compressed hydrogen storage, in particular, is highlighted as relevant for hybrid power systems in ships.
- Challenges of Hydrogen Fuel Cell Integration: While hydrogen fuel cells offer significant advantages, their integration into maritime applications poses challenges. High-purity hydrogen requirements, onboard storage considerations, safety concerns, and the relatively high cost of fuel cells compared to traditional internal combustion engines are identified as hindrances. Hybridisation with energy storage systems is seen as a favourable approach to address rapid load variations and enhance overall system efficiency.
- Alternative Fuels for Decarbonization: Apart from hydrogen, other alternative fuels such as ammonia and methanol are considered for decarbonizing the shipping industry. The articles evaluate their viability in reducing greenhouse gas emissions and achieving zero-emission shipping. Each fuel has its own advantages and challenges, including emissions, toxicity, storage requirements, and costs. Techno-economic assessments are conducted to evaluate their potential for future adoption.
- Environmental Impact and Cost Considerations: The environmental impact of alternative fuel and power generation systems is a key consideration. Life cycle assessments (LCAs) and techno-economic evaluations are conducted to compare different options' environmental performance and cost-effectiveness. These assessments consider factors such as emissions, energy efficiency, total cost of ownership, and infrastructure requirements.

The articles highlight the maritime industry's efforts to address stricter emissions regulations and environmental concerns through innovative ship design, alternative fuels, and power generation systems. Hydrogen, fuel cells, and other alternative fuels are being explored as promising options to achieve zero emissions and reduce the industry's environmental impact. However, challenges related to hydrogen storage, safety, cost-effectiveness, and fuel cell integration must be overcome for widespread adoption. The integration of fuel cells with other power sources, renewable energy integration, and hybridisation with energy storage systems are avenues being explored to optimise performance and efficiency. Techno-economic evaluations and environmental assessments play a crucial role in assessing the viability and feasibility of these solutions.

These topics demonstrate the increasing interest and exploration of hydrogen and fuel cells as promising solutions for reducing emissions and achieving sustainable transportation in various sectors. The studies highlight the advantages, challenges, and potential applications of hydrogen fuel cells while emphasising factors such as cost-effectiveness, energy efficiency, environmental impact, and power allocation strategies. Further research and development efforts are necessary to overcome the challenges and drive the transition towards sustainable and efficient propulsion systems.

4 E-SHyIPS

The e-SHyIPS (Effective Introduction of Hydrogen in the Passenger maritime transport Sector) project is a 48-month initiative to accelerate hydrogen adoption in the marine passenger transport industry. The project recognises the crucial role of the naval sector in achieving a competitive and resource-efficient transport system within the European Union (EU). The project focuses on developing and implementing hydrogen-based fuels as a viable and sustainable solution to address the growing need for reducing emissions, particularly carbon dioxide (CO2).

The project has five main objectives:

- Generate Knowledge: The project aims to fill the gaps in the maritime transport sector's normative and technical hydrogen-related knowledge. It seeks to define a comprehensive and standardised database and a methodology for gathering data on the arrangement and installation of hydrogen-based fuel systems for propulsion and auxiliary purposes.
- Provide Experimental Data: The project intends to generate unique and valuable experimental data to establish mandatory criteria for arranging and installing machinery, equipment, and systems for vessels operating with hydrogen-based fuels. The objective is to minimise risks to the ship, crew, passengers, and the environment.
- Pre-Standardization Plan: e-SHyIPS aims to propose a pre-standardization plan for updating the International Code of Safety for Ships using Gases or Low-Flashpoint Fuels (IGF Code) specific to hydrogen-based fuel passenger ships. This plan will contribute to developing international regulations and standards that ensure hydrogen-powered vessels' safe and efficient operation.
- Roadmap for Hydrogen Economy: The project aims to create a roadmap that outlines the steps required to boost the adoption of hydrogen-based fuels in the maritime sector. The roadmap will support the transition toward a hydrogen economy by identifying key milestones and strategies and contribute to a cleaner and more sustainable maritime industry.
- Develop Tools and Models: e-SHyIPS seeks to develop computational fluid dynamics (CFD) models and other tools that support ship design and safety assessment. By leveraging the potential of Complex System Simulation software and High-Performance Computing (HPC), the project aims to enhance the understanding of hydrogen-powered ship systems and ensure their safe integration.

The e-SHyIPS project follows a structured program based on five main pillars of research. Each pillar represents a distinct line of investigation that contributes to the overall project objectives:

- Pillar 1: State-of-the-Art and Theoretical Studies
- Pillar 2: Ship Design Experiments
- Pillar 3: Safety System Experiments
- Pillar 4: Material and Components Experiments
- Pillar 5: Port-Bunkering-Ship Interface Experiments

The project adopts an ecosystem approach involving key stakeholders from the maritime and hydrogen sectors, research institutions, and industry. This collaborative effort ensures a comprehensive understanding of the challenges and opportunities associated with the adoption of hydrogen in the maritime passenger transport sector.

The project incorporates theoretical studies, simulation and laboratory experiments, and real-world testing to gather knowledge, develop guidelines, and establish best practices. It leverages digital twin models, climate chambers, and physical refuelling stations to simulate and evaluate different scenarios, design alternatives, and safety considerations. The expected outcomes of the e-SHyIPS project include contributing to the development of a normative framework specific to hydrogen-based fuels in the maritime sector, guiding the arrangement, installation, and use of machinery, equipment, and systems to ensure the safety, reliability, and environmental sustainability of hydrogen-powered vessels. The project aims to create a roadmap that outlines the steps required to boost the adoption of hydrogen-based fuels in the maritime sector, support the transition toward a hydrogen economy, and contribute to a cleaner and more sustainable maritime industry.

4.1 CASE STUDY

e-SHiYPS is a project aimed at exploring the feasibility of using hydrogen as a fuel for maritime transport, with the goal of reducing the environmental impact of the shipping industry. The project is working closely with the International Maritime Organization (IMO) to identify gaps in current standards and explore areas that have not yet been explored.

The shipping industry is responsible for approximately 2.5% of global greenhouse gas emissions, with the majority of these emissions coming from the burning of fossil fuels. As the demand for shipping continues to grow, it is essential to find more sustainable ways to power vessels. Hydrogen is a promising alternative, as it can be produced using renewable energy sources and is emissions-free when used as a fuel.

To determine the feasibility of hydrogen as a fuel for maritime transport, e-SHiYPS is studying three different scenarios that represent different types of vessels and usage patterns.

Scenario 1: Small Scenario:

The boat in this scenario is designed to work mainly in rivers and close to the shoreline. It uses compressed hydrogen at 350 bar as fuel. Refueling is done on a daily basis, and it takes around 30 minutes.

Scenario 2: Medium Scenario

This scenario involves a ferry that is a moderate large vessel mainly transporting vehicles in the Mediterranean. Initially, the idea was to use compressed hydrogen at 700 bar, as in the small scenario. However, due to the low energy density of compressed hydrogen, the decision was made to use liquefied hydrogen instead. Refueling is done every two to three days, and it takes around an hour and a half.

Scenario 3: Large Scenario

This scenario involves a luxury cruise line that will also use liquefied hydrogen as fuel. Refueling is done every eight days, as the destinations are farther away and some areas are difficult to service. The project is trying to get the refueling time down to under 3 hours.

All three scenarios utilise fuel cells that are directly fed, generating electricity from both the cathode and anode sides. Currently, the project is using a multi-stack of proprietary fuel cells developed by a partner in Germany. These cells generate electricity that powers the electric propulsion.

Fuel cells are an attractive alternative to internal combustion engines for several reasons. They are more efficient, producing more energy from the same amount of fuel, and they produce fewer emissions. They are also quieter and require less maintenance.

Producing hydrogen is an energy-intensive process, and e-SHiYPS is primarily looking to use renewable energy sources. Three large factories planned for northern Germany, Finland, and Norway will exclusively use renewables to produce hydrogen. The main question is whether producing hydrogen is actually energy-efficient. There are several options being considered, but the goal is to use renewable energy sources primarily.

One of the challenges of using hydrogen as a fuel is that it has a low energy density compared to fossil fuels. This means that more hydrogen is required to produce the same amount of energy. However, this problem can be mitigated by using fuel cells, which are more efficient at converting hydrogen into energy.

There are several options for refueling with compressed hydrogen:

- The first option is interchangeable tanks. These tanks are long tubes and racks that are lifted and placed onto the roof of the vessel.
- The second option is through a pipeline or direct transfer of compressed hydrogen from another storage tank somewhere within the port.
- The third option is to use mobile tankers, which are semi-trucks that carry liquefied hydrogen. A compressor is attached to convert the liquefied hydrogen to gas, which is then transferred to the vessel.

However, only a few tanks have been approved so far. Type three and type four tanks are typically used when refueling with compressed hydrogen. The main issue is ensuring that these tanks meet ISO standards and are approved by the International Maritime Organization (IMO). Unfortunately, only a few tanks have been approved so far. In the automotive industry, there are more options available, such as composite tanks made of carbon fiber and kevlar reinforcement. These tanks can handle higher pressures, but their feasibility and practicality have not yet been fully proven.

For medium and large scenarios, there are two options for refueling:

- The first option still uses tankers, which is not very efficient for large vessels as it takes two or three hours to refuel. Such as in the Mediterranean, Greece, Italy, and even Puerto de Valencia in Spain, using trucks to transfer is still preferred.
- The second option uses a crane to directly pipe from a storage center into the vessel, which is the preferred method. However, this method requires a large amount of infrastructure. In areas where infrastructure can be built and there are enough financial resources, that's the preferred method.

Safety is a primary concern with using hydrogen as a fuel, due to its high flammability. To ensure safety, large cryogenic coolers, reinforced hulls, sealed bulkheads, and ventilation shafts are necessary. With compressed hydrogen, tanks can be placed on the roof, making it safe in case of an explosion. However, with liquefied hydrogen, the tanks have to be inside the hull, and the design has to be such that in the events of an explosion, the vessel doesn't essentially break into two parts.

While the project is not currently building, all designs must go through the same risk assessment and analysis required if they were to be built. The technology maturity will likely be there in five to seven years, but realistically, the project is ten years away from seeing the necessary infrastructure to support hydrogen as a fuel for maritime transport.

4.2 DISCUSSION

The case study presented in section 4.1 of this document discusses the e-SHyIPS project, which is exploring the feasibility of using hydrogen as a fuel for maritime passenger transport. The project aims to reduce the environmental impact of the shipping industry by reducing its carbon footprint and reliance on fossil fuels. The project is studying three different scenarios that represent different types of vessels and usage patterns, and all three scenarios utilise fuel cells that are directly fed, generating electricity from both the cathode and anode sides.

Producing hydrogen is an energy-intensive process, and e-SHyIPS is primarily looking to use renewable energy sources. The project incorporates theoretical studies, simulation, and laboratory experiments, and real-world testing to gather knowledge, develop guidelines, and establish best practices. The study of existing literature and research, along with the technical feasibility, economic viability, and environmental benefits of using hydrogen for ship propulsion, contributes to the ongoing research and development in utilising hydrogen and fuel cells for sustainable and efficient power generation in the maritime industry.

The expected outcomes of the e-SHyIPS project include contributing to the development of a normative framework specific to hydrogen-based fuels in the maritime sector and guiding the arrangement, installation, and use of machinery, equipment, and systems to ensure the safety, reliability, and environmental sustainability of hydrogen-powered vessels. While there are several challenges to overcome, including the limited options for refuelling and safety concerns associated with using hydrogen as a fuel, e-SHyIPS has significant implications for the shipping industry's future.

The adoption of hydrogen in the maritime industry will require significant investment to create the necessary infrastructure for hydrogen production, storage, and distribution. However, the potential of hydrogen and fuel cells in mitigating environmental impacts and achieving sustainable transportation in the maritime sector is considerable. Continued research and development, including the e-SHyIPS project, will be crucial in advancing the technology further and reducing the costs associated with hydrogen implementation.

Overall, the e-SHyIPS project is a promising initiative that will contribute to the development of a normative framework specific to hydrogen-based fuels in the maritime sector, guide the arrangement, installation, and use of machinery, equipment, and systems, ensure the safety, reliability, and environmental sustainability of hydrogen-powered vessels. With continued research and development, adopting hydrogen as a fuel source in the maritime industry could lead to a more sustainable future for the shipping industry, reducing its carbon footprint and reliance on fossil fuels.

e-SHiYPS is exploring a promising avenue for reducing the environmental impact of maritime transport. The project has the potential to pave the way for a more sustainable future for the shipping industry, reducing its carbon footprint and reliance on fossil fuels. However, there are several challenges to overcome, including the energy-intensive process of producing hydrogen, the limited options for refueling, and the safety concerns associated with using hydrogen as a fuel. With continued research and development, e-SHiYPS could have significant implications for the shipping industry's future.

5 CONCLUSION

In conclusion, the maritime industry faces a critical challenge in reducing its environmental impact and achieving sustainable transportation. Stricter regulations and environmental concerns have driven the exploration of innovative ship designs, alternative fuels, and power generation systems. Hydrogen and fuel cells, along with other alternative fuels, have emerged as promising options to achieve zero-emission shipping.

This document provides an in-depth overview of the potential of hydrogen in the maritime industry. The increasing interest and exploration of hydrogen and fuel cells reflect the urgent need to reduce greenhouse gas emissions and achieve sustainable transportation in the maritime sector.

Hydrogen and fuel cells are among the most promising options for achieving zero-emission shipping. The advantages of hydrogen as a propulsion source include its environmental impact, energy storage and grid balancing, versatile applications, clean and sustainable nature, high energy density, renewable energy integration, energy security and independence, technological advancements, circular economy potential, and global collaboration.

However, adopting hydrogen in the maritime sector poses several challenges related to production, storage, and infrastructure, safety risks, material considerations and transportation challenges, energy efficiency concerns, cost implications, and carbon footprint considerations. To address these challenges, integrating fuel cells with other power sources, renewable energy integration, and hybridisation with energy storage systems are being explored to optimise performance and efficiency. Techno-economic evaluations and environmental assessments play a crucial role in assessing the feasibility and viability of these solutions.

The e-SHyIPS project is an ongoing initiative to accelerate hydrogen adoption in the marine passenger transport industry. The project aims to fill knowledge gaps, generate experimental data, establish best practices, and contribute to developing a normative framework specific to hydrogen-based fuels in the maritime sector. The project incorporates theoretical studies, simulation and laboratory experiments, and real-world testing to gather knowledge, develop guidelines, and establish best practices.

The expected outcomes of the e-SHyIPS project include contributing to the development of a normative framework specific to hydrogen-based fuels in the maritime sector, guiding the arrangement, installation, and use of machinery, equipment, and systems to ensure the safety, reliability, and environmental sustainability of hydrogen-powered vessels. The project aims to create a roadmap that outlines the steps required to boost the adoption of hydrogen-based fuels in the maritime sector, support the transition toward a hydrogen economy, and contribute to a cleaner and more sustainable maritime industry.

However, several challenges must be addressed to ensure the widespread adoption of hydrogen and fuel cells in the maritime sector. The ongoing research and development, including the e-SHyIPS project, will play a crucial role in advancing the technology further and reducing the costs associated with hydrogen implementation. Achieving zero-emission shipping is a critical goal for the maritime industry and requires collaborative efforts from stakeholders, policymakers, and researchers to develop and implement sustainable and efficient propulsion systems.

The potential of hydrogen and fuel cells in mitigating environmental impacts and achieving sustainable transportation in the maritime sector is considerable. The challenges and opportunities associated with the adoption of hydrogen in the maritime passenger transport sector have been discussed in detail in this document. Hydrogen and fuel cells represent promising solutions for the shipping industry's environmental challenges. Continued research and development are necessary to overcome the challenges and drive the transition towards sustainable and efficient propulsion systems.

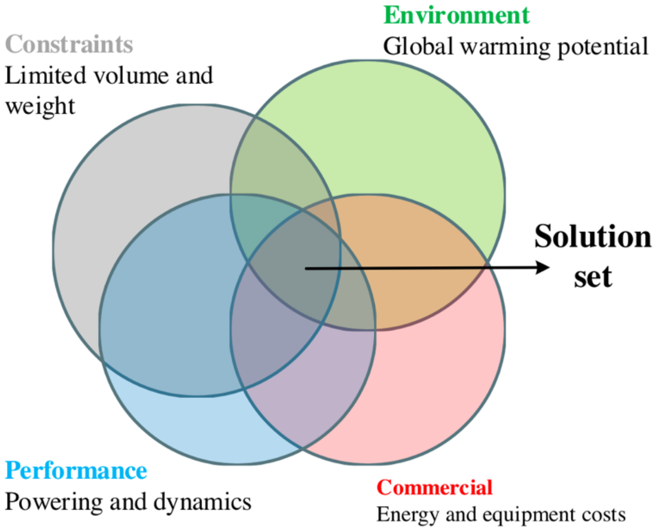


FIGURE 13 The considerations to get to the solutions

SOURCE: [6]

In conclusion, the adoption of hydrogen and fuel cells in the maritime industry represents a promising avenue for reducing the environmental impact of maritime transport. The e-SHyIPS project explores the feasibility of using hydrogen for maritime transport. It aims to contribute to developing a normative framework specific to hydrogen-based fuels in the maritime sector. Achieving zero-emission shipping is a critical goal for the maritime industry and requires collaborative efforts from stakeholders, policymakers, and researchers to develop and implement sustainable and efficient propulsion systems. The potential of hydrogen and fuel cells in mitigating environmental impacts and achieving sustainable transportation in the maritime sector is considerable, and continued research and development are necessary to overcome the challenges and drive the transition towards sustainable and efficient propulsion systems.

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