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Current Trends and Solutions for Port Energy Supply Transformation: A Systematic Literature Review

Aivis KĻAVIŅŠ[1*], Vladimirs KIRSANOVS[2], Ieva PAKERE[3], Andrej DÁVID[4]

[1–3]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, LV-1048 Riga, Latvia*

[4]*Department of Water Transport, Faculty of Operation and Economics of Transport and Communications, University of Zilina, Univerzitna 8215/1, 010 26 Zilina, Slovakia*

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***Abstract* – The energy sector is changing rapidly today. Global warming and other environmental challenges contributed to several international agreements aimed at fostering fossil-to-renewables debt. The energy sector consists of several interconnected sectors. Classically, the focus is on the transformation of the heating and electricity sectors, which has led to significant progress in the transformation of these sectors. The transport sector is an important sub-sector of energy, which can account for up to a third of all energy consumption in some regions and countries of the world. Despite all efforts to promote the greening of the transport sector, the pace of the process and the result achieved are very low. These are a number of reasons, one of which is the diversity of the transport sector. This study focuses on port infrastructure as the most important part of the maritime transport sector. The aim of the study is to identify current directions in relation to port energy infrastructure, main accelerating challenges, as well as possible solutions. The results of the studies show that decarbonisation receives the greatest attention and that active research and development of a number of solutions, including hydrogen, electrification and methanol, are underway.**

***Keywords* – Bibliometric analysis; decarbonisation, energy sector transformation; hydrogen; ports infrastructure.**

1. INTRODUCTION

1.1. Overview of the Current Situation

The shipping sector currently contributes approximately 2–3 % to global greenhouse gas (GHG) emissions, but in the absence of effective mitigation strategies, the risk of increased emissions is undeniable [1]. Efforts to achieve net zero sea GHG emissions are growing to reach efforts by other industries to curb global warming [2]. To underscore this growing sense of urgency, member states of the International Maritime Organization (IMO) have adopted enhanced objectives for international shipping to reach net-zero GHG emissions by or around 2050 [3]. As countries work towards fulfilling these obligations, it becomes imperative to identify and deeply investigate emerging issues on the pathways to achieving net-zero shipping [4].

* Corresponding author.
E-mail address: aivis.klavins97@gmail.com

The maritime sector is a key pillar of the global economy, as most of the world's cargo is transported by ship. Passenger transport is also a significant economic activity along with the transport of goods. The total number of passengers embarked and disembarked at EU ports in 2022 was 348.6 million, with Greece having the largest maritime passenger transport country in EU in the same year [5].

Researchers performed multicriteria decision analysis to evaluate the preferential ranking of alternative fuels across a wide array of Swedish maritime stakeholders and found that fuel producers, engine manufacturers, and shipowners ranked fuel price as the single most important criterion for adopting alternative maritime fuels. Considering the scale of infrastructure investments required to produce and bunker marine fuels, costs can add up. The most marginal difference in costs between fuels can easily amount to millions of dollars when bunkering these volumes. Prices not only differ between alternative fuel options, but also independently vary considerably across the world's ports. Therefore, decisions for fleet operators not only involve what to bunker with, but also where to bunker. Similar logic follows in decisions regarding infrastructural investments into alternative fuelling, which may result in increased availability of certain fuels at different ports of the world. Even before the crisis, alternatives have had difficulty competing with conventional fuels on a fuel cost basis, and indeed biofuels are considerably more expensive. Increasingly stringent IMO maritime emissions regulations, and the introduction of carbon mitigation instruments such as a carbon tax on maritime fuels, may change the future economic playing field and level price differences [6].

The emerging research agenda for shipping decarbonization is a vibrant and pressing topic, with scholars increasingly exploring key questions that reflect the current research status and development trends in this field. Research [7] has explored the management of green shipping and the construction of green ports, identifying future research opportunities aimed at improving operational efficiency, reducing emissions and achieving zero emissions through technological innovation and optimisation strategies [8]. However, this sector is responsible for a high proportion of GHG and other pollutants, which is particularly important given their local impact (i.e., port environment). In addition, a number of long-term economic and energy scenarios foresee an increase in emissions in the near future due to rapid growth in the sector, which foresees significant environmental challenges to overcome [9].

1.2. Necessity for Decarbonisation

As it transports 80 % of the world's trade by volume, international shipping is vital to the world economy [10]. However, the maritime sector is characterised by significantly high levels of committed greenhouse gas (GHG) emissions [11]. According to the fourth GHG study of the IMO [9], international shipping emitted 1076 $MtCO_2$ a year in 2018, corresponding to some 2.89 % global GHG emissions, and such emissions could grow by 90–130 % by 2050, despite improvements in carbon intensity. If the sector were a country, it would be the 6th largest emitter in the world. In the European Union (EU), the shipping sector covered by the EU Monitoring, Reporting and Verification (MRV) regulation emitted 138 $MtCO_2$ in 2018, corresponding to some 11 % of all EU transport CO_2 emissions and 3–4 % of total EU CO_2 emissions [12].

Air pollution in ports has a negative impact on people and nature near the port. Air pollution is the greatest health hazard, mainly caused by exposure of human lungs to fine particles with an aerodynamic diameter <2.5 µm (PM 2.5) [1]. Emissions from internal combustion engines, including marine engines, contribute to emissions of black carbon, organic carbon, and other particulate matter. Secondary emission particles formed from exhaust gases – mainly nitrogen oxides (NO_x) and sulphur oxides (SO_x) also have adverse effects on humans [13]. The study

[13] mentions that more than 238 000 people have died prematurely because of fine particle impacts based on 2021 data, while 49 000 worldwide in 2020 [1].

Along with the global initiatives undertaken by the IMO, the EU legislators has recently agreed on legislation for decarbonisation of the maritime sector, amongst which is the inclusion of shipping in the European Union Emissions Trading System (EU ETS), 2 the FuelEU Maritime regulation and the Alternative Fuels Infrastructure Regulation (AFIR). The Council of the European Union (Council) and the European Parliament (EP) reached a political agreement on the FuelEU Maritime legislation in March 2023, constituting a major policy change. Since the initial IMO climate strategy falls short of taking appropriate measures to decarbonise the sector, FuelEU Maritime is an opportunity to set the global standard for the sector. So far, it is the world's most ambitious policy to decarbonise the shipping industry. Under the FuelEU Maritime regulation, each shipping company will need to improve vessels to be able to operate on alternative fuel or power source so as not to exceed the GHG intensity limit, which will become stricter over the years from 2025 to 2050 [14].

1.3. Decarbonisation Solutions for Ports

Ports have many technological solutions available to increase energy efficiency and reduce greenhouse gas emissions. Renewable energy systems (RES) are ideal for such cases, but they do not ensure a sustainable supply of RES energy to port infrastructure [15]. The best way is to achieve synergies between systems capable of storing energy, renewable energy systems (RES) and an energy management system called the hybrid renewable energy system (HRES) to achieve a stable supply of electricity to port infrastructure at a time when RES conditions are not sufficiently stable [15].

One way, how to reduce the gases that cause the greenhouse effect, is to automate handling operations in ports. In automated container terminals, some container handling equipment operates without direct human interaction. Drivers of the cranes have been physically removed, or they have remained in their cabins, but they are not needed for the entire duty cycle [16], [17]. They use various types of automated handling equipment that carry containers between different parts of the terminal.

Automated guided vehicles (AGVs) have been used for handling operations in automated container terminals since the 1990s. They transport containers between ship-to-shore gantry cranes and the blocks of the container yard at the water-side transfer area. Not only they reduce the downtimes in terminals, but they also minimize the accident rates, the number of port workers, and staff costs. The first of them used to have diesel engines. In the last few years, they have been replaced by AGVs that have electric engines (e.g., the Container Terminal Altenwerder, the port of Hamburg). The batteries are charged twice a day, and they obtain electricity from renewable sources energy (wind power plants located in the port area).

In the container yard, diesel rubber-tired gantry cranes are being replaced by rail-mounted gantry cranes. In automated container terminals, two types of cranes are used. The first type of crane stacks and moves containers in the blocks of the container yard that are perpendicular to the wharf.

The second type of crane is used in receipt and delivery operations at the rail station of the land-side transfer area where it moves containers between wagons and semi-trailer trucks. These cranes usually have large spans and may stack the containers up to 6 tiers.

Hydrogen was recently set to become the most promising energy provider to store energy in a secure cost-effective and nature-free process that could replace conventional energy systems. The use of hydrogen technology in HRES is aimed at conserving excess energy into chemical energy, if necessary, with a view to later transforming into electricity [15]. As emissions rules become increasingly stringent, the need for an alternative source of energy is crucial to meet the requirements of the regulations and the demand for energy from the port so that it can function effectively. Despite the continued global increase in interest in the merger of hydrogen and port infrastructure technologies, there are still many unsolved research challenges.

One of the main paths of research is to solve global hydrogen demand. Already in 2019, hydrogen demand was estimated at 339 TWh, rising dramatically to as high as 2300 TWh in 2050 under the European Hydrogen Flagship Initiative [18]. One option currently under investigation is the production of hydrogen from offshore wind turbines. There are studies where information was collected on the three main connections of offshore wind turbines to the H_2 electrolysis system – onshore, centralized offshore – shore and decentralized offshore wind farms and electrolysis projects [19]. Such project models were theoretically compared in the study [20] and looked at what to do with ageing oil and gas platforms, which are not financially beneficial to move back ashore, but it is beneficial to transform them into large hydrogen electrolysis plants and storage tanks using wind power plants as a source of electricity.

While there are countries that theoretically study hydrogen production and development, there are also countries that are already practically trying to produce hydrogen and transport it between continents. Number one in the world of hydrogen production is Australia and the first to export a cargo of an LH2 vessel from Australia to Japan. The Australian government has indicated in its hydrogen production strategy that it wants to become one of the world's leading hydrogen exporters and as the largest exporter to the Asian market by 2030 [21]. Norway is one of the best options for developing hydrogen production in Europe. The Norwegian government said in its hydrogen strategy that it is possible to produce and export H_2 to Europe. The Norwegian government will install offshore wind farms capable of producing up to 30 GW of electricity capacity by 2040 to boost hydrogen exports [22]. The Port of Egersund has the potential to become the first an exporting port for hydrogen in Europe [23].

A study [24] has been carried out on the conversion of the largest emitters in port infrastructure into hydrogen-powered installations such as port trucks, cold ironing systems for vessels while the vessel is docked, electricity needed for port building ventilation systems as well as fuel use on ship. There is also a study [25] research whether storing hydrogen is economical and more beneficial in metal hydrides compared to hydrogen in liquid form.

The objective of the work is to clarify the possibilities for improvement of the infrastructure of the Free Port of Riga, using alternative energy resources to ensure production, storage, and utilization of green hydrogen/ammonia.

1.4. Measures and Aspects of Port Decarbonisation

Some of port decarbonisation (PD) measures are applied in cooperation with industrial associations and/or private sector, such as support to the production of alternative fuels, including bunkering etc. Therefore, they have some challenges (technical issues, costs, and varying abatement potential). Feasibility studies should be conducted as most of the measures are used in combination to achieve the maximum abatement potential with a better cost benefit ratio [26]. the measures include technologies and actions (alternative fuels, electrification, energy efficiency and renewable energy utilisation, among others) to decarbonise the port operation (cargo handling equipment (CHE), e.g., cranes, derricks, forklifts, port trucks and vehicles, etc.) and other marine service activities (e.g., tugs, tows, and pilot boats). Due to their importance, alternative fuels have been addressed in recent studies. The deployment of shore hydrogen has been investigated in green ports, considering reconstruction of the port and the retrofitting of the vessels calling at the port as ways to decarbonise ports [27], [28]. Port logistics are used to allow intermodal transportation in between the three main port areas (quayside, yard side, landside – Fig. 1) and between port areas and the inland.

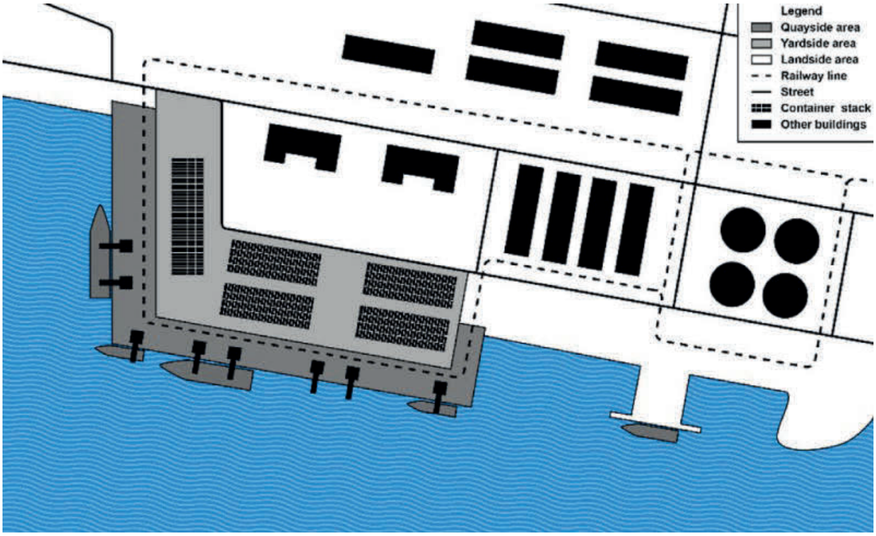

Fig. 1. Simplified schematic of typical container terminal.

To date, logistics play a dominant role in shaping port key attributes fulfilling the desired trade-off between: operation performance and attractiveness (i.e. depending on productivity, automation level, and connectiveness with distribution networks), compliance to EN16001 or ISO50001 (i.e. energy efficiency improvement, RES-based energy production, energy management), compliance to ISO14001 (i.e. air and water systems management), economic competitiveness, and safety and security [29]–[31]. Hydrogen-based technologies are expected to positively affect most of the previously listed attributes, especially in terms of energy efficiency and decarbonization potential [32], and improvements can be developed according to two different approaches [31], [33].

With the first one, a port is considered as a whole, stand-alone system: port operational strategies are characterized and controlled with the aim of optimizing their management. Here, a promising action consists in improving the level of automation of both infrastructures and equipment, by introducing for example self-driving and/or autonomous lifting vehicles.

A second approach consists in installing and upgrading port equipment and infrastructures to the best available technologies, mostly involving the equipment dedicated to port cargo handling operations within quayside, yards and landside areas as well as with the management of inter-port logistics. In a well-established hydrogen economy, ports could play an even more fundamental role within the energy trade. Countries with exceeding energy production via RES could sell their surplus in form of hydrogen: the Australian Government already proposed the development of hydrogen hubs in proximity of port facilities to promote hydrogen export and identified the most suitable thirty national ports for their establishment [34]. In the Netherlands, the development of hydrogen-based infrastructures mixed within industrial clusters and port areas are becoming a key pre-requisite for further sustainability improvements due to the closed connections between ports and industries, as well as to the development of pilot-demo projects focused for achieving a climate-neutral industrial sector by 2050. In addition, the International Renewable Energy Agency (IRENA) estimated that about 614 MtH_2/year will be necessary to limit the 1.5 °C increase of global temperature by 2050 and that about the 25 % of the total hydrogen demand (153 Mt hydrogen per year) is going to be traded in 2050. It is summarized as the 55 % of the globally traded hydrogen is estimated to be transported via pipelines, 45 % is estimated to be transported via ship, 40 % as NH3 and 5 % as LH2 [35].

The literature analysis carried out shows that there are several challenges to achieving sustainable port energy supply. The purpose of this study is to identify more significant research directions in the field of port energy supply, as well as to identify existing solutions and methods for assessment of solutions.

2. METHODOLOGY

For a more complete understanding, the purpose of the study is to identify the most important directions of the study in the field of port energy supply, as well as to identify existing solutions and methods for assessment of solutions in port territory to understand which is the less studied direction, the author used a bibliometric review with the visualization program *VoSviewer*, which provides well established methods that provide an overview of research trends in the chosen field. The bibliometric review is based on the use of different approaches to characterize quantitative, qualitative, and structural changes in scientific research [13]. Key information for bibliometric analysis is derived from journal articles, authors, publishing authorities, countries, keywords, and references [14]. As stated in the article [15], the main advantage of bibliometric analysis is to get a helicopter view of a particular area of research.

As part of this study, a four-step analysis methodology was applied (Fig. 2). The methodology includes a combined approach with bibliometric analysis (step 1–3) and a review of classical literature studies (step 4). The objective of bibliometric analysis is to carry out screening of existing studies and to identify those studies that require in-depth attention. Step 4, or the review of identified literature studies, aims to identify the possibilities of methods of research that will form the basis of its analysis study to launch a study in the field of choice.

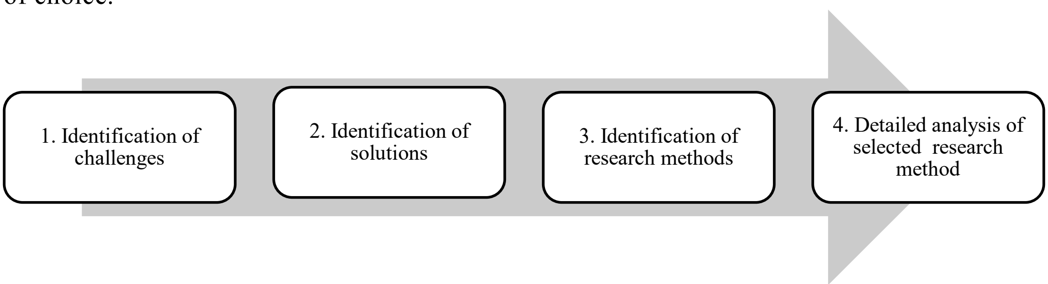

Fig. 2. Steps of research methodology.

2.1. Research Topic Identification

In carrying out bibliometric analysis, it is important to understand the key concepts related to the subjects of the selected study. In bibliometric research, to get a detailed understanding of the domain's core research topics and their interrelationships at microlevel, researchers must select different keywords that reflect the most relevant research topics in the domain [16]. Choosing suitable keywords can be challenging and often difficult. This is because different authors can use synonyms of words (e.g., synonyms of terms, units of measurement, etc.) [17], this can make it harder for keywords to be accurate and representative in research. Without a feasibility study and a comprehensive list of synonyms, the starting point for bibliometric analysis may be an incomplete understanding of the situation [18].

2.2. Database Selection

Currently, the most widely used databases to obtain information for bibliometric analysis are the Web of Science (WoS) [19] and Scopus [20]. As the subject of the article relates to the engineering industry, additional alternative databases have been sought [18]; information on them is summarized in Table 1.

TABLE 1. CHARACTERISTICS OF THE DATABASES USED IN THE ENGINEERING FIELD [21]

Database	Subscription	Data download	Record export limit	API	Formats
WoS	Yes	Yes	500 or 1000 records, depending on the content of the record	Yes	Plain text, Tab delimited Win
Scopus	Yes	Yes	First 2000 records	Yes	Plain text, RIS, BibTeX, CSV
GS	Free	No	–	No	–
MA	Free	Using the API	–	Yes	–
Dimensions	Free	Yes	500 or 2500 records, depending on export format	Yes	RIS, BibTeX, CSV, XLSX

The main problem limiting the use of bibliometric analysis is the acquisition of information from databases. The WoS, Scopus, and Dimensions databases allow information downloads, but there is a limited amount of data that can be retrieved in one download time. In this respect, the Dimensions database offers the most comprehensive options. The maximum number that can be downloaded at one time is 2500 articles per query, and all modern file export formats are available. The main benefits of a Dimensions database are free access to data and download options, unlike WoS and Scopu*s* databases. However, it is not possible to select certain bibliometric parameters in the free version of the Dimensions database, so it was decided, as part of that study, not to use that database. The authors chose to use the Scopus database, its high pattern qualities, and its ability to export large amounts of articles at a time [22].

2.3. Bibliometric Parameters Selection

Defining bibliometric analysis parameters indicates which criteria articles will be searched for in the selected database. The main limiting factors are:

- Time period: a period of 2000–2023 was set to view interest in the topic from the beginning of the 21st century;
- Subject: all research areas with an emphasis on energy, ports, and environmental science;
- Type of document: publications of all kinds;
- Country/territory: the whole world;
- Language: publications are in all languages in which English is abstract;
- Quotation: total quotations, including self-quotation;
- Data export options: Download the CSV file format by selecting quotation information (such as author(s), year, citation count, etc.), abstract, and keywords.

3. RESULTS

The maritime sector is a very broad and versatile segment, so it was previously found that the scientific article aims to identify more relevant research directions in the field of port energy supply, as well as identify existing solutions and methods for evaluating solutions. Some marine and port synonyms were therefore put forward to cover as broadly as possible the sector the authors want to explore. The research's fine-tuning keyword “infrastructure” was added, and finally, segments of infrastructure the authors want to know how the port area is developed, such as “energy”, “energy sector”, and “energy supply”.

In Fig. 3 the classic bibliometric analysis results are shown. The keyword network gives information about the width research area in the maritime industry with a view to determining current research directions. It is possible to divide the keyword network into four clusters.

The green cluster shows a strong energy efficiency and energy efficiency. It can also be seen that the ways in which this could be achieved through the development of the maritime sector have been clearly demonstrated.

The yellow cluster shows a highly in-depth exploration of electricity in the maritime sector. Research into renewable electricity and ways of generating it has also become popular.

The purple cluster shows decarbonisation and emission reduction associated with all other keywords. That is why the authors chose to study the subject in depth through the energy sector.

Last but not least, blue with the red cluster, shows a very important part of the exploration of the maritime sector – financial investment and sustainable development.

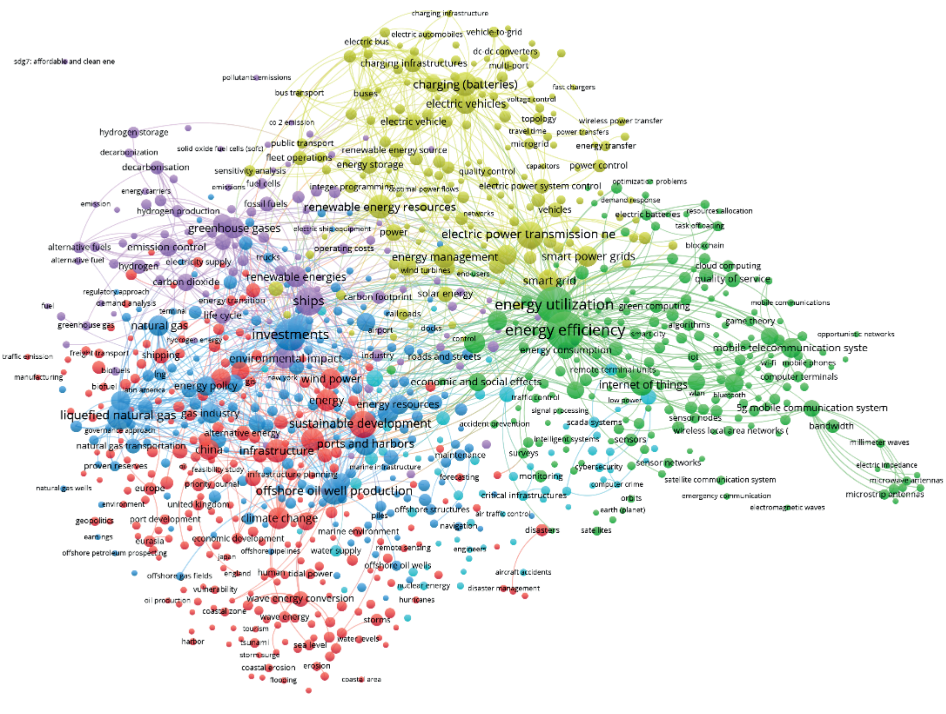

Fig. 3. Keyword network to determining current research directions in maritime sector.

3.1. Maritime Challenges

In Fig. 3, clusters of all colours show the three key words "decarbonisation", "emission reduction", "energy efficiency" have been studied the most to understand which of the most popular and studied topics in the ports' energy sector in recent years, which is why these keywords were further explored in depth.

In Table 2 most common research topics are shown for a seaport. The publications starting from the year 2000 are included in further analysis. The three most popular research sectors in the maritime sector were identified. Decarbonisation is the most popular research route since it involves a wide range of studies and is the main reason for many European Union regulations. As shown in Fig. 4, research on decarbonisation has increased in the last five years when the Paris Agreement first came into force in 2018.

TABLE 2. NUMBERS OF ARTICLES FOUND DEPENDING ON THE RESEARCH TOPIC

Research topic	Defined queries used in Scopus database search	Number of publications
Decarbonisation	((maritime OR terminal OR harbour OR port OR dock OR berth OR nautical) AND infrastructure) AND ({decarbonization} OR {decarbonise} OR {decoke} OR renewables)	369
Emission reduction	((maritime OR terminal OR harbour OR port OR dock OR berth OR nautical) AND infrastructure) AND ({emission reductions} OR {cut emissions} OR {emission abatement} OR reducing emissions)	102
Energy efficiency	((maritime OR terminal OR harbour OR port OR dock OR berth OR nautical) AND infrastructure) AND ({energy security} OR {environmental policy} OR {energy safety} OR energy supply security)	88

Emission reduction and energy efficiency in maritime sector is important because emissions from internal combustion engines, including marine engines, contribute to emissions of black carbon, organic carbon, and other particulate matter. Secondary emission particles formed from exhaust gases – mainly nitrogen oxides (NO_x) and sulphur oxides (SO_x) also have adverse effects on humans. Energy efficiency in the other hand needs to be implemented to meet ambitious emissions reduction targets and remain competitive seaport in maritime industry.

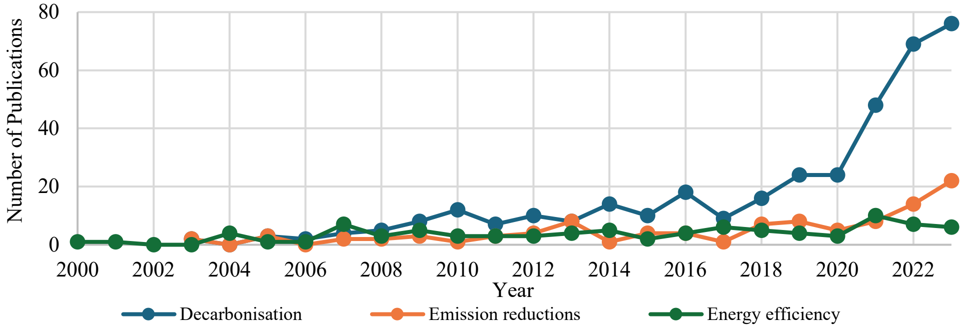

Fig. 4. Trends in the number of publications by year in the most common maritime research topic.

The number of publications on the most common seaport research topics has increased only in the past five years between 2019 and 2023. The annual number of publications on decarbonisation has increased 31.5 %. That is an average of 48.2 publications a year, see Fig. 5.

The most publications come from the United States (90 publications), the United Kingdom (58 publications), and Italy (42 publications). It reflects the goals and strategies necessary to foster, develop and promote these countries maritime industry and merchant fleet to meet nation`s economic and national security needs. Maritime industry is critical to these countries' national security strategies and sustainability.

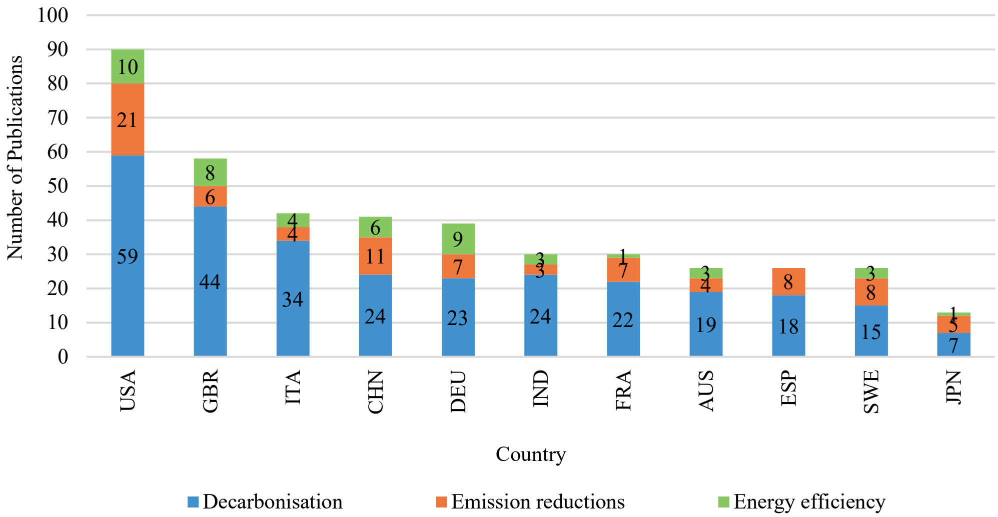

Fig. 5. Breakdown by research countries of the number of publications for maritime industry.

The keyword map (Fig. 6) from *VoSviewer* shows that everything is divided into four clusters of different colours. The green colour cluster indicates electrification and renewable energy possibilities in port area. For example, charging infrastructure, wind power, microgrids, energy storage systems and cost effectiveness. The blue-coloured cluster points to the ships and maritime transports, their possible upgrades to alternative fuels and best alternative fuels – hydrogen, methanol and ammonia – to reduce gas emissions and greenhouse gas emissions. The red colour cluster points to legislation, economic and financial challenges to meet the IMO targets set by 2050. The yellow cluster shows that all these themes are united by a common goal – developing ports and berths and reducing the carbon footprint of maritime transport globally.

Decarbonisation is the most popular topic in the maritime sector, in recent years as shown in Fig. 6. Three of the most popular decarbonisation techniques in port infrastructure are hydrogen, electrification and methanol, have been found from the cluster keywords shown in Fig. 5. Therefore, these three methods of decarbonisation were further investigated.

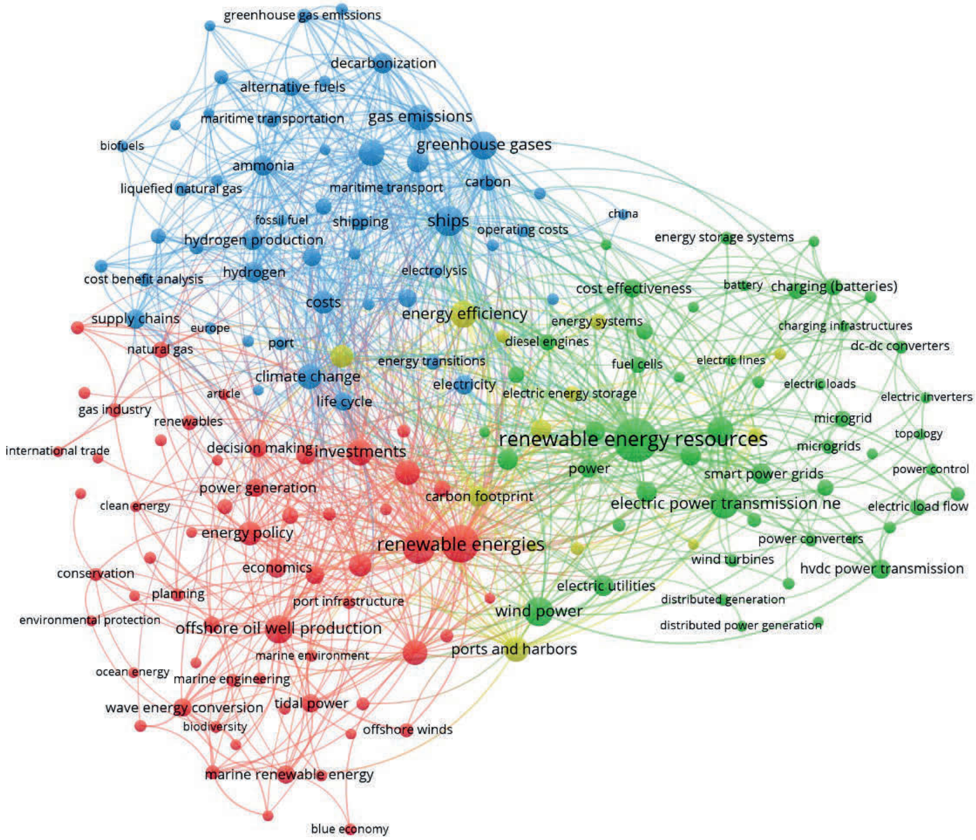

Fig. 6. Network visualization of most common keywords related to port decarbonization.

3.2. Decarbonisation Solutions

Table 3 shows the ports` most popular decarbonization development by number of publications in period from early 2000 till 2023. The three most popular ways to achieve port decarbonisation are shown in Table 3. Interest in hydrogen is growing, because it has potential to reach net-zero shipping, the maritime industry will need a secure supply of fuels that are carbon free or carbon-neutral from well-to-wake perspective.

Electrifying the maritime industry may face the challenge of reducing the volume of residential and cargo tanks on ships due to energy storage, which will lead to greater long-term losses for ship owners. Compared to methanol, which is already starting to be used as fuel on board ships, ship owners have only had to improve their internal combustion engines to adapt them to methanol and improve safety measures that are more beneficial than rebuilding the ship to store the required amount of batteries on board. Hydrogen gained great recognition because it can be produced from water that is widely available in the maritime industry, thus producing zero-emission fuel. Of course, there is still much to be explored and developed about the impact of hydrogen in the maritime sector because it is difficult and expensive to store, so research needs to continue to be done to find ways to improve it.

TABLE 3. NUMBERS OF ARTICLES FOUND DEPENDING ON THE RESEARCH TOPIC

Research topic	**Defined queries used in Scopus database search**	**Number of publications**
Hydrogen	((maritime OR terminal OR harbour OR port OR dock OR berth OR nautical) AND infrastructure) AND ({decarbonization} OR {decarbonise} OR {decoke} OR renewables) AND ({hydrogen} OR {green hydrogen} OR {renewable hydrogen} OR {hydrogen fuel} OR {green port})	57
Electrification	((maritime OR terminal OR harbour OR port OR dock OR berth OR nautical) AND infrastructure) AND (decarbonization OR decarbonise OR decoke OR renewables) AND ({port electrification} OR {electrification} OR {green port})	23
Methanol	((maritime OR terminal OR harbour OR port OR dock OR berth OR nautical) AND infrastructure) AND (decarbonization OR decarbonise OR decoke OR renewables) AND ({methanol} OR {green methanol} OR {renewable methanol} OR {green port})	14

The number of publications on the most common directions of decarbonization in the maritime sector (Fig. 7) has increased only in the past three years between 2020 and 2023. The annual number of publications on decarbonization has increased 11.1 %. That is an average of 7.7 publications a year (Fig. 8).

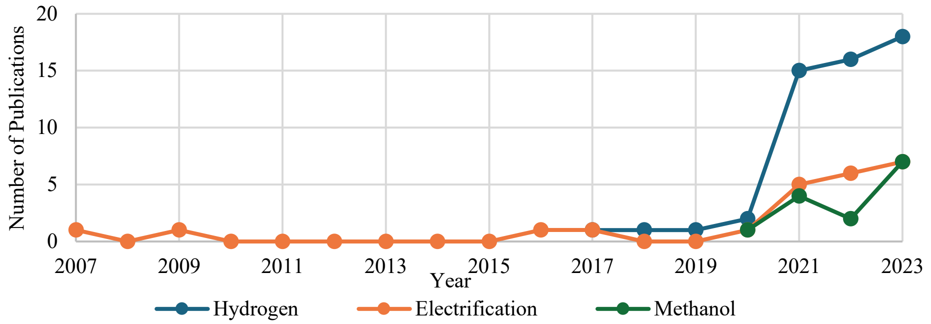

Fig. 7. Trends in the number of publications by year in the most common directions of decarbonisation in maritime sector.

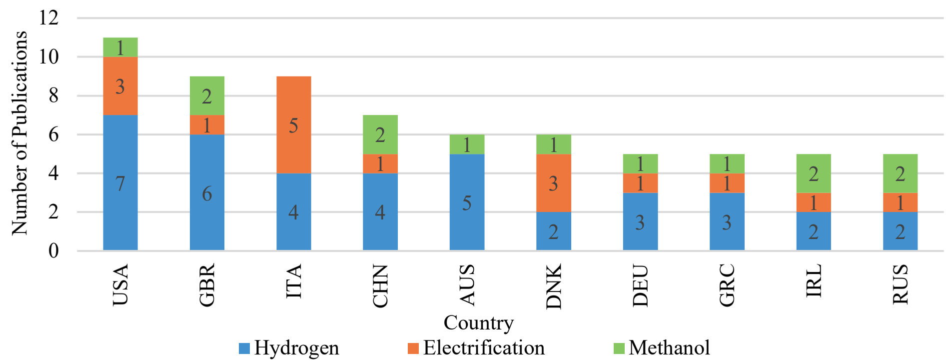

Fig. 8. Breakdown by research countries of the number of publications for directions of decarbonisation of maritime sector.

The most publications come from the United States (11 publications), the United Kingdom and Italy (9 publications). The rapid growth of these countries in research and science, specifically on green port and hydrogen technologies is due to the fact that they are the countries where fairways and port crossings are generally the largest in the world. The main impact was caused by the initial IMO strategic plan adopted in 2018 to reduce GHG. The plan stated that all new ships under construction after 2018 must comply with the energy efficiency design index (EEDI). The EEDI shall be increased every five years to require the development of old vessels or the construction of new ones with as little carbon dioxide emissions as possible per nautical mile per ton of fuel travelled on board. The current reduction in CO_2 emissions for new vessels under construction from 2020 to 2025 and thereafter is set at 30 %. As a result, world ports are also forced to evolve to ensure the ability of such ships to operate in the port area while the ship is being loaded or unloaded or repaired in dry dock.

3.3. Research Methods to Promote the Development of Ports towards Decarbonisation

VoSviewer, therefore, sought to establish the scientific method by which decarbonisation in seaports can be analysed. A number of methods were defined to identify the most popular currently used in research to promote the development of ports towards their decarbonisation. Information collected and displayed on Fig. 9.

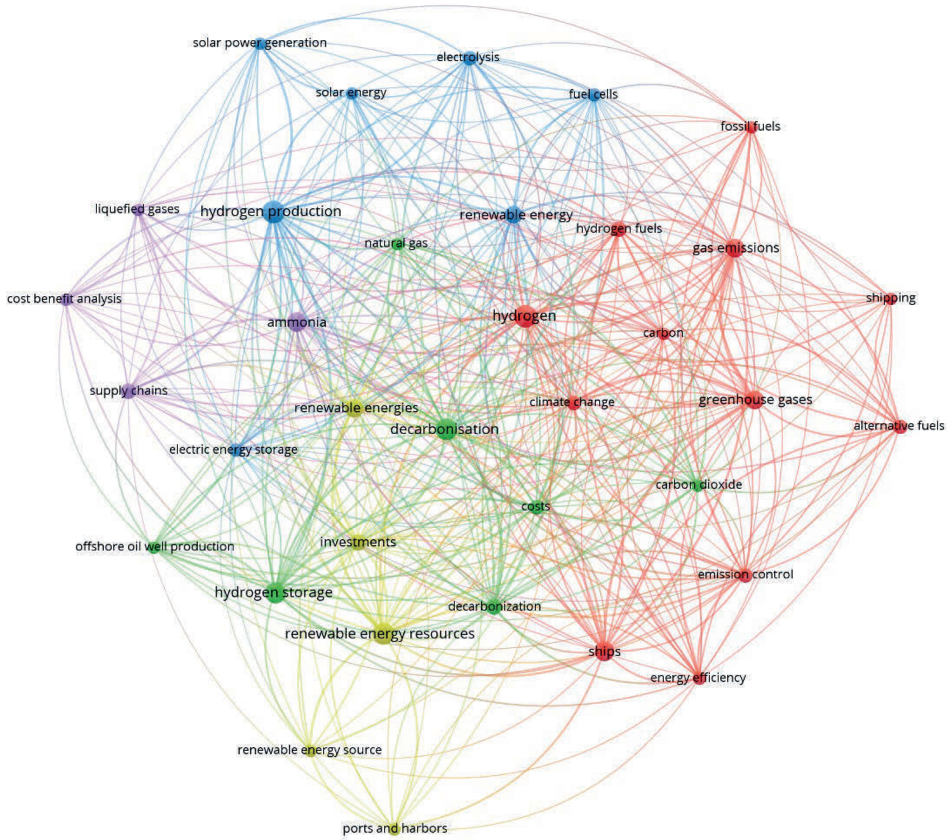

Fig. 9. Network visualization of the most popular research methods used to port decarbonization.

Looking for an answer to what scientific methods are used to determine the sustainable harbour development model, it was understood that this was a set of several methods that included different categories. In defining the categories, the following was identified as the greatest use being made of techno-economic assessment, as technological development and its costs are the most important and primary source of research in the development of the port, followed by everything else. It is therefore important to understand the sustainability and resilience of new technologies in the relevant port infrastructure. Techno-economic research method has become popular relatively recently, only from 2017.

The harbour resilience research method for infrastructure, related to renewable energy, has become popular only in the past three years. Studying scientific articles, it was understandable that the researchers used mathematical modelling to create a model for a given port or territory and could determine the outcome depending on different variables. Environmental and social assessment is also an integral part of the port infrastructure, as many of the world's ports are located in the urban environment or very close to the city, which can have long-term consequences for the well-being and health of the population, so these assessments should also be taken into account in future studies.

As the most applied scientific method for the development of port infrastructure is techno-economic, an in-depth analysis of these articles was carried out in order to find further methods used, as well as what might still be unexplored or recommendations that should be further investigated in order to further develop port infrastructure and meet the IMO requirements by 2050. Information is summarized in Table 4, see Annex.

A total of 9 available studies were identified and analysed in depth. The analysis of the studies was summarised in several sub-paragraphs:

- Description of the method used for maritime infrastructure.
- Analysis object and scale.
- Main results and conclusion.

The review of literature shows different decarbonisation methods for methodological approach to Maritime Infrastructure that can be used both global level and locally in the port infrastructure itself, determining the decarbonisation of a particular port area with a different approach. Therefore, there are also different results and recommendations for similar ports or port regions in order to increase decarbonisation and port sustainability. Principles for increasing a decarbonisation and sustainability of port include:

1. Uses decision theory and systems analysis and integrates the risk preference.
2. Shipping Analysis Tool, ships route cost calculations and Cost Analysis for the planning and implementation of decarbonisation projects for ports with biggest impact on "Green corridors".

Regarding the development and planning of the port decarbonisation, the main requirement for increasing decarbonisation can be identified as:

1. Mainly ports need large number of investments to start building infrastructure for green fuel production.
2. Many green fuels don't allow vessels to cross far distances, so there is also need for ship`s engines upgrade and fuel storage on ships and shore.
3. Also, huge society impact slows down port decarbonisation, because people are not pleased with alternative energy sources and how they affect the urban landscape.
4. Steel green hydrogen is the best way of port decarbonisation but for that we need to decrease the price of hydrogen production technologies.

4. Conclusion

A systematic literature review of current trends and solutions for port energy supply transformation was done. A combined approach was followed with bibliometric analysis and classical literature research analysis. The methodology consists of four steps: 1) Identification of challenges; 2) Identification of solutions; 3) Identification of research methods; 4) Detailed analysis of selected Research method. The bibliometric analysis carried out screening of existing studies and identified studies that required in-depth attention.

The results of the study show that the most current challenges link with port energy infrastructure is 1) Decarbonisation (369 articles); 2) Emission reduction (102 articles) and Energy efficiency (88 articles). A particularly rapid increase in research is observed with 2020. The highest number of studies identified relate to the USA, the United Kingdom, Italy, China and Germany, which can be explained by the particular importance of the maritime transport sector in these countries as well as the existing high scientific capacity. The main solutions for decarbonising ports, based on the bibliometric analysis carried out, are hydrogen, electrification and methanol. The technique of techno-economic analysis has a pronounced preponderance for the study of the decarbonisation of ports with hydrogen.

All available techno-economic studies were selected, and an in-depth analysis of these studies was carried out in several directions: 1) Description of the method used for Maritime Infrastructure; 2) Analysis object and scale; 3) Main results and conclusion. The analysis carried out, points to the diversity of existing research problems and possible assessment methods. Key aspects and ideas for carrying out new research in the future were identified.

The stated objective of the study has been achieved; the tasks have been fulfilled. The study carried out demonstrated the effectiveness of the methodology of the studies established. The established methodology can be adapted and applied to perform other similar studies and to receive feedback through systematic literature review.

Annex

https://zenodo.org/records/14503603

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