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Review

Decarbonising maritime ports: A systematic review of the literature and insights for new research opportunities

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A R T I C L E I N F O

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A B S T R A C T

Maritime ports have become pivotal players in reducing greenhouse gas emissions. While most of the existing literature has investigated specific decarbonisation measures, a comprehensive review to clarify how different decarbonisation measures could be combined remains absent. A systematic literature review was conducted by analysing 124 articles to identify the research topics concerning the decarbonisation of ports, highlighting the relationship between the different measures, thereby potentially serving as an initial step in developing decarbonisation strategies for ports. A bibliometric analysis was conducted to understand the prevailing trends within the literature selected. The measures were organised into 4 main categories: clean energy sources, operational measures, energy systems, and conservative measures. A thematic analysis was performed to identify the most studied countries, the investigation strategies used, and the decarbonisation measures considered. A cluster analysis was executed to discern the primary research topics organised into 3 main research areas: energy systems, emissions management, and clean energy sources. The review underscored the complexity and the need to combine technological innovations, regulatory frameworks, and stakeholder collaboration. Further, the cluster organisation proposed helps us to understand how ports could start a decarbonising process by combining specific measures. The main aim of this work is to highlight a path towards sustainable maritime ports. Potential opportunities for future research are proposed for each cluster.

1. Introduction

At the present rate of climate change, actions to achieve Sustainable Development Goals are increasingly needed (Buettner, 2022). Global carbon neutrality by 2050 is considered one of the most urgent missions for the planet (Guterres, 2020) by the United Nations. However, the decarbonisation gains from energy efficiency and low-carbon options have been largely wiped out by increases in demand, revealing limited progress towards neutrality (Lamb et al., 2021). Globally, across all sectors, and particularly in transport and industry, greenhouse gas (GHG) emissions continue to rise (Dhakal et al., 2022).

Long-distance transport, like shipping, is a difficult-to-decarbonise service but also essential and urgent because it is difficult to provide without causing more emissions and has rapidly growing demand, long lead times for technology development, and long lifetimes of infrastructures (Davis et al., 2018). The importance of shipping to globalisation and the transportation of goods, its reputation as the most efficient mode of transportation, and the need for the sustainability of maritime terminals reinforce the significant role of seaports for carbon neutrality (Alzahrani et al., 2021; dos Santos et al., 2022; Styhre et al., 2017; Zhou et al., 2022). Such importance becomes even more evident by realising that seaports handle 80% of the global trade in volume and more than 70% in value (UNCTAD, 2017; Zhou et al., 2022).

Due to their location and exposure to the impacts of climate change, port authorities are particularly interested in new practical approaches to incorporate climate actions in new projects (Loza and Veloso-Gomes, 2023). While maritime transport has a less relevant carbon footprint than other means of transport (Boschiero et al., 2019; Singh, 2015), the increased congestion from ships in ports causes tremendous logistical and technical difficulties, and their neighbouring cities experience substantial pollution levels as a result (Alzahrani et al., 2021; Fruth and

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Nomenclature

AI – Artificial Intelligence
BDA – Big Data Analytics
CCU/CCS/CCUS – Carbon Capture, Utilisation, and Sequestration
CO2 – Carbon Dioxide
ESS – Energy Storage Systems
GHG – Greenhouse Gas
ICT – Information and Communication Technologies
LNG – Liquefied Natural Gas
JIT – Just-in-Time
OPS – Onshore Power Supply
PCS – Port Community System
PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RE – Renewable Energy
RQ – Research Questions
SLR – Systematic Literature Review
TAT – Turnaround Time

Teuteberg, 2017). Also, a relatively arduous problem might be found in the definition of a decarbonisation strategy (dos Santos et al., 2022), as a single and "one-size-fits-all" measure for port decarbonisation is unlikely to be the way forward. This makes it challenging to develop effective decarbonisation policies and forces stakeholders to identify the best combination of measures (Alamoush et al., 2020; Harahap et al., 2023). According to Bouman et al. (2017), emissions can be reduced by more than 75% through measures, policies, and regulations by 2050. However, each port has its own unique context and characteristics, so much more needs to be done towards an effective port decarbonisation and the crucial role of stakeholder collaboration should be accepted.

Due to the complexity of the problem and the appearance of new avenues of research, the decarbonisation of ports has already received some attention. Some studies about the above-mentioned theme have already been done (Table 1).

However, existing reviews on port decarbonisation fall short of providing a comprehensive strategy. Most literature focuses on specific areas, overlooking the need for a multifaceted approach. For example, Fruth and Teuteberg (2017) focused on digitisation, Bouman et al. (2017) and Oloruntobi et al. (2023) addressed only shipping, and Raeesi et al. (2023) covered only container terminals. Additionally, the remaining studies that do cover various measures lack clarity on how these measures should be combined. Therefore, identifying the leading research topics could guide ports in strategically combining their decarbonisation efforts. Moreover, it would be helpful to visualise how the main research topics are organised to understand the relationships between different research opportunities. The fact that the current literature on port decarbonisation lacks identification of research clusters increases the complexity of analyses and tends to disperse research opportunities. A summary and organisation of research opportunities through grouping, based on similarity, would increase the efficiency in studying the decarbonisation of ports.

The following research questions (RQ) are presented.

1) What are the main research topics concerning the decarbonisation of maritime ports, and how are they organised?
2) What are the gaps in the research concerning the decarbonisation of maritime ports and the most promising research lines?

A systematic literature review (SLR) was adopted since it is one of the most used techniques to aggregate information, bring the elements of a specific field closer together, and discover new unexplored themes (Carrera-Rivera et al., 2022; Tranfield et al., 2003). SLR have multiple benefits, from updating researchers with the most critical and current literature about a subject to highlighting methodological issues in recent studies, making future directions for further studies much more precise (Chalmers and Glasziou, 2009; Kitchenham et al., 2009). An inductive approach and mixed methods (quantitative and qualitative) were adopted to analyse the selected documents, and bibliometric, thematic and cluster analyses were employed. Cluster analysis is a widely used procedure to clearly define research groups, minimise within-group variance and depict the research dynamics (Lascialfari et al., 2022; Milcu et al., 2013). Examples of identifying research clusters in the maritime literature include a review of ship energy efficiency (Jimenez et al., 2022). Through this systematic and evidence-based study, we expect to highlight a path towards more sustainable maritime transport and help port authorities draw up their context-specific decarbonisation roadmaps.

The article is structured as follows. Section 2 establishes the background for the study by providing a general overview of decarbonisation measures. The research methodology is explained in Section 3. Section 4

Table 1
Studies about the decarbonisation of ports.

References	*Conclusions and Limitations*
Davarzani et al. (2016)	Through a systematic review of the literature on green ports and maritime logistics, the authors examined the evolution of the field and identified the established and emerging research clusters. However, the work is limited to bibliometric and network analyses.
Fruth and Teuteberg (2017)	The level of digitisation in the maritime industry is studied, and existing problems and ways to improve them are identified. The authors concluded that evaluating each digital technology individually is essential to benefit from its advantages, like efficiency, safety, and energy saving. The areas of sustainability and emissions reduction were found to need more consideration in the literature.
Bouman et al. (2017)	By reviewing the measures' potential to reduce carbon dioxide (CO2) emissions, it was possible to identify promising areas, such as technologies and operational practices. The authors state that more than one measure is required to decarbonise the shipping sector. The focus on maritime transport forces the scope of research to expand to other aspects of the maritime network.
Alamoush et al. (2020)	This study systematically analyses diverse measures to reduce GHG emissions in ports and enhance energy efficiency. A combination of measures is essential for effective port decarbonisation. While the study provides valuable insights, it acknowledges potential limitations, notably the potential heterogeneity in categorisation. This categorisation process opens the door to interpretations of the identified measures by establishing distinct clusters.
Alzahrani et al. (2021)	Initiatives to reduce seaport carbon emissions were reviewed, stressing the shift towards smarter and greener operations. The components of green and smart seaports were identified, but during the development of this work, the lack of experience in smart port approaches and the port authority's inability to deal with climate challenges were pointed out.
Sifakis and Tsoutsos (2021)	This review identifies several research opportunities to achieve the goal of a nearly Zero Energy Port. Such a port's characteristics would include high demands for energy and its responsibility as a provider of supply activities. Most measures are under-exploited in ports but still have high value in decarbonisation. One conclusion is the need for more research regarding the less established measures.
Raeesi et al. (2023)	The unprecedented pressure to lower emissions has led to operational research combined with Big Data Analytics (BDA) techniques. Interdisciplinary research to optimise port operations, improve energy management, and implement net-zero technology is an essential direction for future research.
Oloruntobi et al. (2023)	Information and communication technologies, unmanned autonomous vehicles, and low energy and emission systems enhance port productivity and support energy transition. However, the focus on new measures has led to the need to clarify how existing practices might influence the decarbonisation of ports more in the future.

describes the data collection and processing phase. Section 5 describes the results of the bibliometric, thematic and cluster analyses. Section 6 identifies future lines of research. Finally, Section 7 summarises the main findings and conclusions of the study.

2. General review of decarbonisation measures for ports

The International Maritime Organisation proposed a strategy to reduce GHG emissions and several measures for energy efficiency (IMO, 2018). The International Maritime Organisation also recommended that efforts to reduce emissions must be implemented as early as possible (dos Santos et al., 2022). Implementing measures at all ports, regardless of size or management practices, is necessary (Alamoush et al., 2020). However, the variability in the potential for CO2 reduction of existing measures is still considerable (Bouman et al., 2017; Solomon et al., 2007), and different variables and factors (cost, complexity, adaptability, reliability, and sustainability, among others) need to be considered to analyse the potential of all possible measures (Alamoush et al., 2020; Loza and Veloso-Gomes, 2023). For example, Ramos et al. (2014) concluded that the implementation of a tidal farm near the Port of Ribadeo was feasible from the technical point of view, but other factors should be considered in future works, such as installation and maintenance costs or the impacts on the marine environment. The following subsections provide detailed explanations of individual measures.

2.1. Alternative fuels

Alternative fuels, such as Liquefied Natural Gas (LNG), hydrogen, biodiesel, methanol, and ammonia, are low-carbon energy source options (dos Santos et al., 2022). Ports are responsible for the supply and further incentives for ships to use cleaner fuels (dos Santos et al., 2022; Gilbert et al., 2018; Styhre et al., 2017). LNG was found to have a potential reduction of between 20% and 30% of emissions, while other options are not so present in the literature (Balcombe et al., 2019; dos Santos et al., 2022). Biodiesel is highlighted as an alternative to heavy fuel oils, one of the most widely used marine fuels, because they have similar properties (dos Santos et al., 2022).

However, the potential reductions in local air pollutants that the fuel shift entails cannot overshadow its possible adverse effects (Winnes et al., 2015). LNG has a significant warming potential if leaks of methane happen (Alamoush et al., 2020). The increased number of LNG-fuelled vessels, leaks in the LNG supply chain and a vessel's un-combusted methane slip are some of the reasons for the 150% growth in methane emissions from the shipping industry between 2012 and 2018 (IMO, 2020). Additionally, when ships' power decreases below 50%, the methane slip increases significantly (Lindstad et al., 2020).

Hydrogen and ammonia are the worst options due to the energy consumed and high production costs (Law et al., 2021) and are also expected to have difficulties entering some market segments, such as deep-sea shipping (Xing et al., 2020). For a large-scale adoption of biodiesel, issues associated with competition for land availability and high manufacturing and feedstock costs should be addressed, while for methanol, the barriers rely on the primary source to be fossil natural gas and the lack of literature regarding bio-methanol (dos Santos et al., 2022). Moreover, safety, security, supply, and market issues must also be addressed to allow ports to develop all the required infrastructures (Alamoush et al., 2020).

2.2. Renewable energy

Maritime port locations potentiate renewable energy (RE) production. RE are energy sources naturally restored within a short timescale. Solar energy production equipment can be installed in open fields, near ports, or on the rooftops of buildings. Wind energy production is very restricted due to the lack of available space, so typically, ports make contracts with wind farm developers. The primary sources of ocean energy are tidal and wave converters; however, both are seriously hampered by their ecological and environmental factors, high costs, and technological immaturity (Alamoush et al., 2020). The percentage of energy from renewable sources could be a critical Key Performance Indicator to monitor in sustainable ports (Acciaro et al., 2014b).

2.3. Information measures

Information measures include collecting data, tracking GHG emissions and energy consumption, and reporting these values to develop and implement environmental measures while improving a port's image (Alamoush et al., 2020). The culture of monitoring and auditing is believed to be well-established in European ports (Sdoukopoulos et al., 2019). However, in 2019, the Vrije Universiteit Brussel surveyed seaport sustainability reporting practices. The survey collected 97 responses, with European ports dominating the sample (around 61%), and two of the main conclusions are that 25% of ports do not report on sustainability, and 35% recognise a need for sector-specific standards (Verhoeven et al., 2020).

Real-time measuring energy consumption values would allow greater flexibility of the ports' energy management systems. However, collection and control in real-time result in increased costs, as it requires special equipment and software. The lack of records of energy consumption levels makes implementing energy efficiency measures harder (Iris and Lam, 2019). The safe and effective exchange of information between stakeholders in port communities can be achieved through the implementation of a Port Community System (PCS), a platform to optimise, manage, and automatize port processes (Musolino et al., 2022; Verhoeven et al., 2020).

2.4. Energy efficiency measures and energy management systems

Energy efficiency measures can reduce ports' energy consumption and minimise wasted energy (Acciaro et al., 2014b; Alamoush et al., 2020; Styhre et al., 2017). Several systems, technologies, and methods are available to implement a strategy for energy efficiency and saving (Iris and Lam, 2019). Energy-saving examples are using motion sensors, designing buildings to minimise energy demands or eco-driving restrictions (Alamoush et al., 2020). Energy management systems and technologies could include: energy management plans, energy storage systems (ESS), smart grids, microgrids, or smart load management (Acciaro et al., 2014b; Bayindir et al., 2016).

2.5. Equipment measures

Measures relating to equipment could be implemented by replacing old equipment or retrofitting to implement cleaner and more energy-efficient technologies. Also, good equipment maintenance could save energy and reduce excess emissions (Alamoush et al., 2020). Digitalisation helps identify, monitor, and aggregate data to improve efficiency and protect the environment. Remote sensing, BDA (Fruth and Teuteberg, 2017; Munim et al., 2020), the Internet of Things (Ozturk et al., 2018; Yen et al., 2023), and cloud computing (Ranjan et al., 2020; Xia et al., 2021) can help manage logistics flows and as a result, reduce fuel consumption. Container terminal automation using automated guided vehicles (AGV) (Drungilas et al., 2023; Schmidt et al., 2015), automated machinery (Yen et al., 2023), drones, autonomous guided vessels (Oloruntobi et al., 2023), gate automation, and scheduling yard trucks (Hong et al., 2023; Ranjan et al., 2020) increases operational efficiency and reduces costs.

2.6. Land transport measures

Hinterland transport emissions are described as part of the ports' responsibility, and considering those emissions is essential for the efficiency of the whole intermodal transportation chain (Behdani et al., 2020). However, only 20% of ports are estimated to apply green hinterland emission reduction measures (Gonzalez Aregall et al., 2018). Port terminal efficiency and reducing emissions are possible when intermodal transportation or modal shifts are employed (moving cargo to rail, short sea shipping or inland waterways) (Behdani et al., 2020; IMO, 2018). Dry ports or inland intermodal terminals emerge as a solution for the need for ports to move more inland (Behdani et al., 2020). An intelligent inter-terminal transportation schedule, a truck appointment system combined with an automated gate processing system, and a peak hour traffic fee are some measures that would allow trucks to select a specific schedule to enter the terminal, which would decrease congestion outside the ports' gates while also decreasing ports' emissions overall (Alamoush et al., 2020; He et al., 2013).

2.7. Ship turnaround time

Reduced turnaround time (TAT) for the ships at berth would directly affect the total emissions. The TAT can be shortened by: increased productivity, reduced waiting time, reduced congestion, more efficient clearance procedures, crane equipment efficiency, and berth availability (Styhre et al., 2017; Winnes et al., 2015). Reducing TAT also allows shipping companies to increase transport work, reduce the speed at sea, and increase the berth capacity for the port (Styhre et al., 2017). Usually, ships berth on a first-come-first-served basis, which was found to increase the total TAT and CO2 emissions, and as a result, ports should provide enhanced alternative service policies, like booking berths before arrival (Alamoush et al., 2020).

2.8. Just-in-time berth and vessel speed reduction

Through information sharing, it is possible to bring all the stakeholders together on just-in-time (JIT) berthing, vessel speed reduction, and slow steaming (Gibbs et al., 2014). A well-elaborated strategy of slow steaming to reduce the vessels' speed while approaching ports can reduce fossil fuel consumption and result in lower emissions (Armstrong, 2013; Gibbs et al., 2014; Poulsen et al., 2018; Winnes et al., 2015). Several authors have recommended the benefits of JIT berthing to reduce shipping emissions (Alamoush et al., 2020; Misra et al., 2017b; Poulsen et al., 2018). An international alliance for the JIT arrival of ships is being developed to support low-carbon maritime transport (Verhoeven et al., 2020).

2.9. Onshore power supply

Onshore power supply (OPS), also referred to as cold ironing, is an essential measure recommended to reduce CO2 emissions in port areas and is one of the most discussed in the literature (Alamoush et al., 2020; Williamsson et al., 2022). OPS means ships in ports can turn off their auxiliary engines because they are connected to the electric grid while at berth (Williamsson et al., 2022). The reduction in GHG emissions could be very high, but that depends on the electric power source, so the best results are when the energy sources come from RE (Styhre et al., 2017; Winnes et al., 2015). However, the complexity of implementing OPS requires collaborative and collective approaches from ports, ship operators, ship manufacturers and other stakeholders to make joint investments (Styhre et al., 2017; Williamsson et al., 2022).

2.10. Offset programmes

Offsetting is a mechanism to compensate for emissions through direct prevention of the release of, reduction in, or removal of an amount of GHG emissions outside the operational boundaries of the organisation or indirectly through the purchase of carbon credits (ISO/TR 14069:2013, 2013). Port authorities could offer clients the possibility to invest in verified and reliable offset projects. Offset programmes broaden the impact of port climate change mitigation, with a potentially high reduction in emissions and relatively low investment (Alamoush et al., 2020). These programmes should always be considered additional support, forcing seaports to adopt new technologies, even though they may require more resources (EIT InnoEnergy, 2022).

2.11. Carbon capture, utilisation, and sequestration

Like the offset programmes, carbon capture, utilisation, and sequestration (CCU/CCS/CCUS) programmes can lead to significant carbon reductions with low investment compared to other technologies (Alamoush et al., 2020). CCU/CCS/CCUS technologies are being studied to substitute conventional marine fuels; however, large-scale applications are still in the early phases (Xing et al., 2020). CCU/CCS/CCUS systems handle vast quantities of CO2, and if a significant CO2 leak happens, it could result in widespread loss of life and create barriers to the acceptance of CCU/CCS/CCUS projects (Holt and Simms, 2021).

3. Methods

The methodology used to answer the initial RQ is discussed in this section. The methodological procedure is presented in Fig. 1 and follows the SLR method. For Denyer and Tranfield (2009), SLR consists of identifying, selecting, analysing, and summarising the research on a particular topic.

An SLR is an extensive research method and a more complete practice than other review forms (Kumar et al., 2023). Moreover, SLR is a widely employed methodology to examine various aspects of supply chains (Magalhães et al., 2021; Zimmermann et al., 2016). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique (Moher et al., 2009) was used to define the literature selection and data analysis. The PRISMA guidelines assure valid and reliable results. To categorise, organise, and analyse the literature, the 3 authors participated in and validated the several steps of the process based on a consensus between all. Most of the data preparation and analysis was performed manually using *Excel*, and the cluster analysis was conducted through the *VOSviewer Software*.

4. Data collection and processing

The literature was collected using the *Scopus* database, an acknowledged online scientific database covering different subject areas and frequently used for searching the literature (Culot et al., 2020; Guz and Rushchitsky, 2009). A group of keywords were selected and combined, according to the relevance of the terms to the research, to identify studies about the decarbonisation of ports. Different sets of keywords were developed and utilised for a combined search ("OR" to aggregate keywords within the sets; "AND" to group the sets). The list of keywords and how they were aggregated and grouped is presented in Table 2. These keywords were searched for in the titles, abstracts, and keywords of the papers (see Table 2).

Fig. 2 shows how PRISMA was applied in this study. In the first search, 3420 documents were obtained, covering the period until May 2023. Only English-language articles and reviews were selected, and 1470 results came from this first round of screening. A preliminary eligibility analysis was performed on these articles by checking the titles and, if needed, the abstracts. 442 papers were selected, and their essential information was collected.

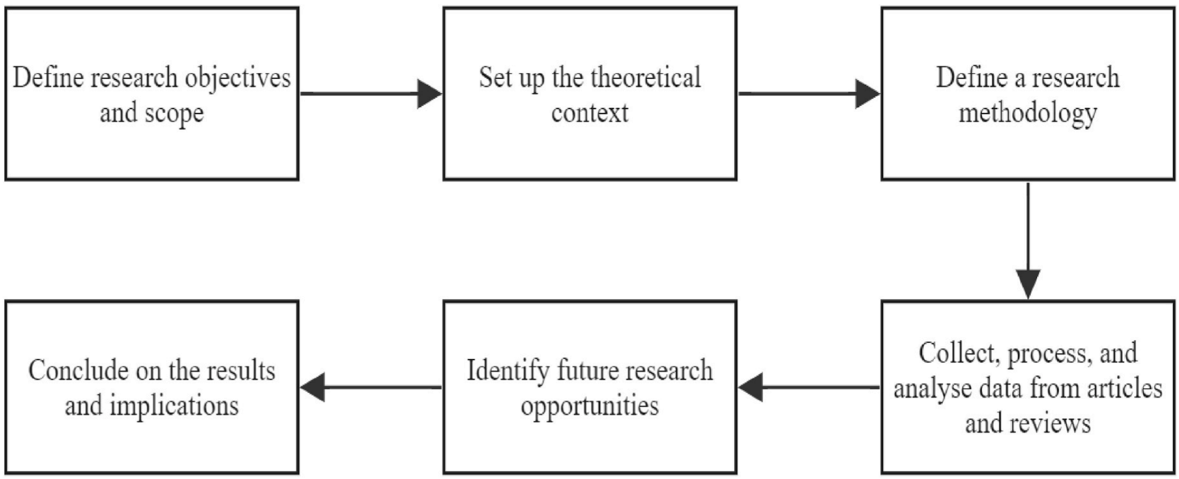

Fig. 1. Research Methodology: Flowchart of the research methodology.

Table 2
List of keywords used during the search of the documents.

Strings of keywords	1. Measures	renewable energy OR alternative fuel* OR low carbon fuel* OR renewable fuel OR state of the art technologies OR end-to-end maritime transport OR industry 4.0 OR information system* OR ICT OR internet of thing* OR cloud computing OR AI OR big data OR blockchain* OR PCS OR virtual reality OR electric vehicle OR electrification
	2. Objectives	decarboni* OR net-zero OR energy efficien* OR low carbon emission* OR greenhouse gas* reduction* OR GHG reduction* OR greenhouse gas* emission OR GHG emission*
	3. Area of Application	maritime sector OR shipping sector OR international shipping sector OR maritime transport* OR seaport OR port OR harbour OR container
Number of results	3420 documents in the *Scopus* database	

The 3 authors conducted an assessment separately and independently to avoid influencing each other and ensure reliability. The evaluation was made according to the title, the abstract, and the full text when necessary. After that, the articles were selected or excluded from the study based on the agreement between all authors. Finally, 124 English-language articles and reviews about the decarbonisation of ports were selected, and with the sample obtained, the papers selected were analysed. Since researchers use different terminology for the same concepts, an inductive approach was adopted (Culot et al., 2020; Mittal et al., 2016). More information about the papers selected is provided in Annex A.

5. Data analysis and results

In the next subsections, bibliometric, thematic and cluster analyses will follow. The bibliometric analysis intended to understand the prevailing trends within the literature. A thematic analysis was performed to identify the most studied countries, the investigation strategies used, and the decarbonisation measures considered. The cluster analysis allowed us to discern how the research topics are organised.

5.1. Bibliometric analysis

The distribution of the 124 papers by year of publication, covering the period from 2011 until May 2023, is presented in Fig. 3, which shows an increase in the number of documents since 2019. The high number of publications in 2021 and 2022 demonstrates a growing interest in the decarbonisation of ports as a current topic.

The chosen articles were published in 64 journals; the most relevant are presented in Fig. 4. The most pertinent journals, with 3 or more selected articles, represent 19% of the total number of sources, and together, they represent more than 53% of the papers selected in the study. These journals cover mainly energy-related topics, but some focus on sustainability, transportation, and maritime themes.

By analysing the first authors' productivity, in a total of 114 first authors, we can identify 7 researchers with more than one paper published (Fig. 5). We can also conclude that in 124 articles, the 7 authors identified are responsible for a relatively low number of only 17 documents. In this sense, the investigation on the decarbonisation of ports is quite widely distributed regarding the number of primary researchers.

In terms of citations, the top 10 most cited articles are presented in Fig. 6. Only 2 of these articles are signed by 2 authors identified as the most productive. By further analysis, it is possible to conclude that 5 of the most cited articles were published in journals interested in transportation-related themes.

When analysing the country of affiliation of the first authors of each paper, it is possible to identify 9 countries with 5 or more occurrences (Fig. 7). China leads with a significant advance over other countries, with 18 documents. Italy and Greece follow, with 9 and 8 articles, respectively. The United States, the United Kingdom, and India are accountable for 7 papers. There are 6 papers, with the first authors affiliated with Norwegian institutions. Finally, Germany and Sweden each produced 5 documents.

5.2. Thematic analysis

5.2.1. Countries studied

The several countries mentioned throughout the 124 documents collected using the SLR methodology were compiled in this section. The full results can be seen in Annex A. Corresponding to almost 75% of the total papers (92 out of 124 papers), the top 15 countries that studied the decarbonisation of their ports are summarised in Fig. 8. Germany has the

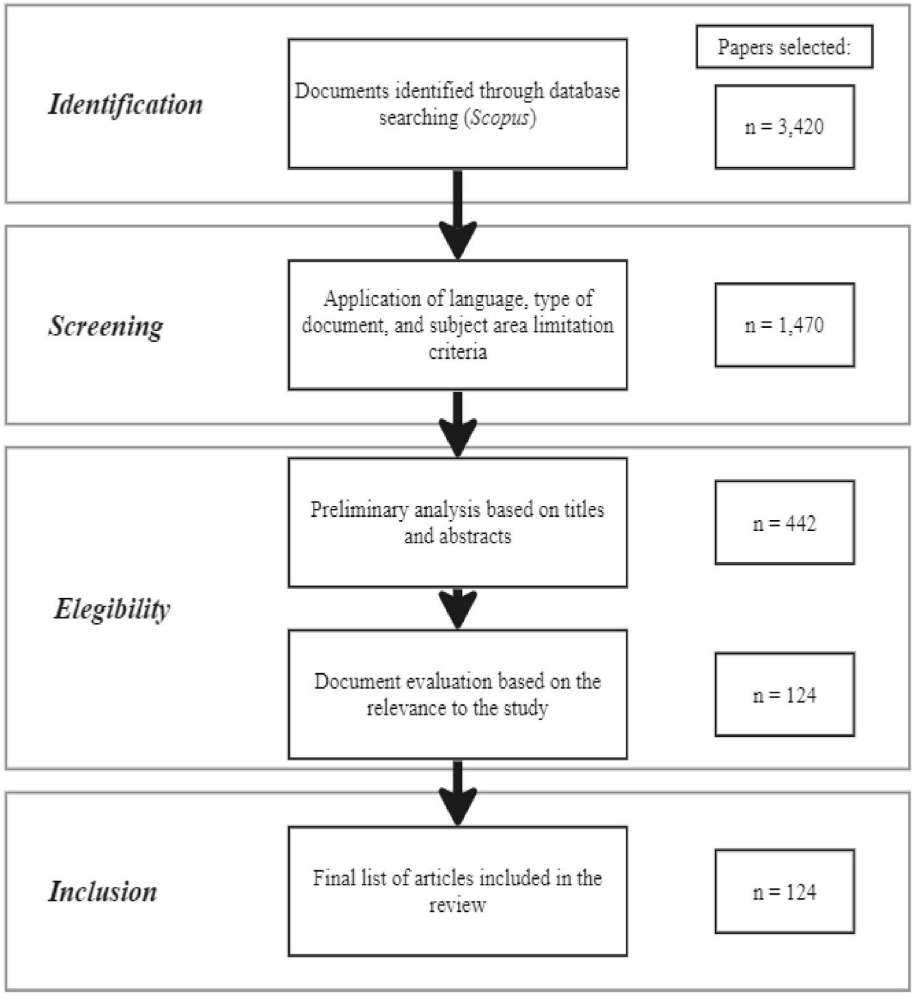

Fig. 2. PRISMA: Document selection process, following the PRISMA approach.

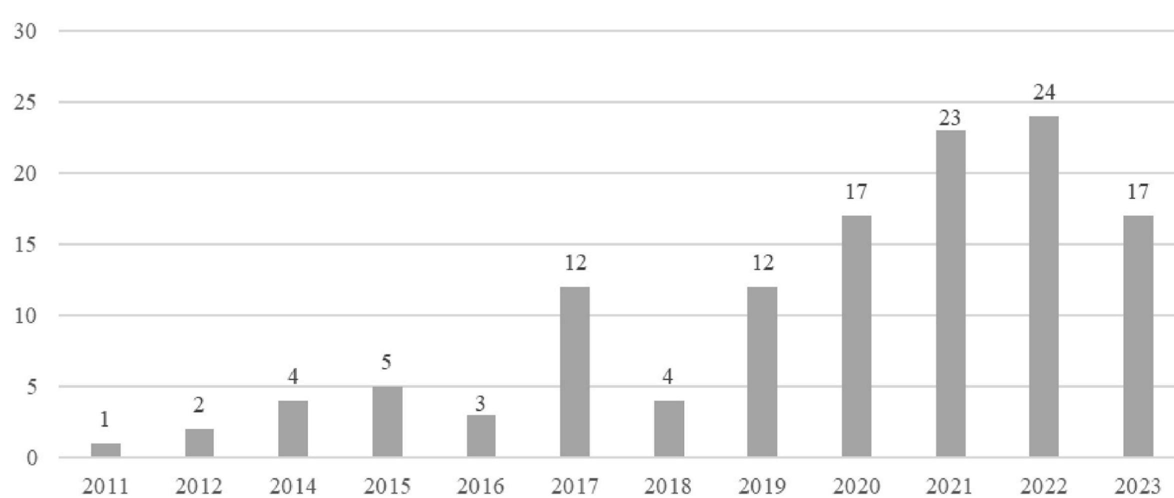

Fig. 3. Distribution per year: Number of articles per year.

most studies about decarbonising its ports, with 19 studies. The Netherlands and Italy have 13 studies, the United Kingdom and Spain have references in 11 papers, Sweden with 10 studies, Belgium with 8 articles, France, Greece, and Norway with 7 mentions, and Denmark with 6 references. Some of the most studied European ports are the ports of: Hamburg (Acciaro et al., 2014b; Holly et al., 2020; Schmidt et al., 2015), Gothenburg (Styhre et al., 2017; Winnes et al., 2015), Rotterdam (Bosman et al., 2018; Schneider et al., 2020), and Genoa (Acciaro et al.,

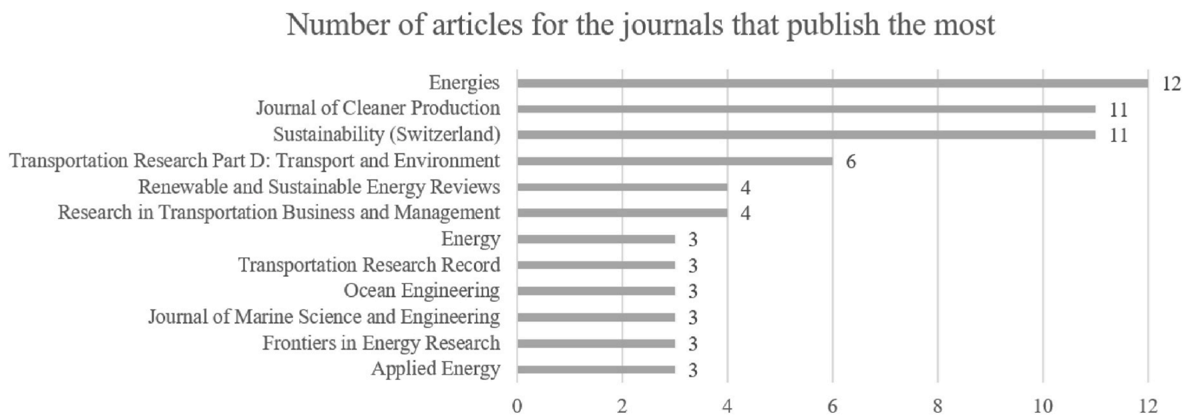

Fig. 4. Distribution per journal: Number of articles for the journals that publish the most.

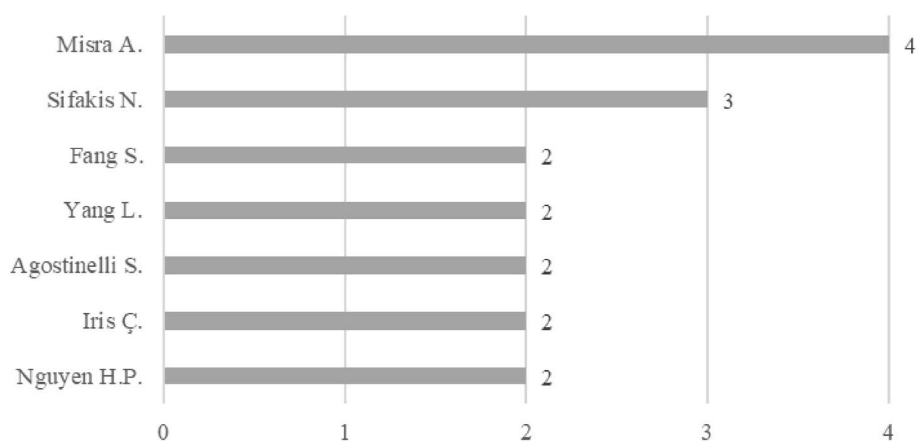

Fig. 5. Distribution per author: Number of articles for the most productive authors.

2014b; Castellano et al., 2020; Lavidas et al., 2020).

Besides European countries, Chinese ports can be identified in 18 documents, as well as the United States. The San Pedro Bay Port Complex, which includes the ports of Los Angeles and Long Beach in southern California, was investigated as a case study several times (Amar et al., 2017; Kim et al., 2012; Zhu et al., 2022). Singapore and India are the last 2 countries in the top 15, with 8 and 6 references, respectively.

5.2.2. *Research methodologies employed*

The first conclusion of this analysis is related to the prevalence of case studies in the decarbonisation of maritime ports research. Almost

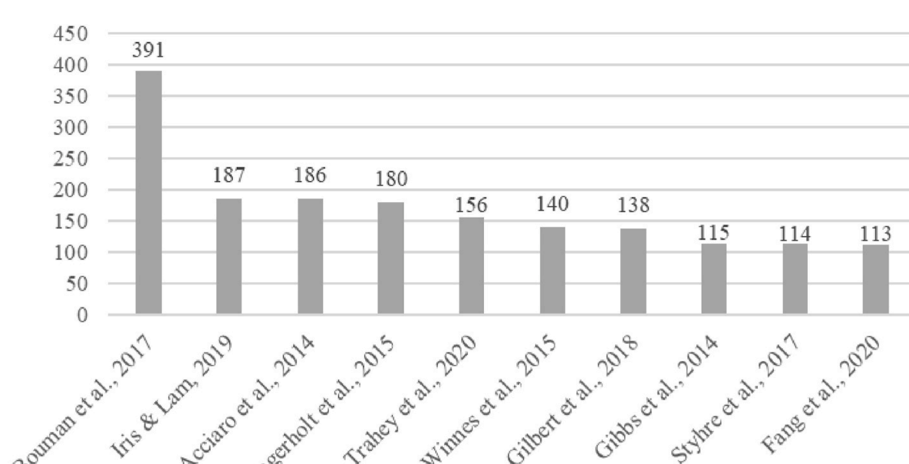

Fig. 6. Distribution per number of citations: Top 10 most cited articles.

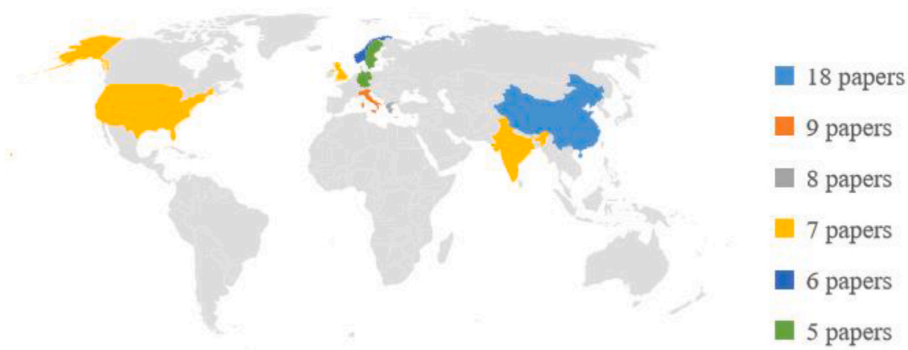

Fig. 7. Distribution per author affiliation: Countries with the most papers published.

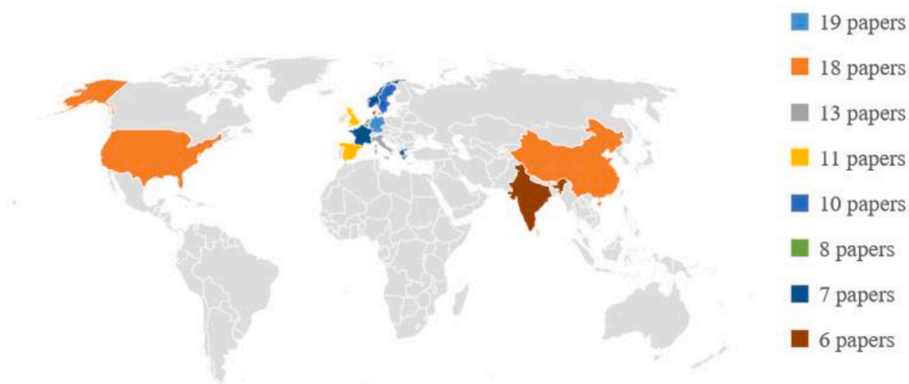

Fig. 8. Distribution per country: Top 15 countries studied.

Table 3
Summary of methodologies used in the study of the decarbonisation of ports.

Investigation Strategy	Count
Mixed Strategies	5
Archival Research	30
Ethnographic Observation	1
Case Study	85
Survey	3
Total	124

69% of the papers selected applied a case study method, and only 5 of the 124 documents used a mixed-method strategy (see Table 3). Also, only 3 studies performed a survey as an investigation strategy. Since surveys are especially critical when working on beliefs, attitudes, or opinions, more studies could be conducted using this investigation strategy (Bennett et al., 2011). For more details, please consult Annex A.

Of the 30 studies that used Archival Research as their investigation strategy, 8 conducted Systematic Literature Reviews, and 4 performed a Bibliometric Analysis. The decarbonisation of ports was studied 6 times while using interviews as one of the investigation techniques. 7 papers applied a carbon footprint analysis or a life cycle analysis. Simulation, optimisation, and computation are the most used techniques. Those techniques were identified 60 times throughout the selected documents.

5.2.3. *Measures investigated*

A categorisation was developed to simplify the presentation and examination of the port decarbonisation measures and was based on other documents (e.g., Alamoush et al., 2020; Alzahrani et al., 2021; Gibbs et al., 2014; Gonzalez-Aregall et al., 2018; IMO, 2018; Iris and Lam, 2019; Misra et al., 2017b; Poulsen et al., 2018; Xing et al., 2020). Similarly to existing studies, the classification in this review includes the most essential decarbonisation measures (clean energy sources, operational measures, and energy systems) but also conservative measures often overlooked in the literature. The development of practical solutions to mitigate GHG emissions and evaluate the effectiveness of measures over time are essential steps for the port-related industry that should be assisted by information measures, like a GHG inventory (Misra et al., 2017b), serving as a first step of a route to port decarbonisation. Fig. 9 summarises the classification of the measures applied in this work, resulting in 4 main categories and 11 subcategories. The categories will be detailed below for further analysis, and in Annex A, it is possible to identify which measures were addressed in each article.

5.2.3.1. Clean energy sources. Alternative fuels, like LNG, hydrogen, biodiesel, and ammonia, are the most mentioned in the literature. However, ethanol, nuclear, methanol, and methane are some other alternatives with the potential to replace heavy fuels with low-sulphur options (Alamoush et al., 2020; Ampah et al., 2021; Mallouppas and Yfantis, 2021). Alternative fuels could be considered in mixtures to increase their reduction potential (Foretich et al., 2021; Taneja et al., 2021). The use of RE may be considered individually (solar, wind, wave, tidal, geothermal, biomass) or combined (Balbaa and El-Amary, 2017; Rolan et al., 2019; Spaniol and Hansen, 2021). An RE community is a new concept to be studied, which could escalate the potential for reducing GHG emissions in ports (Agostinelli et al., 2022b).

5.2.3.2. Operational measures. By far, the measures related to information are the most studied. Information measures focus mainly on collecting, tracking, and reporting data (Gibbs et al., 2014). However, they could also include: the management of PCS (Alzahrani et al., 2021), integrating port-city objectives (Bosich et al., 2023), development and fulfilment of green policies in ports (Bouman et al., 2017; Winnes et al., 2015), and promoting digitalisation (Agostinelli et al., 2022a; Fruth and Teuteberg, 2017; Ullah Khan et al., 2022).

Energy efficiency measures, like energy management plans, virtual

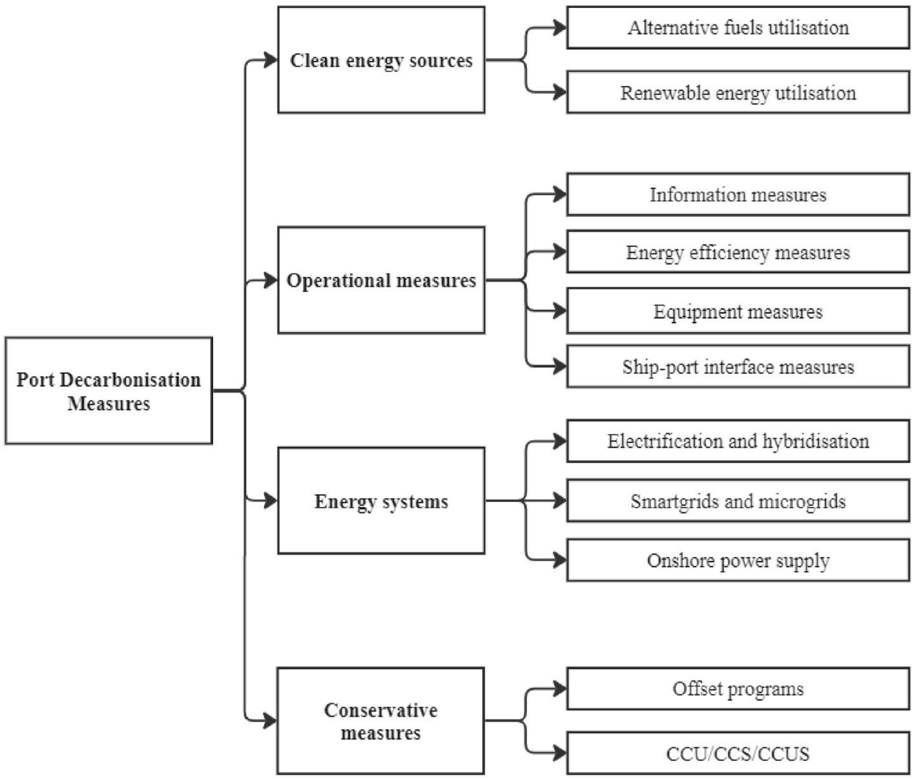

Fig. 9. Categorisation of port decarbonisation measures.

power plants, smart load management, and peak shaving, are essential for efficient and resilient power systems, as well as minimising overall energy consumption (Acciaro et al., 2014b; Alzahrani et al., 2021; Iris and Lam, 2019).

Some examples of equipment measures are: intermodal transportation (Kurtulus and Cetin, 2019), truck appointment (Poulsen and Sampson, 2020), automated guided vehicles (Drungilas et al., 2023), container terminal automation (Al-Fatlawi and Jassim Motlak, 2023), waste management systems (Di Vaio et al., 2019), radio frequency identification (Choi et al., 2012), unmanned aerial vehicle assisted data (Oloruntobi et al., 2023), wireless signals (Ozturk et al., 2018), engine technical development (Foretich et al., 2021), and equipment maintenance, replacement, or retrofitting (Alamoush et al., 2020).

One of the most studied ship-port interface measures is the reduction of ship turnaround time through berth allocation, yard allocation and scheduling, automated mooring systems, and mid-stream operations (Alamoush et al., 2020; Mao et al., 2022; Styhre et al., 2017). Virtual arrival (Sinha and Roy Chowdhury, 2022), JIT berthing (Gibbs et al., 2014), and vessel speed reduction (Yun et al., 2018) are other critical measures. Moreover, ship design and vessel handling should be adapted according to the local conditions to limit any impacts on the ecosystem (Lindstad et al., 2015).

5.2.3.3. Energy systems. Energy systems focus primarily on the electrification and hybridisation (Daniel et al., 2022) of electric cargo handling equipment (Iris and Lam, 2021; Taneja et al., 2021), like cranes (Alasali et al., 2019), and vehicles, like all-electric ships (Bakar et al., 2021; Fang et al., 2020; Kumar et al., 2019), trucks (Amar et al., 2017; Hong et al., 2023), railways (Kurtulus and Cetin, 2019), or automated guided vehicles (Drungilas et al., 2023). Another prevalent measure in the literature is using OPS for ships in ports to reduce emissions (Sciberras et al., 2016; Yun et al., 2018). Intelligent energy networks in harbour grid configurations, like smart grids (Alzahrani et al., 2021; Kanellos et al., 2019; Rolan et al., 2019) and microgrids (Kinnon et al., 2021; Misra et al., 2017b; Parise et al., 2016), are essential to electrify ports, incorporate ESS (Sifakis et al., 2021; Trahey et al., 2020; Vahabzad et al., 2021), and create revenue streams with the extra electricity produced (Balbaa and El-Amary, 2017).

5.2.3.4. Conservative measures. Offset measures are relatively low investment mitigation strategies with potentially high emission reduction (Misra et al., 2017b), and they can be adapted depending on the willingness to pay (Argyriou et al., 2022). Some examples are: carbon pricing (Yang et al., 2019), port charges based on their productivity levels and stakeholders' performance (Iris and Lam, 2021), penalties for vessels that use non-clean fuel (Kim, 2022), and discounts for shippers transporting cargo by intermodal transport (Sinha and Roy Chowdhury, 2022). CCU/CCS/CCUS are being studied as potential alternatives to integrate with cleaner fuels (Mukherjee et al., 2020).

5.3. Cluster analysis

After conducting bibliometric and thematic analyses, we employed *VOSviewer Software* to perform cluster analysis, thereby identifying and categorising the most significant research topics. *VOSviewer Software* is a tool to represent bibliometric maps and allows researchers to analyse research topics, elaborate on co-occurrence networks, and identify research clusters (Jimenez et al., 2022; Souza Piao et al., 2023; Van Eck and Waltman, 2009). Being easy to use and providing multiple features makes *VOSviewer Software* a widely used tool (Orduña-Malea and Costas, 2021). A co-word analysis was conducted using *VOSviewer Software* to create a conceptual structure using the titles and the abstracts of the 124 documents. The terms considered had to have a minimum of 10 occurrences and were selected according to their relevance to the study. To create a map of research clusters focused on port decarbonisation, without redundancy, it was necessary to standardise similar concepts. The final map presented in Fig. 10 has 3 main groups and 15 items.

It is possible to see which of the papers selected for the SLR contribute to each cluster in Annex A. The first cluster (red) and the second cluster (blue) are considered the most prominent clusters, with

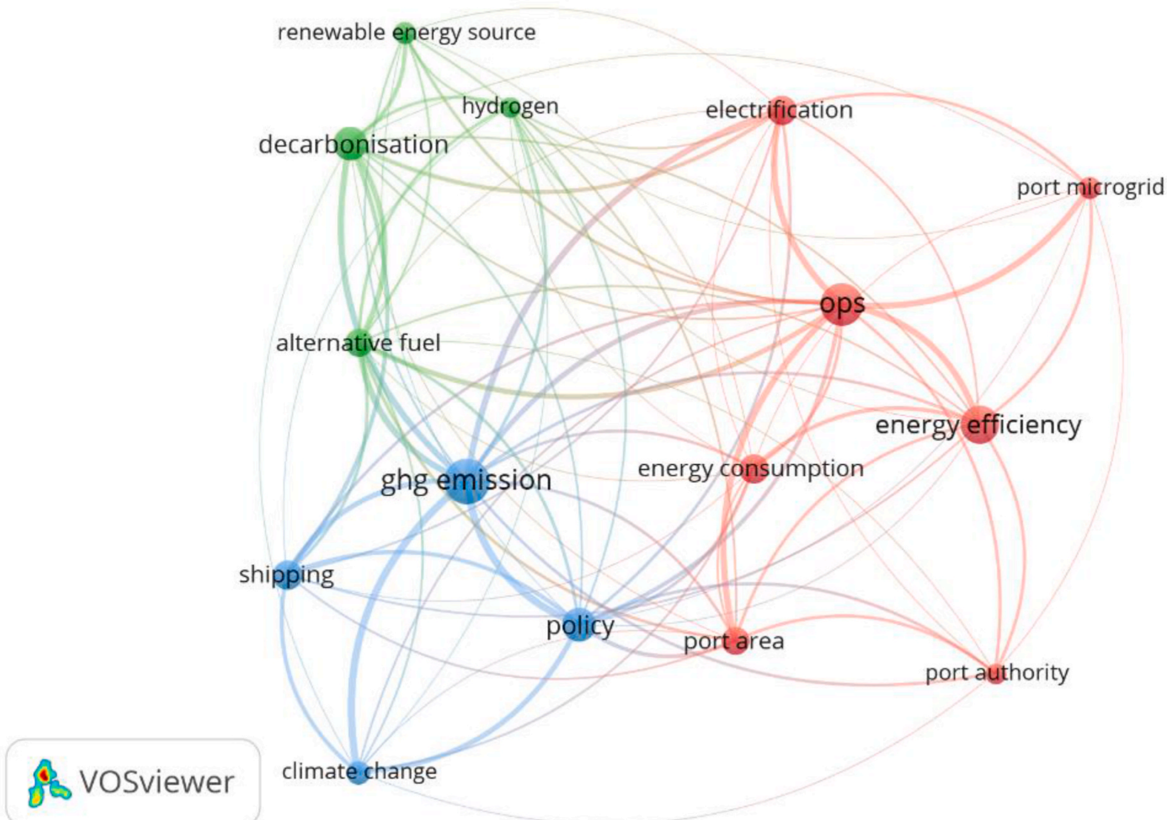

Fig. 10. Final map of the research clusters.

42% and 35% of the total number of references, respectively. The green cluster is the smallest since only 23% of the documents refer to at least one of the research topics in the third cluster. For a more in-depth look at the 3 research clusters identified, 3 subsections will follow with a detailed description of the research in each group. The top 10 research papers in every cluster, according to the number of citations, were selected to reduce the sample of analysis and propose more concrete conclusions, which is a common practice in systematic and bibliometric studies (Bashir, 2022; Fahimnia et al., 2015; Souza Piao et al., 2023). For all the clusters, the top 10 most cited documents correspond to more than 50% of the total of citations in each cluster, revealing a concentration of the total of citations: for the red cluster 56% (1116 out of 1995 citations); for the blue cluster 64% (1570 out of 2472 citations); and for the third cluster 69% (1186 out of 1711 citations).

5.3.1. *Cluster 1 (red) - energy systems*

Ports are required to manage their electrical power distribution in microgrids (Parise et al., 2016). A roadmap to manage a grid in ports should be based on 4 pillars: energy supply, energy storage, energy demand management, and optimal management and communication (Iris and Lam, 2019). In port microgrids, various issues can be resolved by technical and operational measures, such as power-sharing, increased power quality, and voltage regulation rules (Fang et al., 2020). Compared to traditional designs, implementing port microgrids results in considerable cost savings and can escalate when ESS are deployed since they help store energy for later utilisation or sell back to the main grid at higher prices (Iris and Lam, 2021). Energy management is part of the strategic positioning of the port as a response to societal pressure or as a new alternative to improve the port's competitive position (Acciaro et al., 2014b). Ports can start by developing local corporate policies for energy management and efficiency (Iris and Lam, 2019).

Electrification of all equipment and using electricity as the primary energy source are the first steps for many seaports that want to contribute to mitigating climate change issues (Iris and Lam, 2021). With the trend of seaport electrification, the connections between the land and ships are no longer limited to a logistics vision but to an energy optimisation problem (Fang et al., 2020). Using BDA and artificial intelligence (AI) can serve as a step for the digital transformation required to address energy efficiency problems (Munim et al., 2020). Ports should invest in electrification projects to enhance the system's flexibility and mitigate environmental issues (Fang et al., 2020; Lindstad et al., 2015). Port authorities should consider the locations and the equipment within the port area with the highest potential to reduce emissions (Winnes et al., 2015). OPS could reduce CO2 emissions substantially, particularly in ports with a large share of high-frequency shipping lines (Styhre et al., 2017). However, despite the current technological improvements, the mere development of technical solutions will not have any effects until they have spread throughout the global shipping industry (Munim et al., 2020).

5.3.2. *Cluster 2 (blue) - emissions management*

The second cluster focuses on: reaching sustainability goals, reducing the impact of climate change, stabilising the increase in GHG emissions, and ensuring the sector's sustainability. Ports should provide infrastructures to reduce global shipping emissions while reducing their emissions (Gibbs et al., 2014). International cooperation towards stricter regulations is a fundamental factor, and to overcome local issues, a port-city perspective could be more important than a global vision (Winnes et al., 2015). Emerging digital technologies would promote more reliable and efficient management systems across the industry (Fruth and Teuteberg, 2017). Moreover, the possible reduction of GHG emissions in the port area depends on how often a ship revisits a port (it is easier to implement decarbonisation measures for high-frequency lines) (Styhre et al., 2017).

Bouman et al. (2017) reported a substantial variation in the potential to reduce emissions according to the studies that have already been done, meaning that decarbonisation measures must be chosen from a case-by-case perspective and that no single action is sufficient to achieve neutrality targets. Reductions in GHG emissions and local pollutant levels are vital challenges, and to understand the full implications of the reduction of emissions, a complete life-cycle perspective should be adopted (Gilbert et al., 2018). Operational measures may look more attractive since ports may have difficulties offering incentives for measures requiring high levels of financial investment, but they are insufficient to achieve neutrality targets (Styhre et al., 2017; Winnes et al., 2015). Industry 4.0 measures have several benefits for emissions management at a relatively low cost. However, risks, such as data abuse or cybercrime, must be considered (Fruth and Teuteberg, 2017).

5.3.3. Cluster 3 (green) - clean energy sources

Alternative fuels as a cleaner practice, using RE as a significant cost-saving measure, and hydrogen as an emerging solution are recognised to contribute to the decarbonisation of ports (Ampah et al., 2021; Gilbert et al., 2018; Iris and Lam, 2019; Winnes et al., 2015). Ports worldwide must assess the potential to implement clean energy sources and identify where crucial barriers may be located, for example, low availability of technology, reduced readiness of alternative fuels or lack of knowledge of future economic savings (Gilbert et al., 2018; Iris and Lam, 2019). Further, data concerning the shipowners' interest how much such measures are adopted would also help identify barriers and ways to tackle them (Ampah et al., 2021). One thing is clear: any chosen practice should be analysed thoroughly to understand its advantages and limitations. For example, energy outputs, site-specific efficiency, availability, and capacity factors should all be considered when using an RE source (Ramos et al., 2014). Besides the previously mentioned measures that could motivate structural changes in ports, other initiatives could be highly efficient in achieving decarbonisation targets. Reductions in the speed of vessels to reduce the amount of fuel consumed (Styhre et al., 2017) or ESS to help address the variability in RE production (Trahey et al., 2020) are examples of other measures.

6. Discussion of results

Future research opportunities will be presented to complete the SLR analysis.

6.1. Future research opportunities for cluster 1 (red) - energy systems

Opportunities for future research for the first cluster could explore simulations to integrate different measures for energy efficiency (Iris and Lam, 2019). The stakeholders' participation in appropriate scenario building would also be of significant value (Winnes et al., 2015). For example, the surrounding communities must participate in the discussion when ports want to serve as microgrids for the neighbouring area to sell any extra energy produced inside the port. When adopting OPS, if the electricity is required from external sources, ports need to make sure the grid is not dependent on fossil fuels, and that it has the production capability required. Future research about port electrification would need to include a distributed control framework, adaptive energy management techniques, efficient ESS management (Fang et al., 2020), and hybrid power solutions (Lindstad et al., 2015).

In the context of the maritime industry, studies are needed to accelerate the diffusion and adoption of technologies besides technological development. This includes more research on identifying the drivers and barriers to increase the transparency needed to overcome any legal obstacles to the future institutional changes necessary in the maritime industry (Munim et al., 2020). Some examples of legal challenges include how to determine the appropriate regulatory roles for different regulatory bodies, how to harmonise global policies and regional laws to reduce emissions from global maritime transport, and how to balance the interests of developed and developing states. There is a need to clarify where and how the port authority could operate to increase energy efficiency in the port area while investigating the port industry from a benchmarking perspective, particularly for energy management (Acciaro et al., 2014b).

6.2. Future research opportunities for cluster 2 (blue) - emissions management

For this cluster, the opportunities for future research are: obtaining more precise data concerning ship speeds, fuel consumption rates, sailing time, and cargo turnover. Port emissions need to be analysed from their source to their impact, according to the different scopes of emissions, while considering the ship types and energy efficiency levels. Additionally, emission reduction solutions need to be tested before progressing to "industrial" levels (Gilbert et al., 2018; Winnes et al., 2015). Also, limiting GHG emissions by using environmentally differentiated port charges must be tested (Styhre et al., 2017). Research on decarbonisation policies for ports should be carried out, and improvements in collaboration projects concerning shipping-related themes between different institutions, countries, or authors should be facilitated (Ampah et al., 2021). Incentives for further enhancements in maritime transport emission efficiency are recurrent in the industry. However, they are not always implemented due to existing barriers (restrictive contracts, lack of proper information, lack of control over operations, among others) that should be studied as they restrict potential economic benefits (Styhre et al., 2017).

6.3. Future research opportunities for cluster 3 (green) - clean energy sources

Some areas for future research in this cluster are: operational, technological, economic, and environmental analyses of RE sources and viability assessment, technological developments, and feasibility analysis for pilot hydrogen projects (Iris and Lam, 2019; Xing et al., 2020). Modelling a port energy management system based on RE sources under uncertain conditions (disruptions, natural events, among others) and combining it with other technologies is critical (Iris and Lam, 2021). Apart from the aspects relating to implementing clean energy sources, additional requirements need to be investigated, such as installation and maintenance costs, ESS facilities, and any potential impacts on the marine environment (Ramos et al., 2014).

It is also necessary to conduct studies on the characteristics and performance of different fuel sources so that stakeholders can evaluate the feasibility of alternative fuels more thoroughly (Ampah et al., 2021). Further, a method to conduct international benchmarking studies more easily is required to make meaningful comparisons of clean sources in ships and ports (Styhre et al., 2017; Winnes et al., 2015). More research on how legal requirements, market-based measures, and voluntary programmes could accelerate the adoption of alternative fuels and RE (Xing et al., 2020). Some obstacles are economic considerations regarding the high capital costs for investments required for new infrastructures, or regulatory uncertainty and global policy instability preventing the large-scale deployment of clean energy sources.

7. Conclusions

With the growth of the literature on port decarbonisation, there was a need to clarify how different measures, regulatory frameworks, and technological innovations could be combined to develop context-specific port decarbonisation strategies that assure stakeholder collaboration. By identifying the major trends, categorising the most important decarbonisation measures, and representing the research clusters of port decarbonisation, the insights gleaned from this study contribute with practical implications for maritime industry practitioners, policymakers, and researchers alike. As the world accelerates its pursuit of a sustainable future, it is evident that the role of ports in global decarbonisation efforts is paramount.

To answer the RQs proposed, a summarised answer to each question is presented below.

1) After performing the cluster analysis using *VOSviewer Software*, the main research topics have been organised into 3 clusters. Cluster 1, represented in red, is focused on the role of port authorities in the management of port areas and the implementation of energy systems such as microgrids, OPS, and equipment electrification. Some of the pathways in the second cluster are the need to monitor and reduce GHG emissions, assess the impact of climate change policies, or evaluate the role of shipping in achieving global neutrality. The last cluster is the green cluster, and it explores some of the most essential decarbonisation measures for ports, RE sources and alternative fuels, such as hydrogen.
2) Generally, the new insights described above indicate a benchmarking opportunity to understand the level of decarbonisation in ports. More simulation and optimisation studies are needed to establish the best mix of measures for each specific port. The participation of more port stakeholders in the decarbonisation process should be encouraged, and the drivers and barriers to adopting measures should be identified.

The study's main limitations include the authors' and reviewers' bias. One consequence of that bias might be that some articles pertinent to this work were not selected because of the keywords chosen. This could also happen due to the definition of inappropriate keywords or alternative names for the same concept. The selection, inclusion, categorisation, and analyses of the articles were naturally influenced by the authors' and reviewers' subjectivity.

The main opportunities for future research are: the need for more research in ports located in African, South American, and Oceanic countries, more studies to identify the measures most prioritised by ports, and exploring different combinations of measures to decrease the effects of emissions, like RE, electrification, and OPS. In conclusion, the insights gained after synthesising the existing literature have presented a compelling case for embracing technological advances to curtail GHG emissions in maritime ports. Our collective responsibility is to usher in an era of sustainable practices that safeguard our planet for future generations.

CRediT authorship contribution statement

André Fadiga: Writing – original draft, Writing – review & editing. **Luís Miguel D.F. Ferreira:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **João F. Bigotte:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142209.

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