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A comprehensive analysis of strategies for reducing GHG emissions in maritime ports

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ABSTRACT

IMO green initiatives emphasize the urgency of reducing greenhouse gas (GHG) emissions in shipping, extending beyond open sea operations to include emissions from ships in ports. This study systematically reviews 139 studies to identify trends in estimating GHG emissions from ships in ports, presenting a comprehensive analysis of twelve indicators across four aspects of the GHG emission estimation process: data quality, metrics, models and simulations. The findings emphasize the need for high-resolution databases with consistent standards to improve data quality. Additionally, the study advocates for the adoption of diversified and standardized emission intensity metrics to provide more comprehensive insights. Revising emission parameters, such as shipping emissions at berths and in ports, using updated data is crucial. A balanced approach between interpretability, data requirements, and model accuracy is essential to enhance emission estimates. Moreover, it is vital to account for interactions between strategies when simulating decarbonization scenarios. A significant research gap is identified in the performance of multi-port strategies based on unified databases.

1. Introduction

The rise in greenhouse gas (GHG) emissions is bringing the world closer to a serious climate crisis, making it necessary for the shipping industry to scrutinize its environmental footprint. Shipping plays a crucial role in facilitating global trade by transporting more than four-fifths of the world's commodities via ships and ports [106]. Although the shipping industry has lower GHG emissions per unit of cargo, it is nonetheless widely acknowledged as a significant global contributor to GHG emissions. In 2023, it accounted for around 3 % of the total global CO2 emissions. Without further intervention, these emissions are expected to increase significantly. The International Maritime Organization (IMO) projects that, if no action is taken, increases in CO2 emissions from ships could range between 0 % and 50 % by 2050 compared to 2018 levels, potentially reaching an equivalent of 90–130 % of 2008 levels [49]. The IMO has implemented decarbonization initiatives to achieve a minimum 40 % decrease in CO2 emissions per voyage by 2030 and a 70 % decrease by 2040 in total yearly GHG emissions from international shipping, relative to the levels recorded in 2008 [50]. However, achieving decarbonization in the shipping industry necessitates a collective effort involving all relevant parties, such as shipping companies and port authorities.

Ports are a critical component of the global transportation network, serving as junctions for both water and land-based transport and crucial components of the infrastructure supporting global trade and commerce, significantly influencing economic growth and development. The concentration of many ships in small port areas leads to very high levels of emissions [121]. Port configurations vary widely, ranging from small-scale ports exclusively engaged in straightforward cargo transport operations to larger ports hosting a mix of industrial, commercial, and cargo activities. The type of port operations and how they are conducted will affect the identification of different emission sources. Research over the past decade has identified ship emissions as a major contributor to port GHG emissions, accounting for 47–80 % of the total. Although no clear trend in the share of ship emissions over time has been observed, it exceeds 50 % in most ports [9,21,74,93,107]. Effectively addressing GHG emissions from ships in ports has emerged as a crucial area of focus.

This paper differs from previous systematic literature reviews in two main ways. First, it focuses on GHG emissions from ships in ports, a topic that has yet to be systematically reviewed. As attention to GHG emissions from ships in ports grows, more relevant publications are emerging, underscoring the need for a comprehensive review. Second,

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while earlier reviews have primarily focused on GHG emissions estimation models, they have neglected the critical roles of data quality, emission metrics and simulations of decarbonization strategies in the estimation process. This review incorporates these three aspects to provide a more complete understanding of estimating GHG emissions from ships in ports.

Therefore, the main contribution of this paper lies in its comprehensive review and analysis of GHG emissions from ships in ports, an essential yet under-explored area. Through the systematic review of 139 studies, this paper examines twelve indicators across four critical aspects of the GHG emission estimation process: data quality, metrics, models, and decarbonization strategy simulations. This study identifies gaps in the existing literature and proposes new directions for future research. Unlike previous reviews, this paper uniquely addresses the entire estimation process of estimating GHG emissions, including often-overlooked aspects like data quality and metrics, thereby offering a more complete understanding of the challenges and opportunities in this field.

This paper is organized into six sections. Section 2 reviews previous systematic literature reviews on port emissions to clarify the motivation behind the four research questions. Section 3 outlines the systematic literature review protocol. Section 4 summarizes the review results, focusing on the four key aspects of the GHG estimation process. In Section 5, we address the four research questions and discuss the findings. Finally, Section 6 highlights the research gaps identified in the existing literature.

2. Literature review

Previous literature reviews on maritime emissions fall into two primary categories. The first category addresses sustainable or green ports, encompassing emissions from operating ships within port harbors, land transport equipment, and port infrastructure, etc. [72]. Lim et al. [72] has explored the concept of "green ports and maritime logistics", identifying directions for future research. Furthermore, recent studies focus on reviewing technical and operational measures that assess policymakers in enhancing port sustainability and reducing GHG emissions [1,7,110]. The second category centers on optimizing shipping emissions. Several studies have worked on developing new methods for measuring ship gas emissions in port areas [8,103]. Additionally, Yang et al. [118] and Chen and Yang [19] provided a critical review of big data application in the context of port emission.

Based on the literature, the typical process of GHG emission estimation begins with the collection of raw data from ports or databases, followed by the selection of relevant emission metrics to assess port performance. Next, GHG emission estimation models are developed in alignment with the research objectives. These models are then applied in simulation experiments to evaluate various decarbonization strategies. Consequently, GHG emission estimation from ports involves four key aspects: Data, Metrics, Models, and Simulations. However, research gaps and challenges remain in each of these areas.

2.1. Data quality

Data quality is a major problem in quantitative research, and maritime emission estimation research is certainly not immune to this problem. Big data and machine learning have significant implications for data-driven decision-making in the maritime industry, similar to their impact in other industries [71]. Recognized as a transformative innovation on par with diesel engines and containerization, big data technology has revolutionized shipping operations over the past decade, including the collection and analysis of ship GHG emissions data. Numerous studies emphasize the critical role of data quality in accurately measuring GHG emissions from ships in ports [11,63,66]. Tian et al. [100] found that lower data sampling frequencies often lead to underestimating actual emissions. Furthermore, Nunes et al. [82] and Sorte et al. [96] noted that outdated default parameters could introduce considerable uncertainties, sometimes leading to errors ranging from 20 % to 50 %. Data quality not only affects the precision of the results but also limits the applicability of GHG estimation models. Certain models require specific data types, restricting their scalability on a macro scale [3]. Model requirements for data quality underscore the need for standardized data collection practices within and across ports, tailored to emission calculation models [66,77]. Until a uniform database is established, imputing missing data remains a crucial approach for maintaining data integrity.

2.2. Metrics

Emission metrics are also important in the calculation of ship GHG emissions in port [6,14,117]. GHG emissions are not only contributed by carbon dioxide, but also include other emissions such as methane and nitrogen dioxide [92]. Ports need to update their emissions metrics to quantify and compare the relative and absolute climate change contributions of different GHG emissions. Most current metrics rely on a single, absolute value to assess the emission performance of all ships [41]. The environmental impact of a ship can vary based on its characteristics, with different ship types affecting the environment in distinct ways. Therefore, using the same metrics for all ships is not appropriate. Current ship emission metrics are fragmented and a more comprehensive approach is needed [73]. Quantifying port emissions and assessing mitigation measures for these sources is challenging due insufficient emissions data and incomplete evaluation of emissions metrics [52]. Furthermore, standardized emission metrics would enable better comparison of environmental performance between ports.

2.3. Models

Extensive research over the past two decades has focused on developing estimation and prediction models to mitigate emissions at various geographical scales, including inter-regional, national, and local levels. Drawing from maritime studies [8,35,82] and broader GHG estimation research [95,113], these models can be broadly categorized along two dimensions: the modelling approach and the modelling structure. In terms of approach, models are divided into bottom-up and top-down. In terms of structure, models are classified into three types: white box models (WBMs), black box models (BBMs), and grey box models (GBMs).

The literature on ship emission estimation, particularly regarding GHG emissions in ports, utilizes two primary modelling approaches: top-down and bottom-up. The top-down approach estimates how much fuel ships consume at a port, then calculates emissions based on fuel-related emission factors [38]. Notable top-down models include the Methodologies for estimating air pollutant emissions from transport (MEET) [105] and The Intergovernmental Panel on Climate Change (IPCC) model for national greenhouse gas inventories [26]. These approaches facilitate emission estimates on a regional scale or across multiple ports. For example, Johansson et al. [57] used a top-down model to estimate ship emissions at a macro-level, while DE Meyer et al. [25] applied it to four Belgian ports (i.e. Antwerp, Ghent, Ostend and Zeebrugge). Pitana et al. [86] and Ju and Hargreaves [59] studied the $CO2$ emissions from ships in the Madura Strait and the Western Singapore Straits, respectively. The top-down model also simplifies long-term emission calculations, as seen in studies covering several years to decades [5,30,84,91,119]. However, despite its suitability for regional-scale, yearly estimates and its lesser data requirements, the accuracy of the top-down model can be limited.

Recent studies suggest that bottom-up estimation models, supported by Automatic Identification System (AIS) data, tend to be more accurate [67]. Some literature compares bottom-up and top-down approaches and finds a 24 % difference between their estimated $CO2$ emissions [27]. AIS provides high-resolution ship movement data, which is reliable in capturing ship activities such as timing, direction, and average speed between two AIS records. This data can be utilized to map ship trajectories [68]. Notable bottom-up models include ENTEC Limited (ENTEC) models, European Monitoring and Evaluation Program / European Environment Agency (EMEP/EEA) models, U.S. Environmental Protection Agency/ California Air Resources Board (USEPA/CARB) models, Ship Traffic Emission Assessment Model (STEAM), and IMO models. Each model is designed to meet specific organizational or port needs, with STEAM particularly influential in recent research. In summary, while the top-down model is effective for broad, less data-intensive studies, the bottom-up approach, with its detailed ship-by-ship analysis, offers greater accuracy and continues to evolve with advancements in data collection, such as AIS.

The ENTEC report, commissioned by the Department for Environment, Food and Rural Affairs (Defra), aims to provide a comprehensive dataset on ship emissions [31–33]. In these reports emissions are calculated by summing the output of main and auxiliary engines during ship activity periods. The European Monitoring and Evaluation Program/European Environment Agency (EMEP/EEA) model, part of air pollutant emission inventory guidebook developed by the European Environment Agency [28], offers technical guidance for preparing national emission inventories, including shipping emissions. Similar to ENTEC, the EMEP/EEA model uses more detailed emission factors for its calculations. In the U.S., both the U.S. Environmental Protection Agency (USEPA) and the California Air Resources Board (CARB) have proposed similar port emissions inventory guidance to monitor GHG emissions from ocean-going vessels in ports [15,34]. The USEPA/CARB model accounts for boiler emissions and calculates the power load of the main engine using real-time speed data. The STEAM is a widely used model, first proposed by Jalkanen et al. [54]. Three years later, the more advanced STEAM2 was developed by Jalkanen et al. [55], and many researchers have since adopted this model [46,101,123] to estimate ship emissions. The STEAM model is more complex, as it calculates the real-time power of the ship's main engine based on weather conditions and ship resistance. The IMO has also developed models included in its port emissions toolkit and GHG study report [48,49]. The IMO model is similar to the USEPA/CARB model, though it differs in the definitions of operational modes. The application of different modelling approaches can impact port emissions estimates, with results from various bottom-up models varying by 24–46 % [85,96].

Three primary modelling structures are utilized: White Box Models, Black Box Models, and Grey Box Models, as outlined by Rouse and Morris [89]. White box models are based on the mechanism analysis of ship emissions, incorporating both static and activity ship data. They derive GHG emissions from voyage data and equipment parameters and are straightforward due to their transparent model structure. Black box models, on the other hand, are data-driven, encompassing statistical and machine-learning models. They rely solely on the relationship between data response and predictor variables [70]. For example Liu and Duru [75] projected future emissions of Chinese ports without control measures, based on factors such shipping trade volume growth, ship type distribution and fuel consumption. Mandal et al. [79] used Autoregressive Integrated Moving Average (ARIMA) models to forecast emissions based on historical data. Yu et al. [120] used a combined model to enhance the reliability of port emission prediction by integrating a statistical model with a machine learning algorithm. Their findings indicate that, without regulations and emission policies, emissions will increase significantly each year. Grey box models are a hybrid approach that strikes a balance by combining mechanical formulas with data-driven models.

2.4. Simulations

Decarbonization strategies are essential to global efforts to mitigate environmental impacts in the transport sector. As major emission sources and logistics hubs, ports play a central role in these initiatives. Numerous studies have demonstrated that incorporating emissions estimation models into simulation experiments can enhance port energy efficiency and reduce emissions cost-effectively [7,114,122]. Wang et al. [110] suggest that simulation experiments show the potential for energy efficiency measures in ports to reduce emissions by 25–70 %, while operational optimization can offer reductions of 30–50 %. Drawing from Bouman et al. [10] and other systematic literature reviews, decarbonization strategies in shipping can be categorized into three main areas: alternative fuels, alternative energy sources, and operational improvements. Each strategies uses distinct methodologies to apply GHG emissions estimation models to simulate their reduction effects. The use of simulation experiments to evaluate decarbonization strategies is a crucial application of GHG emissions models, providing decision support for port authorities [1,110].

2.5. Existing gaps and research questions

Existing systematic literature reviews predominantly focus on models, with limited attention given to data, metrics and simulations. Table 1 provides a summary of predominant systematic review studies on port emissions, detailing the study period they cover, the databases used, their aim, focus, and research theme group. At present, there are no systematic literature review studies specifically addressing GHG emissions from ships in ports. Furthermore, there is insufficient literature to support a systematic review of these vessel types. The emissions from the aforementioned ships are a significant part of port emissions and are distinctly different from port land-side emission patterns [37]. With a growing body of literature on GHG emissions from ships at ports, it is imperative to systematically analyze, categorize and critically evaluate this extensive research. Unlike existing systematic literature reviews, this paper provides a comprehensive and practical review of GHG emissions from ships in ports, covering four key aspects of emissions estimation: Data, Metrics, Models and Simulations. Organizing the existing literature into various research directions, this review provides a valuable resource for government transportation management departments, port authorities and operators, and other stakeholders. In addition, this review provides researchers with a comprehensive overview of emissions from ships in ports and provides guidance for future research.

The following research questions aim to address the critical four aspects of the GHG emissions estimation framework discovered from the literature.

Research Question 1: What are the challenges and gaps in data quality concerning GHG emissions from ships at ports?

Research Question 2: Which metrics are prevalent in current research for measuring GHG emissions from ships at ports?

Research Question 3: What methods and tools are used in previous studies for estimating and predicting GHG emissions from ships in ports?

Research Question 4: How can GHG emission estimation models be applied to simulate the effects of decarbonization strategies?

This paper focuses on container ships, bulk/general cargo ships, tankers and cruise ships. While miscellaneous vessels, such as tugboats, are frequently active within port waters and have distinct activity patterns, their emission share is typically low, ranging from 1 % to 5 % [18,39,68,102]. In addition, different ports use varying boundaries for calculating ship emissions. The purpose of setting emission inventory boundaries is to ensure that the port can influence and reduce the sources of emissions [48]. Consequently, the maritime boundary for port emissions should encompass all port-related activities of ships. Typically, the emission boundary includes the following five areas [34].

1. Transit areas: where ships approach or depart from the port at sailing speed.
2. Restricted speed areas: where ship speed is limited due to geographic constraints, environmental considerations, or safety, usually in the waterways leading to the port.

Table 1
Previous reviews of port emissions studies.

Reference	Study duration	Database	Research Aim	Aspects of GHG Emission in port	Research theme group
Nunes et al. [82]	2010–2017	Scopus Google Scholar Science Direct PubMed	Evaluate atmospheric emissions from ships using activity-based methodology	Model	Ship emission estimation
Bjerkan and Seter [7]	2010–2018	Google Scholar Web of Science	Build a typology on tools and technologies for sustainable ports	Model	Port sustainability
Lim et al. [72]	1990–2017	Scopus Google Scholar Web of Science EBSCO[a] Emerald Insight	Analyze port sustainability performance and evaluation	Metric	Port sustainability
Toscano and Murena [103]	2004–2017	Scopus Google Scholar	Summarize atmospheric ship emissions in ports	Model	Ship emission estimation
Yang et al. [118]	2003–2018	Scopus Google Scholar Sciences Citation Index	Review the applications of Automatic Identification System (AIS) data	Data	Ship emission estimation
Alamoush et al. [1]	2007–2019	ISI Web of Science Elsevier Science IEEE Explore Library Database EBSCO	Summarize port GHG emission and energy efficiency	Model, Simulation	Port sustainability
Bojić et al. [8]	2008–2021	Scopus Google Scholar Web of Science	Determine port-related shipping gas emissions	Model	Ship emission estimation
Wang et al. [110]	2000–2022	Web of Science CNKI[b]	Investigate emission sources in port and summarize emission reduction methods	Model, Simulation	Port sustainability
Chen and Yang [19]	2015–2022	Web of Science Springer, MDPI Science Direct	Discuss the development of the bottom-up approach based on AIS and identify the main sources of uncertainty	Data, Model	Ship emission estimation

[a] Elton B. Stephens Company
[b] China National Knowledge Infrastructure

3. Maneuvering areas: inside the harbor, where large ships typically require assistance from tugs.
4. Berthing areas: where ships berth, moor and dock while loading and unloading cargo and passengers.
5. Anchorage zones: waters where ships wait for further instructions for berthing.

3. Methodology

This study employs a systematic literature review methodology to investigate GHG emissions from ships in ports. As defined by Gough et al. [42], a systematic literature review identifies, evaluates, and synthesizes existing works of scholars and practitioners. The methodology employed in this study follows the traditional three-step approach of planning, conducting, and reporting, as outlined by Tranfield et al. [104]. The research questions in this paper focus on GHG emissions from ships at ports. To address these questions, it is necessary to access literature databases containing journals, conference proceedings, and books in areas such as environmental science, maritime studies, transportation, and energy. Implementing a systematic literature review requires databases with advanced search capabilities. Therefore, this study utilizes Web of Science, Scopus, Springer and EBSCO as primary search databases. Web of Science and Scopus cover many studies related to ports and environmental sciences and provide access to a wide range of journals, including Marine Policy, Transport Research Part D: Transport and Environment, and Journal of Marine Science and Engineering. The Springer database offers additional maritime and environmental journals, such as Maritime Economics & Logistics, WMU Journal of Maritime Affairs, and Environmental Monitoring and Assessment. EBSCO further expands access to a broader collection of e-books and research reports. Gray literature, including government and technical reports from consulting firms, was also retrieved from official websites, guided by citations found in the academic literature. Google Scholar is the literature database with the broadest coverage. However, its low search precision and lack of advanced search features make it unsuitable as a primary database for a literature review [43]. The databases selected for this study ensure a comprehensive and diverse range of search results, providing a solid foundation for manual selection. Additionally, search functionalities vary between these databases. In Web of Science, searches were conducted by topic, where in Scopus, searches were performed using titles, abstracts, and keywords. For Springer, which allows only full-text or title searches, a title search with port-related terms was conducted, followed by a full-text search, using the same terms. In EBSCO, searches were carried out by title and abstract.

The subsequent step is the generation of search terms. Derived from the research questions and the research topic of this paper, search terms were categorized into four groups: Port, Emission, Activity and Ship. "*Port*" and "*Emission*" were identified as essential keyword groups. The "*Port*" group includes the term "port" and its near synonyms are used to search for studies whose scope is limited to the port area. The group *"Emission"* includes GHG-related terms to limit the types of gases emitted. By reviewing previous literature [7,53,72,110,111], the keywords for both groups are obtained. The "*Activity*" and "*Ship*" groups encompassed terms related to ship operations and types, respectively. The former refers to the mode of operation of a ship in a harbor and adds to the literature that is likely to be missed in the search, such as studies of emissions in the berthing or hoteling mode of a ship [4,109]. The latter restricts the studies to those within ports. The search terms for these two groups were obtained from the technical report literature [15,29,33,34,49].

Different keyword combinations were tested to identify the most effective approach, as summarized in Table 2. For example, searching for "*Port* + *Emission*" yielded an overwhelming number of papers

Table 2
Results of search term group combinations.

	Port+Emission	Port+Activity+Emission	Port+Ship+Emission	Port + (Activity OR Ship) + Emission
Web of Science	45,834	818	1789	2435
Scopus	58,562	596	2424	2757
Springer	214	37	151	151
EBSCO	45,477	767	1657	2302
Total	150,087	2218	6021	7645

(150,087), many of which were duplicates. Conversely, narrowing the search to "*Port* + *Activity* + *Emission*", resulted in a potentially limited scope. The most effective combination was found to be "*Port* + (*Activity* OR *Ship*) + *Emission*" as shown in Fig. 1. The final search term used was ((port OR seaport OR harbor OR berth OR terminal OR seaside) AND ((ship OR vessel OR tanker) OR (hoteling OR berthing OR "at berth" OR maneuvering OR anchored OR moored OR "slow transit")) AND (CO2 OR CO2e OR GHG OR "greenhouse gas" OR decarbonization OR NetZero OR Zero-CO2 OR Green OR Carbon))

Developing precise inclusion and exclusion criteria is a crucial step in conducting a systematic literature review. For this study, the period from January 2000 to June 2024 was selected as the time period. The year 2000 marks a significant juncture, as the IMO began commissioning studies to estimate GHG emissions from shipping, laying the groundwork for research on ship GHG emissions in ports, (see, for example, [47]). These studies have become a cornerstone for evidence-based decision-making and a global reference for GHG emissions estimation in international shipping. Recognizing the importance of grey literature in maritime research, this study includes grey literature to capture a broader spectrum of perspectives. This is particularly relevant in the maritime sector, where many classic models and concepts originate from international organizations or port authorities, often documented in technical reports and guidelines. This study limits its scope to literature available in full text and English. To remain focused on GHG emissions and sustainable port development, studies on general atmospheric emissions were excluded.

As shown in Fig. 1, the initial literature search across four databases yielded 7645 articles. This number was narrowed to 5367 after filtering by article type, publication date and language. After removing duplicates, 2530 articles remained. Screening the titles for relevance to port emissions reduced this number to 536. Subsequently, a further review of abstracts and full text excluded articles that lacked full text access or employed qualitative research methods. Articles unrelated to GHG emissions or those that did not focus on emissions from ship activities in ports were also excluded. After a final full text assessment, 139 articles were selected for inclusion in this systematic literature review. The list of selected articles is presented in supplementary material. To systematically extract data, each selected paper underwent a thorough reading and coding process. The detailed inclusion and exclusion criteria are outlined in Fig. 1.

4. Results and findings

A total of 139 relevant papers were selected from the systematic literature review after a comprehensive evaluation. From Fig. 2 one can notice a concentration of these studies within a limited number of journals. The top 13 journals published account for 46 % (64 documents), with "Journal of Marine Science and Engineering" and "Transportation Research Part D-Transport and Environment" the most common. Both are known for being traditional transportation journals, with 14 articles and 11 articles, respectively. Other prominent journals include "Sustainability" and "Journal of Cleaner Production", all of which are recognized for their environmental focus. All 13 journals depicted in Fig. 2 focus on transportation and/or environmental issues.

Fig. 3 provides an overview of the publication trends and citation patterns of the selected papers, with key milestones in green shipping marked alongside. The timeline highlights important events in the field, such as the adoption of the Energy Efficiency Design Index (EEDI), various IMO GHG studies, and the implementation of the Data Collection System (DCS) and short-term measures (EEXI and CII). The chart also tracks the number of aspects of the GHG emission estimation process from ships in ports addressed in the literature each year. There has been a steady increase in publications and citations in this domain, especially after 2017. Despite a minor decrease in publications between

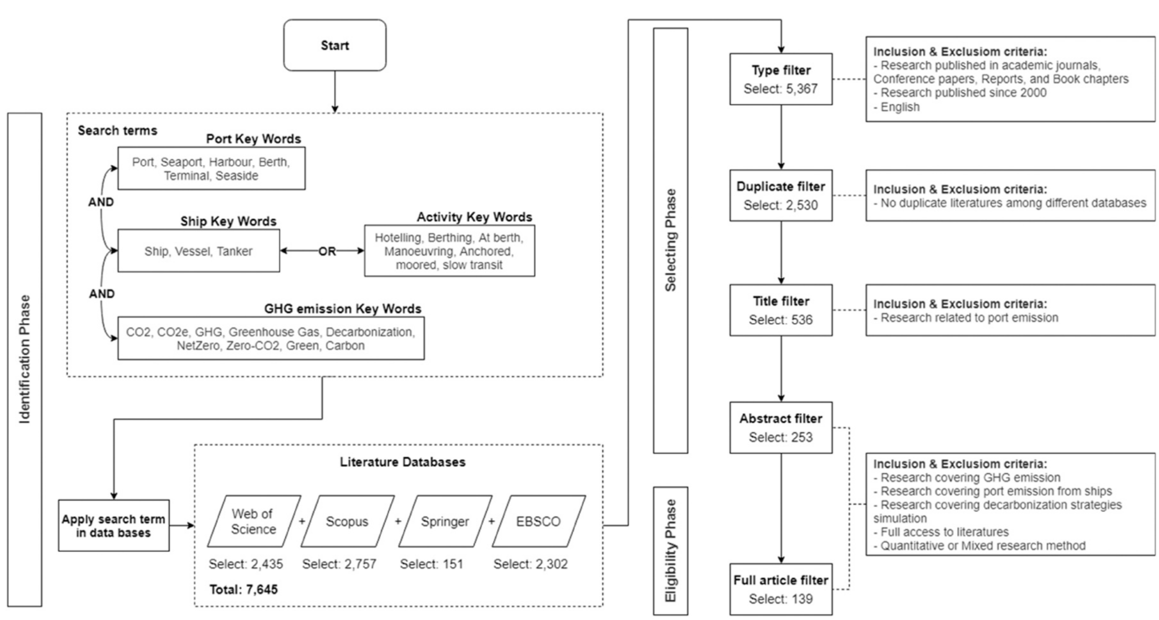

Fig. 1. Overview of the systematic literature review process.

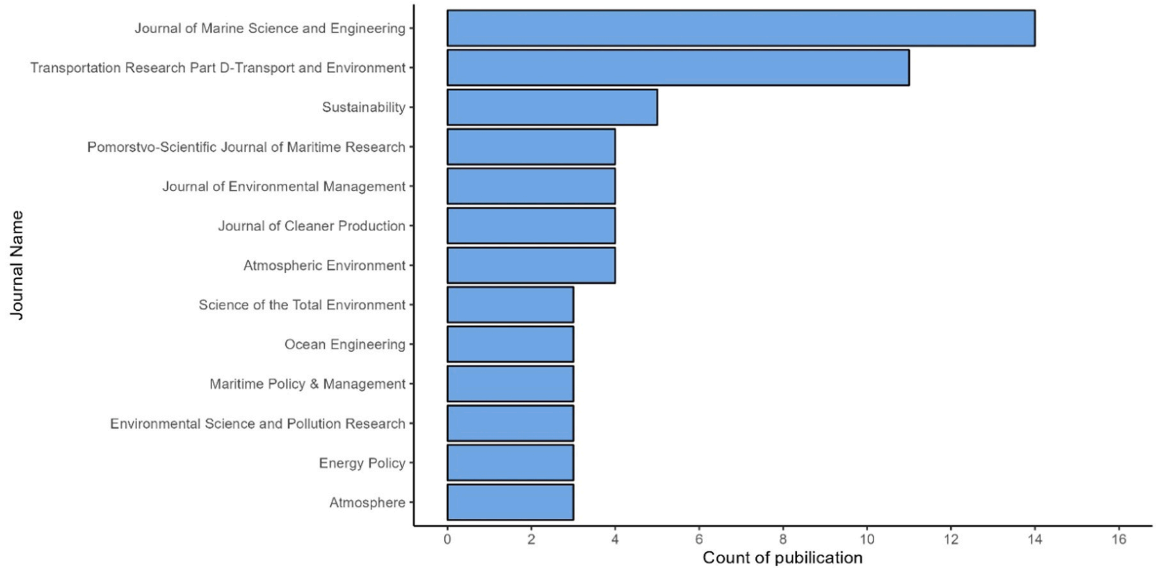

Fig. 2. Distribution of top journals.

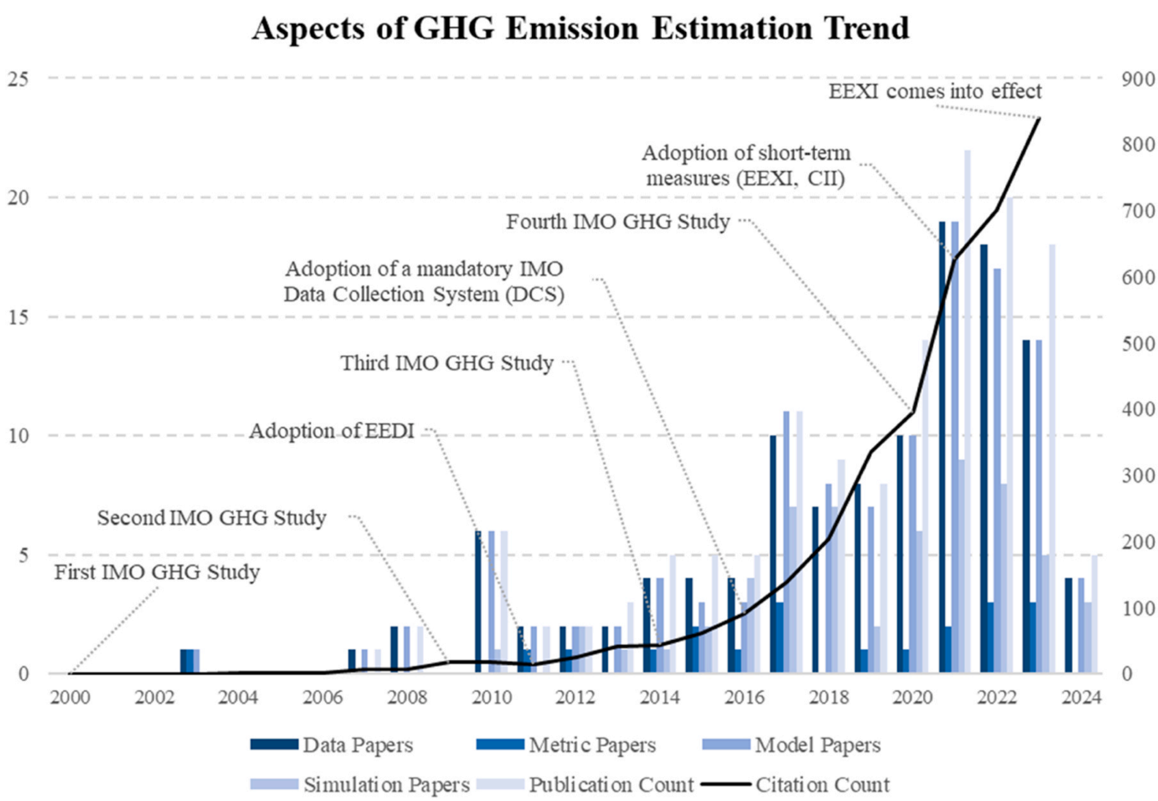

Fig. 3. Publication trend & citation patterns (Source: Authors).

2022 and 2023, the rising trend in citations underscores the continuing importance and relevance of research in this area. The trends across the four aspects; data, metric, methods and simulations have shown different patterns over time. Until 2010, most studies focused primarily on data and methods. However, since 2015, research on decarbonization strategy simulations has increased annually. Additionally, there has been an upward trend in the number of studies on metrics in recent years, reflecting the growing emphasis on quantitative measures in GHG emissions research.

In the following section, we analyze the selected literature for the systematic literature review, based on the research questions. Each study addresses one or more aspects of GHG emission estimation process from ships at port. Overall, 85 % of the selected studies focus on data quality, 83 % on models, 42 % cover simulations and only 14 % address metrics.

4.1. Data quality

4.1.1. Data attributes

The selected studies from the systematic literature review are descriptively analyzed based on data attributes, with a focus on data size, duration, and frequency. Most studies (62 %) examine data from a single port, while around 14 % encompass more than ten ports. Large-scale studies [25,40,62,83,94,97,108] are often national or regional in scope, requiring extensive data and inter-institutional cooperation, which explains their relatively limited number. Fleet-focused studies examining specific vessels in a port constitute 3 % of the total. Fig. 4 highlights the temporal aspects of data samples. The majority (65 %) of the studies use data spanning more than one year but less than three years, likely due to the accessibility of such data. In contrast, only 7 % of the studies cover a duration of less than one month, typically representing early research or analyses of fleet activity in ports [44,65,98,109,116,124]. These shorter-duration studies are generally suited for micro-level analysis. Studies with data extending beyond five years are also limited (11 %), mainly due to challenges in accessing long-term maritime data, often related to privacy concerns [58]. Regarding data sampling frequency, yearly calculations are predominate, with only 16 % studies provide daily GHG emission estimates in ports. This trend reflects the common practice of ports releasing data on an annual basis.

4.1.2. Data source

Calculating GHG emissions from ships requires both ship activity and static data. Ship activity data, primarily collected through the Automatic Identification System (AIS), reflects the real-time status of the ship, including its position, speed, and heading [46]. "Static data" refers to ship characteristics that remain constant over time and under various conditions [64]. In this study, static ship data includes dimensions (e.g., overall length, beam), engine specifications (e.g., main engine power), and other constants (e.g., service speed).

Shipping databases are broadly categorized into commercial, port authority, and private databases. Commercial databases, like those provided by Lloyd, Clarkson, Marine Traffic, etc., offer global coverage with uniform standards but often lack the accuracy and detail of port authority databases. Port authority databases, developed by individual port authorities, vary in detail depending on the port's size and investment in information systems, and they are generally more comprehensive than commercial alternatives. Independent databases, which consist of data collected directly by researchers, are less common in the literature.

Fig. 5 shows the distribution of database sources used in studies. Most rely on port authority data, with 74 % of ship static data and 88 % of ship activity data sourced from these databases. This indicates potential for further development of commercial databases, especially for activity data. The heavy reliance on port authority data also explains why most current studies are limited in scope to single ports and durations of 1–3 years. Obtaining large-scale, multi-port data from port authorities is challenging due to confidentiality concerns and data accuracy issues [80]. These insights highlight a gap in current research: the lack of consistent, long-term data across multiple ports with high sampling frequency for estimating ship GHG emissions. However, the complexity of managing such large datasets poses additional challenges for model calculations. In addition to dataset size, several studies highlight the need for improved data quality, noting the presence of significant amounts of missing or abnormal data within the datasets [24,112,119]. Low-quality data can negatively impact the accuracy of estimation results.

4.2. GHG emissions metrics

This section synthesizes the metrics used to measure ship GHG emissions in ports, as identified in the systematic literature review. These metrics fall into two categories: emission totals and emission efficiency. Metrics like CO2 emissions, CO2e emissions, and Global-warming potential (GWP) represent emission totals, quantifying absolute GHG emissions from ships in ports. Emission efficiency metrics, including the Energy Efficiency Existing Ship Index (EEXI), Energy Efficiency Design Index (EEDI), Energy Efficiency Operating Indicator (EEOI), Carbon Intensity Indicator (CII), Environmental Ship Index (ESI), and CO2 emissions per TEU delivered, evaluate the efficiency of ship equipment and operations. The results indicate that most studies (87 %) utilize emission total metrics, while only 13 % focus on emission efficiency. Emission total metrics are typically uniform across studies, encompassing CO2 emissions, fuel consumption and social and environmental costs. The latter two indicators reflect the economic and environmental impacts of air pollution caused by ships and ports [115]. Fuel consumption directly correlates with the magnitude of GHG emissions. However, emission efficiency metrics vary depending on research objectives. For instance, CO2 emissions per ton of cargo or Deadweight Tonnage (DWT) are used as metrics to assess the environmental efficiency of different ship types and sizes [12,88,107]. Real-time monitoring of ships using the Environmental Ship Index (ESI) in ports [36] and tracking the potential CO2 reductions from improved ship equipment using EEXI, EEDI, and CII [23] are other approaches. CO2 emissions per nautical mile in ports and per hour at berth are crucial for understanding the relationship between speed, emissions and port operational efficiency [16,61,81].

While organizational reports and literature predominantly focus on total emission metrics, offering a clear picture of GHG emission levels and trends, emission efficiency metrics are essential for comparing ships or berths across multiple ports. These metrics provide insights into the emissions of various ship types, enabling targeted optimization strategies. However, a gap remains in the current research, there is a need for a comprehensive review of how emission efficiency metrics evaluate GHG emissions performance in port activities and for a uniform standard for these metrics.

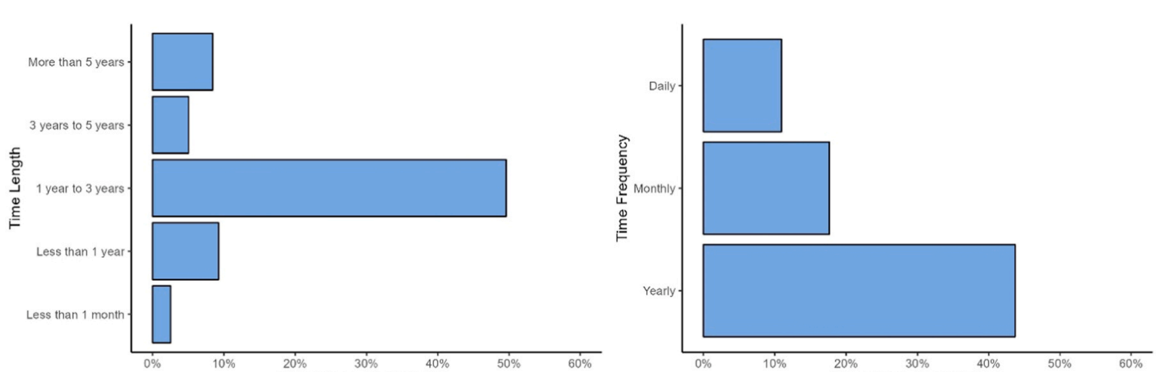

Fig. 4. Data time length and frequency distribution.

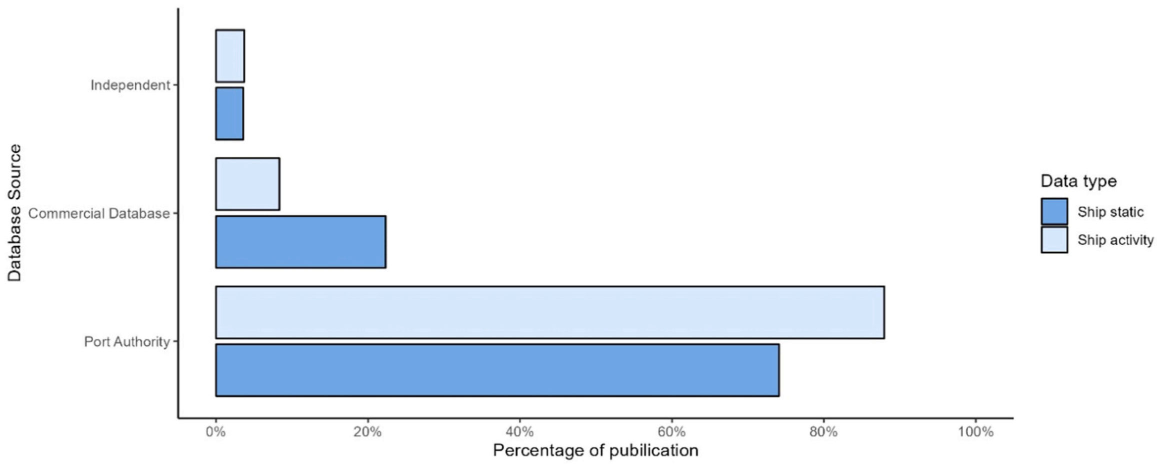

Fig. 5. Data source category distribution.

4.3. GHG emissions estimation model

Based on the selected literature, 116 articles include detailed information of the GHG emissions estimation model used in the analysis. White box models present in 83 % of these studies, while black box models account for 13 %. One study by Cooper [20] collected GHG emissions data directly from sensors, a model less suited for large-scale data collection. Fig. 6 depicts the distribution of modelling approaches, with bottom-up models being the most common and top-down models used less frequently. Machine learning and direct data collection methods are rarely employed (7 %). ENTEC model is the most utilized (21 %), followed by USEPA/CARB (20 %), other bottom-up models (18 %) and EMEP/EEA (14 %). The ports studied in these methods often have sophisticated data collection systems that enable detailed research. However, there is a notable absence of standard benchmarks using actual data to verify estimation accuracy in current studies. In summary, while current estimation models require high-resolution data for optimal results, incorporating statistical modeling or machine learning could enhance accuracy and balance interpretability with data requirements.

Emission factors, crucial in GHG emission estimation model, need to be updated consistently [66]. These factors typically consist of emission factors and default technical parameters. Emission factors are used to convert the amount of energy and fuel consumed into specific emission quantities. Default technical parameters, such as the power load of the main engines, auxiliary engines or boilers while ships are berthed, are calculated based on empirical averages [8,112]. These empirical averages depend on large datasets of historical ship data, meaning that calculation factors can be updated as new data becomes available. Fig. 7 illustrates the distribution of emission estimation factors, with ENTEC and USEPA/CARB being the most commonly used due to their extensive empirical data. Notably, a category termed 'independent emission factor' ranks third, indicating that a significant number of studies develop custom emission factors tailored to specific port conditions. Recent studies suggest that port-specific factors are necessary, as using outdated or non-localized emission factors can lead to increased errors in estimations [87,112].

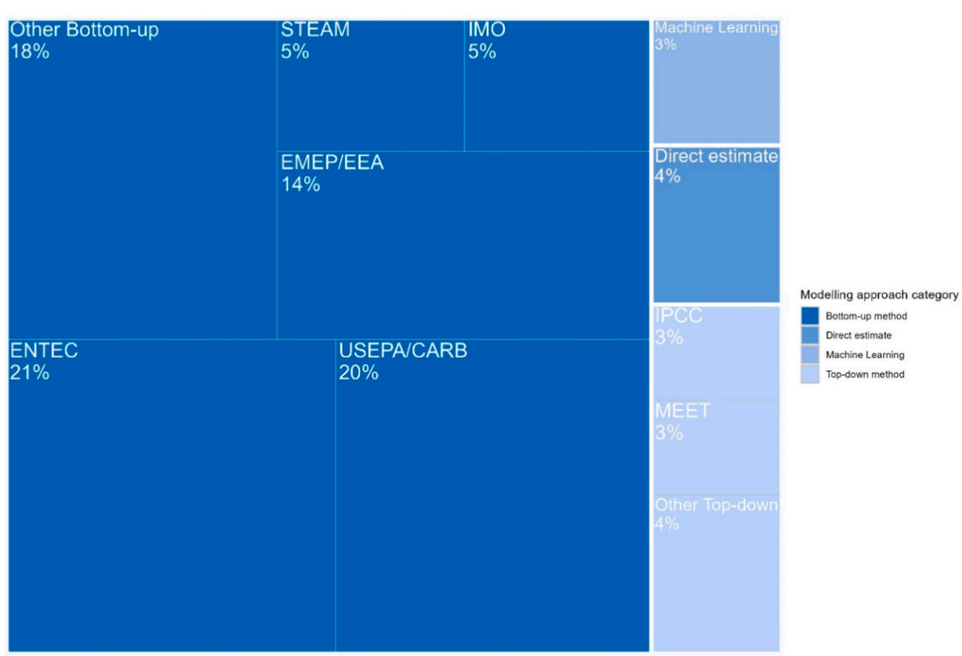

Fig. 6. Emission estimation model.

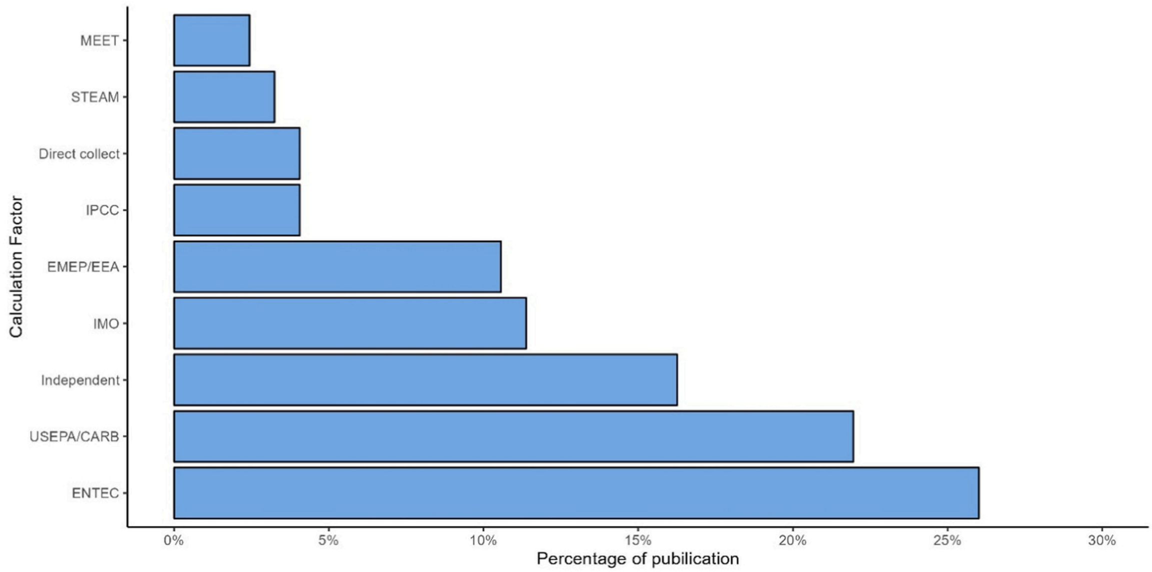

Fig. 7. Emission calculation factor source.

4.4. Decarbonization strategy simulation experiment

Out of the selected literature, 58 papers use GHG emission estimation models to simulate the impact of different decarbonization strategies. Fig. 8 categorizes the simulated decarbonization strategies from these studies. The two predominant categories are operations and alternative energy sources, mentioned in 42 % and 39 % of the studies, respectively. Alternative fuels are discussed less frequently, appearing in 19 % articles. Fig. 8 also highlights specific methods, showing that shore power is the most frequently mentioned emission reduction strategy unique to ports (39 %), nearly three times more frequent than other methods. Alternative fuels, speed optimization, and port efficiency optimization are discussed with similar frequency, while berth optimization is mentioned less often, indicating a need for further research in this area.

There are distinctions in how GHG emission estimation models are applied to simulate decarbonization strategies. For shore power, most studies first use GHG emission estimation models to calculate emissions from ships in ports under normal conditions, then calculate emissions from the grid when shore power is used, based on the time the ship is at berth [24,45,51]. For alternative fuels, the impact of switching fuels is evaluated by adjusting the fuel emission factor within the GHG emission estimation model [76,78,79]. For berth and port efficiency optimization, GHG emission estimation models are incorporated into the constraints and objective function, allowing the simulation to find optimal solutions in multi-objective scenarios [2,90,109]. For speed optimization, AIS data related to ship speed is adjusted and input into the emission estimation model to simulate the effects of optimized speeds [17,56,69]. However, when different decarbonization strategies are applied simultaneously at a port, their respective effectiveness can be diminished [60,76,122]. For example, the use of shore power can lead to ship delays, potentially reducing berth efficiency and increasing overall port emissions [22]. Therefore, interactions between decarbonization strategies must be considered in simulations, and scenarios involving multiple strategies should be included to more accurately simulate emissions from ships in ports.

Furthermore, this paper employs meta-analysis to extract simulation

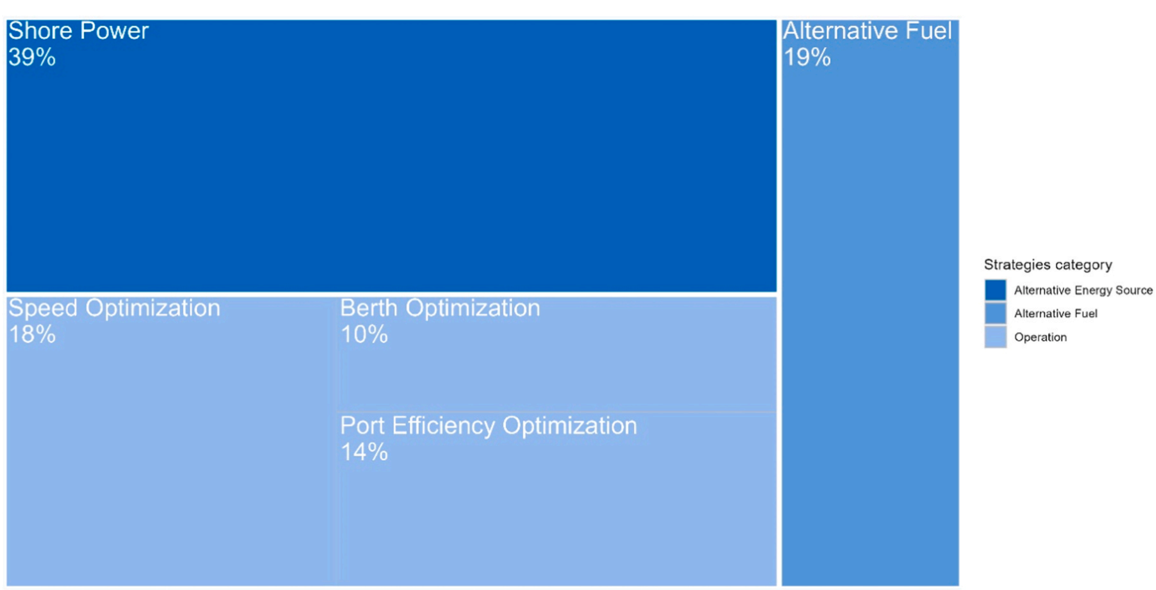

Fig. 8. Decarbonization strategies distribution.

results of decarbonization strategies based on GHG emission estimation model from the literature, and the findings presented in Fig. 9. The effectiveness of decarbonization strategies varies across different ports, as noted by Styhre et al. [99]. We can see that shore power has the highest average reduction rate for emissions (looking at the 50th percentile), with an average emission reduction rate of 33 % and a large number of samples to support the data. It is worth noting firstly that the efficiency of shore power varies greatly from port to port, and secondly that there is a risk of increasing GHG emissions by using shore power. This is due to two factors, the most important of which is that ports have different sources of shore power generation, and the use of non-renewable energy sources can significantly increase GHG emissions [44,45,97]. Ship speed optimization, berth optimization and alternative fuel can reduce the emission reduction rate by 26 %, 23 %, and 17 %, respectively. Again, a number of studies are available for each decarbonization strategies, and there is variability in the results. This variability highlights the need for a standardized method to simulate decarbonization strategies, enabling the assessment of emissions across different port types using a consistent database and GHG emission estimation model. Such an approach would enhance the efficiency and applicability of decarbonization strategies across diverse port environments.

5. Discussion

Despite the increasing number of studies on GHG emissions from ships in ports, significant research gaps remain that warrant further exploration. This section presents these gaps and outlines future research directions, derived from the systematic literature review across the four key research aspects. Fig. 10 summarizes the limitations of previous studies and proposes future research directions for addressing GHG emissions from ships in ports.

5.1. Challenges and gaps in the data quality

Critical challenges in data quality for GHG emissions from ports include issues related to data resolution, accuracy, accessibility and standards. Many studies, particularly earlier ones, rely on annual data from individual ports, and the low resolution of these datasets reduces the accuracy of emission calculations. Accessibility is also hindered by the restricted nature of port authorities' databases, often due to security concerns, resulting in missing data and anomalies that complicate multi-

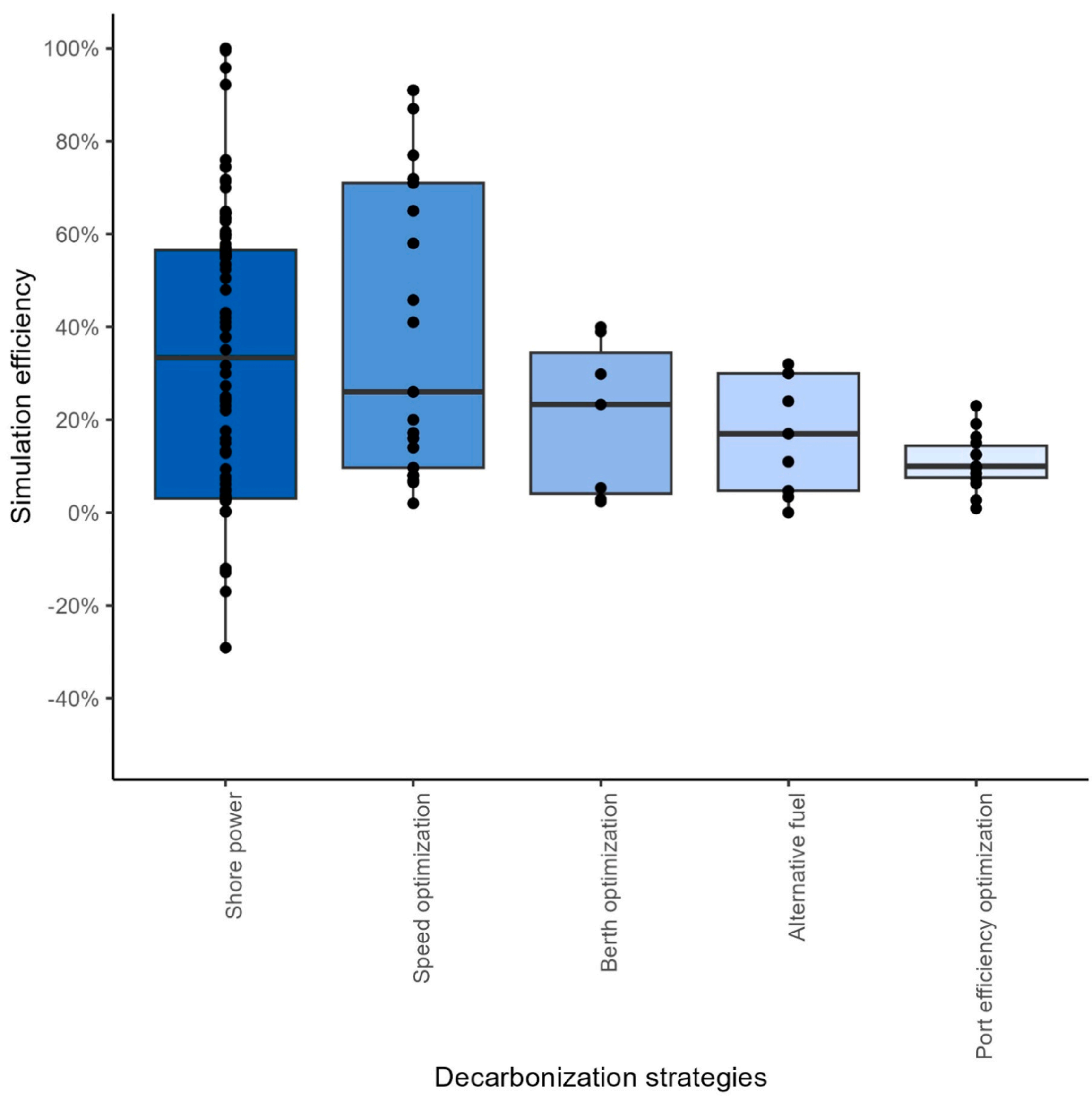

Fig. 9. Decarbonization strategies effectiveness summary.

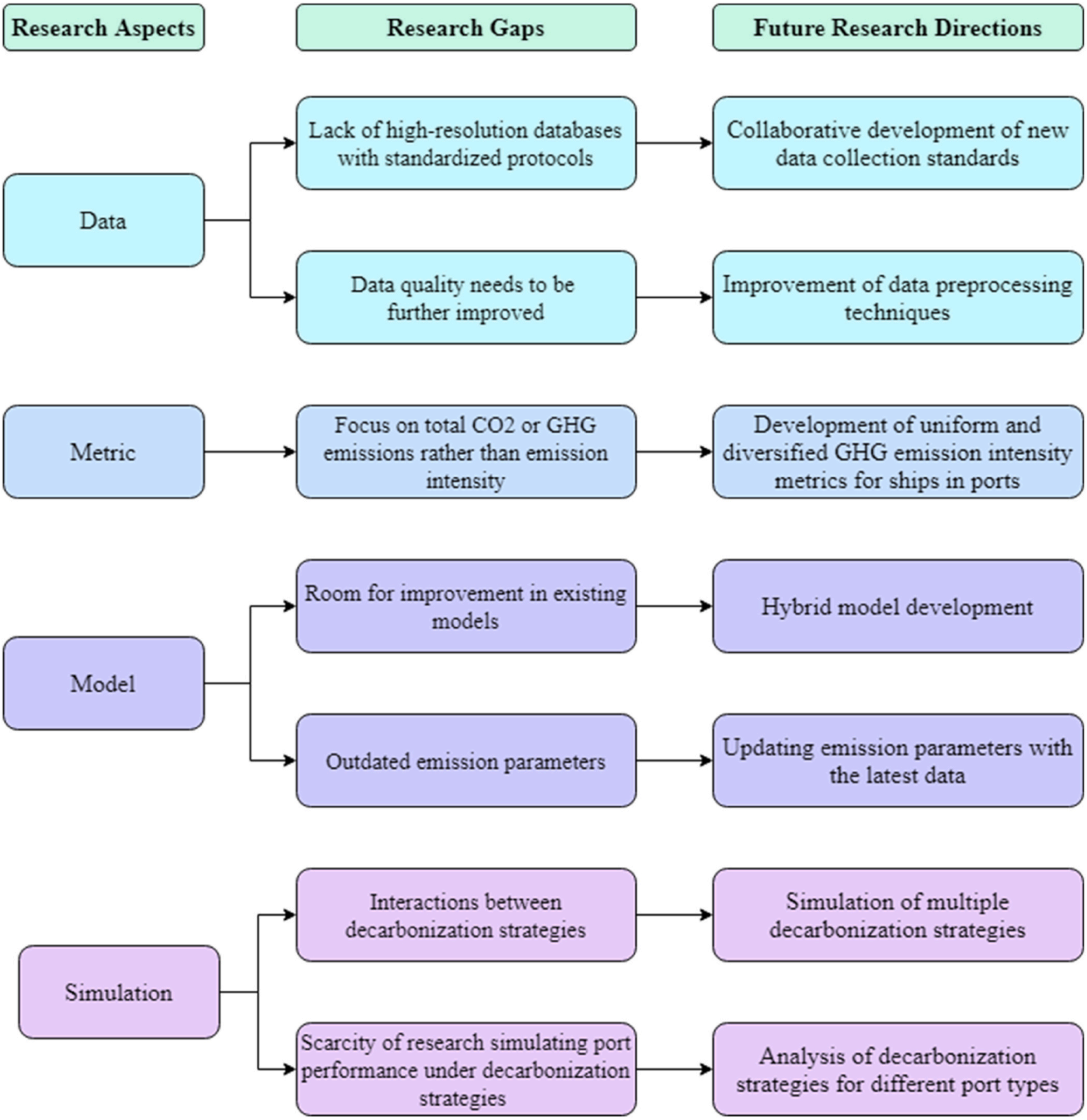

Fig. 10. Future directions of GHG emissions from ships in ports.

port studies. Future research could focus on improving pre-processing techniques for ship static and activity data from ship. Effective pre-processing reduces data noise, leading to more robust and accurate model training outcomes.

In addition, the varying standards of data collection by ports, shipping companies, commercial databases, and international organizations present significant challenges when attempting to merge data from different sources. Therefore, research aimed at fostering collaboration between organizations and developing standardized methods for GHG emissions data collection would be highly valuable. Standardized databases would streamline initial efforts for future studies and improve consistency and interpretability across different research projects.

5.2. Metrics for measuring GHG emissions

Total emissions are the most used metric, providing a clear picture of port GHG emissions. Social cost is another frequent quantitative indicator assessing the economic impact of emissions. However, emission intensity metrics should be utilized more extensively. The use of different metrics makes it difficult to analyze the causes of variability in emission patterns across ports. Future studies should incorporate uniform and diversified metrics to better understand the emissions performance of different ship types and ports, aiding port authorities evaluate the effectiveness of decarbonization strategies.

5.3. Methodologies and tools for estimating emissions

Port GHG emissions can be categorized according to the modelling approach (top-down and bottom-up) and structure (white-box, black-box, and grey-box models). Prominent models include USEPA/CARB, EMEP/EEA, ENTEC, STEAM, IMO, IPCC, MEET, and various independent models. Bottom-up models, while accurate, are often region-specific, whereas top-down models offer broader applicability but need more precision. In terms of modelling structure, white-box models are highly interpretable, allowing users to understand how results are derived. However, their accuracy is constrained by the data quality, often making them less precise than black-box models. On the other hand, black-box models, commonly implemented through machine learning algorithms, offer higher accuracy but need better interpretability, making it challenging to understand the underlying process of their results. Therefore, the challenge lies in balancing model accuracy, applicability, and interpretability.

Additionally, emission factors can significantly impact estimation results. Emission factors are typically derived from real-world emission testing of ship. However, emission testing is both expensive and complex, leading to a scarcity of actual emissions data [96]. Testing results can also vary due to several factors, such as differences in port or vessel cleaning technologies, emission testing protocols, resulting in an uncertainty range of approximately 20–50 % in estimating emission factors [33]. Therefore, the selection and regular updating of emission factors that are used in calculation of shipping emissions are crucial for achieving accurate results.

5.4. Simulation experiment for decarbonization strategies in ports

Decarbonization strategies for ships in ports primarily include alternative fuels (e.g. LNG, cleaner MDOs), alternative energy sources (e.g. shore power), and operational strategies (e.g. speed optimization, berth optimization, port efficiency optimization). GHG emission estimation models are increasingly used to simulate the effectiveness of these strategies. However, most simulation experiments focus on the impact of a single decarbonization strategy on port emissions, with limited consideration of interactions between different strategies. Future research could propose new objective functions and incorporate additional constraints into port emission optimization simulations to evaluate the synergistic or antagonistic effects of combined emission reduction strategies.

Moreover, not all ports implement the same decarbonization strategies. Factors such as port size and type of ships at anchor, etc. affect the efficiency of these decarbonization strategies [13]. There is a lack of systematic and comprehensive simulation experiments on decarbonization policies based on a consistent database for different port types. Future research should explore the advantages and limitations of emission reduction strategies across various port environments. This would provide accurate and actionable insights for policymakers.

6. Conclusions

This research highlights the complexities and opportunities in addressing GHG emissions from ships in ports. Accurate data collection, diverse metrics, advanced modelling techniques, and effective decarbonization strategy simulations are essential. The systematic literature review conducted in this paper reveals several gaps in the current understanding of ship GHG emissions in ports and provides direction for future research. First, there is a lack of high-resolution databases with standardized protocols for estimating GHG emissions in ports. Limited access to comprehensive and reliable data hinders large-scale port emissions analysis, and improving the quality of available data is crucial for enhancing accuracy. Second, the metrics used in current studies predominantly focus on total CO2 or GHG emissions, overlooking valuable insights that could be gained from examining emission intensity across different ships and berths. A uniform metric for ship GHG emissions in ports is needed to assess and compare port performance more effectively across different contexts. Third, existing models for estimating ship GHG emissions in ports have room for improvement. A hybrid approach combining traditional models with machine learning techniques could strike a better balance between interpretability, complexity, and accuracy. Fourth, many emission parameters currently used in models are outdated, updating these parameters with the lates data is essential for improving estimation accuracy and providing more reliable results. Fifth, interactions between different decarbonization strategies should be incorporated into simulations. The effects of applying multiple strategies simultaneously need to be considered to provide a more comprehensive assessment of their combined impact on emissions reduction. Last, there is a scarcity of research that simulates port performance under various decarbonization strategies using consistent databases and GHG emission estimation models. Addressing this gap could lead to more accurate and comparable assessment of decarbonization efforts across ports.

6.1. Recommendations and future directions

Future efforts should focus on improving data quality, expanding the use of metrics, and developing standardized methodologies for policy evaluation. Collaborative efforts between ports, governments, and researchers are essential for achieving significant emissions reductions. To address GHG emissions from ships in ports effectively, a multi-dimensional approach is needed. Port authorities, shipping companies, and international organizations must collaborate to establish standardized data collection protocols, ensuring consistency and accuracy in emissions reporting. Future research should also aim to enhance pre-processing techniques for ship static and activity data, thereby improving the quality of inputs used in emissions estimation models.

There is also a critical need to develop uniform and diversified GHG emission intensity metrics tailored specifically to ports, as current metrics predominantly focus on ships at sea. Moreover, hybrid models combining statistical and machine learning techniques should be explored to balance interpretability, complexity, and accuracy in emissions estimation. Emission parameters in models should be regularly updated with the latest data to ensure accuracy, and simulations should consider the combined effects of multiple decarbonization strategies. Finally, researchers should evaluate decarbonization strategies for various port types to identify the most effective approaches for different contexts. These collective efforts will lead to more efficient emissions reduction in ports worldwide.

CRediT authorship contribution statement

Emrah Demir: Writing – review & editing, Supervision. **Wessam Abouarghoub:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andrew Potter:** Writing – review & editing, Supervision. **Ruikai Sun:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106455.

Data availability

Data will be made available on request.

References

[1] A.S. Alamoush, F. Ballini, A.I. Ölçer, Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: a review, Mar. Pollut. Bull. 160 (2020) 111508.
[2] H. An, F. Bahamaish, D.W. Lee, Simulation and optimization for a closed-loop vessel dispatching problem in the middle east considering various uncertainties, Appl. Sci. 11 (2021) 18.
[3] R. Aronietis, E.V. Hassel, T. Vanelslander, Maritime data collection framework for container port benchmarking, J. Mar. Sci. Eng. 11 (2023) 1557.
[4] B. Bacalja, M. Krčum, M. Slišković, A line ship emissions while manoeuvring and hotelling—a case study of port split, J. Mar. Sci. Eng. 8 (2020) 1–18.
[5] V.C. Ballester, V.G. Lo-Iacono-Ferreira, M.A. Artacho-Ramírez, S.F. Capuz-Rizo, The carbon footprint of Valencia Port: a case study of the port authority of Valencia (Spain), Int. J. Environ. Res. Public Health 17 (2020) 16.
[6] E. Benhakoun, E. Van De Voorde, Y. Shiftan, The daily port and shoreline emission inventory model, Marit. Policy Manag. 51 (2023) 588–616.
[7] K.Y. Bjerkan, H. Seter, Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports? Transp. Res. Part D: Transp. Environ. 72 (2019) 243–260.
[8] F. Bojić, A. Gudelj, R. Bošnjak, Port-related shipping gas emissions—A systematic review of research, Appl. Sci. 12 (2022) 3603.
[9] C. Botana, E. Fernández, G. Feijoo, Towards a green port strategy: the decarbonisation of the Port of Vigo (NW Spain), Sci. Total Environ. 856 (2023) 9.
[10] E.A. Bouman, E. Lindstad, A.I. Rialland, A.H. Strømman, State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–A review, Transp. Res. Part D: Transp. Environ. 52 (2017) 408–421.
[11] M. Buber, A.C. Toz, C. Sakar, B. Koseoglu, Mapping the spatial distribution of emissions from domestic shipping in Izmir Bay, Ocean Eng. 210 (2020) 10.
[12] M.A. Budiyanto, M.R. Habibie, T. Shinoda, Estimation of CO2 emissions for ship activities at container port as an effort towards a green port index, Energy Rep. 8 (2022) 229–236.
[13] S. Bullock, E. Higgins, J. Crossan, A. Larkin, Improving shore power project economics at the Port of Aberdeen, Mar. Policy 152 (2023) 10.
[14] Çalışkan, U.Y. & Zincir, B. Necessity of Ecological Efficiency Indicator Modal of Air Pollutants and Emissions from Ships in Maritime Transportation: Policy Perspective. International Symposium on Energy Management and Sustainability, 2022. Springer, 123-132.
[15] CARB 2021. 2021 California Ocean-Going Vessels Emissions Inventory California Air Resources Board.
[16] C.C. Chang, C.W. Jhang, Reducing speed and fuel transfer of the Green Flag Incentive Program in Kaohsiung Port Taiwan, Transp. Res. Part D. -Transp. Environ. 46 (2016) 1–10.
[17] C.C. Chang, C.M. Wang, Evaluating the effects of green port policy: case study of Kaohsiung harbor in Taiwan, Transp. Res. Part D. -Transp. Environ. 17 (2012) 185–189.
[18] S. Chen, Q. Meng, P. Jia, H. Kuang, An operational-mode-based method for estimating ship emissions in port waters, Transp. Res. Part D: Transp. Environ. 101 (2021) 103080.
[19] X. Chen, J. Yang, Analysis of the uncertainty of the AIS-based bottom-up approach for estimating ship emissions, Mar. Pollut. Bull. 199 (2024) 115968.
[20] D.A. Cooper, Exhaust emissions from ships at berth, Atmos. Environ. 37 (2003) 3817–3830.
[21] K. Cullinane, S. Cullinane, Atmospheric emissions from shipping: the need for regulation and approaches to compliance, Transp. Rev. 33 (2013) 377–401.
[22] L. Dai, H. Hu, Z.J. Wang, Is Shore Side Electricity greener? An environmental analysis and policy implications, Energy Policy 137 (2020) 9.
[23] H. Daniel, J.P.F. Trovao, D. Williams, Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier, Etransportation 11 (2022) 17.
[24] H. Daniel, J.P.F. Trovão, D. Williams, L. Boulon, Unlocking shore power in St. Lawrence and Great Lakes for cargo ships, Transp. Res. Part D: Transp. Environ. 131 (2024) (N.PAG-N.PAG).
[25] P. DE Meyer, F. Maes, A. Volckaert, Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports, Atmos. Environ. 42 (2008) 196–206.
[26] Eggleston, H., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. 2006. 2006 IPCC guidelines for national greenhouse gas inventories.
[27] A. Ekmekçioglu, K. Ünlügençoglu, U.B. Çelebi, Container ship emission estimation model for the concept of green port in Turkey, Proc. Inst. Mech. Eng. Part M-J. Eng. Marit. Environ. 236 (2022) 504–518.
[28] Emep/Eea, EMEP/EEA air pollutant emission inventory guidebook 2019, European Environment Agency, 2019.
[29] EMEP/EEA, EMEP/EEA air pollutant emission inventory guidebook 2023, European Environment Agency, 2023.
[30] Ø. Endresen, E. Sørgård, H.L. Behrens, P.O. Brett, I.S. Isaksen, A historical reconstruction of ships' fuel consumption and emissions, J. Geophys. Res.: Atmospheres (2007) 112.
[31] ENTEC, Quantification of Emissions from Ships Associated with Ship Movements Between Ports in the European Community. UK: ENTEC Limited, European Commission, 2002.
[32] ENTEC, Service Contract on Ship Emissions: Assignment. Abatement and Market-Based Instruments. UK: ENTEC Limited, European Commission, 2005.
[33] ENTEC, Defra UK ship emissions inventory. ENTEC Limited, European Commission, 2010.
[34] EPA 2022. Ports Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions. U.S. Environmental Protection Agency.
[35] A. Fan, J. Yang, L. Yang, D. Wu, N. Vladimir, A review of ship fuel consumption models, Ocean Eng. 264 (2022) 112405.
[36] P. Fenton, The role of port cities and transnational municipal networks in efforts to reduce greenhouse gas emissions on land and at sea from shipping–An assessment of the World Ports Climate Initiative, Mar. Policy 75 (2017) 271–277.
[37] S. Filom, A.M. Amiri, S. Razavi, Applications of machine learning methods in port operations–A systematic literature review, Transp. Res. Part E: Logist. Transp. Rev. 161 (2022) 102722.
[38] G. Fuentes García, J.M. Baldasano Recio, R. Sosa Echeverría, E. Granados Hernández, E. Zamora Vargas, R. Antonio Duran, J.W. Kahl, Estimation of atmospheric emissions from maritime activity in the Veracruz port, Mexico, J. Air Waste Manag. Assoc. 71 (2021) 934–948.
[39] X. Gao, W. Dai, Q. Yu, Analysis of emission characteristics associated with vessel activities states in port waters, Mar. Pollut. Bull. (2024) 202.
[40] G.F. García, R.S. Echeverría, J.M.B. Recio, J.W.D. Kahl, E.G. Hernández, A.L. A. Jímenez, R.E.A. Durán, Atmospheric Emissions in Ports Due to Maritime Traffic in Mexico, J. Mar. Sci. Eng. 9 (2021) 19.
[41] M. Gibson, A.J. Murphy, K. Pazouki, Evaluation of environmental performance indices for ships, Transp. Res. Part D: Transp. Environ. 73 (2019) 152–161.
[42] D. Gough, J. Thomas, S. Oliver, An introduction to systematic reviews, Introd. Syst. Rev. (2017) 1–352.
[43] M. Gusenbauer, N.R. Haddaway, Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources, Res. Synth. Methods 11 (2020) 181–217.
[44] W.J. Hall, Assessment of CO2 and priority pollutant reduction by installation of shoreside power, Res. Conserv. Recycl. 54 (2010) 462–467.
[45] A. Herrero, A. Ortega Piris, E. Diaz-Ruiz-Navamuel, M.A. Gutierrez, A.I. Lopez-Diaz, Influence of the Implantation of the Onshore Power Supply (OPS) System in Spanish medium-sized ports on the reduction in CO2 emissions: the case of the Port of Santander (Spain), J. Mar. Sci. Eng. (2022) 10.
[46] L. Huang, Y.Q. Wen, X.Q. Geng, C.H. Zhou, C.S. Xiao, Integrating multi-source maritime information to estimate ship exhaust emissions under wind, wave and current conditions, Transp. Res. Part D. -Transp. Environ. 59 (2018) 148–159.
[47] IMO 2000. First IMO Greenhouse Gas Study 2000. International Maritime Organization.
[48] IMO 2018. Port Emissions ToolkitGuide No.1: Assessment of port emissions. International Maritime Organization.
[49] IMO 2020. Fourth IMO Greenhouse Gas Study 2020. International Maritime Organization.
[50] IMO. 2023. *2023 IMO Strategy on Reduction of GHG Emissions from Ships* [Online]. International Maritime Organization. Available: ⟨https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx⟩ [Accessed 08.24 2024].
[51] A. Innes, J. Monios, Identifying the unique challenges of installing cold ironing at small and medium ports – The case of aberdeen, Transp. Res. Part D: Transp. Environ. 62 (2018) 298–313.
[52] P. Iodice, G. Langella, A. Amoresano, A numerical approach to assess air pollution by ship engines in manoeuvring mode and fuel switch conditions, Energy Environ. 28 (2017) 827–845.
[53] Ç. Iris, J.S.L. Lam, A review of energy efficiency in ports: operational strategies, technologies and energy management systems, Renew. Sustain. Energy Rev. 112 (2019) 170–182.
[54] J.-P. Jalkanen, A. Brink, J. Kalli, H. Pettersson, J. Kukkonen, T. Stipa, A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area, Atmos. Chem. Phys. 9 (2009) 9209–9223.
[55] J.-P. Jalkanen, L. Johansson, J. Kukkonen, A. Brink, J. Kalli, T. Stipa, Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide, Atmos. Chem. Phys. 12 (2012) 2641–2659.
[56] H.Y. Jia, R. Adland, V. Prakash, T. Smith, Energy efficiency with the application of Virtual Arrival policy, Transp. Res. Part D. -Transp. Environ. 54 (2017) 50–60.
[57] L. Johansson, J.-P. Jalkanen, J. Kukkonen, Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution, Atmos. Environ. 167 (2017) 403–415.
[58] M. Jović, E. Tijan, R. Marx, B. Gebhard, Big data management in maritime transport, Pomor. Zb. 57 (2019) 123–141.
[59] Y. Ju, C.A. Hargreaves, The impact of shipping CO 2 emissions from marine traffic in Western Singapore Straits during COVID-19, Sci. Total Environ. 789 (2021) 148063.
[60] S.L. Kao, W.H. Chung, C.W. Chen, AIS-based scenario simulation for the control and improvement of ship emissions in ports, J. Mar. Sci. Eng. 10 (2022) 17.
[61] M.Y. Khan, H. Agrawal, S. Ranganathan, W.A. Welch, J.W. Miller, D.R. Cocker III, Greenhouse Gas and Criteria Emission Benefits through Reduction of Vessel Speed at Sea, Environ. Sci. Technol. 46 (2012) 12600–12607.
[62] A. Kiliç, C. Deniz, Inventory of shipping emissions in Izmit Gulf, Turkey, Environ. Prog. Sustain. Energy 29 (2010) 221–232.

[63] H. Kim, H.D. Bui, S.S. Hong, Estimation of air pollution from ships in port area: a case study of Yeosu and Gwangyang Ports in Korea, Atmosphere 13 (2022) 17.
[64] S.-H. Kim, M.-I. Roh, M.-J. Oh, S.-W. Park, I.-I. Kim, Estimation of ship operational efficiency from AIS data using big data technology, Int. J. Nav. Archit. Ocean Eng. 12 (2020) 440–454.
[65] A.M. Kotrikla, T. Lilas, N. Nikitakos, Abatement of air pollution at an aegean island port utilizing shore side electricity and renewable energy, Mar. Policy 75 (2017) 238–248.
[66] J.W. Kwon, S.L. Yeo, W.J. Lee, Assessment of shipping emissions on Busan Port of South Korea, J. Mar. Sci. Eng. 11 (2023) 18.
[67] L.T. Le, G. Lee, H. Kim, S.-H. Woo, Voyage-based statistical fuel consumption models of ocean-going container ships in Korea, Marit. Policy Manag. 47 (2020) 304–331.
[68] H. Lee, H.T. Pham, M.W. Chen, S. Choo, Bottom-up approach ship emission inventory in Port of Incheon Based on VTS Data, J. Adv. Transp. 2021 (2021) 16.
[69] J.-U. Lee, W.-J. Lee, E.-S. Jeong, J.-H. Noh, J.-S. Kim, J.-W. Lee, Algorithm for monitoring emissions based on actual speed of ships participating in the Korean vessel speed reduction program, Energies 15 (2022) 9555.
[70] A. Lepore, M.S. DOS Reis, B. Palumbo, R. Rendall, C. Capezza, A comparison of advanced regression techniques for predicting ship CO2 emissions, Qual. Reliab. Eng. Int. 33 (2017) 1281–1292.
[71] T.-P. Liang, Y.-H. Liu, Research landscape of business intelligence and big data analytics: a bibliometrics study, Expert Syst. Appl. 111 (2018) 2–10.
[72] S. Lim, S. Pettit, W. Abouarghoub, A. Beresford, Port sustainability and performance: a systematic literature review, Transp. Res. Part D: Transp. Environ. 72 (2019) 47–64.
[73] J. Lister, R.T. Poulsen, S. Ponte, Orchestrating transnational environmental governance in maritime shipping, Glob. Environ. Change 34 (2015) 185–195.
[74] Liu, B. & Wang, Y. Simulation-based emission calculation method for container terminal production operation system. IOP Conference Series: Earth and Environmental Science, 2021. IOP Publishing, 012028.
[75] J. Liu, O. Duru, Bayesian probabilistic forecasting for ship emissions, Atmos. Environ. 231 (2020) 117540.
[76] S. López-Aparicio, D. Tonnesen, T.N. Thanh, H. Neilson, Shipping emissions in a Nordic port: assessment of mitigation strategies, Transp. Res. Part D. -Transp. Environ. 53 (2017) 205–216.
[77] Y. Mamatok, C. Jin, An integrated framework for carbon footprinting at container seaports: the case study of a Chinese port, Marit. Policy Manag. 44 (2017) 208–226.
[78] A. Mandal, J. Biswas, Z. Farooqui, S. Roychowdhury, A detailed perspective of marine emissions and their environmental impact in a representative Indian port, Atmos. Pollut. Res. 12 (2021) 13.
[79] A. Mandal, J. Biswas, S. Roychowdhury, Z.M. Farooqui, Appraisal of emissions from ocean-going vessels coming to Kolkata Port, India, J. Inst. Eng. (India): Ser. A 98 (2017) 387–395.
[80] J. Martínez-Moya, B. Vazquez-Paja, J.A.G. Maldonado, Energy efficiency and CO2 emissions of port container terminal equipment: evidence from the Port of Valencia, Energy Policy 131 (2019) 312–319.
[81] D.S.-H. Moon, J.K. Woo, The impact of port operations on efficient ship operation from both economic and environmental perspectives, Marit. Policy Manag. 41 (2014) 444–461.
[82] R.A.O. Nunes, M.C.M. Alvim-Ferraz, F.G. Martins, S.I.V. Sousa, Assessment of shipping emissions on four ports of Portugal, Environ. Pollut. 231 (2017) 1370–1379.
[83] S. Papaefthimiou, A. Maragkogianni, K. Andriosopoulos, Evaluation of cruise ships emissions in the Mediterranean basin: the case of Greek ports, Int. J. Sustain. Transp. 10 (2016) 985–994.
[84] S. Pettit, P. Wells, J. Haider, W. Abouarghoub, Revisiting history: can shipping achieve a second socio-technical transition for carbon emissions reduction? Transp. Res. Part D: Transp. Environ. 58 (2018) 292–307.
[85] A.O. Piris, E. Díaz-Ruiz-Navamuel, C.A. Pérez-Labajos, J.O. Chaveli, Reduction of CO2 emissions with automatic mooring systems, case Port. Santander *Atmos. Pollut. Res.,* 9 (2018) 76–83.
[86] T. Pitana, E. Kobayashi, N. Wakabayashi, Estimation of exhaust emissions of marine traffic using Automatic Identification System data (case study: Madura Strait area, Indonesia). OCEANS'10 IEEE SYDNEY, IEEE (2010) 1–6.
[87] A.I.G. Rivera, V. Mugica-Alvarez, R.S. Echeverría, P.S. Alvarez, V.M. Rueda, G. V. Cruz, A. Retama, Air quality and atmospheric emissions from the operation of the Main Mexican Port in the Gulf of Mexico from 2019 to 2020, J. Mar. Sci. Eng. 11 (2023) 24.
[88] G.D. Rodríguez, E. Martin-Alcalde, J.C. Murcia-González, S. Saurí, Evaluating air emission inventories and indicators from cruise vessels at ports, Wmu J. Marit. Aff. 16 (2017) 405–420.
[89] W.B. Rouse, N.M. Morris, On looking into the black box: prospects and limits in the search for mental models, Psychol. Bull. 100 (1986) 349.
[90] T.H. Shao, W.J. Du, Y. Ye, H.Q. Li, J.X. Dong, G.Y. Liu, P.J. Zheng, A novel virtual arrival optimization method for traffic organization scenarios, Sustainability 16 (2024) 17.
[91] K. Shin, J.-P. Cheong, Estimating transportation-related greenhouse gas emissions in the Port of Busan, S. Korea, Asian J. Atmos. Environ. 5 (2011) 41–46.
[92] K.P. Shine, The global warming potential—the need for an interdisciplinary retrial, Clim. Change 96 (2009) 467–472.
[93] J. Sim, A carbon emission evaluation model for a container terminal, J. Clean. Prod. 186 (2018) 526–533.
[94] M. Simonsen, S. Gössling, H.J. Walnum, Cruise ship emissions in Norwegian waters: a geographical analysis, J. Transp. Geogr. 78 (2019) 87–97.
[95] J. Sjöberg, Q. Zhang, L. Ljung, A. Benveniste, B. Delyon, P.-Y. Glorennec, H. Hjalmarsson, A. Juditsky, Nonlinear black-box modeling in system identification: a unified overview, Automatica 31 (1995) 1691–1724.
[96] S. Sorte, V. Rodrigues, R. Lourenco, C. Borrego, A. Monteiro, Emission inventory for harbour-related activities: comparison of two distinct bottom-up methodologies, Air Qual. Atmosphere Health 14 (2021) 831–842.
[97] T. Spengler, B. Tovar, Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: the state-owned Spanish port system case, J. Environ. Manag. 279 (2021) 11.
[98] G. Spiliopoulos, D. Zissis, J. De La Cueva, I. Kontopoulos, Modelling and simulating vessel emissions in real time based on terrestrial AIS data. Global Oceans 2020: Singapore–US Gulf Coast, IEEE (2020) 1–4.
[99] L. Styhre, H. Winnes, J. Black, J. Lee, H. Le-Griffin, Greenhouse gas emissions from ships in ports – Case studies in four continents, Transp. Res. Part D: Transp. Environ. 54 (2017) 212–224.
[100] Y.J. Tian, L.L. Ren, H.Y. Wang, T. Li, Y.P. Yuan, Y. Zhang, Impact of AIS data thinning on ship air pollutant emissions inventories, Atmosphere 13 (2022) 11.
[101] M. Tichavska, B. Tovar, D. Gritsenko, L. Johansson, J.P. Jalkanen, Air emissions from ships in port: Does regulation make a difference? Transp. Policy 75 (2019) 128–140.
[102] A. Tokuslu, Estimating greenhouse gas emissions from ships on four ports of Georgia from 2010 to 2018, Environ. Monit. Assess. 193 (2021) 20.
[103] Toscano, D. & Murena, F. 2019. Atmospheric ship emissions in ports: A review. Correlation with data of ship traffic. *Atmospheric Environment: X,* 4, 100050.
[104] D. Tranfield, D. Denyer, P. Smart, Towards a methodology for developing evidence-informed management knowledge by means of systematic review, Br. J. Manag. 14 (2003) 207–222.
[105] Trozzi, C. & Vaccaro, R. 1999. Methodologies for estimating future air pollutant emissions from ships. *Techne Report MEET RF98b*.
[106] UNCTAD 2023. Review of Maritime Transport 2023. New York and Geneva: United Nations.
[107] G. Villalba, E.D. Gemechu, Estimating GHG emissions of marine ports—the case of Barcelona, Energy Policy 39 (2011) 1363–1368.
[108] Z. Wan, S.J. Ji, Y.T. Liu, Q. Zhang, J.H. Chen, Q. Wang, Shipping emission inventories in China's Bohai Bay, Yangtze River Delta, and Pearl River Delta in 2018, Mar. Pollut. Bull. 151 (2020) 10.
[109] Z. Wan, T. Zhang, M. Sha, W. Guo, Y. Jin, J.J. Guo, Y.T. Liu, Evaluation of emission reduction strategies for berthing containerships: a case study of the Shekou Container Terminal, J. Clean. Prod. 299 (2021) 12.
[110] B. Wang, Q. Liu, L. Wang, Y.J. Chen, J.S. Wang, A review of the port carbon emission sources and related emission reduction technical measures? Environ. Pollut. 320 (2023) 26.
[111] L. Wang, Y. Li, Estimation methods and reduction strategies of port carbon emissions-what literatures say? Mar. Pollut. Bull. 195 (2023) 115451.
[112] P. Wang, Q.Y. Hu, W.X. Xie, L. Wu, F. Wang, Q. Mei, Big data-driven carbon emission traceability list and characteristics of ships in maritime transportation-a case study of Tianjin Port, Environ. Sci. Pollut. Res. 30 (2023) 71103–71119.
[113] I.S. Wing, The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technologies and the cost of limiting US CO2 emissions, Energy Policy 34 (2006) 3847–3869.
[114] H. Winnes, L. Styhre, E. Fridell, Reducing GHG emissions from ships in port areas, Res. Transp. Bus. Manag. 17 (2015) 73–82.
[115] D. Woo, N. Im, Estimation of the Efficiency of Vessel Speed Reduction to Mitigate Gas Emission in Busan Port Using the AIS Database, J. Mar. Sci. Eng. 10 (2022) 14.
[116] Z.C. Xia, Z.J. Guo, W.Y. Wang, Y. Jiang, Joint optimization of ship scheduling and speed reduction: a new strategy considering high transport efficiency and low carbon of ships in port, Ocean Eng. 233 (2021) 13.
[117] W.X. Xie, Y. Li, Y. Yang, P. Wang, Z.S. Wang, Z.X. Li, Q. Mei, Y.Q. Sun, Maritime greenhouse gas emission estimation and forecasting through AIS data analytics: a case study of Tianjin port in the context of sustainable development, Front. Mar. Sci. 10 (2023) 17.
[118] D. Yang, L. Wu, S. Wang, H. Jia, K.X. Li, How big data enriches maritime research–a critical review of Automatic Identification System (AIS) data applications, Transp. Rev. 39 (2019) 755–773.
[119] Y. Yoo, B. Moon, T.G. Kim, Estimation of pollutant emissions and environmental costs caused by ships at Port: a case study of Busan Port, J. Mar. Sci. Eng. 10 (2022) 21.
[120] Y. Yu, R. Sun, Y. Sun, Y. Shu, Integrated carbon emission estimation method and energy conservation analysis: the Port of Los Angles case study, J. Mar. Sci. Eng. 10 (2022) 717.
[121] Y. Yu, R. Sun, Y. Sun, J. Wu, W. Zhu, China's Port carbon emission reduction: a study of emission-driven factors, Atmosphere 13 (2022) 550.
[122] P. Yun, L.I. Xiangda, W. Wenyuan, L.I.U. Ke, L.I. Chuan, A simulation-based research on carbon emission mitigation strategies for green container terminals, Ocean Eng. 163 (2018) 288–298.
[123] Y. Zhang, J. Gu, W. Wang, Y.Q. Peng, X.J. Wu, X.J. Feng, Inland port vessel emissions inventory based on ship traffic emission assessment model-automatic identification system, Adv. Mech. Eng. 9 (2017) 9.
[124] Zhu, W., Liu, X., Chen, C. & Li, H. Estimation of Marine Emissions in Zhanjiang Port Area Based on AIS Data. 2019 4th International Conference on Electromechanical Control Technology and Transportation (ICECTT), 2019. IEEE, 150-153.