

Review

Research Hotspots and Evolution Trends of Port Emission Reduction: A Bibliometric Analysis Based on CiteSpace

Kebiao Yuan *, Lina Ma  and Renxiang Wang *

School of Economics and Management, Ningbo University of Technology, Ningbo 315212, China

* Correspondence: ykbjob@163.com (K.Y.); wrx@nbut.edu.cn (R.W.)

Abstract: As a key node in the transportation network, ports connect the inland hinterland with the outside world, providing strong guarantees for the sustainable development of domestic trade and economy. However, the increasing port activities, while promoting regional economic growth, have also brought increasingly serious environmental problems to the local area. Promoting port emission reduction is a key way and important lever for China's transportation industry to promote ecological civilization construction. By using CiteSpace to systematically review the literature on port emission reductions in recent years in the China National Knowledge Infrastructure (CNKI) and Web of Science databases, it was found that significant achievements have been made in port emission reduction technology, policy system construction, and emission reduction effect evaluation. However, there are still problems such as insufficient research on regional differences and insufficient in-depth analysis of emission reduction costs and benefits. Analyzing the hotspots and trends of port emission reduction research at home and abroad can provide reference for the theoretical research and practical path of coordinated emission reduction governance in Chinese ports. Future research on port emission reduction should focus on regional differences, cost–benefit analysis, and in-depth exploration of the synergistic effects of port emission reduction and regional economic development, in order to provide more comprehensive theoretical support and practical guidance for the green sustainable development of ports.



Academic Editor: Giada La Scalia

Received: 17 January 2025

Revised: 8 February 2025

Accepted: 10 February 2025

Published: 11 February 2025

Citation: Yuan, K.; Ma, L.; Wang, R. Research Hotspots and Evolution Trends of Port Emission Reduction: A Bibliometric Analysis Based on CiteSpace. *Sustainability* **2025**, *17*, 1474. <https://doi.org/10.3390/su17041474>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: green sustainable port; CiteSpace; visualized analysis; knowledge graph

1. Introduction

Analyzing the hotspots and trends in domestic and international port emission reduction research can provide references for theoretical research and practical pathways in China's collaborative governance of port emission reduction. Future port emission reduction research should focus on regional differences, cost–benefit analysis, and in-depth exploration of the synergistic effect between port emission reduction and regional economic development, aiming to provide more comprehensive theoretical support and practical guidance for the green development of ports.

These studies not only provide theoretical support but also offer practical guidance for port emission reduction operations. However, existing research still has deficiencies in systematicness, comprehensiveness, and depth, particularly in terms of regional differences, cost–benefit analysis, and the synergistic effect between port emission reduction and regional economic development, which require further deepening and expansion. In view of this, this paper aims to systematically sort through the research literature in the field of port emission reduction in recent years, analyze the current research status and deficiencies,

and explore future research directions. By summarizing and analyzing relevant domestic and international research, this paper expects to provide more comprehensive theoretical support and practical guidance for port emission reduction, contributing to the realization of green, low-carbon, and sustainable development in the port industry. Additionally, this paper will also provide beneficial references and inspirations for policy makers, port managers, and researchers, jointly promoting the progress and development of the global port emission reduction cause.

2. Research Methods and Literature Statistical Analysis

This paper took into account the time span from January 2008 to October 2024, selecting the Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) databases for article retrieval, and included statistics on the publication time, quantity, authors, etc., of relevant literature.

There are many academic databases, such as WOS, CNKI, Scopus, and IEEE Xplore, but there is substantial overlap between literature in Scopus and IEEE Xplore and WOS. In our experience, WOS covers most of the high-quality literature of Scopus and IEEE Xplore, especially the core literature in the field of port emission reduction. Scopus and WOS databases overlap by about 40–60%. The main overlapping content is high-influence journal papers. Scopus and IEEE overlap by about 20–40%, and the main overlap is IEEE journal papers. WOS and IEEE databases overlap by about 15–30% for selected IEEE journals. The other databases overlap by less than 5%; the main overlapping content is a few Chinese and English bilingual journals. Therefore, the Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) databases were selected for the literature search.

2.1. Research Method

CiteSpace-6.3.1 is a science visualization software package developed by Professor Chen Chaomei, a Chinese–American scholar, based on Java, specifically designed as a tool for scientific literature citation analysis. It has gradually developed in the context of scientometrics and data visualization, presenting the structure, laws, and distribution of scientific knowledge through the means of visualization. By constructing a keyword co-occurrence network map, it intuitively reveals the core terms and their interconnections in the research field, thereby revealing the hot topics of research. Meanwhile, the clustering map groups similar themes, helping to identify sub-areas and frontier trends in research.

In addition to CiteSpace, several other bibliometric tools, such as VOSviewer and BibExcel, are widely used for scientific literature analysis. However, CiteSpace offers unique advantages that make it particularly suitable for this study. Compared to VOSviewer, which is more focused on static network visualization, CiteSpace excels in temporal evolution analysis, allowing researchers to track the development of research hotspots and trends over time. This capability is crucial for understanding the dynamic evolution of port emission reduction research from 2008 to 2024. Furthermore, CiteSpace provides advanced features such as keyword clustering and burst detection, which are essential for identifying emerging trends and frontier topics in the field. In contrast, BibExcel, while useful for basic bibliometric analysis, lacks the sophisticated visualization and clustering functionalities offered by CiteSpace. Therefore, CiteSpace was chosen for its ability to provide a comprehensive and dynamic analysis of the research landscape, making it the most appropriate tool for this study.

When using CiteSpace software, the relevant parameters were set as follows: time slice was set to 2008–2024, with the time slice interval set to 1 year; node type selected

was “Keyword”; threshold was set to Top 50; cut mode selected were “Pathfinder” and “Pruning sliced networks”; and algorithm selected was LLR cluster.

2.2. Literature Retrieval

To enhance the accuracy and completeness of article retrieval related to energy conservation and emission reduction strategies for green container ports, and to avoid potential risks of article omission and misidentification, it was necessary to construct a retrieval vocabulary that can comprehensively and accurately reveal the core information in this field. Therefore, this study followed four key steps to systematically determine the relevant retrieval terms for energy conservation and emission reduction strategies for green container ports.

Step 1: Preliminary selection of retrieval terms. In the article retrieval for “research on port emission reduction” the search condition for WOS can be set as “Port Emission Reduction” and for CNKI, it can be set as “port emission reduction”. To avoid the influence of journal quality, instead of selecting all journals, we directly chose CSSCI, Beijing University Core, and journals with high impact factors.

Step 2: Expand the scope of retrieval terms. We checked the retrieval results from Step 1 to confirm whether the main journals and articles related to this research appear in the retrieval results and expanded the scope of retrieval terms based on the professional nouns and terms that can represent the research theme appearing in the titles, abstracts, keywords, chapter titles, or full text of the retrieval results, such as “Green Port”, “green port strategy”, “emission reduction technology”, and “green port”.

Step 3: Streamline article types. On the basis of Step 2, we excluded unnecessary article types, such as conference papers, editorial materials, revisions, letters, retracted publications, etc.

Step 4: Selection of Irrelevant Search Terms. We conducted searches using the expanded search terms and examined the search results to filter out articles and research areas that are not relevant to this review. We identified irrelevant search terms, such as “Port History Development” and “Port Culture” and updated the search term structure accordingly.

Searching the WOS (Web of Science) database and CNKI (China National Knowledge Infrastructure) database following the above procedures finally identified 1012 WOS core collection database references and 137 references from the CNKI core journal database, as shown in Table 1.

Table 1. Number of articles searched.

Database	Initial Retrieval (Step 1)	Expand the Search Range (Step 2)	Simplify the Types of Articles (Step 3)	Remove Duplicates (Step 4)	Final Selection
WoS	1500	1830	1315	1200	1012
CNKI	200	266	184	180	137

2.3. Publication Analysis

The publication trend in the field of port emission reduction from 2008 to 2024 is illustrated in Figure 1. Globally, the annual publication volume in the field of port emission reduction grew relatively slowly between 2008 and 2015, with a total of 174 publications. However, from 2016 to 2024, it increased rapidly, with a total of 838 publications, indicating a surge in research on port emission reduction after 2016. In contrast, the publication volume in the domestic field of port emission reduction remained stable between 2008 and 2024, averaging 8 publications per year, with a total of 137 publications. Comparing the international and domestic trends, it can be observed that the international annual publication volume has been increasing rapidly, while the domestic publication volume has

remained stable. The rapid increase in international annual publication volume suggests that, with the development of the global economy, port emission reduction has gained significant attention and prominence on the international stage. The stability in domestic annual publication volume may be attributed to several factors. Firstly, in-depth research has led to a longer publication cycle. Secondly, many domestic scholars prefer to publish in international journals for better academic exchange.

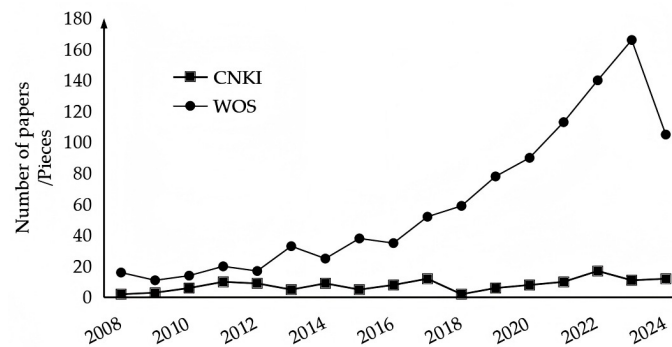


Figure 1. Changes in annual publication volume in the field of port emission reduction from 2008 to 2024.

3. Dynamic and Hotspot Analysis of Port Emission Reduction Research

3.1. Keyword Co-Occurrence Analysis

CiteSpace software was used to form a keyword co-occurrence map. Keywords, as words indexing the content characteristics of a paper, often represent the core and main content of an article, highly summarizing the research theme. By setting the node type to “keyword”, the size of the keyword node represents the frequency of its occurrence. The higher the frequency, the greater the node’s influence. As shown in Figure 2, the WOS keyword co-occurrence map has 290 nodes, 446 connections, and a network density of 0.0106. The keyword with the highest co-occurrence frequency is “performance”, reaching 147. Other keywords with higher co-occurrence frequencies include “emissions”, “reduction”, and “impact”, indicating that in port operation management, enhancing performance while reducing emissions and achieving environmental protection and emission reduction have become the focus of industry’s attention. Especially against the current background of increasing global climate change and environmental pressure, ports, as important transportation hubs and logistics nodes, play a particularly important role in emission reduction. By adopting advanced environmental protection technologies and equipment and optimizing port operation processes, ports can not only significantly improve their operational efficiency but also effectively reduce emissions and lower their environmental impact. Meanwhile, measures to reduce emissions can also enhance the overall sustainability of ports, strengthening their adaptability to future challenges and providing strong support for constructing green, low-carbon, and efficient port operation modes. As shown in Figure 3, the CNKI keyword co-occurrence map has 219 nodes, 341 connections, and a network density of 0.0143. The keyword with the highest co-occurrence frequency is “green port”, reaching 30. Other keywords with higher co-occurrence frequencies include “port”, “energy conservation”, “emission reduction”, “waterway transport”, and “evolutionary game”, indicating that building green ports and achieving energy conservation and emission reduction are key to the transformation and upgrading of the port industry. In the context of globally rising environmental awareness, port emission reduction is crucial for promoting the green development of the transportation industry.

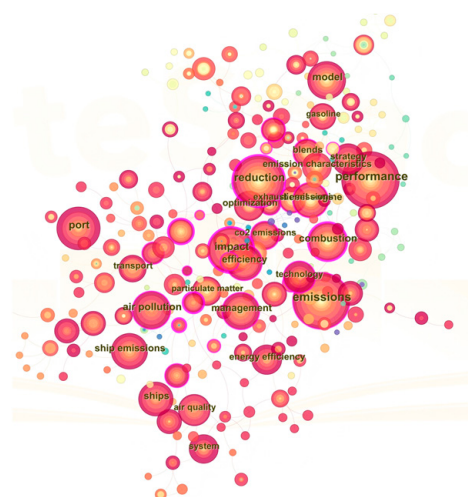


Figure 2. Keyword co-occurrence map from WOS.

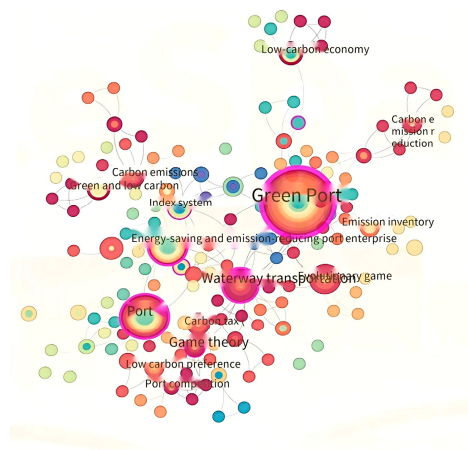


Figure 3. Keyword co-occurrence map from CNKI.

Betweenness centrality is a metric used to measure the significance of a node within a network, reflecting its capacity to serve as a mediator in the entire network. Nodes with a centrality value greater than 0.1 are designated as key nodes. A higher betweenness centrality indicates a higher frequency of co-occurrence with other keywords. As shown in Table 2, from 2008 to 2024, the keywords “reduction”, “climate”, “impact”, “combustion”, and “air pollution” exhibited betweenness centrality values exceeding 0.1 on the international stage. This reveals their crucial role as connectors in the global research network on climate change and environmental protection, forming key nodes and core issues in strategies to address climate change and reduce air pollution. Globally, combustion activities, as major sources of greenhouse gas and air pollutant emissions, have profound impacts on the climate system, prompting the international community to prioritize the urgent need to reduce combustion emissions and mitigate climate change. Concurrently, domestic research from 2008 to 2024 indicates that the keywords “green port”, “waterway transport”, “port”, “energy conservation and emission reduction”, “indicator system”, and “port enterprise” also have betweenness centrality values greater than 0.1. This demonstrates the significant importance of these concepts in the field of port development and environmental protection in China. It suggests that the Chinese port industry is actively responding to the national call for energy conservation and emission reduction by establishing a green port system, optimizing waterway transport efficiency, implementing energy conservation and emission reduction indicator systems, and taking other measures. These efforts aim to promote the transformation and upgrading of port enterprises, striving to significantly

reduce the negative environmental impact of port operations while ensuring economic development. The construction of green ports not only fosters harmonious coexistence between ports and their surrounding environments but also provides valuable practical experience and technical demonstrations for the global community in addressing the challenge of climate change. This exemplifies China's leadership and responsibility in the field of port emission reduction.

Table 2. Comparison of keywords in the field of port emission reduction between WOS and CNKI from 2008 to 2024.

2008 to 2024 WOS			2008 to 2024 CNKI		
Keywords	Frequency	Betweenness Centrality	Keywords	Frequency	Betweenness Centrality
performance	147	0.07	green port	30	0.61
emissions	146	0.13	port	18	0.33
reduction	104	0.27	energy conservation and emission reduction	14	0.32
impact	84	0.22	waterway transportation	9	0.38
port	78	0.01	evolutionary game	7	0.05
combustion	68	0.22	indicator system	5	0.13
air pollution	67	0.19	carbon emissions	5	0.09
model	65	0	low-carbon economy	4	0.09
ship emissions	59	0.06	green and low carbon	4	0.08
diesel engine	58	0.16	carbon tax	4	0.06
management	57	0.16	shore power	4	0.01
efficiency	57	0.13	port enterprises	3	0.13
ships	52	0	game theory	3	0.11
strategy	45	0.01	environmental protection	3	0.06
blends	43	0.16	carbon emission reduction	3	0.05

3.2. Keyword Cluster Analysis

Utilizing the CiteSpace software and the log-likelihood ratio (LLR) algorithm, a keyword clustering map was generated. Clusters are formed by refining and summarizing research topics based on the hotspot network map, visually presenting the primary research areas. As shown in Figures 4 and 5, the top 18 clusters from the WOS and the top 12 clusters from the CNKI are presented. The cluster number is inversely proportional to its size, with the largest cluster labeled #0. For the WOS, the modularity value $Q = 0.7951$, and the average silhouette value $S = 0.8887$; for the CNKI, $Q = 0.812$, and $S = 0.9546$. With Q values greater than 0.3 and S values greater than 0.7, these results indicate that the clustering structure is reasonable and highly effective.

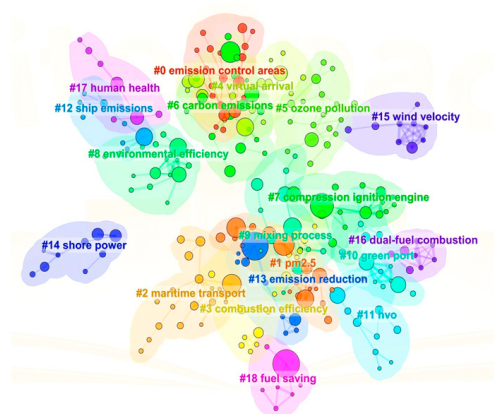


Figure 4. Keyword clustering map from WOS.

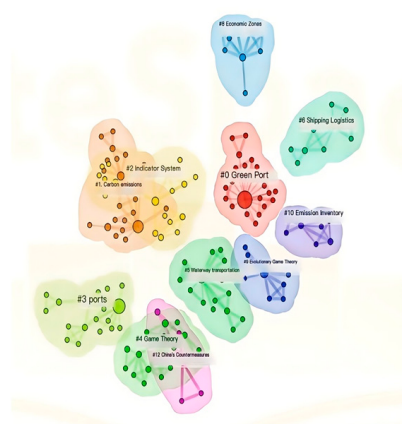


Figure 5. Keyword clustering map from CNKI.

Based on the data from the top 18 keyword clusters, further integration and summarization reveal that international research on port emission reduction primarily focuses on the following three aspects:

- (1) Emission control areas and air quality improvement (#0 #1 #5 #12 #13). This theme focuses on effectively reducing port emissions within emission control areas to improve air quality and protect human health (#17) [1]. With the increasing global concern over air quality issues, the establishment of emission control areas has become a key measure to reduce port emissions and decrease PM2.5 concentrations (#1) and ozone pollution (#5) [2,3]. Research concentrates on implementing stringent emission control policies, such as restricting the use of high-sulfur fuels and promoting low-sulfur fuels [4] and green port technologies (#10), to reduce ship emissions (#12) and overall carbon emissions (#6) [5]. Simultaneously, the positive impacts of emission reduction strategies (#13) on enhancing environmental efficiency (#8) and human health and well-being are explored, providing a scientific basis for policy formulation.
- (2) Transport efficiency and combustion optimization (#2 #3 #7 #16). This theme revolves around improving maritime transport efficiency (#2) and combustion efficiency (#3) to reduce port emissions and fuel consumption. The application of compression ignition engines (#7) [6] and dual-fuel combustion technologies (#16) [7] has emerged as a crucial pathway to enhance combustion efficiency and reduce the carbon footprint. Research focuses on optimizing ship engine designs to improve combustion efficiency and reduce the generation of greenhouse gases and harmful emissions. Additionally, optimizing port logistics through technologies such as virtual arrival (#4) reduces ship waiting times and fuel consumption, achieving fuel savings (#18) [8]. These measures not only contribute to enhancing environmental efficiency (#8) but also enhance port competitiveness.
- (3) Green port technologies and sustainable development (#9 #10 #11 #14 #15). This theme emphasizes the adoption of green port technologies and innovative strategies to promote sustainable port development. The construction of green ports (#10) involves multiple aspects, including the promotion of clean energy sources such as hydrogenated vegetable oil (HVO, #11) [9] and shore power (#14) as well as optimizing port layouts and operational processes to reduce emissions. Research focuses on the development and application of efficient and environmentally friendly port equipment and technologies, such as the utilization of renewable energy sources like wind energy (#15), to reduce carbon emissions (#6) and environmental pollution. Furthermore, exploring the significance of green port technologies in enhancing the overall environmental performance of ports and promoting coordinated economic and environmental development of ports is crucial. By implementing these green

technologies and strategies, ports can not only reduce emissions but also improve operational efficiency and sustainability, contributing to the global effort to address climate change challenges.

Based on the data from the top 11 keyword clusters in the CNKI, further integration and summarization reveal that domestic research on port emission reduction primarily focuses on the following three aspects:

- (1) Green port construction and carbon emission management (#0 #1 #2). This theme focuses on how to construct green ports and effectively manage carbon emissions for sustainable development. Green port construction is a key initiative in the port industry to address climate change challenges, aiming to reduce carbon emissions during port operations through optimized operational methods and the adoption of clean energy sources (#1). To achieve this goal, a scientific and comprehensive carbon emission indicator system (#2) needs to be established to accurately measure and monitor port carbon emissions. Meanwhile, green port construction must comprehensively consider the economic, environmental, and social aspects of ports to ensure that carbon emissions are reduced without compromising normal port operations and sustainable development (#3).
- (2) Port emission reduction strategies and game theory applications (#3 #4 #9). This theme focuses on the formulation and implementation of port emission reduction strategies and the application of game theory in this context. As important nodes in waterway transportation (#5) and shipping logistics (#6), China considers environmental protection issues while promoting the economic development of port cities and their surrounding areas, enhancing the environmental adaptability of the port industry [10]. Therefore, theoretical tools such as game theory (#4) and evolutionary game theory (#9) are utilized to analyze the impacts of different emission reduction strategies on ports and their stakeholders, seeking optimal emission reduction solutions. The application of game theory provides a better understanding of cooperation and competition in the process of port emission reduction, providing a basis for formulating scientific and reasonable emission reduction policies.
- (3) China's port emission reduction countermeasures and practices (#10 #12). This theme emphasizes proposing effective emission reduction countermeasures tailored to the specific conditions of Chinese ports and implementing them in practice. As a globally significant shipping country, China's port emission reduction efforts are of great significance to global climate governance. Research priorities include compiling detailed port emission inventories (#10) [11] to accurately grasp port emission status and exploring port emission reduction countermeasures suitable for China's national conditions (#12), such as promoting the use of clean energy and optimizing port layouts and operational methods. Through practical exploration, the technical system and management mechanism for port emission reduction are continuously improved, providing valuable experience for port emission reduction efforts in China and globally.

4. Evolution Path of Research on Port Emission Reduction

4.1. Analysis of Burst Terms in the Literature

Burst terms refer to key terms that suddenly increase in frequency or experience a significant growth in usage within a certain period. By analyzing burst terms, we can identify cutting-edge research and future trends in the field of port emission reduction. The burst terms in the field of port emission reduction from the WOS between 2008 and 2024 are shown in Figure 6.

Top 25 Keywords with the Strongest Citation Bursts

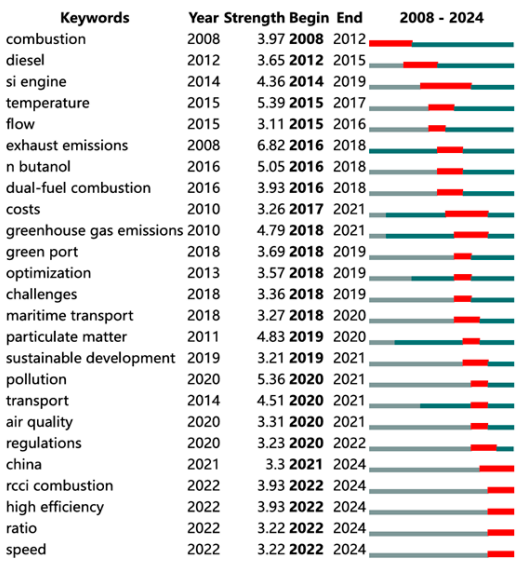


Figure 6. Burst detection of keywords in the field of port emission reduction in Web of Science (WOS) from 2008 to 2024.

The top five burst terms internationally are, in order, “exhaust emission”, “temperature”, “pollution”, “particular matter”, and “greenhouse gas emission”. From a temporal perspective, the burst terms prior to 2019 include “combustion”, “diesel”, “temperature”, “exhaust emission”, “dual-fuel combustion”, “costs”, “greenhouse gas emission”, “green port”, and “optimization”. These keywords emerged successively from 2008, reflecting that early environmental research primarily focused on the use of traditional energy sources and their environmental impacts. In particular, ports, as significant sources of energy consumption and exhaust emissions, have begun to attract attention regarding energy conservation and emission reduction. At the same time, this indicates that the port industry is seeking more environmentally friendly and efficient development paths, striving to reduce environmental impacts while ensuring economic development. The burst terms after 2019 are “sustainable development”, “air quality”, “RCCI combustion (Reactive Controlled Compression Ignition combustion)”, “high efficiency”, “ratio”, and “speed”, marking a substantial step forward in international environmental protection efforts. This shift from singular pollution control to a more comprehensive sustainable development strategy further reflects the active exploration and innovation of the port industry in emission reduction technologies and energy efficiency. “Exhaust emission” first appeared in 2008, but related research experienced an explosive growth in 2016, becoming the keyword with the highest burst strength. This is likely closely related to the severe situation of global climate change and the promotion of international environmental protection policies. “Green port” emerged in 2018, further driving practice and innovation in environmental protection within the port industry. A green port not only means reducing exhaust and greenhouse gas emissions but also encompasses improving resource utilization efficiency, protecting the ecological environment, promoting community harmony, and other aspects. It is an important path for the port industry to achieve sustainable development. The burst terms in the field of nitrogen removal from wastewater in the CNKI from 2008 to 2024 are shown in Figure 7.

The top five keywords with the highest burst strength in China are “ports”, “energy conservation and emission reduction”, “evolutionary game theory”, “green and low-carbon”, and “ecological ports”. From a temporal perspective, the keywords that emerged

before 2015 include “ecological ports”, “environmental protection”, “energy conservation and emission reduction”, “low-carbon”, “indicator system”, and “development strategy”. These keywords have successively appeared since 2008, reflecting that China’s port industry, after joining the WTO, faced with the dual pressures of international competition and environmental protection, began actively exploring new paths for ecological port construction and energy conservation and emission reduction. By constructing scientific and reasonable indicator systems and formulating development strategies in line with their own characteristics, the port industry has gradually increased its investment in environmental protection while ensuring economic development. The keywords that emerged after 2015 are “green and low-carbon”, “emission reduction”, “green development”, “evolutionary game theory”, “carbon neutrality”, “emission reduction strategies”, and “port enterprises”, marking that the port industry has taken more solid steps in emission reduction. In particular, the introduction of the concept of “green and low-carbon” not only emphasizes the need for ports to reduce carbon emissions and environmental pollution during operations but also advocates for a new development concept and model. The emergence of “green and low-carbon” in 2018 is closely related to the Chinese government’s high attention and active promotion of green and low-carbon development. Against this background, the port industry has actively responded to the national call by adopting advanced emission reduction technologies, optimizing energy structures, improving resource utilization efficiency, and other measures to reduce carbon emissions and environmental pollution. At the same time, port enterprises have also begun actively exploring new paths for green and low-carbon development, aiming to achieve a win-win situation in terms of both economic and environmental benefits by constructing a green and low-carbon port ecosystem.

Top 19 Keywords with the Strongest Citation Bursts

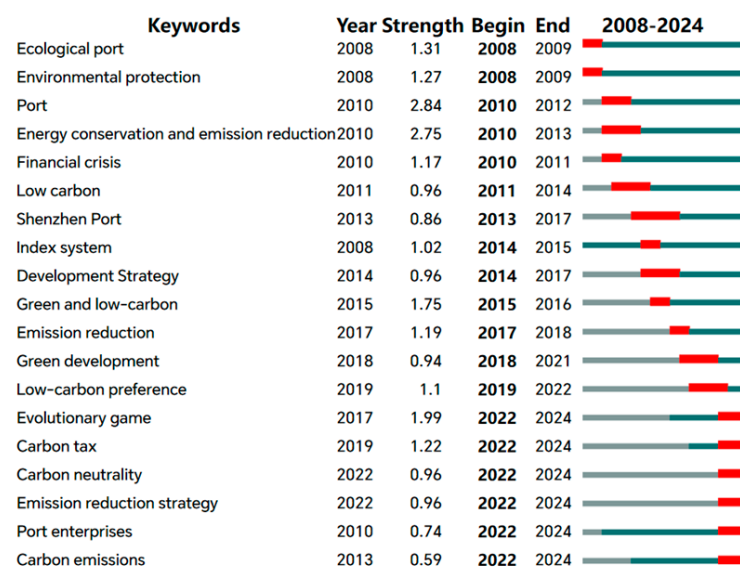


Figure 7. Burst detection of keywords in the field of port emission reduction in CNKI from 2008 to 2024.

4.2. Analysis of the Timeline Map of Keywords

Utilizing the “TimeLine View” function within the CiteSpace software, we have constructed a timeline map of keywords. By observing the changes in keywords across different years or time periods, Figures 8 and 9 below reveal the evolutionary process of port emission reduction research both domestically and internationally.

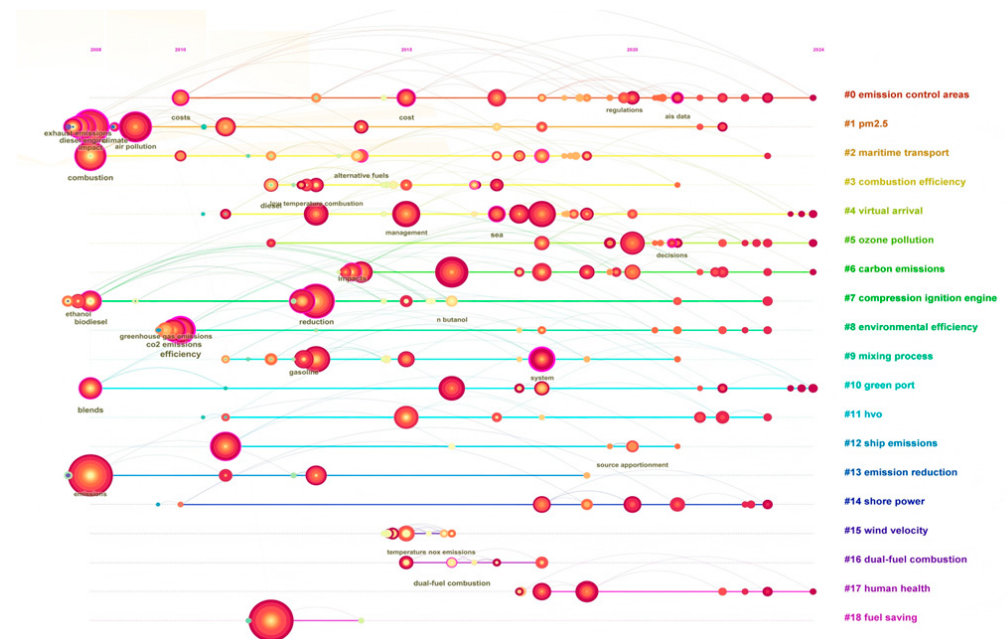


Figure 8. The evolutionary process of research in the field of port emission reduction internationally.

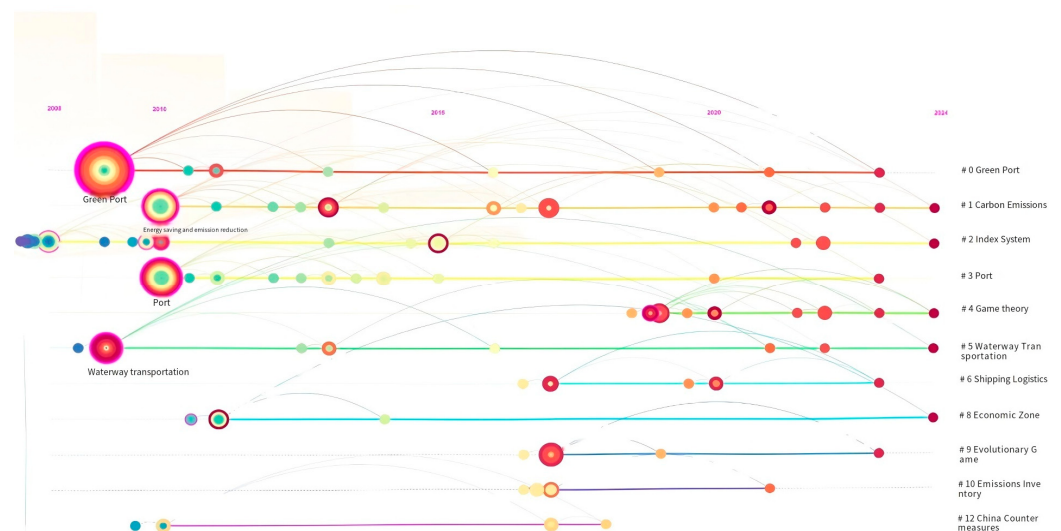


Figure 9. The evolutionary process of research in the field of port emission reduction in China.

Phase One: Initial Exploration Period (2008–2015)

During this phase, research primarily focused on quantifying port emissions and exploring preliminary reduction strategies. In 2007, the International Association of Ports and Harbors (IAPH) issued a resolution on the Clean Air in Ports Program, emphasizing the need to pay greater attention to air quality in port areas and to make every effort to reduce air emissions from port operations. Various emission sources in port operations include loading and unloading equipment, buildings, lighting, and emissions from ships at ports [12]. For instance, ship emissions at ports have emerged as significant emission sources. In 2011, the International Maritime Organization (IMO) adopted the first set of international mandatory measures to improve ship energy efficiency. Subsequently, in 2015, the Central Committee of the Communist Party of China and the State Council issued the “Opinions on Accelerating the Construction of Ecological Civilization”, proposing to strengthen pollution control at ports and ships, actively address ship pollution, and enhance pollution prevention capabilities at ports and terminals. Song [13] estimated and listed the

emission inventory of ships within Shanghai Yangshan Port (including CO₂, CH₄, N₂O, PM₁₀, PM_{2.5}, NO_x, SO_x, CO, and HC), revealing their significant impact on air pollution in port cities. Researchers emphasized the importance of air pollution reduction strategies, such as the use of alternative fuels and shore power systems. The use of hydrogen and ammonia as clean fuels was widely mentioned in research [14], with hydrogen already being used in fuel cells and ammonia being used for power generation and propulsion. Additionally, ports will utilize renewable fuels and biomass for power generation. Vehicles at ports can use mixtures of biofuels and fossil fuels, reducing greenhouse gas emissions and achieving a balance between resource utilization and the environment. The use of shore power technology by ships at berth is crucial technology for reducing environmental pollution at ports. In 2009, the United States enacted regulations on ship emissions, requiring 50% of ships to use shore power during berthing from 1 January 2014, with an annual increase, and achieving the goal of 80% of ships using shore power by 1 January 2020. The regulations mandate the installation of shore power systems in new terminals and require modifications to existing terminals within a specified timeframe, imposing mandatory requirements. Nowadays, shore power is defined as providing electrical power to moored seagoing or inland waterway vessels [15]. Sulligoi et al. [16] conducted a retrospective study on the components of shore power, including shore-based equipment, shipboard equipment, shore–ship interfaces, applications, and specific functions. Peterson, K.L. et al. [17] introduced the development, standardization, and implementation of shore power systems, detailing their composition, application examples, ship adaptability, and cable management, while emphasizing the important role of standard-setting in promoting the development of shore power systems. These studies provided a theoretical foundation for the subsequent construction of green ports. Research during this period not only raised awareness about port emissions but also laid the groundwork for subsequent emission reduction efforts.

Phase Two: Rapid Development Period (2016–2020)

During this phase, research shifted towards the development and application of green port technologies and the construction of green port management systems. Scholars began exploring the use of renewable energy in ports, such as solar and wind energy, as well as the electrification trend of port equipment like electric cranes and electric trucks. For example, in 2014, the port of Los Angeles implemented a mandatory shore power policy, requiring docked ships to use shore power. This policy has significantly reduced NO_x and PM_{2.5} emissions by 95% and 90%, respectively, demonstrating the effectiveness of shore power technology in reducing port emissions. Solar energy production involves either photovoltaics or solar hot water [18]. For example, Kotrikla A.M. [19] assessed solar energy resources, simulated the installation and use of solar power generation facilities, and analyzed their environmental benefits, exploring the potential of solar energy resources to reduce air pollution at ports on the Aegean islands. Numerous studies simulated the benefits of using photovoltaic power generation in different ports, such as Ukrainian ports [20], the Port of Damietta in Egypt [21], and other Egyptian ports [22]. Li et al. [23] studied the optimization of offshore wind power generation and hybrid renewable energy storage in container terminals. Jonathan Y.C.E. and S.B.A. Kader [24] researched the electrification of RTG cranes at the Port of Tanjung Pelepas in Malaysia, while Musolino G. et al. [25] studied electric vehicles for passenger and freight transport at ports. Additionally, research on green port management strategies increased, with Correcher, J.F. et al. [26] exploring research on port berth allocation problems, providing methodological support for resource optimization and efficiency improvement in green port operations. During this period, the port industry achieved significant results in green transformation and technological inno-

vation, which not only helped reduce port carbon emissions and environmental pollution but also laid a solid foundation for the sustainable development of ports.

Phase Three: Application Maturity Period (2021–2024)

Research during this phase further focused on the intrinsic link between port emission reduction and sustainable development, as well as the monitoring and reporting system for port carbon emissions. The Port of Rotterdam, for instance, launched a large-scale solar and wind energy project in 2018, utilizing idle land and buildings within the port area to install solar panels and construct wind turbines around the port. This initiative reduced the port's annual CO₂ emissions by approximately 100,000 t, showcasing the potential of renewable energy in port emission reduction. Scholars began exploring how to achieve the dual goals of environmental protection and social responsibility while ensuring port economic development. For instance, Cai et al. [27] proposed a multi-equipment integrated scheduling strategy for port emission reduction based on multi-objective optimization. By comprehensively considering port operation efficiency and energy consumption, they constructed a three-objective mixed-integer programming model under different operational goals and constraints to improve the efficiency and sustainability of port operations. Meanwhile, as the global climate change issue becomes increasingly severe, the monitoring and reporting system for port carbon emissions has gradually become a research focus. Kao S.L. et al. [28] established a scientific and accurate carbon emission monitoring system and constructed a ship emission scenario simulation model to identify key factors for emission reduction, providing data support for port emission reduction and promoting regular reporting of carbon emissions by port enterprises to strengthen social supervision. Under the guidance of carbon neutrality goals, the port industry is gradually constructing a modern port system that is low-carbon, efficient, and environmentally friendly through smart management, technological innovation, and supply chain collaboration.

First Phase: Initial Exploration Period (2008–2012)

During this phase, domestic ports experienced rapid development; however, environmental awareness and emission reduction technologies lagged behind, gradually revealing emission issues at ports. Research primarily focused on the introduction of the concept of green ports, the establishment of energy-saving and emission-reduction evaluation index systems, and preliminary exploration of energy-saving and emission-reduction technologies.

The introduction of the green port concept brought a new perspective to the development of domestic ports. During this period, scholars began to pay attention to the environmental impact of ports and emphasized the importance of building green ports. Wu Penghua [29] elaborated on the meaning of green ecological seaports from the perspective of environmental protection progress and greening needs of domestic and foreign seaports. Li Wei [30] highlighted the importance of green port construction for the sustainable development of ports, based on the trend of transformation from transportation centers to integrated logistics centers, and further to green ports. Meanwhile, due to the lack of environmental protection awareness and inadequate pollution treatment facilities at ports, environmental legacy issues at Chinese ports were prominent, making the construction of green ecological ports an urgent need [31]. With the introduction of the green port concept, domestic scholars embarked on establishing energy-saving and emission-reduction evaluation index systems. For example, Liu Cuilian et al. [32] systematically established an energy-saving and emission-reduction evaluation index system for Chinese ports and constructed a hierarchical fuzzy comprehensive evaluation model to conduct an empirical analysis of the energy-saving and emission-reduction level of Qingdao Port. Simultaneously, Chen Minhui et al. [33] conducted related research based on this, further improving the methods and systems for evaluating energy saving and emission reduction at ports.

From there, the transition was made to the application of emission reduction technologies at ports. For instance, Liu Hongbo et al. [34] introduced the practical application of RTG (Rubber-Tired Gantry Crane) “oil-to-electricity” technology in energy saving and emission reduction at ports, which provided an effective way to resolve the contradiction between port development and energy consumption by reducing port operating costs. The research and application of these technologies provided strong support for the construction of green ports. Most of the research and practice during this period were exploratory and had not yet formed a systematic theory and technology system for emission reduction.

Second Phase: Rapid Development Period (2013–2019)

From 2013 to 2019, domestic research on port emission reduction and green logistics entered a rapid development phase. The research during this phase not only inherited the achievements of the initial awakening period but also conducted more in-depth and extensive explorations based on those achievements.

The concept of green ports gained wider dissemination and acceptance during this period. Scholars no longer solely focused on the introduction of the concept but began to delve into the specific paths and implementation strategies for green port construction. Wang Shurui and Wang Yuanyuan [35] conducted a detailed analysis of the current status and challenges faced by green port construction in China and proposed corresponding construction ideas and countermeasures. The establishment of energy-saving and emission-reduction evaluation index systems and evolutionary game models were further refined and detailed during this phase. Scholars not only paid attention to the overall energy-saving and emission-reduction level of ports but also began to focus on the energy-saving and emission-reduction effects of various links and specific operations at ports. For example, Ouyang Bin et al. [36] constructed a comprehensive, systematic, and distinctive evaluation index system for green and low-carbon ports and conducted an empirical analysis of major ports in Guangzhou. In addition, Xu Yan et al. [37] constructed an evolutionary game model for emission reduction between local governments and port enterprises, providing an effective reference for promoting the construction of green ports in the future.

During this phase, the application of energy-saving and emission-reduction technologies at ports was researched more extensively and deeply. Scholars not only focused on the optimization and improvement of traditional energy-saving and emission-reduction technologies but also began to explore the potential application of emerging technologies in energy saving and emission reduction at ports. Jin Yi et al. [38] systematically summarized new technologies for energy saving and emission reduction at ports, such as RTG oil-to-electricity conversion, hybrid RTGs, RTG and truck oil-to-gas conversion, and a shore-based variable frequency power supply, along with their application cases, providing important references for the promotion and application of energy-saving and emission-reduction technologies at ports. Specifically, Jiang Lun [39] discussed the specific application of RTG “oil-to-electricity” technology, while Tan Jian and Han Jun [40] reviewed ship-to-shore power supply systems, detailing their composition, basic principles, and application status. Research during the rapid development phase not only stayed at the theoretical level but also emphasized practical applications and technological innovations, forming a relatively complete emission reduction technology system and management mechanism.

Third Phase: Mature Application Period (2020–2024)

Entering 2020, China clearly put forward the “dual carbon” goals. The Opinions of the State Council on Completely, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Peaking Carbon Emissions and Achieving Carbon Neutrality pointed out the need to promote the normalization of ship-to-shore power use during port calls; raise energy efficiency standards for fuel vehicles and vessels;

improve the energy efficiency labeling system for transportation equipment; and accelerate the elimination of old, high-energy-consuming, and high-emission vehicles and vessels. This propelled research and practice in port emission reduction into a phase of deepening innovation. Researchers began to examine port emission reduction issues from a broader perspective, not only focusing on the emission reduction effects of individual ports but also discussing collaborative emission reduction strategies for port clusters, supply chains, and even the entire logistics system. Wang and Liu [41] took the Bohai Rim port cluster as the research object and constructed an evaluation index system for its energy-saving and emission-reduction efficiency. Liu et al. [42] studied investment strategies for emission reduction technologies in sustainable port-shipping supply chains by constructing static and dynamic linkage models. Research on comprehensive optimization of port resources primarily focused on the coordinated scheduling of two types of resources. Guo et al. [43] emphasized joint optimization methods for berths and yards in container ports, while Fan et al. [44] constructed a joint scheduling optimization model for berths and quay cranes addressing discrete berth allocation and time-varying quay crane scheduling problems. Research during this phase not only emphasized technological innovation and application but also highlighted the combined effects of policy guidance, market mechanisms, and social participation, jointly driving the comprehensive development of port emission reduction efforts.

Furthermore, the government has increased support for port emission reduction, issuing a series of incentive and restraint policies to encourage port enterprises to enhance environmental protection investments and technological innovations. The Ministry of Transport released the Green Port Grade Evaluation Guide (2020), providing standards for the construction and evaluation of green ports. The Measures for the Management of Ship-to-Shore Power Supply (2020) aimed to reduce atmospheric pollutant emissions during ship calls at ports and regulate the construction, use, and related activities of the ship-to-shore power supply at ports. The State Council issued the Guiding Opinions on Accelerating the Establishment and Improvement of a Green, Low-Carbon, and Circular Development Economic System (2021), which proposed, among other things, the development of green logistics at ports, active adjustment of transportation structures, promotion of green and low-carbon transportation means, and acceleration of the construction of ship-to-shore power supply facilities at ports.

The evolution process of the research field at home and abroad is summarized as shown in Tables 3 and 4.

Table 3. Overview of the evolution process of the domestic port emission reduction research field.

Phase	Time	Research Focus	Representative Technology/Policies
Initial Exploration Period	2008–2015	Emission quantification and shore power technology	IMO energy efficiency standards, U.S. shore power regulations
Rapid Development Period	2016–2020	Renewable energy applications	Solar power generation, RTG electrification
Application Maturity Period	2021–2024	Carbon monitoring and cross-regional collaboration	Blockchain carbon tracing, Guangdong–Hong Kong–Macao carbon trading

Table 4. Overview of the evolution process of the international port emission reduction research field.

Phase	Time	Research Focus	Representative Technology/Policies
Initial Exploration Period	2008–2012	Introduction of philosophy and establishment of indicator system	RTG “oil to electric” technology, port energy conservation, and emission reduction evaluation index system
Rapid Development Period	2013–2019	Technical optimization and emerging technologies	Hybrid RTG, shore power system for ships, green and low-carbon port evaluation index system
Mature Application Period	2020–2024	Collaborative emission reduction technology	Port group energy-saving and emission-reduction efficiency evaluation, berth and yard joint optimization

5. Research Areas and Future Prospects

Amidst the escalating global environmental crisis, ports, serving as pivotal hubs connecting world trade, have emerged as significant contributors to carbon emissions generated during their operations, thereby becoming a crucial topic in global climate change research. From 2008 to 2024, both academic and industry circles at home and abroad have conducted comprehensive and in-depth research on port emission reduction, exploring a series of effective strategies and technological pathways for mitigation. Building upon this foundation, this paper aims to further deepen our understanding of the research field of port emission reduction and provide insights into future development trends.

5.1. Key Research Areas

By reviewing the literature on port emission reduction both domestically and internationally in recent years, we can categorize the main research areas into three broad categories: quantification and assessment of port carbon emissions, technologies and strategies for port emission reduction, and research on the synergistic effects of port emission reduction and regional economic development.

(1) Quantification and Assessment of Port Carbon Emissions

Quantification and assessment of port carbon emissions serves as the foundation for research on port emission reduction. Scholars have conducted comprehensive and accurate quantitative analyses of carbon emissions generated during port operations by establishing carbon emission accounting systems. Sorte et al. [45] divided port emission sources into two categories: mobile emission sources and stationary emission sources. Mobile emission sources primarily include transportation tools such as ships and trucks, while stationary emission sources specifically refer to port handling and loading/unloading equipment. They conducted an in-depth analysis of port carbon emission status. Oksas et al. [46] explored the total carbon emissions produced by container handling equipment used in port operations at the Ambarli Container Port and formulated corresponding carbon emission reduction strategies based on climate change adaptation policies. Wang Chen et al. [47] proposed a method for calculating port carbon emissions by comprehensively considering fuel consumption, electricity consumption, and ship activity consumption, and conducted a quantitative analysis of the carbon emission level of Ningbo-Zhoushan Port. Cui et al. [48] introduced a “bottom-up” carbon emission calculation model for ports based on fuel consumption. This model enables more accurate assessment of carbon emissions by predicting port throughput and provides quantitative analysis of carbon emission reduction strategies implemented at ports. These studies not only provide data support for port emission

reduction but also offer a scientific basis for formulating subsequent emission reduction strategies. Additionally, with continuous advancements in carbon emission monitoring technology, real-time and accurate carbon emission data acquisition has become feasible, providing strong support for the dynamic management and effectiveness evaluation of port emission reduction. Guo and Liu [49] conducted an in-depth discussion on methods for collecting port energy consumption data and established a port energy consumption monitoring database and dynamic analysis system platform using advanced technologies such as the Internet of Things and the Internet. This platform can simultaneously monitor the energy consumption and operating status of port machinery, enabling real-time monitoring of energy consumption and timely responses to energy consumption changes. Zhong et al. [50] explored the design and visualization implementation of a smart port energy consumption management system. By constructing a B/S architecture system based on the C# and .Net platforms, they achieved dynamic monitoring and digital management of energy consumption and energy-consuming equipment in the port area, providing strong technical support for achieving port energy conservation and emission reduction targets.

(2) Technologies and Strategies for Port Emission Reduction

Technologies and strategies for port emission reduction are key areas of research. Scholars have effectively reduced carbon emissions from port operations by exploring and promoting clean energy, optimizing port energy structures, and improving energy utilization efficiency. Jiang et al. [51] believed that adopting clean energy is an effective pathway for green and low-carbon development of ports and proposed a development model for integrated energy systems in ports with multi-energy integration. Song et al. [52] introduced an Integrated Port Energy System (IPES) that comprehensively considers integrated demand response and energy interconnection to optimize port energy structures. Guo and Liu [49] developed an online monitoring system for the energy consumption of port energy-consuming equipment, providing data support for optimizing port energy structures. Song [53] studied the energy management of low-carbon port microgrids and proposed corresponding distributed energy management methods to improve port energy utilization rates. Meanwhile, electrified logistics equipment such as quay cranes, yard cranes, conveyor belt systems, and transfer vehicles used to handle containers and dry bulk cargo at ports [54] offers a new technological pathway for port emission reduction. Furthermore, scholars have also studied strategies such as port logistics optimization and ship emission control to further reduce port emissions. Han et al. [55] studied the architecture of a comprehensive port logistics service platform based on cloud computing and Internet of Things technologies. Ji and Chu [56] conducted optimization research on hub-and-spoke port logistics networks with dynamic hinterlands, providing theoretical support for the layout and optimization of port logistics networks. Peng [57] reviewed the formulation process of China's ship emission control area policies and analyzed the implementation effects and existing issues of these policies. Liu and Yang [58] explored the impact of ship emission control area policies on shipping enterprises in the Qiongzhou Strait and proposed corresponding countermeasures and suggestions.

(3) Research on the Synergistic Benefits of Port Emission Reduction and Regional Economic Development

Research on the synergistic benefits of port emission reduction and regional economic development has been an emerging research area in recent years. By exploring the synergistic effects of port emission reduction on regional industrial structure optimization, hinterland economy, and ecological environment improvement, scholars have revealed the important role of port emission reduction in promoting regional sustainable development. Yu and Wang [59] studied the relationship between port logistics in Zhuhai City and

the regional industrial structure and proposed suggestions for optimizing the industrial structure. Luo [60] studied the relationship between port logistics in Zhanjiang City and the optimization of the regional industrial structure, analyzing the important role of port logistics in regional economic growth and industrial structure optimization. Cao and Fan [61] studied the synergistic development relationship between Taicang Port logistics and the hinterland economy. By constructing a composite system synergy degree model and a gravity model, they analyzed the synergy degree and gravity value between Taicang Port and the hinterland economy. These studies not only provide a broader perspective and ideas for port emission reduction but also offer comprehensive strategies for policymakers and port managers to integrate port emission reduction into regional economic development planning.

5.2. Research Outlook

Despite significant achievements made by scholars both domestically and internationally in the field of port emission reduction, several issues and challenges remain. Future research on port emission reduction should focus on the following aspects:

- (1) Deepening the quantification and assessment of port carbon emissions. With continuous advancements in carbon emission monitoring technology and the increasing availability of relevant data, future research should delve deeper into the quantification and assessment of port carbon emissions to gain a more accurate understanding of the actual situation and trends in port emissions.
- (2) Expanding the innovation and application of port emission reduction technologies and strategies. Future efforts should continue to explore and promote new emission reduction technologies and strategies, such as the widespread adoption of clean energy and the electrification trend of port equipment, to further reduce carbon emissions from port operations. Meanwhile, emphasis should also be placed on the economic and feasibility analysis of these technologies, providing more comprehensive technical support for port emission reduction.
- (3) Strengthening synergistic research between port emission reduction and regional economic development. Future research should pay greater attention to studying the synergistic effects between port emission reduction and regional economic development, exploring comprehensive strategies to integrate port emission reduction into regional economic development planning. By optimizing regional industrial structures, strengthening hinterland economies, improving ecological environments, and taking other measures, we can promote positive interactions and sustainable development between port emission reduction and regional economic development.
- (4) Research on new approaches to reduce port emissions. The digital transformation of ports, through the integration of advanced technologies such as blockchain and the Internet of Things, can optimize the logistics chain, increase transparency, and reduce the idle time of goods. For example, blockchain-based smart contracts can dynamically allocate berths and cargo routes, potentially reducing the repositioning of empty containers and emissions; cross-regional carbon trading mechanisms and pilot projects carried out in port clusters such as the Guangdong–Hong Kong–Macao Greater Bay Area can establish a carbon quota trading platform. This mechanism can generate economic benefits annually, while market-driven policy incentives promote emission reduction.

In summary, future research on port emission reduction should further deepen and expand the research content and methodologies in related fields, facilitating the smooth implementation and sustainable development of port emission reduction efforts. Meanwhile, policymakers, port managers, and researchers should work together, strengthen

cooperation and exchanges, and jointly advance the progress and development of global port emission reduction initiatives.

6. Conclusions

Despite significant achievements in port emission reduction research, several deficiencies remain, limiting the applicability and effectiveness of current findings. These deficiencies include insufficient attention to regional differences, inadequate cost–benefit analysis, and a lack of comprehensive research on the synergistic effects between port emission reduction and regional economic development. To address these gaps, future research should focus on the following areas:

- (1) Deepening regional difference research. Future studies should strengthen comparative research on emission reduction technologies, policies, and management measures among ports in different regions. By exploring region-specific pathways and strategies, researchers can provide tailored solutions that account for varying economic, environmental, and infrastructural contexts. This will enhance the applicability and generalization of research findings.
- (2) Enhancing the cost–benefit analysis of emission reduction. A systematic quantitative analysis of the costs and benefits of port emission reduction is essential. Future research should conduct economic evaluations to provide policymakers and port managers with a clear understanding of the financial implications of emission reduction initiatives. This will enable more informed decision making and ensure the economic feasibility of the proposed measures.
- (3) Exploring the synergistic effect between port emission reduction and regional economic development. Research should integrate port emission reduction into regional economic development planning. By studying the interactive relationship between emission reduction and regional economic growth, scholars can propose comprehensive strategies that promote both environmental sustainability and economic prosperity. This approach will help optimize regional industrial structures, strengthen hinterland economies, and improve ecological environments.

To operationalize the theoretical insights and align with China’s national strategies, the following actionable policy framework is proposed:

- (1) Policy tools such as carbon taxes and implementing a carbon tax on port operations: this measure will encourage ports to adopt cleaner technologies and reduce emissions by internalizing the environmental costs of carbon emissions such as green credit, providing interest rate discounts to port enterprises investing in coastal power generation systems and renewable energy facilities; this financial mechanism will accelerate the transition to low-carbon infrastructure by alleviating the financial burden on port operators.
- (2) Implementation entities: The Ministry of Transport develops emission reduction policies, coordinates inter-departmental cooperation, and monitors national progress. The ministry should also provide technical and financial support to ensure the successful implementation of these policies; port authorities implement policies at the regional level, implement emission reduction targets, and provide technical guidance for port enterprises, and port authorities should also establish monitoring systems to track progress and ensure compliance with national standards.
- (3) Timeline: 50% coverage by 2025 will significantly reduce emissions from berthing ships and improve air quality in port cities; 100% coverage at all major ports by 2030 is in line with China’s national goal of peak carbon emissions by 2030 and becoming carbon neutral by 2060.

In summary, future research on port emission reduction should further deepen and expand the research content and methodologies in related fields, facilitating the smooth implementation and sustainable development of port emission reduction efforts. Meanwhile, policymakers, port managers, and researchers should work together, strengthen cooperation and exchanges, and jointly advance the progress and development of global port emission reduction initiatives. By addressing the identified deficiencies and implementing the proposed policy framework, the port industry can achieve significant progress in reducing emissions, promoting sustainable development, and contributing to global climate change mitigation efforts.

Author Contributions: Conceptualization, K.Y. and L.M.; methodology, L.M.; software, L.M.; validation, K.Y.; resources, R.W.; data curation, R.W.; writing—review and editing, K.Y.; visualization, L.M.; supervision, R.W.; funding acquisition, K.Y. and R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Research Project of Zhejiang Federation of Humanities and Social Sciences (grant no. 2025N161), the Ningbo Philosophy and Social Sciences Planning Project (grant no. G2024-1-06), and the Zhejiang Province Philosophy and Social Sciences Planning Project (grant no. 22CCG28).

Data Availability Statement: The data are available upon request from the corresponding author due to participant privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tichavska, M.; Tovar, B. Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. *Transp. Res. Part E Logist. Transp. Rev.* **2015**, *83*, 126–140. [\[CrossRef\]](#)
2. Misra, A.; Panchabikesan, K.; Gowrishankar, S.K.; Ayyasamy, E.; Ramalingam, V. GHG emission accounting and mitigation strategies to reduce the carbon footprint in conventional port activities—A case of the Port of Chennai. *Carbon Manag.* **2016**, *8*, 45–56. [\[CrossRef\]](#)
3. Martinez-Moya, J.; Vazquez-Paja, B.; Gimenez Maldonado, J.A. Energy efficiency and CO₂ emissions of port container terminal equipment: Evidence from the Port of Valencia. *Energy Policy* **2019**, *131*, 312–319. [\[CrossRef\]](#)
4. Krantz, G.; Moretti, C.; Brandão, M.; Hedenqvist, M.; Nilsson, F. Assessing the Environmental Impact of Eight Alternative Fuels in International Shipping: A Comparison of Marginal vs. Average Emissions. *Environments* **2023**, *10*, 155. [\[CrossRef\]](#)
5. Sdoukopoulos, E.; Boile, M.; Tromaras, A.; Anastasiadis, N. Energy Efficiency in European Ports: State-Of-Practice and Insights on the Way Forward. *Sustainability* **2019**, *11*, 4952. [\[CrossRef\]](#)
6. Tadros, M.; Ventura, M.; Soares, C.G. Review of current regulations, available technologies, and future trends in the green shipping industry. *Ocean Eng.* **2023**, *280*, 114670. [\[CrossRef\]](#)
7. Altinkurt, M.D.; Merts, M.; Tunér, M.; Turkcan, A. Effects of split diesel injection strategies on combustion, knocking, cyclic variations and emissions of a natural gas-diesel dual fuel medium speed engine. *Fuel* **2023**, *347*, 128517. [\[CrossRef\]](#)
8. Jia, H.; Adland, R.; Prakash, V.; Smith, T. Energy efficiency with the application of Virtual Arrival policy. *Transp. Res. Part D Transp. Environ.* **2017**, *54*, 50–60. [\[CrossRef\]](#)
9. Carvalho, F.; Portugal-Pereira, J.; Junginger, M.; Szklo, A. Biofuels for maritime transportation: A spatial, techno-economic, and logistic analysis in brazil, europe, south africa, and the usa. *Energies* **2021**, *14*, 4980. [\[CrossRef\]](#)
10. Shao, Y.B.; Shao, Y.B. Evaluation of Carbon Emission Efficiency of Major Ports along “the Belt and Road” in China. *Econ. Probl.* **2023**, *5*, 22–30.
11. Liu, H.; Shang, Y.; Jin, X.X.; Fu, X.L. Review of methods and progress on ship emission inventory studies. *Acta Sci. Circumstantiae* **2018**, *38*, 1–12.
12. Villalba, G.; Gemechu, E.D. Estimating GHG emissions of marine ports-the case of Barcelona. *Energy Policy* **2011**, *39*, 1363–1368. [\[CrossRef\]](#)
13. Song, S. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. *Atmos. Environ.* **2014**, *82*, 288–297. [\[CrossRef\]](#)
14. Boretti, A.A. Novel heavy duty engine concept for operation dual fuel H₂–NH₃. *Int. J. Hydrogen Energy* **2012**, *37*, 7869–7876. [\[CrossRef\]](#)

15. Tseng, P.H.; Pilcher, N. A study of the potential of shore power for the port of Kaohsiung, Taiwan: To introduce or not to introduce? *Res. Transp. Bus. Manag.* **2015**, *17*, 83–91. [\[CrossRef\]](#)
16. Sulligoi, G.; Bosich, D.; Pelaschiar, R.; Lipardi, G.; Tosato, F. Shore-to-ship power. *Proc. IEEE* **2015**, *103*, 2381–2400. [\[CrossRef\]](#)
17. Peterson, K.L.; Chavdarian, P.; Islam, M.; Cayan, C. Tackling ship pollution from the shore. *IEEE Ind. Appl. Mag.* **2008**, *15*, 56–60. [\[CrossRef\]](#)
18. Alamoush, A.S.; Ballini, F.; Ölçer, A.I. Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review. *Mar. Pollut. Bull.* **2020**, *160*, 111508. [\[CrossRef\]](#)
19. Kotrikla, A.M.; Lilas, T.; Nikitakos, N. Abatement of air pollution at an aegean island port utilizing shore side electricity and renewable energy. *Mar. Policy* **2017**, *75*, 238–248. [\[CrossRef\]](#)
20. Yarova, N.; Vorkunova, O.; Khoteyeva, N. Economic assessment of the alternative energy sources implementation for port enterprises. *Econ. Ann. XXI* **2017**, *166*, 46–50. [\[CrossRef\]](#)
21. El-Amary, N.H.; Balbaa, A.; Swief, R.A.; Abdel-Salam, T.S. A reconfigured whale optimization technique (RWOT) for renewable electrical energy optimal scheduling impact on sustainable development applied to Damietta seaport, Egypt. *Energies* **2018**, *11*, 535. [\[CrossRef\]](#)
22. Balbaa, A.; Swief, R.A.; El-Amary, N.H. Smart Integration Based on Hybrid Particle Swarm Optimization Technique for Carbon Dioxide Emission Reduction in Eco-Ports. *Sustainability* **2019**, *11*, 2218. [\[CrossRef\]](#)
23. Li, X.; Peng, Y.; Wang, W.; Huang, J.; Liu, H.; Song, X.; Bing, X. A method for optimizing installation capacity and operation strategy of a hybrid renewable energy system with offshore wind energy for a green container terminal. *Ocean Eng.* **2019**, *186*, 106125. [\[CrossRef\]](#)
24. Jonathan YC, E.; Kader, S.B.A. Prospect of emission reduction standard for sustainable port equipment electrification. *Int. J. Eng.* **2019**, *31*, 1347–1355.
25. Musolino, G.; Rindone, C.; Vitetta, A. Passengers and freight mobility with electric vehicles: A methodology to plan green transport and logistic services near port areas—ScienceDirect. *Transp. Res. Procedia* **2019**, *37*, 393–400. [\[CrossRef\]](#)
26. Correcher, J.F.; Van den Bossche, T.; Alvarez-Valdes, R.; Berghé, G.V. The berth allocation problem in terminals with irregular layouts. *Eur. J. Oper. Res.* **2019**, *272*, 1096–1108. [\[CrossRef\]](#)
27. Cai, L.; Li, W.; Li, H.; Zhou, B.; He, L.; Guo, W.; Yang, Z. Incorporation of energy-consumption optimization into multi-objective and robust port multi-equipment integrated scheduling. *Transp. Res. Part C Emerg. Technol.* **2024**, *166*, 104755. [\[CrossRef\]](#)
28. Kao, S.L.; Chung, W.H.; Chen, C.W. AIS-based scenario simulation for the control and improvement of ship emissions in ports. *J. Mar. Sci. Eng.* **2022**, *10*, 129. [\[CrossRef\]](#)
29. Wu, P.H. Study on construction of green port. *Mar. Environ. Sci.* **2009**, *28*, 338–340+344.
30. Li, W. Implications of the Fourth-generation Ports on Chinese Port Development. *Reform. Strategy* **2011**, *27*, 151–154.
31. Zhang, Y. Comment on Port and Shipping Center Construction based on Green and Ecological Principle. *J. Ind. Technol. Econ.* **2012**, *31*, 154–160.
32. Liu, C.L.; Liu, J.M.; Li, J.; Ma, R. Evaluation of port energy saving based on AHP-Fuzzy comprehensive method. *Port Waterw. Eng.* **2012**, *4*, 80–83+97.
33. Chen, M.H.; Feng, X.J.; Wang, W. Evaluation of port energy conservation and emission reduction based on multi-attribute comprehensive evaluation. *Port Waterw. Eng.* **2012**, *4*, 75–79.
34. Liu, H.B.; Wang, F.; Zhang, Z.P. Application of “electricity instead of oil” technology to RTGs for port energy conservation and pollution reduction. *Port Waterw. Eng.* **2011**, *9*, 123–125.
35. Wang, S.R.; Wang, Y.Y. The current situation and countermeasures of green ecological port construction in our country. *World Shipp.* **2013**, *36*, 9–12+25.
36. Ouyang, B.; Wang, L.; Huang, J.; Gao, A. Research and application of green and low-carbon port evaluation index system. *Port Waterw. Eng.* **2015**, *4*, 73–80.
37. Xu, Y.; Meng, Y.P. Evolution game between government and port enterprises under mandatory emission reduction. *JUSTC* **2019**, *49*, 762–772.
38. Jin, Y.; Huang, T.; Huang, X.X. Research on Port's Energy Saving and Consumption Reduction. *Sci. Technol. Ports* **2015**, *3*, 34–38.
39. Jiang, L. Transformation and efficiency of “changing of power supply from fuel to electricity” in RTG for container yards. *Port Waterw. Eng.* **2014**, *4*, 103–105.
40. Tan, J.; Han, J.; Gui, S.R.; Li, H.; Zhao, H. Development and application of shore power supply system. *J. Shanghai Marit. Univ.* **2017**, *38*, 90–95.
41. Wang, S.; Liu, Z.H. Study on the efficiency evaluation of energy conservation and emission reduction of ports around Bohai Sea-Analysis based on ccr-sbm and Malmquist index model. *Price Theory Pract.* **2022**, *4*, 98–101+206.
42. Liu, J.-g.; Kong, Y.-d.; Zhen, L. Research on Sustainable Investment of Maritime Supply Chain Considering Double Equilibrium. *Chin. J. Manag. Sci.* **2022**, *30*, 142–153.

43. Guo, W.W.; Ji, M.J.; Zhu, H.L. Container Terminal Berth and Yard Coordination Allocation Model and Algorithm. *Syst. Eng.* **2020**, *38*, 64–72.
44. Fan, L.X.; Wang, X.Y.; Yi, J.B. Joint Scheduling of Berth-Quay Crane Based on Fair Principle. *Ind. Eng. Manag.* **2017**, *22*, 60–68.
45. Sorte, S.; Rodrigues, V.; Lourenço, R.; Borrego, C.; Monteiro, A. Emission inventory for harbour-related activities: comparison of two distinct bottom-up methodologies. *Air Qual. Atmos. Health* **2021**, *14*, 831–842. [[CrossRef](#)]
46. Oksas, O. Carbon emission strategies for container handling equipment using the activity-based method: A case study of Ambarl container port in Türkiye. *Mar. Policy* **2023**, *149*, 105480. [[CrossRef](#)]
47. Wang, C.; Yang, M.; Lv, M.J.; Wang, C.L. Estimation of Carbon Emissions and Low-carbon Development for Ningbo Port. *Ningbo Univ. Technol.* **2015**, *27*, 69–74.
48. Cui, X.B.; Zhong, M.; Li, L.F.; Ma, X. Assessment of Disaggregate Carbon Emissions and Methods for Achieving Carbon Neutrality in Container Ports Based. *Transp. Inf. Saf.* **2024**, *5*, 1–12.
49. Guo, X.; Liu, L. Research on construction technology of energy consumption online monitoring system for port energy equipment. *Waterw. Harb.* **2018**, *39*, 746–752.
50. Zhong, X.; Chen, Q.; Wang, X.; Tang, D.; Zhang, Q.; Dong, M. Energy consumption management system design of intelligent ports and visualization. *Port Waterw. Eng.* **2023**, *6*, 185–191+230.
51. Jiang, Y.P.; Yuan, C.Q.; Yuan, Y.P.; Dong, M.; Jiang, T.; Zhong, X.; Tong, L. Pathway for Integrated Development of Port and Clean Energy Under Strategy of Carbon Peaking and Carbon. *Transp. Inf. Saf.* **2023**, *41*, 139–146.
52. Song, T.; Li, Y.; Zhang, X.P.; Wu, C.; Li, J.; Guo, Y.; Gu, H. Integrated port energy system considering integrated demand response and energy interconnection. *Electr. Power Energy Syst.* **2020**, *117*, 105654. [[CrossRef](#)]
53. Song, J. Research on Distributed Energy Management Methods for Port Microgrid under the Low Carbon. Master's thesis, Dalian Maritime University, Dalian, China, 2023.
54. Fang, S.; Zhao, C.; Ding, Z.; Zhang, S.; Liao, R. Port Integrated Energy Systems Toward Carbon Neutrality (Part I): Typical Topology and Key Problems. *Proc. CSEE* **2023**, *43*, 114–135.
55. Han, H.; Qi, D.; Feng, B. Construction of Port Logistics Service Platform Based on Cloud Computing and Internet of Things. *Comput. Sci.* **2013**, *40*, 232–235+261.
56. Ji, M.-J.; Chu, Y.-L. Optimization for Hub-and-Spoke Port Logistics Network of Dynamic Hinterland. *Phys. Procedia* **2012**, *33*, 827–832.
57. Peng, C.Y. Development and perfection of ship discharge control area policy in China. *Shipp. Manag.* **2020**, *42*, 1–6.
58. Liu, X.L.; Yang, X.H. Study on the Impact of Emission Control Areas on Shipping Enterprises in the Qiongzhou Strait. *Pearl River Water Transp.* **2022**, *9*, 49–51.
59. Yu, G.; Wu, J. Empirical Study on Port Logistics and Regional Industrial Structure Optimization: In the Case of Zhuhai. *Logist. Technol.* **2017**, *36*, 114–116+149.
60. Luo, Y.-H. Port Logistics and Optimization of Regional Industrial Structure: An empirical study on Zhanjiang. *J. Beijing Jiaotong Univ. (Soc. Sci. Ed.)* **2016**, *15*, 97–102.
61. Cao, B.; Fan, X. Research on coordinated development of port logistics and Hinterland economy: A case study of Taicang Port. *Geogr. Geo-Inf. Sci.* **2019**, *35*, 126–132.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.