

Seaport decarbonisation: A review of emission sources and reduction measures

Diana Šateikienė, Orinta Laureckytė

Faculty of Business, Klaipėdos valstybinė kolegija / Higher education institution, Lithuania

DOI: <https://doi.org/10.66856/ijmrd.2026.13.3.13388>

Abstract

Seaports are essential nodes in the global logistics and trade system; however, their operations are associated with significant greenhouse gas emissions. This article examines the main emission sources in seaports and analyzes their reduction potential in the context of decarbonization. The findings indicate that the largest share of emissions originates from shipping activities, cargo handling operations, land transport, and infrastructure energy consumption. Key decarbonization pathways are discussed, including electrification, shore power supply, the adoption of alternative fuels, the integration of renewable energy, and the application of digital solutions. The importance of an integrated approach is emphasized, combining technological, infrastructural, and organizational measures while strengthening cooperation among stakeholders. The study also highlights major implementation challenges related to investment requirements, technical readiness, and regulatory complexity. It is concluded that seaports have the potential to become important actors in the energy transition and climate change mitigation process.

Keywords: Seaports, decarbonization, greenhouse gas emissions, electrification, renewable energy, sustainable transport

Introduction

Maritime transport is one of the most important components of global trade, ensuring the movement of the majority of international cargo flows; however, it also significantly contributes to the growth of greenhouse gas emissions. As global trade volumes increase, both shipping activities and related infrastructure intensify, and seaports become key points of emission concentration.^[14] Port operations, including cargo handling, storage, transportation, and vessel servicing, require substantial energy resources, resulting in significant emissions of CO₂, NO_x, SO_x, and other pollutants.^[4, 17] For this reason, seaports are increasingly recognized as strategic assets in the implementation of climate change mitigation policies.

In contemporary scientific literature, seaports are increasingly conceptualized as complex socio-technical systems integrating logistics, energy, industrial, and information processes.^[1] This perspective expands their role, positioning ports not only as emission sources but also as potential hubs of energy transition, where low-carbon technologies can be deployed and integrated energy systems developed. In the context of international climate targets, seaport decarbonisation has become a critical condition for the transition towards a climate-neutral economy.^[9]

The literature extensively discusses various decarbonisation measures, including electrification, shore power systems, alternative fuels, and the integration of renewable energy.^[5] In addition, the role of digitalisation and smart technologies in optimising energy consumption and reducing emissions is increasingly emphasised.^[17] However, despite the growing number of studies, a significant level of fragmentation remains in the literature. Most research focuses on individual technologies or isolated solutions, while comprehensive approaches that integrate emission sources, their interactions, and coordinated mitigation measures are still lacking.^[4, 14]

Furthermore, insufficient attention is paid to the broader supply chain context, despite the fact that a substantial share

of indirect emissions (particularly Scope 3) is generated within it. As a result, many decarbonisation solutions are assessed in isolation, without considering the potential shifting of emissions between different transport and logistics segments. This highlights the need for a systematic evaluation of emission structures in seaports and their linkage with integrated decarbonisation strategies.

In response to these gaps, this study aims to conduct a literature review on seaport decarbonisation by identifying key emission sources, systematising mitigation measures, and evaluating their implementation challenges. The study contributes to the existing body of knowledge by providing an integrated perspective that connects emission sources, technological solutions, and practical implementation aspects. Such an approach supports the development of more coherent and effective decarbonisation strategies in seaports and across the broader transport system.

Literature Review

1. Sources of emissions in seaports

The analysis of emission sources in seaports is a fundamental prerequisite for developing effective decarbonisation strategies, as it enables the identification of key pollution sources and the prioritisation of mitigation actions. In the scientific literature, ports are defined as complex socio-technical systems in which emissions arise across multiple interconnected operational segments.^[1] Therefore, emission assessment must be systematic and include both direct (Scope 1) and indirect emissions (Scope 2 and Scope 3)^[14].

Shipping activities as a primary emission source. One of the most significant sources of emissions in seaports is shipping activity, particularly during berthing and manoeuvring. During these stages, vessels operate auxiliary engines to generate electricity, burning fossil fuels and emitting CO₂, NO_x, SO_x, and particulate matter (Papalexopoulos, Prousalidis, Manos and Andrianesis^[11]). Studies indicate

that these emissions can account for a substantial share of total port emissions, especially in high-traffic ports.^[17]

Cargo handling and terminal equipment emissions. Cargo handling equipment represents another major emission source. Traditionally, RTG cranes, terminal tractors, forklifts, and other heavy machinery operate on diesel fuel, generating significant amounts of CO₂ and NO_x.^[4] The scale of these emissions depends directly on operational intensity and the level of technological development.

Impact of land transport on emissions. Land transport, including truck and rail traffic, constitutes a significant but often underestimated share of emissions. Intensive traffic flows in port access areas generate considerable CO₂ and NO_x emissions.^[14] These emissions are typically classified as Scope 3 and may represent the largest portion of the overall carbon footprint.^[15]

Infrastructure energy consumption and indirect emissions. A substantial share of emissions is associated with electricity consumption in port infrastructure. Lighting, storage, and cooling systems contribute to indirect CO₂ emissions depending on the energy generation source.^[17]

Role of industrial and energy-related activities. Additional emissions arise from industrial activities within ports, including oil, chemical, and energy facilities. These sources can significantly increase total emission levels and complicate their management.^[1]

In summary, the emission structure of seaports is complex and includes both direct and indirect sources across multiple operational segments. The main emission sources and their characteristics are summarised in Table 1, providing a structured basis for evaluating their origins and potential mitigation measures. This systematic approach forms the foundation for further analysis of decarbonisation strategies.

Table 1: Main emission sources in seaports and their characteristics

Emission source	Type of Emissions	Main Causes of Formation	Possible Reduction Measures
Ships at berth and during maneuvering	CO ₂ , NO _x , SO _x , PM	Operation of auxiliary engines, fuel combustion while idle	Shore power supply, alternative fuels
Cargo and terminal equipment	CO ₂ , NO _x	Diesel-powered heavy machinery, RTG cranes, tractors	Electrification, hybrid systems, automation
Land transport (trucks, railways)	CO ₂ , NO _x	Intensive traffic flows in port access areas	Logistics optimization, alternative fuels, intermodality
Port infrastructure energy consumption	Indirect CO ₂ emissions	Electricity consumption in buildings, lighting, cooling systems	Renewable energy, energy efficiency
Industrial and energy activities in the port	CO ₂ and other GHG	Oil, chemical, and energy facilities	Integrated energy transformation, alternative energy sources

Sources: Alamoush et al.^[1], Fadiga et al.^[4], Song,^[14] Zhang et al.^[17], Papalexopoulos et al.^[11]

2. Seaport decarbonisation measures

Seaport decarbonisation is a complex process encompassing a combination of technological, infrastructural, and organisational solutions. The literature emphasises that the implementation of isolated measures is insufficient to achieve significant emission reductions; therefore, an integrated approach is required, addressing the entire port system and its interaction with the broader supply chain.^[9] Decarbonisation measures are commonly classified by type, but in practice their effectiveness depends on the ability to combine them coherently.

Electrification as a key decarbonisation pathway. Electrification is considered one of the primary measures for reducing direct emissions in ports. It involves the transition of cargo handling equipment, terminal machinery, and internal transport from diesel fuel to electricity. Electrification of RTG cranes, terminal tractors, and other heavy equipment can significantly reduce CO₂ and NO_x emissions while improving energy efficiency.^[16] However, the literature highlights that the effectiveness of electrification depends directly on the carbon intensity of the electricity used—if electricity is generated from high-emission sources, the overall reduction effect may be limited.^[14]

Shore power systems. Shore power is regarded as one of the most effective solutions for reducing ship emissions within port areas. It enables vessels to switch off auxiliary engines while at berth and use electricity supplied from the port grid (Papalexopoulos, Prousalidis, Manos and Andrianesis^[11]). Studies indicate that this technology can significantly reduce CO₂, NO_x, and SO_x emissions; however, its implementation

depends on grid capacity, infrastructure readiness, and vessel compatibility.^[12]

Alternative fuels and energy transition solutions. The use of alternative fuels is a key pathway for reducing carbon intensity in maritime transport systems. The literature highlights hydrogen, biofuels, liquefied natural gas, and ammonia as potential solutions applicable to both shipping and port operations.^[5] However, their development is constrained by infrastructure limitations, high investment costs, and uncertainty regarding future technological standards.^[8] As a result, decision-making is often delayed or implemented in stages.

Integration of renewable energy and energy efficiency. Ports are increasingly being transformed into energy hubs, integrating renewable energy sources and advanced energy management systems. The deployment of solar and wind technologies, combined with energy efficiency measures, contributes to reducing indirect emissions and enhancing energy flexibility.^[2] At the same time, the effectiveness of these solutions depends on their integration into the wider energy system. The transition from traditional, fossil-fuel-based port operations to low-carbon and fully integrated energy systems is gradual and involves multiple stages, including electrification, the adoption of alternative fuels, and digital optimisation. This transition pathway is illustrated in Figure 1, which conceptualises the evolution from conventional to green port systems. Table 1 highlights that emissions originate from interconnected port activities, suggesting that isolated measures are insufficient and must be replaced by system-level decarbonisation strategies.

Digitalisation and emission management systems. Digitalisation plays an increasingly important role in

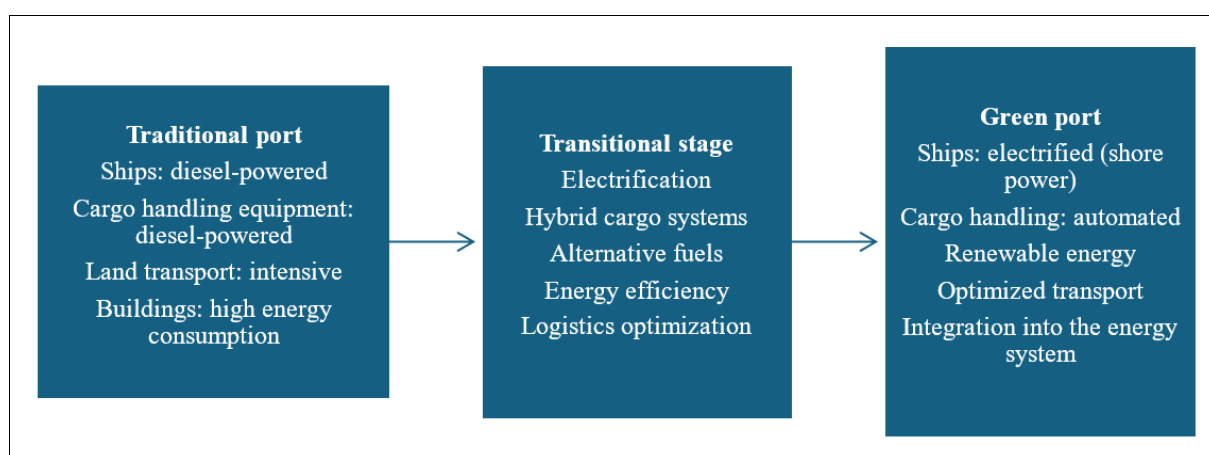
decarbonisation by enabling more precise monitoring and management of emissions. Artificial intelligence, the Internet of Things, and big data analytics allow real-time tracking of energy consumption, identification of emission sources, and optimisation of operations.^[17] Digital twins further support scenario modelling and evaluation of different measures prior to implementation.^[3]

Logistics optimisation and intermodality. Optimisation of logistics processes is an important, though often less emphasised, decarbonisation pathway. Managing transport flows, reducing waiting times, and promoting intermodality can decrease energy consumption and emissions across the supply chain.^[4] These measures are particularly relevant for reducing indirect (Scope 3) emissions.

Green shipping corridors as a systemic solution. Green shipping corridors are considered one of the most significant systemic decarbonisation initiatives, as they extend beyond individual technologies to encompass the transformation of

the entire transport chain. They rely on coordinated cooperation among stakeholders to ensure the availability of alternative fuels, infrastructure development, and the implementation of common standards.^[6]

Implementation conditions and limiting factors. The implementation of decarbonisation measures depends on technical, economic, and institutional readiness. The literature highlights the importance of grid capacity, infrastructure compatibility, and data availability.^[13] High upfront investments and long payback periods often constrain the adoption of advanced technologies.^[10] Regulatory differences, organisational challenges, and lack of coordination among stakeholders also remain significant barriers.^[7] Together, these factors indicate that seaport decarbonisation is a systemic transformation process requiring not only technological deployment but also institutional and organisational adaptation.



Source: compiled by the author based on Alamoush *et al.*^[1], Song,^[14] Papalexopoulos *et al.*^[11].

Fig 1: Transitional process of seaport decarbonisation from traditional to green ports

Research Methodology

This study employs a structured literature review approach to analyse seaport decarbonisation, focusing on the identification of emission sources and the systematisation of mitigation measures. The research is based on secondary data obtained from peer-reviewed scientific publications in the fields of maritime transport, energy systems, and sustainability.

The literature search was conducted using major scientific databases, including *Scopus*, *Web of Science*, and *ScienceDirect*. A set of predefined keywords was applied to ensure consistency and relevance of the search process, including *seaport decarbonisation*, *port emissions*, *green ports*, *shore power*, *port electrification*, *alternative fuels*, and *sustainable maritime transport*. The selection was limited to peer-reviewed journal articles published primarily between 2023 and 2025 to ensure the inclusion of recent developments and current research trends.

The selection process followed relevance-based criteria. Studies were included if they addressed at least one of the following aspects: (i) identification of emission sources in seaports, (ii) analysis of decarbonisation technologies or strategies, or (iii) evaluation of implementation challenges. Studies with limited relevance to seaports or lacking analytical contribution were excluded.

A qualitative content analysis was applied to the selected literature. The analysis was conducted using a thematic

approach, whereby the extracted information was categorised into two main dimensions:^[1] emission sources (e.g., shipping, cargo handling, land transport, infrastructure), and^[2] decarbonisation measures (e.g., electrification, alternative fuels, digitalisation, energy efficiency). This categorisation enabled a structured comparison of findings across different studies.

To enhance analytical consistency, the results from individual studies were systematically compared and synthesised. This process allowed the identification of recurring patterns, dominant approaches, and key differences in the literature. Particular attention was given to the relationships between emission sources and corresponding mitigation measures, as well as to the conditions affecting their implementation.

Despite its structured approach, this study is subject to certain limitations. The analysis is restricted to publicly available scientific literature and does not include empirical data or case-specific evaluations. In addition, the focus on recent publications may limit the inclusion of earlier foundational studies.

Results and Discussion

The literature analysis reveals that the emission structure of seaports is complex and spans multiple interconnected operational segments. The largest share of emissions is associated with shipping activities, particularly during

berthing and manoeuvring, when auxiliary engines are used and fossil fuels are combusted. Significant contributions also originate from cargo handling equipment and land transport, generating both direct and indirect emissions. In addition, energy consumption in port infrastructure and industrial activities further increases the overall carbon footprint. These findings confirm that emissions in seaports are distributed across the entire operational system rather than concentrated in a single activity, highlighting the need for system-level analysis.

The results further indicate that a substantial proportion of emissions falls under indirect categories, particularly Scope 3 emissions related to supply chain activities. This suggests a structural limitation in conventional emission assessment approaches, which are often restricted to port boundaries. As a result, current evaluation practices may underestimate the actual environmental impact of seaports and overlook emission shifting between different segments of the logistics chain.

In terms of mitigation measures, the analysis confirms that technological solutions, particularly electrification and shore power systems, play a central role in reducing direct emissions. However, their effectiveness is strongly dependent on external conditions, most notably the carbon intensity of the electricity supply. This indicates that the impact of these technologies cannot be assessed in isolation, as their environmental benefits are contingent upon broader energy system transformation. Without such alignment, there is a risk that emission reductions within ports may be offset by increased emissions in the energy sector.

Alternative fuels are widely recognised in the literature as a key pathway for decarbonisation, yet their practical implementation remains limited. This gap between theoretical potential and real-world application reflects infrastructural constraints, high investment requirements, and uncertainty regarding future technological standards. Consequently, ports often adopt a cautious, incremental approach to implementation, which may slow down the overall decarbonisation process.

The findings also highlight the increasing role of digitalisation and emission management systems. These solutions enable more precise monitoring, data-driven decision-making, and operational optimisation. Their importance is particularly evident in complex environments such as seaports, where multiple emission sources interact. However, the literature suggests that digital solutions are often treated as supportive tools rather than as integral components of decarbonisation strategies, which may limit their full potential.

Logistics optimisation and intermodality are identified as important but relatively underexplored areas in the context of emission reduction. While technological measures receive the majority of attention, organisational improvements—such as reducing congestion and improving transport coordination—can significantly contribute to lowering indirect emissions. This imbalance indicates a tendency in the literature to prioritise technological innovation over systemic efficiency.

The discussion further reveals that one of the key challenges in seaport decarbonisation is the fragmented implementation of measures. Although a wide range of solutions is identified, their effectiveness depends on their integration into a coherent and coordinated system. The absence of such integration may lead to suboptimal outcomes, including

emission shifting or underutilisation of available technologies. This suggests that the current approach to decarbonisation remains partially siloed.

In addition to technological factors, economic and institutional constraints play a decisive role. High upfront investment costs, long payback periods, and regulatory inconsistencies across regions hinder the large-scale deployment of decarbonisation measures. Furthermore, insufficient coordination among stakeholders limits the effectiveness of implementation. These findings indicate that technological readiness alone is insufficient and must be complemented by institutional capacity and policy alignment.

This study contributes to the existing literature by demonstrating that the effectiveness of seaport decarbonisation depends not only on the availability of technological solutions but also on their systemic integration, highlighting the limitations of fragmented approaches and the need for coordinated, system-level strategies.

Conclusion

The literature analysis confirms that seaport emissions are generated across multiple interconnected operational segments, including shipping, cargo handling, land transport, and infrastructure energy use, requiring a system-level approach to their assessment and mitigation.

A significant share of emissions is linked to indirect (Scope 3) sources, indicating that port-level evaluations alone are insufficient and must be extended to the broader supply chain.

Electrification and shore power systems are identified as key measures for reducing direct emissions, although their effectiveness depends on the carbon intensity of the energy supply. Alternative fuels provide additional potential but remain limited by infrastructural and technological constraints.

The findings further highlight the role of digitalisation, energy efficiency, and logistics optimisation in supporting emission reduction, particularly through improved operational management.

Overall, seaport decarbonisation is constrained by economic and institutional factors, emphasizing the need for integrated solutions that combine technological, organisational, and policy-level measures.

References

1. Alamoush AS, Dalaklis D, Ballini F, Ölcer AI. Consolidating port decarbonisation implementation: Concept, pathways, barriers, solutions, and opportunities. *Sustainability*,2023;15(19):14185. <https://doi.org/10.3390/su151914185>
2. Buonomano A, Del Papa G, Giuzio GF, Palombo A, Russo G. Future pathways for decarbonization and energy efficiency of ports: Modelling and optimization as sustainable energy hubs. *Journal of Cleaner Production*,2023;420:138389. <https://doi.org/10.1016/j.jclepro.2023.138389>
3. Eom J-O, Yoon J-H, Yeon J-H, Kim S-W. Port digital twin development for decarbonization: A case study using the Pu-san Newport International Terminal. *Journal of Marine Science and Engineering*,2023;11(9):1777. <https://doi.org/10.3390/jmse11091777>

4. Fadiga A, Ferreira LMDF, Big-otte JF. Decarbonising maritime ports: A systematic review of the literature and in-sights for new research opportunities. *Journal of Cleaner Production*,2024;452:142209. <https://doi.org/10.1016/j.jclepro.2024.142209>
5. Holder D, Percy SD, Yavari A. A review of port decarbonisation options: Iden-tified opportunities for deploying hydrogen technologies. *Sustainability*,2024;16(8):3299. <https://doi.org/10.3390/su16083299>
6. Ismail AM, Ballini F, Ölçer AI, Alamoush AS. Integrating ports into green shipping corridors: Drivers, challenges, and pathways to implementation. *Marine Pollu-tion Bulletin*,2024;209:117201. <https://doi.org/10.1016/j.marpolbul.2024.117201>
7. Karagkouni K, Boile M. Electrifica-tion in ports: Barriers, drivers and evaluation through PESTLE analysis. *Journal of Sus-tainability Research*, 2025. <https://doi.org/10.20900/jsr20250015>
8. Klopott M, Popek M, Urbanyi-Popiołek I. Seaports' role in ensuring the availability of alternative marine fuels—A multi-faceted analysis. *Energies*,2023;16(7):3055. <https://doi.org/10.3390/en16073055>
9. Minh TTN, Hoang H-TH, Nam HS, Alamoush AS, Duong PA. Revisit-ing port decarbonization for advancing a sus-tainable maritime industry: Insights from bib-liometric review. *Sustainability*,2025;17(10):4302. <https://doi.org/10.3390/su17104302>
10. Olivari E, Dalla Chiara B, et al. Ports go green: A cost-energy analysis ap-plied to a case study on evaluating the electri-fication of yard tractors. *The Open Transportation Journal*, 2024. <https://doi.org/10.2174/0118744478297251240416093104>
11. Papalexopoulos A, Prousalidis J, Manos A, Andrianesis P. Maritime sector integration in energy markets via port decar-bonization and electrification. *Energy Reports*, 2025.
12. Peddi KP, Ricci S, Rizzetto L. Reduction potential of gaseous emissions in European ports using cold ironing. *Applied Sciences*, 2024. <https://doi.org/10.3390/app14167209>
13. Shen J, Gao W, Lu J, Li F, Feng X. Sources, calculation methods, and reduc-tion strategies for GHG emissions at ports: Current status and future trends. *Frontiers in Marine Science*, 2025. <https://doi.org/10.3389/fmars.2025.1542255>
14. Song D-P. A literature review of seaport decarbonisation: Solution measures and roadmap to net zero. *Sustainability*,2024;16(4):1620. <https://doi.org/10.3390/su16041620>
15. Tombak M-L, Tapaninen UP, Kotta J. Methods for calculating greenhouse gas emissions in the Baltic Sea ports: A com-parative study. *Sustainability*,2025;17(2):639. <https://doi.org/10.3390/su17020639>
16. Wiholm A, Remmen A, Hahn T. Decarbonization of container terminals: An organizational journey. *Transportation Re-search Interdisciplinary Perspectives*,2025;34:101676. <https://doi.org/10.1016/j.trip.2025.101676>
17. Zhang L, Zeng Q, Wang L. How to achieve comprehensive carbon emission reduction in ports? A systematic review. *Journal of Marine Science and Engineering*,2024;12(5):715. <https://doi.org/10.3390/jmse12050715>
18. Zhang Z, Song C, Zhang J, Chen Z, Liu M, Aziz F, et al. Environmental and economic assess-ment of decarbonization strategies in ports: A global perspective. *Science of the Total Envi-ronment*,2024;912:169075. <https://doi.org/10.1016/j.scitotenv.2023.169075>