

Green Port as a Direction of Sustainable Maritime Logistics Transformation

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ABSTRACT

Green ports have become an important research topic because contemporary seaports function not only as cargo-handling nodes, but also as sources of air pollution, greenhouse gas emissions, noise, intensive energy use, and pressure on surrounding urban areas. Against this background, the objective of this article is to analyse how the concept of the green port is defined in the scientific literature, which development directions are treated as central, and which implementation barriers are most frequently identified. The study applies analysis and synthesis of scientific literature and is based on academic sources dealing with port sustainability, decarbonisation, electrification, environmental protection, digitalisation, and port-city interaction. The review shows that the green port is no longer understood as a narrow set of pollution-control measures. Instead, it is described as an integrated transformation model that combines decarbonisation, shore power supply, terminal electrification, waste and water management, data-driven governance, and stronger coordination with urban and regional stakeholders. The analysed literature also indicates that technological solutions alone do not guarantee progress. Implementation depends on investment capacity, institutional coordination, common data standards, and the ability of port authorities to align environmental goals with operational and territorial planning priorities. The article concludes that the green port should be interpreted as a comprehensive and strategic framework for sustainable maritime logistics transformation.

Keywords: green port, decarbonisation, electrification, digitalisation, port-city interaction

INTRODUCTION

Seaports are among the most important nodes in global supply chains because they connect maritime transport, land logistics, and industrial flows (Lim et al., 2019). The economic importance of ports is particularly significant for regions whose trade and industry depend on uninterrupted cargo movement (Stein & Acciaro, 2020). At the same time, port activities generate substantial environmental impacts associated with ship emissions, terminal equipment, heavy vehicle traffic, and energy use (Barberi et al., 2021). For this reason, port development is increasingly assessed not only in terms of economic performance but also from a sustainability perspective (Bjerkkan & Seter, 2019). More recent systematic reviews show that the topic of the green port has evolved from a fragmented set of environmental measures into an independent scientific field (Fadiga et al., 2024).

In the literature, the concept of the green port is generally used to describe a port that systematically reduces negative environmental impacts and improves the efficiency of resource use (Rodrigues & Ensslin, 2024). Earlier studies focused primarily on environmental management systems and monitoring (Darbra et al., 2004). Later, attention shifted to sustainability indicators, energy efficiency, and performance improvement (Peris-Mora et al., 2005). In recent years, the green port has increasingly been analysed together with decarbonisation and energy system transformation (Song, 2024). This shows that the concept now covers far more than pollution control alone (Fadiga et al., 2024).

The scientific literature emphasises that the port sector is under growing pressure to reduce greenhouse gas emissions (Alamouh et al., 2020). This pressure is reinforced by international climate policy goals and the transport sector's decarbonisation agenda (Song, 2024). Port decarbonisation is important because shipping, energy supply, and land logistics systems intersect in ports (Acciaro et al., 2014). Ports are increasingly regarded

as strategic energy hubs where low-emission technologies and new governance solutions can be implemented (Iris & Lam, 2019). Therefore, the concept of the green port is becoming important not only from an environmental perspective, but also in terms of competitiveness and resilience (Lawer, 2021).

Another important aspect is the relationship between ports, the city, and the local community (Taljaard et al., 2021). Air pollution, noise, visual impacts, and the intensity of transport flows often become sources of conflict between port expansion and residential quality of life (Hall et al., 2013). For this reason, the green port is associated in the literature with social acceptability and the broader context of sustainable territorial development (Ng et al., 2014). More recent studies also show that port-city interaction must be considered together with energy, air quality, and public health issues (Di Vaio et al., 2023). This perspective extends the concept of the green port beyond the boundaries of technical infrastructure (Carbone et al., 2018).

The aim of this article is to analyse the concept of the green port, its main development directions, and the most important implementation challenges in the scientific literature.

RESEARCH METHODOLOGY

This study applies a systematic analysis of scientific literature in order to identify the concept of the green port, its main development directions, and key implementation challenges. The analysis is based on peer-reviewed academic articles published in international scientific journals.

The selection of scientific literature was conducted using thematic keywords such as “green port”, “port sustainability”, “port decarbonisation”, “port electrification”, “environmental performance in ports”, “port digitalisation”, and “port-city interaction”, focusing on publications addressing port sustainability and transformation processes. The analysed sources cover the period from 1999 to 2026, allowing the study to capture both the early development of the green port concept and the most recent research trends in this field.

The inclusion criteria for selecting sources were as follows: (1) publications in peer-reviewed scientific journals, (2) direct relevance to the green port concept or its components, (3) theoretical or empirical contribution to the research topic, and (4) relevance and scientific impact of the publications. In total, more than 50 scientific sources were analysed, representing different but interrelated research directions.

The selected literature was examined using qualitative content analysis. During the analysis, the main thematic categories were identified, including: the evolution of the green port concept, decarbonisation and energy transformation, shore power supply and electrification, pollution, waste and water management, digitalisation, and port-city interaction.

Based on the analysis, a synthesis method was applied to integrate the findings and identify common patterns, trends, and frequently discussed implementation challenges. This approach enabled the development of a coherent interpretation of the green port as an integrated framework for sustainable maritime logistics transformation.

The study is theoretical in nature and focuses on the systematisation and interpretation of existing scientific knowledge. Therefore, the results are derived from the analysis of the selected literature sources.

LITERATURE REVIEW

The concept and content of the green port

The concept of the green port in the literature is primarily associated with reducing environmental impacts and ensuring systematic operational management (Wooldridge et al., 1999). Studies on port environmental protection have shown that isolated measures are insufficient if they are not integrated into a broader management system (Darbra et al., 2009). Research on the development of sustainable port indicators highlighted the need to assess port activity comprehensively by covering energy, noise, water, and waste (Peris-Mora et al., 2005). In later publications, the green port began to be associated with sustainable development principles and governance

maturity (Puig et al., 2014). More recent reviews indicate that today the green port is understood as an integrated paradigm of competitiveness and environmental protection (Rodrigues & Ensslin, 2024).

The main analytical dimensions identified in the reviewed literature are summarised in Figure 1.

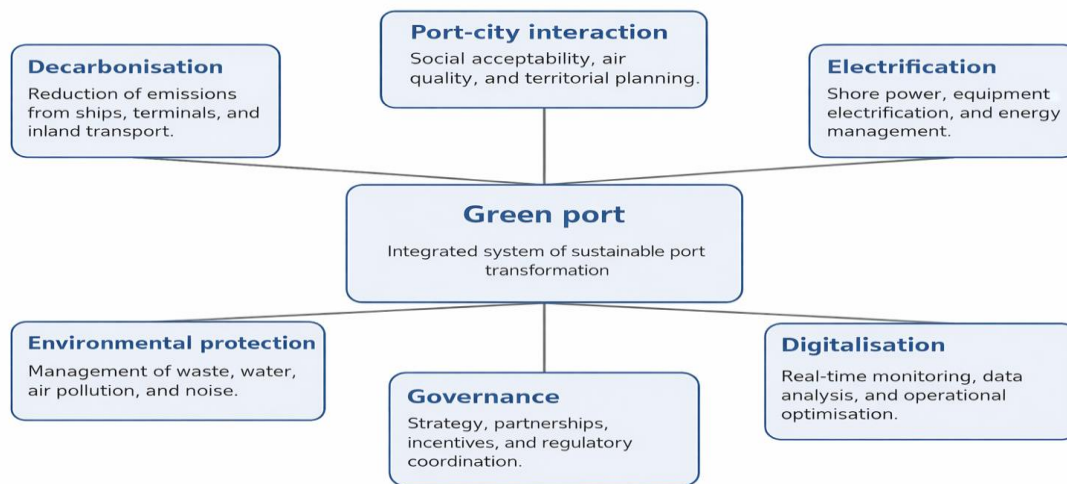


Figure 1. Main directions of the green port (compiled by the author based on the analysed literature).

Studies of environmental performance show that a consistent monitoring process and clear areas of responsibility are important in port management (Saengsupavanich et al., 2009). An analysis of the environmental condition of European ports showed that the maturity of practices varies depending on management culture and institutional structure (Puig et al., 2015). Reviews of port management literature confirm that environmental protection is becoming a strategic competitiveness factor (Stein & Acciaro, 2020). This is consistent with studies examining the relationship between the green port and the United Nations Sustainable Development Goals (Alamouh et al., 2021). Thus, today the green port includes not only emission reduction, but also responsible governance, transparency, and long-term strategy (Lawer, 2021).

Some authors emphasise the distinction between the concepts of the green port and the sustainable port (Sislian et al., 2016). The green port more often refers to environmental interventions and low-emission technologies (Davarzani et al., 2016). The sustainable port also includes social and economic aspects such as occupational safety, community relations, and operational efficiency (Antao et al., 2016). This distinction matters because an overly narrow understanding of greenness may push broader port-city issues aside (Taljaard et al., 2021). Therefore, the literature increasingly suggests analysing these concepts together, but not treating them as identical (Lim et al., 2019).

Decarbonisation and energy transformation

Decarbonisation is currently the central direction of green port research (Song, 2024). Reviews of greenhouse gas emissions in ports show that the largest sources are ships at berth, cargo-handling equipment, and port-related inland transport (Wang et al., 2023). A systematic review of the scientific literature showed that emission reduction in ports cannot be based on a single solution because impacts arise from many operational links (Fadiga et al., 2024). Reviews of energy efficiency further highlighted that the port authority can play an important coordinating role in the transition to low-emission systems (Acciaro et al., 2014). Therefore, decarbonisation in ports is understood in the literature as a combination of technical and organisational actions (Alamouh et al., 2022).

Studies on energy efficiency show that a large share of progress in ports depends on the ability to manage demand and optimise processes (Iris & Lam, 2019). An analysis of European port practices showed that energy-efficiency

initiatives usually begin with lighting, equipment modernisation, and energy monitoring (Sdoukopoulos et al., 2019). However, more recent studies emphasise that energy saving alone is no longer sufficient, because net-zero strategies are becoming increasingly important (Song, 2024). These studies also underline the importance of integrating renewable energy sources (Di Vaio et al., 2018). Therefore, the green port is increasingly described as a transitioning energy system rather than as static infrastructure (Fadiga et al., 2024).

An important part of decarbonisation is the relationship between the port and its hinterland (Aregall et al., 2018). Reviews of green strategies have shown that port emissions are strongly influenced by the organisation of land transport and the level of intermodality (Davarzani et al., 2016). Studies on strategic port networks revealed that the effect of decarbonisation increases when measures cover the entire logistics chain rather than only the port area (Duran et al., 2021). Other studies noted that energy issues are becoming inseparable from the broader sustainability agenda of supply chains (Stein & Acciaro, 2020). This shows that the concept of the green port needs to be extended beyond the terminal boundary (Aregall et al., 2018).

Shore power supply and electrification

Shore power supply is regarded as one of the most significant measures for reducing local ship emissions in ports (Zis et al., 2014). Empirical studies show that connecting ships to shore-side electricity reduces the use of auxiliary engines during berthing (Zis, 2019). In more recent reviews, shore power is linked not only to climate goals but also to improved air quality in port cities (Barberi et al., 2021). Nevertheless, the literature emphasises that its economic efficiency depends on electricity prices and grid structure (Alamouh et al., 2020). For this reason, shore power is most often examined as part of a broader electrification package (Song, 2024).

Electrification in ports includes not only the connection of ships to the grid but also the transformation of terminal equipment, internal transport, and building systems (Iris & Lam, 2019). The effects of equipment electrification are associated with lower noise levels and better air quality (Barberi et al., 2021). At the same time, it is emphasised that electrification increases demands on electricity infrastructure and energy management (Acciaro et al., 2014). Practice-oriented analyses have observed that large ports find it easier to implement such measures because they have greater investment capacity (Bjerkan & Seter, 2019). Smaller ports require more tailored and phased solutions (Darbra et al., 2023).

Some authors emphasise that the success of electrification depends on the decarbonisation of the energy system itself (Fadiga et al., 2024). If electricity generation remains carbon-intensive, the climate benefit of electrification is reduced (Song, 2024). For this reason, the port literature increasingly discusses energy storage, microgrids, and flexible load management (Iris & Lam, 2019). This perspective reinforces the idea that electrification must be planned as a systemic rather than a point-based change (Acciaro et al., 2014). That is why energy management issues are becoming a central part of green port strategy (Sdoukopoulos et al., 2019).

Pollution, waste, and water management

The green port cannot be reduced to carbon dioxide mitigation alone, because the environmental impact of ports is much broader (Barberi et al., 2021). Studies on environmental indicators show that water quality, noise, dust, and accident prevention are also important issues in ports (Puig et al., 2014). Works devoted to port monitoring emphasised that consistent monitoring is a precondition for effective prevention (Darbra et al., 2009). An analysis of European ports showed that air pollution and energy became priorities over time, but water pollution issues did not lose their importance (Puig et al., 2015). Therefore, environmental protection remains a multidimensional and integrated field in the literature (Rodrigues et al., 2021).

Waste management in ports is often analysed as one of the domains of mature environmental governance (Di Vaio et al., 2019). Studies show that various waste streams are generated in ports from ships, terminals, and maintenance activities (Roos & Neto, 2017). Waste issues are increasingly linked to the logic of the circular economy and resource efficiency (Stein & Acciaro, 2020). Reviews of practical measures show that in the most advanced ports, waste management is shifting from disposal toward reuse and recycling models (Hua et al., 2020). Therefore, in this field the green port is increasingly understood as a centre for material-flow management (Taljaard et al., 2021).

Water-environment issues remain important, especially where port activities are closely connected with coastal urban space (Ng et al., 2014). The quality of port waters depends on wastewater, spill risk, and the organisation of cargo-handling processes (Wooldridge et al., 1999). Studies on environmental performance show that water indicators often remain less visible than air emissions, even though their impacts are long term (Vega-Munoz et al., 2021). For this reason, some authors propose integrating the water dimension more broadly into port sustainability reporting (Rodrigues et al., 2021). This approach helps preserve the broader content of the green port and avoids the dominance of a single issue (Rodrigues & Ensslin, 2024).

Digitalisation and the smart green port

Digitalisation has become one of the fastest-growing directions in green port research (Datta & Misra, 2024). Recent studies show that sensors, Internet of Things solutions, and real-time data analysis enable more accurate monitoring of energy use and environmental impacts (Siroka et al., 2021). The application of smart solutions is associated with more efficient equipment use and less unnecessary waiting time (Huang et al., 2021). Some authors emphasise that digitalisation helps to better integrate port operations with climate and energy objectives (Hua et al., 2020). Therefore, the smart green port is regarded in the literature not as a separate concept, but as a dimension that strengthens the green transition (Datta & Misra, 2024).

Studies on the effects of digitalisation show that data-driven governance can reduce operational inefficiencies and emissions even without major physical investments (Dong et al., 2019). Analysis of port operational data helps to identify pollution sources more precisely and assess the impact of measures (Vega-Munoz et al., 2021). At the same time, the literature warns that digital solutions will not work without institutional readiness and data standards (Bjerkan & Seter, 2019). Studies of critical success factors show that technological readiness must be accompanied by organisational capabilities (Lawer, 2021). Thus, digitalisation strengthens the green port only when it becomes part of a consistent governance system (Datta & Misra, 2024).

Port-city interaction and social acceptability

The relationship between ports and the city is regarded in the literature as one of the most sensitive dimensions of sustainability (Hall et al., 2013). Studies show that residents most directly experience the effects of air pollution, noise, and intense transport flows (Ng et al., 2014). For this reason, the green port also becomes important as a means of strengthening social legitimacy (Carbone et al., 2018). Works on port-city integration emphasise that environmental measures must be coordinated with territorial planning and the quality of public space (Taljaard et al., 2021). Thus, the green port is both an urban policy issue and a logistics policy issue (Di Vaio et al., 2023).

Some authors note that the quality of the port-city relationship depends on dialogue with stakeholders (Antao et al., 2016). Studies on port sustainability show that social aspects often remain less institutionalised than technical indicators (Lim et al., 2019). However, community trust becomes especially important when ports plan new energy or infrastructure investments (Taljaard et al., 2021). That is why in some studies the role of the port authority is described as mediating between the market, the state, and the local community (Acciaro et al., 2014). This makes it possible to argue that the success of the green port depends not only on reducing emissions but also on the ability to create social value (Stein & Acciaro, 2020).

Main implementation challenges

One of the most frequently mentioned challenges is the high initial investment required for infrastructure, electrification, and data systems (Sdoukopoulos et al., 2019). Studies show that the benefits of such measures are often distributed unevenly among the port, operators, and the urban community (Zis, 2019). For this reason, progress depends on financial incentives and cooperation models (Alamouh et al., 2022). Another challenge is the uneven technological readiness of different ports (Darbra et al., 2023). Therefore, the literature increasingly proposes a phased and context-specific green transition model rather than a single recipe for all ports (Fadiga et al., 2024).

An equally important challenge is the lack of data and governance standardisation (Rodrigues et al., 2021). Studies on digitalisation show that without common data models it is difficult to compare progress and justify

investment decisions (Datta & Misra, 2024). Reviews of environmental performance in ports also draw attention to differences in reporting quality and indicator structures (Rodrigues & Ensslin, 2024). Institutional analyses emphasise that green port strategy requires the coordination of the interests of many different actors (Lawer, 2021). Therefore, real progress depends not only on technology, but also on an effective governance architecture (Stein & Acciaro, 2020).

CONCLUSIONS

The literature analysis showed that the green port should now be understood as an integrated system of sustainable transformation encompassing environmental protection, energy, digitalisation, and governance. The article demonstrated that this concept has long moved beyond a narrow understanding of pollution control and is associated with long-term competitiveness, resilience, and social acceptability.

The analysed sources revealed that the main directions of green port development are decarbonisation, the optimisation of energy use, shore power supply, terminal electrification, waste and water management, digitalisation, and port-city interaction. These directions do not operate separately, but as interconnected processes; consequently, the greatest impact is achieved through their coordinated implementation.

The article also found that progress toward the green port is constrained by high initial investment, uneven technological readiness across ports, a lack of data standardisation, and complex stakeholder coordination. This means that, in practice, the success of the green transition depends not only on technical solutions, but also on the institutional ability to plan, coordinate, and ensure long-term implementation.

In summary, green port development should be based not on isolated measures, but on a coherent strategy that simultaneously addresses environmental impacts, energy transformation, data-driven governance, and the relationship with the port city. Such an approach creates the conditions not only for reducing negative environmental impacts, but also for strengthening the quality of port operations and long-term sustainability.

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