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# Energy Transition in Seaport – Decarbonisation Strategies

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***Abstract:***

***Purpose:*** *This article examines the role of innovative technologies in the Decarbonisation process of seaports, focusing on solutions such as: shore power, alternative fuels, wind farms, green corridors. The aim is to assess their impact on reducing greenhouse gas emissions.*
***Design/Methodology/Approach:*** *The study combined a systematic literature review with bibliometric analysis and a case study of a leading port in the context of Decarbonisation, the Port of Rotterdam, analyzing the energy transformation projects implemented by the port.*
***Findings:*** *The case study results highlighted that a systemic approach to the energy transition in seaports is essential to achieving climate neutrality. Combining the results of the bibliometric analysis with conclusions from the literature and the case study made it possible to develop a coherent picture of the actions necessary for the effective Decarbonisation of seaports.*
***Practical implications:*** *The research results are important for planning Decarbonisation strategies in seaports. The implementation of innovative technologies can contribute not only to environmental protection, but also to improving the image of ports as leaders in sustainable development.*
***Originality:*** *The article presents a comprehensive approach to the Decarbonisation of seaports, analyzing both innovative technologies and their practical implementation on the example of the port of Rotterdam. The combination of bibliometric analysis with a literature review and case study makes an important contribution to the debate on the sustainable development of maritime transport.*

***Keywords:*** *Decarbonisation, green port, innovations, seaports, smart port.*

***JEL classification:*** *L91, O32, Q56.*

***Paper type:*** *Research paper.*

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## 1. Introduction

The global need to reduce greenhouse gas emissions is becoming a key challenge in the maritime sector. As central logistics hubs, seaports are not only a source of significant carbon emissions but also a strategic area for sustainability efforts. All industry sectors need to adapt to the Paris Agreement's target of limiting the global temperature rise to well below 1.5-2°C in order to reduce greenhouse gas emissions. Emissions generated by shipping and ports also contribute to climate change, which means that the entire maritime industry sector requires a Decarbonisation process (Bouman *et al.*, 2017).

The maritime sector is responsible for approximately 800 to 850 million tonnes of carbon dioxide ($CO_2$) emissions per year, representing about 3% of global $CO_2$ emissions, and its impact continues to grow in the face of intensifying international trade (Zadeh *et al.*, 2023; UNCTAD, 2024; Wang *et al.*, 2023).

As a result of the growing problem, the IMO has obliged the shipping industry to reduce its annual greenhouse gas emissions. Targets in the IMO agreement include a 20% reduction in emissions by 2030 and a 70% reduction by 2040 (from 2008 levels), and to achieve zero emissions the shipping industry must accelerate its actions (IMO, 2023).

In the face of the immense challenge of reducing carbon emissions, the key role is to take immediate action, which will involve significant operational changes, implementing innovative solutions, investing in a modern and new fleet, replacing paper documentation and digitalisation, most importantly, introducing cleaner technologies and ships adapted to use alternative energy sources (UNCTAD, 2024).

The purpose of this article is to examine the efforts being made to decarbonise seaports and aims to answer the research question posed:

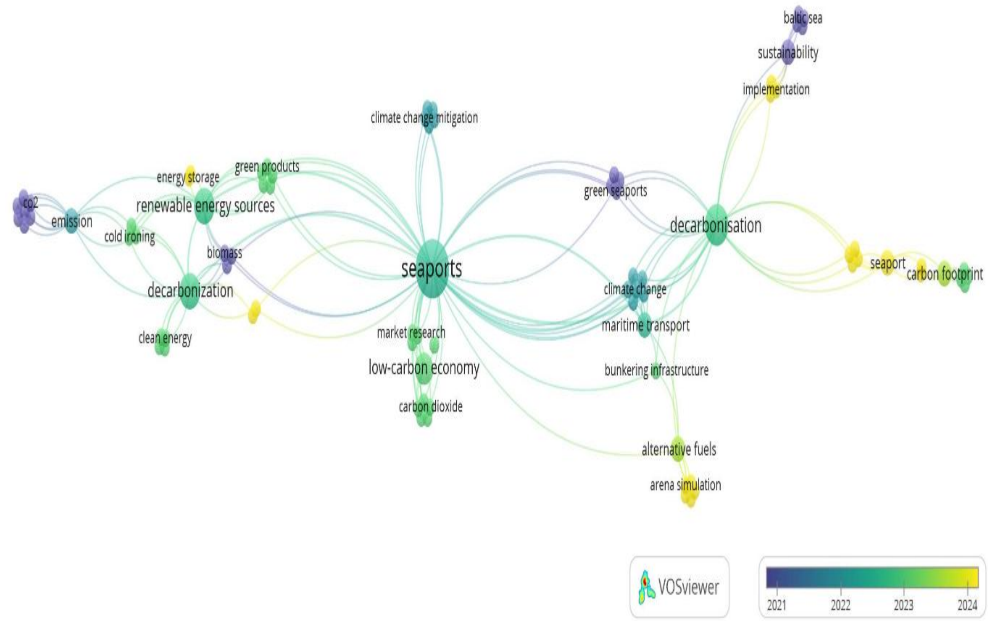
*What cutting-edge technologies are being implemented for the Decarbonisation process of seaports?*

Furthermore, the article outlines how innovative technologies can contribute to reducing the carbon footprint of seaports and what environmental, economic and social benefits result from their implementation.

## 2. Bibliometric Analysis

The map generated with the VOSviewer tool shows the thematic structure related to Decarbonisation and sustainable development of seaports. The central node in this network is ‘seaports’, which indicates the relevance of the topic of ports in the context of energy transition. Numerous links emerge from this node, highlighting its key role in the literature analysed.

***Figure 1.*** *The network visualisation of the links between the keywords „seaport” and “Decarbonisation” and other words*




***Source:*** *Own study.*

Different thematic clusters can be identified from the map:

The green cluster (centred around ‘renewable energy sources’ and ‘Decarbonisation’) highlights the importance of renewable energy sources such as biomass, clean energy and energy storage in Decarbonisation processes.

The yellow cluster (centred around ‘alternative fuels’ and ‘carbon footprint’) focuses on alternative fuels, carbon footprint reduction and simulations related to the use of these fuels.

The blue cluster (clustered around ‘sustainability’ and ‘green seaports’) focuses on sustainability and the concept of green ports, particularly in the context of technological deployment.

The purple cluster (centred around ‘$CO_2$’ and ‘emissions’) addresses the issue of greenhouse gas emissions and their reduction, particularly in the context of ports and the maritime transport industry.

The strong links between the keywords ‘seaports’, ‘Decarbonisation’ and ‘low-carbon economy’ indicate a close interdependence between the Decarbonisation process and the low-carbon economy strategy in ports. Headwords such as 'renewable energy sources' and 'climate change mitigation' have numerous connections to other nodes, suggesting that they are key in the context of the research in question.

The colours of the nodes on the map also reflect the variability of research interest in this topic over time, as older publications (dark blue and purple nodes, e.g. '$CO_2$', 'emissions') focus on the core issues of emissions and their reduction, while newer publications (yellow nodes, e.g., 'alternative fuels', 'carbon footprint') highlight specific technologies such as alternative fuels and sustainable practices in ports.

Clearly, the topic of port Decarbonisation is important and topical and sustainable seaport development is identified as a key direction for contemporary research in publications. The bibliometric analysis indicates a growing need for research on the implementation of technologies in ports and the assessment of their impact on emission reduction and carbon footprint. It is also worth paying more attention to the integration of climate policies into port management practices.

## 3. Literature Review

The Decarbonisation of seaports is one of the key challenges of the global energy and environmental transition. As central transport hubs, seaports play an important role in supply chains, but at the same time contribute significant greenhouse gas emissions from infrastructure operations, ship activity in ports and land-based traffic. The Decarbonisation process requires a multi-faceted approach, taking into account regulatory, economic, social and environmental aspects.

Reducing emissions in seaports is an indispensable part of achieving climate targets set by international institutions such as the International Maritime Organisation (IMO) and the United Nations (UN) (Fadiga *et al.,* 2024). Research indicates that ports have the potential to play a key role in this transformation, both as initiators of change in maritime transport and as integrators of innovative logistics practices (Issa-Zadeh *et al.,* 2023; Karaś, 2022).

However, this requires extensive cooperation between the public and private sectors and the involvement of local communities, which is not easy. From a global perspective, the transformation of ports towards sustainability is a diverse process, depending on local political, social and economic conditions. Seaport Decarbonisation is a multidimensional process, requiring cross-sectoral cooperation and sustainable investments in infrastructure, system solutions and the establishment of rules and regulations for the greening of seaports (Alzahrani *et al.,* 2021).

This process presents significant challenges, but also opens up new opportunities to improve operational efficiency, reduce environmental impacts and build a positive image of ports in the international community.

Seaports can play a key role in meeting global climate goals, but their success will depend on their ability to adapt quickly to changing market and regulatory conditions.

Decarbonisation technologies used in seaports include a wide range of solutions. One key solution is the use of renewable energy sources, such as photovoltaic installations, wind turbines and hydrogen fuel cell systems, which are increasingly being integrated into port energy systems. Elkafas and Seddiek's (2024) research on renewable energy systems in seaports indicates that such technologies not only reduce emissions, but also improve energy efficiency through the use of hybrid energy storage systems (Elkafas and Seddiek, 2024).

Another important step towards Decarbonisation is the electrification of port processes. Onshore Power Supply (OPS) systems allow ships to connect to the harbour electricity grid while at berth, eliminating the need for onboard fossil fuel-fired generators, significantly reducing carbon emissions (Uzun *et al.*, 2024).

In turn, the electrification of vehicles and machinery used in ports, such as terminal tractors and cranes, brings both environmental and operational benefits. Electric vehicles contribute to improving the air quality around ports, while increasing their operational efficiency (Bazemore and Cha, 2024; Cha, 2024).

Another important element of Decarbonisation strategies is the development of infrastructure for alternative fuels such as biofuels, electrofuels or hydrogen, which will allow significant reductions in sulphur oxide and particulate emissions compared to conventional fuels (Urban *et al.*, 2024).

Hydrogen, on the other hand, has potential as a zero-emission fuel, especially when combined with fuel cells, making it a promising solution for ports of the future. It emits no carbon dioxide during combustion and, depending on how it is produced, the amount of carbon dioxide released into the atmosphere can be drastically reduced (Atilhan *et al.*, 2021).

In parallel to the development of energy technologies, ports are introducing advanced digital tools to support Decarbonisation. Digital twins allow the identification of the most energy-efficient solutions through the use of simulation and data analysis, which supports the reduction of emissions and the implementation of sustainable operations in ports. As a result, this technology is seen as a key element in the drive towards carbon neutrality at the port level (Ecom *et al.*, 2023).

Energy management platforms equipped with AI systems can predict energy demand, integrate renewable energy sources and make better use of available resources. AI algorithms can analyse vast amounts of real-time data, including weather conditions, sea currents, vessel speed and engine performance, to determine the most fuel-efficient routes (Durlik *et al.*, 2024; Sanchez-Gonzalez *et al.*, 2019).

However, despite the high potential of seaport technologies, there are significant challenges to their implementation.

## 4. Case study - Port of Rotterdam

As one of the largest seaports in the world, the Port of Rotterdam plays a key role in global trade and logistics. At the same time, as a major industrial centre, it generates significant greenhouse gas emissions, yet in recent years the port has become a leader in Decarbonisation initiatives by implementing advanced technologies and strategies to reduce emissions and support global climate goals. The Port of Rotterdam Authority's strategy for $CO_2$ neutrality is based on four pillars:

- Efficiency and infrastructure,
- A new energy system,
- A new system for raw materials and fuels,
- Making logistics chains more sustainable (Port of Rotterdam, 2024).

The port is currently implementing 15 projects to achieve its goal of becoming $CO_2$ neutral by 2050.

***WarmtelinQ:***
WarmtelinQ is an underground pipeline designed to transport waste heat from the port of Rotterdam to The Hague, where this heat is used to heat homes and businesses located in South Holland. The project is under construction and the first ‘delivery’ is planned for 2027.

***Porthos:***
Porthos is a project to transport and store $CO_2$ from industrial companies in the Port of Rotterdam and stored in empty gas fields under the bottom of the North Sea. Once operational in 2026, Porthos is expected to allow the capture and permanent storage of around 2.5 million tonnes of $CO_2$ per year, supporting the Netherlands' climate goals.

***Rotterdam Hydrogen Pipeline:***
The first section of the new Dutch hydrogen network is being built around the port of Rotterdam. This 32-kilometre hydrogen pipeline will run from Maasvlakte 2 to the Shell Pernis refinery. The pipeline will enable the transport of hydrogen and is expected to help establish and maintain its position as the leading green energy port in Europe.

***Delta Rhine Corridor:***
The DRT is a bundle of pipelines connecting the port of Rotterdam with key industrial centres, running all the way to Germany. This will make the transport of raw materials more efficient and reduce emissions associated with their

transportation, and the corridor is expected to strengthen the strategic and economic position of the Netherlands and Germany.

***Hollandse Kust Zuid Wind Farm:***
The Hollandse Kust Zuid wind farm consists of 139 wind turbines and will generate electricity equivalent to the annual consumption of more than 1.5 million Dutch households. By 2030, further wind farms will provide 7.4 GW of capacity, significantly increasing the region's share of renewable energy.

***Sif Expansion:***
Sif is expanding its production capacity for wind turbine foundations. The port area has been dedicated to the logistics handling of wind turbine foundations, thus strengthening Rotterdam's position in the realisation of offshore wind energy by combining production and heavy lift storage and handling services.

***Holland Hydrogen 1:***
Europe's largest green hydrogen plant is being built at Maasvlakte and is planned to produce 60,000 kilograms of hydrogen per day from 2025, making a significant contribution to the Decarbonisation of the port's industrial sector.

***New Energy Taskforce:***
The New Energy Taskforce is an initiative of the Port of Rotterdam in collaboration with TenneT and Stedin. The project is part of a broader programme that was set up at the end of 2023 to address congestion in and around the port. The programme's objectives include faster grid expansion and better forecasting of electricity demand.

***Europe's Hydrogen Hub:***
It is estimated that the amount of hydrogen passing through Rotterdam could increase to 20 million tonnes by 2050. Apart from local use in Rotterdam and the Netherlands, the majority is destined for use in neighbouring countries. More than 150 hydrogen transport projects are currently underway. The Port of Rotterdam plans to become a hydrogen distribution centre for North West Europe, supporting the transition to renewable energy sources in industry.

***Shell Biofuels Refinery:***
Shell has declared the construction of a biofuel production facility at the former Pernis refinery, which will focus on producing fuels mainly for aviation and fuel from waste. The project aims to reduce emissions to 2.5 million tonnes of $CO_2$ per year from 2024 and is expected to make a significant contribution to the Dutch climate ambition.

***Neste Biofuels Refinery:***
Neste, located on the Maasvlakte site, is also to look into building a biofuels refinery for aviation. The new plant, which will start operating in 2026, will produce sustainable fuels, reducing the environmental impact of the aviation sector.

***Zero Emission Services:***
Zero Emission Services is enabling end-to-end zero-emission IWT projects using a new energy system based on replaceable battery packs (ZESpacks) charged with renewable energy. An example is the Alphenaar vessel, which carries cargo using this technology.

***Shore Power:***
The port is developing shore power installations that allow ships to use electricity while at berth. This reduces emissions of $CO_2$, nitrogen oxides and particulates, and reduces noise from running engines. The city and port's objectives are to implement shore power for ships by 2027.

***Recycle Electric Vehicle Batteries:***
SK tes, which operates at the Port of Rotterdam, recycles used lithium batteries, electric vehicle batteries and scrap from battery production to recover key raw materials containing rare metals, including lithium, cobalt and nickel, which is fed back into the battery supply chain.

***Pryme:***
Expanding its partnership with the port, Pryme recycles plastic waste into new chemical raw materials. The plant processes 40,000 tonnes of waste per year, producing 30,000 tonnes of pyrolytic oil, which can consequently be used in the chemical industry. Plastic recycling fits perfectly with the Port of Rotterdam's goals of making the industry zero-carbon (Port of Rotterdam, 2024).

The Port of Rotterdam is a model example of a Decarbonisation approach in the port sector. Its activities include a wide range of technologies, collaboration with key stakeholders and the integration of innovative solutions in the area of renewable energy and the circular economy. The lessons from this case study can serve as a model for other ports seeking to reduce their environmental impact and support the global energy transition.

## 5. Conclusions

Undoubtedly, seaports and the maritime industry as a whole will play a key role in the Decarbonisation agenda in the near future. As the example of the Port of Rotterdam shows, a complex cross-section of port-supported and collaborative businesses have a huge opportunity to implement technologies that lead to GHG reductions.

In addition to good practices and the flagship example of the Port of Rotterdam, research shows that there has been a growing body of scientific publications in recent years that pave the way for a vision of green seaports, and that the energy transformation of seaports is a significant undertaking on a global scale.

Implementing technologies to decarbonise the maritime and especially the port industry is important and requires, among other things, differentiated implementation strategies, technology standarisation, international rules and regulations, financial support, development and education, incentives and financial benefits.

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