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Decarbonisation Pathways for Medium- and Small-Sized Ports: A Systems Thinking Approach

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***Abstract* – Ports are essential to global trade, yet their high volume of ship traffic significantly contributes to greenhouse gas emissions, necessitating urgent strategies for climate neutrality. This study focuses on medium-sized ports where climate neutrality has not yet become a priority and explores how they can achieve this through a systems thinking approach and sustainable development practices, referencing leading ports like Rotterdam and Hamburg. Using a combination of systems thinking, comparative case studies, and qualitative analysis, the study examines various decarbonization scenarios for port infrastructure. Causal loop diagrams (CLDs) are utilized to map the interactions among environmental, economic, and operational factors affecting port sustainability. Three scenarios – baseline, moderate transition, and ambitious transition – are developed and evaluated based on greenhouse gas emissions reduction, energy efficiency, infrastructure investment, alignment with the United Nations' Sustainable Development Goals (UN SDG), and resilience enhancement. The findings demonstrate that port operations are influenced by reinforcing and balancing feedback loops, where economic growth and customer satisfaction may face challenges from regulatory pressures and climate-related operational costs. The study highlights essential areas for improvement in achieving climate neutrality in medium-sized ports. Key decarbonization techniques identified include electrification, alternative fuels, renewable energy integration, and enhancements to existing infrastructure like automated mooring systems and onshore power supply. Ultimately, the research provides insights into developing a decarbonization strategy for small and medium-sized ports, fostering sustainable development aligned with the UN SDGs and the European Green Deal.**

***Keywords* – Decarbonisation; low-carbon ports; marine transport; renewable fuels; SDG.**

1. INTRODUCTION

As vital centres of global transport and trade, ports play a significant role in influencing climate change. Although recent years have seen the implementation of various initiatives and procedures aimed at enhancing port infrastructure and making it more environmentally sustainable, developments at both global and European levels highlight inconsistencies and differing perspectives on how port operations should support climate neutrality objectives. Specifically, stakeholders may have competing opinions on the preferred technological

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pathways for achieving sustainability, leading to debates over the effectiveness and feasibility of different approaches. Additionally, there are ongoing discussions regarding the overall role of ports in addressing climate change, with some advocating for aggressive action and others raising concerns about the economic implications of such measures [1]. At present, maritime transport contributes approximately 10 % of global transport emissions, while the transport sector as a whole accounts for roughly 24 % of total CO_2 output. This highlights the need for ports to drive the shift toward clean energy [2]. However, ports will not be able to provide climate neutral ship service unless the port infrastructure itself is also designed and developed to meet the objectives of climate neutrality.

On 25 September 2015, the UN SDG Programme was adopted by its Member States, leading to the implementation of the programme by 2030. 17 targets were created to help global prosperity, people and the planet as a whole [3]. As a specialised UN agency, the International Maritime Organization (IMO) operates under the UN system and manages issues related to ship safety and security [4]. The IMO therefore transformed the UN SDG objectives to focus directly on the development of the marine environment and infrastructure to make additional contributions to the maritime industry's growth. The IMO task is to provide guidance to member states to achieve the necessary SDGs in the maritime segment as easily and as quickly as possible. As an example, some of the most important, but not all, are SDG 9 industry, innovation and infrastructure, SDG 13 climate action and SDG 14 life below water [3]. The International Association of Port and Harbors (IAPH) decided to establish the World Port Sustainability Programme (WPSP) to help the IMO promote shared understanding on the need for ports to implement the UN SDGs to collectively reduce carbon emissions in port territory. Many organisations were approached, who also agreed to help, including the European Sea ports Organization (ESPO), the International Association of Ports and Harbours (IAPH), the American Association of Port Authorities (AAPA), the Global Network of Cities and Ports (AIVP) and the World Association for Waterborne Transport Infrastructure (PIANC) [5].

The European Union (EU) has taken the first steps towards climate neutrality and in 2019 launched the European Green Deal, which aims to achieve climate neutrality in all European countries in transport, including ports and other sectors, by 2050. The Green Deal in Europe underlines the need for all countries to contribute to supporting a sustainable strategy for energy, transport, agriculture and industry in the fight against climate change [6]. The European Climate Law outlines targets for achieving the objectives of the European Green Deal strategy, where one of the main objectives is to achieve a 55 % reduction in greenhouse gas emissions compared to 1990 levels [7].

All European Member States must therefore pursue these objectives in order to improve the global climate in the long term and develop their national infrastructure. As key trade and development hub, ports should strive to improve as rapidly and effectively as possible to comply with all the above-mentioned sustainable development plans and adopted laws.

2. Literature Review

Scientific articles on European and global ports were examined, focusing on how they have begun to improve national legislation and port infrastructure to promote port sustainability and climate neutrality in port activities. Examples of good practices in port are summarised in Table 1.

TABLE 1. PORTSIDE GHG EMISSION REDUCTION AND ENERGY EFFICIENCY MEASURES

Measures	Infrastructure	Country (Port)	Ref.
Alternative fuels such as Liquefied Natural Gas (LNG), methanol, hydrogen (fuel cells), ammonia and biofuel	Cranes, derricks, forklifts, port trucks, tugs, tows, pilot boats, fishing boats	Norway (Oslo), The Netherlands (Rotterdam), Germany (Hamburg), Spain (Valencia)	[8]–[10]
Electrification (OPS, battery) and hybridisation (electric diesel)	Cargo handling equipment (CHE), rail mounted gantry, vehicles for passenger transfer, tugboats, trains	US (Los Angeles and Long Beach), Taiwan (Kaohsiung), Canada (Vancouver), Denmark (Copenhagen and Malmö), Germany (Hamburg), The Netherlands (Rotterdam)	[11]–[15]
Renewable energy (RE) utilisation such as solar and wind energy	Solar panels: Navigation buoys, remote beacons, terminals, warehouses, cold storage warehouses. Wind turbines: offshore (power purchase agreement) and onshore	US (Sacramento, San Diego, San Francisco, Baltimore, Long Beach), Spain (Valencia), Croatia (Rijeka), The Netherlands (Amsterdam), Japan (Tokyo), Belgium (Antwerp), UK (Felixstowe), Italy (Genoa), The Netherlands (Rotterdam)	[16]–[20]
Energy saving and management systems: Green roof, HVAC optimisation, environmental training, automatic lighting control and sensors, high mast lighting, navigational system update, building insulation, LEED design building, cold storage curtains, LED light, white painting, slow steaming, eco driving lessons, monitoring systems for reefers and isolation, energy saving tyres, LED flood light, energy storage systems (ESS) and regenerative drives	Building, warehouses, storages, yards, harbour craft, employee, reefers, CHE, ISO 50001, EN 16258	Spain (Valencia), Finland (Helsinki), UK (Felixstowe), The Netherlands (Rotterdam), China (Shanghai), Belgium (Ghent), Denmark (Aalborg), UK (Dover), Belgium (Antwerp), Italy (Genoa, Livorno),	[18], [19], [21]–[24]
Ship turnaround time (TAT) reduction and automated mooring systems (AMS)	Depends on terminal opening hours, stevedore operations, berth availability, efficiency of CHE, mooring systems in ports	Finland (Helsinki), The Netherlands (Rotterdam), Denmark (Aalborg)	[25]–[31]
Modal shift/splits: Improving intermodal transport and moving cargo to rail, barges and short sea shipping	Country railway system, EU concept of TEN-T, inland ports	Sweden (Gothenburg), Belgium (Antwerp), The Netherlands (Rotterdam), Spain (Barcelona), Germany (Hamburg)	[32]–[36]

2.1. Alternative Cleaner Fuels

Alternative fuel production facilities and storage facilities can be set up in the port area to meet its needs in the long term and to meet the objectives of climate neutrality at the same time. One of the first alternative fuels to emerge globally was LNG, which was initially thought to be the fuel that would be able to reduce CO_2 emissions by at least 30 % and improve the overall energy efficiency of systems by 15 % [37]. Methane slip – the accidental release of methane during production, transport, or combustion – is especially worrying because methane is a powerful greenhouse gas. Atmospheric methane levels are now about 2.5 times higher than before the industrial era, worsening climate change. According to the IPCC, methane's global warming potential is 84–87 times that of CO_2 over 20 years and 28–36 times over 100 years, meaning one tonne of methane can warm the climate as much as 28–36 tonnes of CO_2 over a century [38]. Methanol can be efficiently used in internal combustion engines or direct methanol fuel cells, producing energy while emitting mainly carbon dioxide and water. Compared to conventional hydrocarbon fuels, it generates fewer particulates and pollutants, making it an attractive option for transport decarbonization. Its liquid state at ambient conditions also makes storage and handling easier [38]. The port area could produce green hydrogen and ammonia, which would then be used as green fuel to provide port transport [39]. In the ports of Rotterdam and Hamburg, an in-depth well-to-tank-to-wheel analysis was conducted to find out the deficiencies of ammonia as fuel, comparing that to the pros and cons of hydrogen and methanol alternative fuels [40]. The Port of Long Beach (POLB) in the US is at the forefront of other ports around the world, particularly in the use of alternative fuels in CHE, followed by European ports such as Amsterdam, and Genoa, as evidenced by the many EU projects [41]. The third option that could be used is the production of biofuel from biomass, which would open up many opportunities for countless ports in the world, as biomass waste is present in almost every country [19]. A 30 % biofuel blend in diesel can reduce CO_2 emissions by up to 30 % per litre of fuel consumed, corresponding to reductions of 13–26 % per terminal and approximately 21 % across the container sector [42]. One of the most striking examples of a biomass (algae) plant is in the port of Venice, where ethanol, bio methanol and biodiesel are produced [43].

2.2. Electrification and Hybridisation

In recent years, it can often be seen in ports that electricity or hybrid (diesel-electric) is used to operate CHE [44]. CHE uses batteries that can be recharged but require large capital expenditures because each CHE requires at least two sets of batteries to change. Such technology could be widely applied because many ports, such as Copenhagen, Rotterdam and Oslo, use forklift trucks, and stacking cranes in large quantities [33]. The most common examples of port road transport are hybrids of batteries and internal combustion engines, rechargeable batteries, and this alternative is best used in container terminals [44]. According to article [45], reductions in vehicle power consumption are achieved through smart charging systems and auto start-stop technologies, which have been adopted in ports such as Hamburg, Malmö, and Copenhagen.

2.3. Renewable Energy (RE) Utilisation

In recent years, port interest in using renewable electricity for infrastructure energy supply has increased. As a result, world ports are also developing projects to create solar and wind farms, trying to find ways to harness ocean and geothermal energy [46]. Ports that cannot carry out large enough projects themselves can use the renewable Energy Purchase Initiative to secure their daily operations with alternative electricity and reduce GHG emissions [47]. The growth of RE cooperatives in the Port of Rotterdam is examined in article [48].

Photovoltaic (PV) cells and solar thermal heating (STH) systems are widely adopted and relatively simple alternative methods for generating energy. It can also be ideally used for the provision of small electricity systems such as navigation buoys, lighthouses and other auxiliary port navigation systems [17]. A perfect example is Rijeka harbour [21], where such solar panels are used on all the roofs of buildings in the port area, passenger terminals and even freezers. Ports such as Amsterdam, Tokyo Felixstowe also know how to take advantage of solar panels [35]. In ports where large numbers of solar panels and wind turbines have been installed, the use of onshore power supply (OPS) is recommended to more easily maintain a low carbon intensity [49].

The port area is limited in size, so major global ports are investing money to develop wind farms offshore. Currently, some of the world's largest offshore wind farms are owned by Rotterdam (200 MW), Antwerp (45 MW), as well as ports in the US such as NYNJ, San Diego and San Francisco [50].

2.4. Energy Saving and Energy Management Systems

Improving port energy management is another of the key recommendations for improving port energy savings [21]–[23]. The fastest and simplest way to save energy by 50–60 % from lighting is to install Light-Emitting Diodes (LED) in all buildings, warehouses and the port area as a whole [18]. This simple improvement can save up to 20 % of all electricity consumed in the port area [51]. Replacing high-pressure sodium (HPS) lamps with LEDs can achieve up to 1000 tonnes of CO_2 reduction per year [52]. Automatic lighting systems and sensors can also contribute to these improvements. Buildings in the harbour area can be constructed from alternative and environmentally friendly building materials that will also look aesthetic, which will keep warm in winter and cool rooms in summer using green roofs that reduce heat losses and work in a similar way to the passive home, such examples of infrastructure can be found at Ghent and Aalborg ports [24]. High amounts of energy are consumed daily by containers, especially reefer container. Reefer Monitoring System (RMS) and Reefer Sun Protection roofs are needed to avoid this. A port employee can be given guidance and practical lessons on how to use a car to reduce fuel consumption by 10–15 % and tyre wear [18]. The above reduction in tyre wear and fuel consumption may also be used for CHE [24]. Only a few ports have received an ISO 50001 certificate attesting to their high energy performance and management standards. Such ports are, for example, Valencia in Spain, Felixstowe in the United Kingdom and Hamburg in Germany [35].

2.5. Ship Turnaround Time (TAT) Reduction

Unloading, loading and preparing a ship for the next voyage depends on many things, so reducing time and saving in this port activity is crucial [53]. The preparation time of the vessel may be reduced by 37 % if the cargo is handled efficiently, thereby reducing CO_2 emissions [54]. On the other hand, if TAT rises by 30 %, CO_2 emissions rise by 30.7 % per year [55]. By focusing on TAT, it is possible to increase the total energy savings of the port by 2–8 % [56]. Ships typically call according to a first-come, first-served schedule, which lengthens the total TAT. In addition, the port authority may arrange for the ship to enter the port, be unloaded and loaded, and leave the port without delay, provided that the necessary documents are planned and prepared in good time prior to arrival at the port and that the ship's berth is provided immediately [57]. Rotterdam is an excellent example. Additionally, ships benefit from the automated mooring process, which cuts the mooring operation time to a few seconds, lowering the overall ship TAT by 1 to 5 hours [29]–[31]. Hydraulic-actuated arms and remote-controlled Vacuum Pads can be used to moor the ship, which can reduce the ship's CO_2 emissions by nearly 75 % while the ship is docked [58].

2.6. Modal Shift/Split

For major ports around the world, it is advisable to use an intermodal transport system, such as using a railway or smaller boats, to unload the ship as soon as possible, as well as ensuring that the large cargo ship does not have to enter the city area, thus increasing air pollution in the city [59]. Overall, rail transport is considered one of the most ecological and economical freight carriers [32]. The intermodal port structure is widely used in ports such as Hamburg, Antwerp and Rotterdam [34]. The European Union supports the initiative taken by these ports, which is why projects such as TEN-TS and Motorways of the Seas (MoS) have been developed [35]. Models of intermodal ports will not only help reduce port pollution, but overall, across the country will improve cargo turnover and reduce the time until the commodity in question reaches the buyer [60].

2.7. Situation in Europe and World

Techniques for climate neutrality and reducing carbon emissions can drastically differ in each port and country. Table 2 summarises current or planned greenhouse gas reduction measures in global ports. Table 3 illustrates the development and vision for climate neutrality goals globally. European ports, specifically Antwerp, Rotterdam, Hamburg, and Felixstowe, stand out as leaders in implementing these measures, unlike other regional ports [61].

It is therefore also necessary to look at the good examples of Europe and to understand what is necessary for those European countries that find it more difficult to ensure the development of ports in order to reduce the environmental impact of their daily activities and how to reduce port emissions and improve the energy efficiency of the port.

TABLE 2. PORT IMPLEMENTATION OF GHG EMISSION REDUCTION MEASURES BY COUNTRY [62]

Country	Ports	Measures implemented/proposed
Belgium	Antwerp	OPS, wind energy, geothermal energy, energy saving measures, modal shift/split, digitalisation, port city integration, energy management plans, solar energy
Denmark	Copenhagen, Aalborg	OPS, solar energy, energy management plans, hybridisation, energy saving measures, automated mooring systems
Finland	Finnish ports	Energy saving measures, automated mooring system
Germany	Hamburg	Modal shift/split, port city integration, hybridisation, electrification, wind energy, geothermal energy, energy management plans, digitalisation, truck emissions reduction, alternative cleaner fuels (hydrogen)
Italy	Genoa	Information measures, solar energy, energy management plans, OPS
Netherlands	Rotterdam, Amsterdam	Information measures, alternative cleaner fuels, wind energy, solar energy, energy saving measures, energy management plans, digitalisation, container terminal automation and operation system, port city integration, truck emissions reduction, modal shift/split, OPS, alternative fuels bunkering, automated mooring systems, solar energy, wind energy, smart grid, port city integration
Sweden	Gothenburg, Helsingborg, Stockholm	Information measures, energy management plans, modal shift/split, OPS, alternative fuels bunkering, hybridisation, Alternative fuels bunkering, OPS
UK	Felixstowe, Dover, Aberdeen	Information measures, solar energy, energy saving measures, energy management plans, smart load management, land transport, measures, OPS

TABLE 3. COUNTRIES' IMPLEMENTATION OF MEASURES [62]

Region	Country examples	Measure implementation level	Number of implemented measures
North America	USA, Canada	Highly implemented	6–7
South America	Brazil, Argentina, Chile	Rarely implemented	0–1
Europe	Germany, France, Italy, UK, Nordics	Highly implemented	6–7
	Poland, Romania, Bulgaria	Moderately implemented	2–3
Middle East & Africa	Egypt, South Africa, Morocco	Rarely implemented	0–1
Far East of Asia	China, Japan, South Korea	Increasingly implemented	4–5
	India	Moderately implemented	2–3
Oceania	Australia	Rarely implemented	0–1

In the global supply chain, port services – particularly containerization – are currently the most utilized. With ports handling 75 % of all international goods traffic, ports play a crucial role in global trade. The volume of goods processed through European ports is expected to rise by 50 % by 2030, up from 3.7 billion tons in 2011. This growing demand places European ports in a challenging situation, as they must balance increased shipping with the necessity of reducing emissions [63]. Unfortunately, shipping is inherently polluting due to emissions from loading and driving to unloading [64]. According to [65], CO_2 – emissions in ports are linked to the mode of transportation used in the port operations.

ESPO has represented a total of 22 European Union countries since 1993, but only since 2011 has EcoPort been included in ESPO, which has collected top 10 environmental challenges in European ports in recent years, as follows [66]:

- Waste from ships;
- Port development (land related);
- Port relations with residents;
- Water quality;
- Noise;
- Air quality;
- Waste in ports;
- Energy efficiency;
- Climate change;
- Port development (water-related).

2.8. Case of Rotterdam and Hamburg Port

In Europe, the ports of Rotterdam and Hamburg are among the busiest, striving for SDG, including climate neutrality. Also, they are two of Europe`s largest ports by cargo throughput. For example, in the port of Rotterdam total container throughput amounted in 2024 increased to 133.4 million tonnes and by 2.8 % in Twenty-foot Equivalent Unit (TEU) to 13.8 million TEU [67]. In the port of Hamburg cargo throughput amounted to 77.5 million tonnes or 7.8 million TEU [68].

The Port of Rotterdam aligns its initiatives with the UN SDGs. All SDGs can be attributed to port operations, but a few are particularly important, such as: SDG 7 - Affordable and clean Energy, SDG 8 – Decent work and economic growth, SDG 9 – Industry, innovation and infrastructure, as well as Climate action – SDG 13 [69].

Currently ranked among Europe's most climate-neutral ports, the Port of Rotterdam has created a strategy to reach the continent's zero emissions goals by 2030. To achieve its climate neutrality objectives, the Netherlands port has established a circular economy aimed at cutting CO_2 emissions over the next three decades [70]:

- **Pillar 1:** Develop the necessary infrastructure for electricity and hydrogen production, increase the efficiency and productivity of the current equipment.
- **Pillar 2:** Development of the port energy system to switch to alternative energy and green hydrogen.
- **Pillar 3:** Develop material recycling and improve the efficiency of existing fuel systems.
- **Pillar 4:** Make the existing transport system more sustainable.

Pillar 1: Since the energy security of the port infrastructure in Rotterdam is still dependent on fossil fuels, the Paris Agreement plays a major role in the future development of the port, as it aims to reduce pollution from the port as soon as possible [71]. CO_2 emissions decrease as industry efficiency rises. One of Rotterdam's plans is to store CO_2 under the North Sea, places where oil and gas were once extracted. Currently, heat energy is being successfully used as a fuel source for heating port offices and, to a lesser extent, other small buildings. In order to further develop not only this but also other forms of extraction and use of alternative energy sources, the Port of Rotterdam needs to rapidly expand its energy infrastructure in the coming years. If successful, Rotterdam will retain the symbol of Northwest Europe's most developed port [72].

Pillar 2: Rotterdam has long understood that hydrogen and its use to generate electricity, especially from green hydrogen, are crucial to the sustainability of the port, so the port is investing heavily financially in the development of solar panels and offshore wind power plants [71]. Therefore, the above-mentioned intention of storing captured CO_2 from maritime and coastal transport and storing it under the North Sea, called the Porthos project, plays an important role in the development of the port. Additionally, the European Commission granted Porthos PCI (Projects of Common Interest) status [73], indicating that the project can undergo a more streamlined and integrated permitting procedure (e.g. applications can be submitted concurrently as a single, cohesive permit package) to expedite the execution of critical infrastructure projects [74]. In addition, the Port of Rotterdam is working on a project called "Europe's Hydrogen Hub" that will link Porthos, offshore wind energy, and hydrogen production. In 2024, for example, Air Liquide carried out a feasibility study to demonstrate blue hydrogen at its refinery in Botlek, Rotterdam. Additionally, the Port of Rotterdam anticipates connecting its hydrogen infrastructure by 2030 with 7.4 GW of offshore wind power in the North Sea [75]. At present, the port of Rotterdam is undergoing the largest development project ever carried out in the Netherlands before, only to help develop the port infrastructure and steer it in great steps towards the production of green hydrogen and thus the achievement of many other climate SDGs. The largest infrastructure to be built in the next five years is offshore wind turbines and the largest electrolysis plant in the Netherlands. By 2025, the project H_2-Fifty is planned to be developed and establish a 250 MW electrolysis plant to be able to produce up to 185 thousand tonnes of green hydrogen for the Rotterdam industrial and transport sectors within a year [76].

Pillar 3: All of the above are interlinked, where hydrogen and other alternative fuels are at the heart of all these developments, as they can be used not only as heating elements for buildings (Pillars 2 and 4), but also as a raw material for industry, which also opens up many new jobs and attracts industry professionals from around the world (Pillar 3). Green hydrogen production generates excess heat that can be safely supplied to the port and city district heating network. Biofuel production from bio-waste, designed to provide fuel for jet engines and trains, and offers many opportunities to develop the chemical industry in the port area, where it can be directed immediately to exports from other countries or to provide the necessary internal state [77], [78].

Pillar 4: Making logistics chains more sustainable is a multi-track process. Rotterdam Port focuses on sustainable fuel and electricity, efficiency and modal shift. Moving away from fossil fuels to more sustainable, energy-efficient or zero-emission fuels can reduce transport emissions to zero. One of the most effective methods of reducing CO_2 emissions is OPS, as ships arriving at the berth currently use their auxiliary generators in most ports. Here too, the Port Authority of Rotterdam has ruled that all incoming cruise and container ships will have to use the OPS system by 2027 [79]. The introduction of the OPS system in the port area of Rotterdam is now a priority because, compared to other European ports, it is container ships, which are the main users of the system, which enter the Port of Rotterdam the most during the year. Therefore, in order to achieve this objective even more quickly, a special system has been developed whereby the largest container shipments in the Port of Rotterdam help develop their terminals and implement OPS systems in them [80].

Exchangeable energy containers (ZESpacks) are a solution to the port of Rotterdam's improved inland waterway navigation. Technology that can be incorporated into a 20-foot container and uses lithium-ion batteries. The same technology can be used with hydrogen or other alternative fuels. Several charging and exchange points for such containers are currently in place throughout the Port of Rotterdam. ZESpacks is an opportunity to reduce CO_2 emissions by 1000 tonnes and up to 9 tonnes of NO_x per inland vessel per year, it works without noise, thus reducing noise pollution for people living near the port. The shipper's logistics are optimized as a result. Hydrogen and other energy carriers may eventually be incorporated into ZESpacks [81].

With this Pillar development plan, the Port of Rotterdam is on track for sustainable port infrastructure and also meets the UN’s SDGs.

The Port Authority of Hamburg (HPA) sustainability strategy integrates the UN SDGs with the IAPH World Ports Sustainability Program (WPSP) to support the port’s climate neutrality objective [82].

Progress over the last five years is documented in a structured assessment report, which evaluates performance across four areas of action: “The HPA and business performance”, “Infrastructure and traffic”, “Climate and the environment”, and “Values and people” [82].

Infrastructure and traffic. Port of Hamburg has one of the most stable and advanced logistics chains in Europe. Even now, HPA has the fastest growing railway infrastructure, so HPA is also trying to develop other freight modes on an equal footing with rail. However, in view of the geopolitical situation currently prevailing in Europe, the HPA seeks to ensure a high level of protection of the new transport infrastructure. HPA is going through a major shift process as maritime, railway and road transport are digitalised, which will provide easier oversight and control of incoming and outbound cargo at Port of Hamburg in the future. Here, its work focuses specifically on the following areas: e-navigation, networking systems/transport chains, cyber defence, protecting critical infrastructures (KRITIS), and developing new platforms. To achieve the desired objectives, HPA will use digital tools to predict infrastructure development processes as quickly and successfully as possible and will later be used to identify planned maintenance at individual cargo terminals or port facilities [82].

For the Port of Hamburg, digitalisation is important because they manage a huge transport infrastructure, consisting of more than 700 railway stations, 300 kilometres of railway tracks, and also has 73 private railway companies in attendance to ensure the loading and unloading of ships. In the Port of Hamburg, railway is used for a total of more than 51 % of freight.

The significant volume of cargo being processed in the port area, can be attributed to the large number of ships that enter the port of Hamburg on a daily basis, which can exceed as many as 10 000 calls and cargo handling requests per year. It is therefore important that this quantity of vessels is handled effectively. The modal shift/split for incoming and outgoing cargo and port traffic is extremely well-developed in the Port of Hamburg [82].

Climate and the environment. The HPA has monitored energy security for port infrastructure since 2011, which demonstrates very clearly that the port of Hamburg is seeing positive carbon reductions. Based on the available data, in 2012 CO_2 emissions in the port of Hamburg were on average 21 000 tonnes per year, which has fallen in the years to 2020. The HPA has focused heavily on reducing carbon emissions over the past five years, which compared to the first recorded in 1990, has seen more than 51 % reduction thanks to the initiative of Port of Hamburg to use electricity or alternative fuel as its primary source of energy.

The Port of Hamburg is one of Europe's largest city ports, so it is important that port transfer pays much attention to achieving UN SDGs and climate neutrality in the port area. It can be seen from the results of the port of Hamburg that the port will continue to strive to meet all the necessary targets to achieve zero emissions in the port area as soon as possible [82].

3. METHODOLOGY

This study uses a mixed method approach based on systemic thinking through qualitative and comparative case studies analysis. The methodology consists of three main components: application of systems thinking to understand complex interconnections in port sustainability strategies, analysis of the context of the medium- and small-sized port case study and development of a scenario for evaluation of potential decarbonisation routes.

3.1. Defined Approach: Systems Thinking

The study uses a systems thinking approach to holistically assess the multifaceted interactions between environmental, economic, and operational factors influencing port sustainability [83]. A causal loop diagram (CLD) was developed to visualize the feedback loops and leverage points within port systems, particularly concerning energy use, emissions, infrastructure development, and alignment with UN SDGs. This method enables the identification of systemic interventions and the projection of long-term outcomes of various strategies.

The CLD is developed following [84], making each connection between variables a "+" or "–" sign, indicating the direction of influence of variables. A positive "+" polarity means that the variables move in the same direction: an increase in the first variable causes an increase in the second (and a decrease causes a decrease). A "–" polarity indicates an opposite effect: an increase in one variable leads to a decrease in the other, and vice-versa. These polarity assignments are based on conceptual logic, historical patterns, expert knowledge, and empirical observations where available.

Once the causal links have been defined, they are followed through to locate feedback loops within the system. Each loop is then interpreted based on its polarity pattern. When a loop contains an even number of negative causal connections (including none), the overall influence reinforces the initial direction of change, producing what is known as a reinforcing loop (R). Such loops tend to accelerate processes, often resulting in compounding growth or decline. In contrast, a loop with an odd number of negative connections forms a balancing loop (B), where the feedback acts to counter the initial effect, guiding the system toward stability or a target condition [84].

Understanding whether a loop is reinforcing or balancing is essential for interpreting long-term system tendencies. Reinforcing feedback typically pushes the system along an exponential path, while balancing feedback introduces constraints or corrective pressures. Time delays within feedback structures must also be considered, as they can mask which loop dominates at a given moment and contribute to oscillatory or overshooting behaviour before the system settles [84].

3.2. Case Study: Medium and Small-Sized Ports Context

A qualitative case study approach was employed to examine the current conditions and future transition pathways of medium- and small-sized ports in the context of decarbonisation and sustainable development. These ports were selected as the focal point of analysis because, despite their importance for regional economies and supply chains, they often face structural, financial, and operational constraints that differ significantly from those of large hub ports.

The analysis focuses on ports that typically serve regional or national markets, handle moderate cargo volumes, and operate with limited access to capital-intensive infrastructure investments. Such ports are often at an earlier stage of implementing climate neutrality strategies, making them particularly relevant for exploring scalable and adaptable decarbonisation pathways.

Research included:

- Policy documents and regulations (e.g., European Green Deal, European Climate Law, IMO circulars);
- International port strategies (e.g., Port of Rotterdam, Port of Hamburg);
- Technical reports and scientific literature on GHG reduction and renewable energy in ports.

By comparing the characteristics of medium- and small-sized ports with practices adopted in large benchmark ports, the study identifies gaps, constraints, and opportunities for adaptation rather than direct replication. Particular attention is paid to measures that can be realistically implemented within limited financial and spatial capacities, such as energy efficiency improvements, phased electrification, operational optimisation, and selective deployment of renewable energy technologies.

This generalized case study framework supports the development of transferable decarbonisation strategies for medium- and small-sized ports, enabling them to progress toward climate neutrality while maintaining operational viability and competitiveness within regional and global logistics networks.

3.3. Defined Scenarios

In order to better understand how to develop the decarbonisation of ports, three further scenarios were developed and evaluated:

- Baseline scenario – Usual port operations, without significant interference.
- Moderate transition scenario – Gradually introduce carbon reduction scenarios into port infrastructure. (e.g., OPS, energy efficiency management);
- Ambitious transition scenario – Comprehensive adoption of best practices from benchmark ports, including renewable energy integration, modal shift, electrification, and alternative fuel use.

Each scenario was analysed using systems-based evaluation criteria focusing on:

- GHG emissions reductions, CO_2, NO_x, SO_x, $PM_{2.5}$, PM_{10}, VOCs and CO;
- Energy efficiency improvements;
- Infrastructure investment needs;
- Alignment with key UN SDGs (e.g., SDG 6, 7, 9, 12, 13);
- Resilience enhancement.

This structured approach facilitated a balanced comparison between feasibility, impact, and long-term sustainability outcomes.

In this study, port-related emissions are defined as the total quantity of GHGs and air pollutants generated by maritime, logistic, and operational activities directly connected to a port area. These include emissions from:

- Vessels arriving in port, carrying out manoeuvring, berthing and hoteling phase;
- Cargo-handling equipment and terminal operations;
- Hinterland transport and energy use associated with port infrastructure [85].

Major pollutants include CO_2, NO_x, SO_x, $PM_{2.5}$, PM_{10}, VOCs and CO which together constitute the core environmental footprint of port activity [62].

The magnitude and composition of these emissions depend on the scale and type of port operations, vessel traffic, and energy mix. Studies show that between 15% and 30% of total shipping-related emissions occur in coastal and port areas, where they directly influence local air quality and human health [86]. Accordingly, ports are recognized as essential participants in achieving international decarbonization targets under the IMO MARPOL Annex VI and the EU Climate Law [87], [88].

The study presents a conceptual overview that broadly reflects the priorities set by European ports (Rotterdam and Hamburg), which are related to the achievement of the objectives of the overall sustainability strategies for ports set by the UN and IMO, and then, based on examples of benchmark ports, take over good practice and develop in smaller ports, such as the Port of Riga. Each port develops context-specific pathways toward climate neutrality and environmental sustainability.

Building on these global commitments, the framework highlights how European benchmark ports (Rotterdam and Hamburg), have translated international sustainability goals into actionable port strategies. These ports have prioritized several SDGs and embedded them into their long-term strategic development plans. Their actions are guided by the EU Climate Law, including key policy instruments such as the FuelEU Maritime initiative (Fit for 55), the Emission Trading System (ETS), and the Trans-European Transport Network (TEN-T) policies, all of which promote the use of alternative fuels, shore-side electricity, and low-emission technologies.

The Port of Riga (Latvia) is an example of a smaller regional port that adapts best practices from benchmark ports to its own operational context. Riga's sustainability priorities mirror those of leading European ports, with particular attention to climate action, clean energy, and responsible consumption. In 2024, the Port of Riga achieved a new operational milestone by handling more than 5 million tons of containerised cargo, equivalent to approximately 465.4 thousand TEU [89].

4. RESULTS

Fig. 1. represents a diagram with a reinforcing loop (R1) illustrating normal port operation in everyday conditions. The Reinforcing loop (R1) drives port operations to improve customer satisfaction. Customers satisfaction with the operation of the port and the proposed infrastructure security increases the demand for port services. It ensures that the port generates revenue and is able to develop and improve its services. Over time, the port is able to increase the processing of incoming cargo, ensuring further operation and development of the port. R1 reinforcing loop is boosting economic growth. As the port becomes more economically active and efficient, the number of ships entering and berthed will increase. This loop reflects standard operating conditions where the system works well and has not been further explored in this study. Instead, attention is focused to two balancing loops, (B1) and (B2), resulting from the implementation of climate policy and environmental regulations.

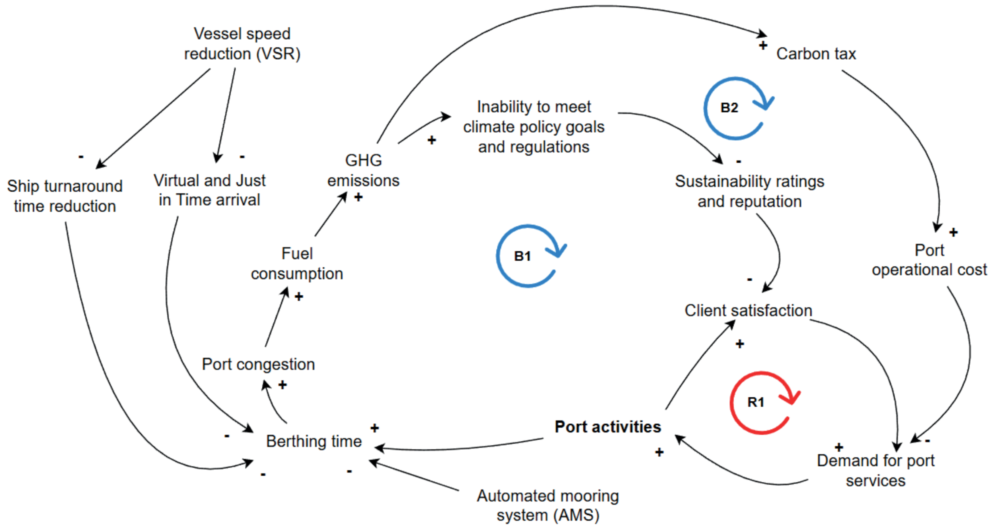

Fig. 1. Causal loop diagram for port sustainability and operational efficiency dynamics.

Balancing loop (B1) is related to climate laws, regulations and the pressure they exert on ports to reduce pollution from port activities. As port activity and cargo turnover continue to increase, this often increases mooring and berthing times, especially when there is also planned maintenance or regular inspections (port state control (PSC), inspections from vessels owners) are also provided for the ship at the berth. Most of these activities are carried out during the berthing of the ship. This contributes to port congestion and higher fuel consumption, especially from auxiliary engines. Increased fuel consumption directly leads to higher GHG emissions.

These emissions make it difficult for the port to comply with national or international climate policy goals and regulations, leading to an inability to meet sustainability criteria. This negatively impacts the port's performance in Environmental, Social, and Governance (ESG) evaluations. Sustainability ratings and ESG considerations influence decision-making in global logistics, affecting port selection. Investors, cargo and vessel owners, logistic partners increasingly prefer low-carbon logistics chains. A GHG intense port risks losing vessels to ports that invest in green infrastructure and practices. Thus, the reputation of port with low ESG ratings suffers, which can reduce client interest and limit future demand. This is balancing loop (B1) for the growth seen in loop (R1).

Balancing loop (B2) is showing economic impact of direct climate change mitigation measures such as carbon tax. This tax increases the operational costs of running the port. As costs rise, the demand of port services decreases, and clients may begin seeking alternative, more cost-efficient or greener ports. Demand for services at the affected port then declines, further slowing down the economic activity captured in the (R1) loop.

But the system also demonstrates possible ways to counteract these adverse dynamics by putting operational plans in place to cut emissions and remain compliant with the law. Berthing time can be decreased through the use of technologies and tactics such as Automated Mooring Systems (AMS), Virtual and Just-in-Time arrivals, and Vessel Speed Reduction (VSR). Reduced berthing periods can ease port traffic, use less fuel, and cut greenhouse gas emissions. These interventions can aid in reducing the strength of loops (B1) and (B2) as well as promoting operational effectiveness and environmental compliance.

Fig. 2 displays a second set of solutions that go beyond operational efficiency. These solutions focus on the kind of energy that ports use for berthing vessels as well as for assisting with port operations in general. These tactics directly address emissions at the energy source level, in contrast to previous initiatives that concentrated on automation and time reduction.

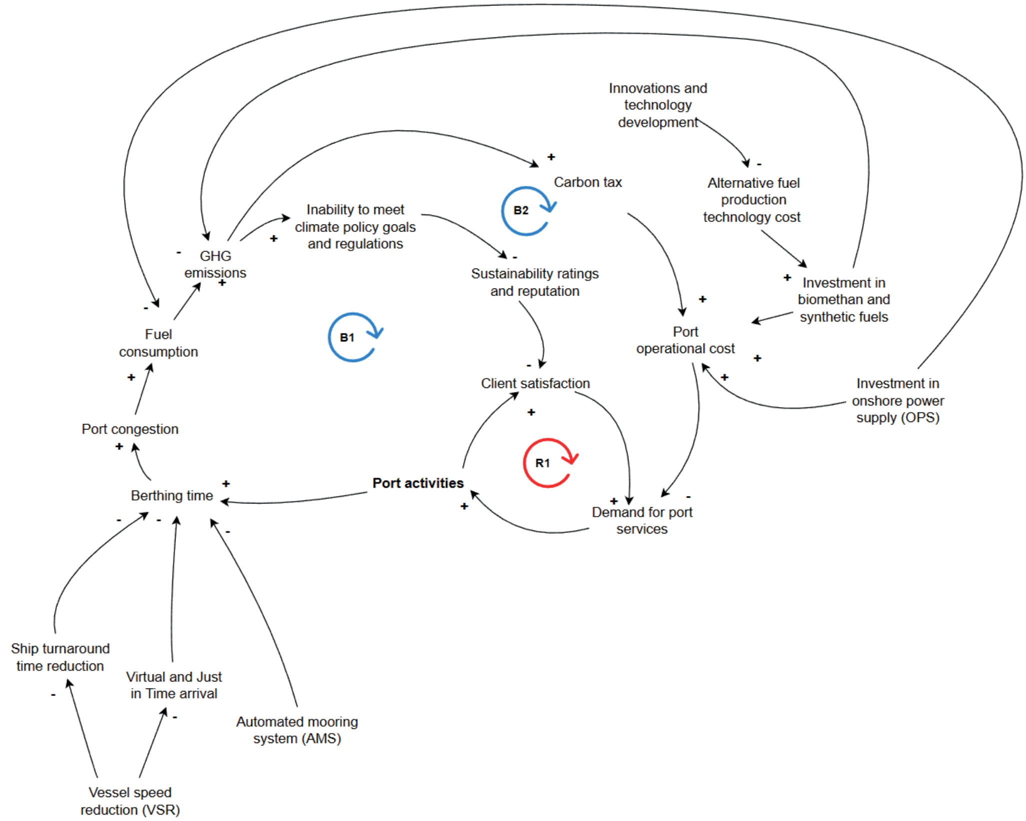

Fig. 2. Causal loop diagram for decarbonisation and technological innovation dynamics in port operations.

Synthetic fuels and renewable fuels like biomethane are included to promote a more comprehensive move away from fossil fuels. Even though the cost and availability of these fuels are higher now, continued technological advancement and investment in this field could reduce production costs and make these alternatives more viable. This produces a situation whereby lower exposure to carbon taxes and more stable regulations may eventually balance out initial cost increases. Thus, the system demonstrates that although port operating costs may increase in the short term, there will be long-term advantages such as increased customer satisfaction among stakeholders who care about the environment and consistent demand for services. In the end, these changes in energy supply make ports less vulnerable to regulatory and reputational risks and offer a strategic way forward to remain competitive in an era of growing climate responsibility. The timing of investment decisions is a crucial factor in this transition. Operational measures like cutting down on berthing time or enhancing vessel traffic coordination may provide more immediate and economic benefits in the early stages, when carbon taxes are still relatively low and the price of alternative fuels is still high. There is also a risk of delay. Investment may come too late if the port waits until the carbon tax has already placed a significant economic burden, despite alternative technologies already reaching the peak of maturity and cost. In such cases, the port would run out of optimal investment time, where the balance between increasing political pressure and declining technology costs could offer the most strategic and financially best transition option.

An assessment of the quantitative modelling is essential in order to identify this optimum window of opportunity for action. This model should simulate different scenarios for the timing of investments, including uncertainty and variability in key parameters such as the pace of innovation, learning curve effects, cost reductions of alternative technologies and the gradual increase of the carbon tax level. Integrating these variables can support evidence-based decision making and help port authorities to balance short-term viability with long-term sustainability. This would ultimately allow for a phased transition strategy, with operational efficiency measures being implemented in the short term and strategic energy transition investments timed to match evolving market conditions, policy trends and technological cost thresholds.

Literature review shows studied in the article that other countries are also trying to achieve port climate neutrality in a similar way by trying to develop and integrate similar ideas. For example, it can be seen from the results that system thinking and CLDs require a focus on environmental pollution mitigation goals, and that this result must be achieved without forgetting the economic benefits and sustainability of port operations.

Similarly, in the literature review is discussed that ports such as Long Beach, Hamburg, Vancouver, also aim to meet the goals of harbour climate neutrality with decarbonisation techniques such as OPS, renewable energy use and alternative fuels. These objectives shall be pursued both in a more cost-effective manner and by improving the functioning of the port so that it is not delayed for too long, as well as by achieving the objectives of climate neutrality. There is a very strong consensus on the role of technology in reducing emissions in the port area and improving the logistics efficiency of port transport. For example, the automated mooring systems, Just-in-Time arrivals, OPS and vessel speed production mentioned in Fig. 2 are already starting to be used in major European ports such as Finland, The Netherlands, Copenhagen and Valencia.

Both the literature review and the results confirm that the production and use of alternative and renewable fuels in port is inevitable over time. Currently it is economically unprofitable, especially for smaller ports, but major ports such as Oslo, Los Angeles, and Tokyo are starting to develop the production and extraction of alternative fuels to be used for port needs.

5. CONCLUSION

This study explores strategies for achieving climate neutrality in ports, with a particular focus on medium-sized European ports. This was achieved by analysing successful established practices from leading European ports such as Rotterdam and Hamburg. The literature review showed different decarbonisation strategies, such as alternative fuels, electrification, renewable energy, are implemented at benchmark ports both globally and in Europe for broader vision and their contribution to UN SDGs. Therefore, three scenarios were developed to represent strategic pathways (baseline scenario, moderate and ambitious) based on observed practices and system interaction identified in literature for decarbonising ports, using systems thinking approach to balance environmental, economic and operational factors, representing these scenarios in two CLDs.

The CLDs show how complicated port activity really is based on results. From results it is clear that there are connections between port infrastructure and how they affect each other, so it can be said that the port, as a public infrastructure, need to be developed to climate neutrality from several points of view at the same time to get the best results. Therefore, CLDs were made so in future research it could be explored in depth how much investment is needed and how to allocate it to technological improvements in port infrastructure so that the CO_2 reduction is worth the investment. The analysis also showed that while stricter climate policies and carbon taxation may initially impose higher operational costs, long-term competitiveness can be achieved through strategic investments in sustainable technologies and renewable energy. The results suggest that ports that invest early in electrification, automation, and renewable energy integration are better positioned to remain economically viable and environmentally compliant in the face of tightening EU and IMO regulations.

Although the study does not provide a step-by-step implementation plan, it conceptually identifies the operational areas within port activities that most strongly influence emissions and sustainability outcomes. Therefore, it proposes a phased roadmap for medium-sized ports such as Riga. Adopting renewable energy, improving efficiency, thus achieving EU, ESPO, IMO and UN climate neutrality and sustainability goals while maintaining economic competitiveness. An in-depth examination of other countries' best practices suggests that three recommendations for implementation can be imposed on medium-sized ports: 1) Short-term – port authorities focus on quick wins like LED lightings, OPS and AMS, 2) Mid-term – invest in renewable energy (solar panels and off shore wind farms) and hybrid CHE, and last but not least 3) Long-term – develop hydrogen/ammonia production, bunkering and circular economy initiatives.

The novelty of the article lies in combining systems dynamics with scenario analysis to tailor decarbonisation pathways for small and medium-sized ports, while gaining the experience of the world's largest ports. The literature review considered, and the results carried out are both theoretical (promoting sustainability modelling) and practical (offering responsive steps for policymakers).

The port is an extensive and complex infrastructure whose activities affect a wide range of interests. From the welfare of port workers to the city, state economy and environmental sustainability. Therefore, this research emphasizes the necessity of considering medium- and small-sized ports individually, as a one-size-fits-all approach is ineffective for port development. This study showed that each port is unique, as well as developing general routes for achieving port sustainability, which can be taken as an example to further explore the example of a particular port and establish a techno-economic model.

The study showed that all ports will have to meet certain objectives in order to meet the SDGs set by the UN, IMO and the EU. However, not all ports will achieve the objectives at the same rate or same level of efficiency. Therefore, every effort must be made to help those ports that have not yet developed their long-term plans in detail.

Future research is very important in order to evaluate various examples of decarbonisation strategies for mid-sized harbours.

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