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Review

A Literature Review of Seaport Decarbonisation: Solution Measures and Roadmap to Net Zero

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Abstract: This paper provides a comprehensive review of the literature related to seaport decarbonisation by combining the academic literature with case studies, industrial reports, newsletters, and domain knowledge. Through the literature review, the emission sources at seaports are categorised according to different criteria for better understanding. One of the criteria is the geographic location, which divides the emission sources into four categories. For each emission source category, the emission reduction measures in the literature are categorised into six structured categories including operational measures, technical measures, fuel and energy measures, infrastructural measures, digitalisation measures, and policy and collaboration measures. The first three categories have a direct impact on emission reductions, whereas the last three categories tend to support and facilitate the development and implementation of the first three categories. Representative case studies are selected from the UK ports to discuss their decarbonisation practices and pathways to net zero. We then propose a generic time-phased roadmap for port decarbonisation towards net zero, which divides the solution measures in each category into three phases to show their progressive processes. We explain the dependence relationships of the solution measures in the roadmap and discuss the challenges and opportunities in the implementation of the roadmap. This paper could offer strategic guidelines to port-associated stakeholders to implement emission reduction strategies and transition to net zero from the system perspective.

Keywords: seaport; decarbonisation; net zero; literature review; case study; roadmap

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1. Introduction

The transport sector is one of the largest contributors to anthropogenic greenhouse gas (GHG) emissions. Maritime transport, as the backbone of world trade and globalisation, plays an indispensable role in achieving a sustainable global economy; however, it accounts for approximately 3% of all global GHG emissions, mainly due to the sheer size of the business and the use of carbon-intensive fuels [1]. Carbon dioxide (CO_2) is the most important greenhouse gas emitted by human activities that causes global warming. The International Maritime Organisation (IMO) has set up a series of ambitious targets for reductions in GHG emissions from the maritime industry. Many countries have announced their own decarbonisation goals.

In 2018, the IMO announced an Initial Strategy for international shipping, which included short-term targets focusing on data collection of ship fuel consumption and transport work, medium-term targets for reducing carbon intensity (which refers to the CO_2 emissions per transport work) by at least 40% in 2030 compared to 2008 levels, and long-term targets of reducing carbon intensity by 70% and absolute GHG emissions by 50% in 2050 compared to 2008 levels. In July 2023, the IMO adopted the 2023 IMO strategy for reductions in GHG emissions from shipping, which included a new level of ambition relating to the uptake of zero or near-zero GHG emission technologies (fuels and/or energy sources are to represent at least 5% of the energy used by international shipping by 2030) and an improved ambition to reach net zero GHG emissions from international shipping (www.imo.org, accessed on 24 September 2023). Net zero refers to a balance situation in which the total amount of GHGs in the atmosphere is not increased by human activity.

Seaports are multimodal interface nodes in shipping logistics networks where various types of vehicles and cargo handling equipment operate. Seaports are regarded as concentration areas producing air pollutants and GHG emissions. As seaports are often located near highly populated coastal cities, port-associated stakeholders are undoubtedly concerned with health-impacting air pollutants such as nitrogen oxides, sulphur oxides, particulate matter (PM), volatile organic compounds, and carbon monoxide. On the other hand, GHG emissions (mainly carbon dioxide and methane) have long-term impacts on climate change and global warming. Therefore, it is imperative to better understand and decarbonise port activities in order to achieve national and IMO net zero decarbonisation goals.

A few review papers in the literature have discussed emission reduction measures in seaports. Bjerkan and Seter [2] reviewed the literature on tools and technologies that are used to achieve sustainable ports. They identified 26 tools and technologies and grouped them into four main categories: port management and plans, power and fuels, sea activities, and land activities. Their focus was on general port sustainability. Iris and Lam [3] conducted a comprehensive literature review on energy efficiency in ports and terminals by grouping the emission reduction measures into three broad categories: operational strategies, technologies, and energy management systems. Sdoukopoulos et al. [4] provided a pragmatic and comprehensive overview of the main policies, technologies, and practices that European ports have adopted to enhance their energy efficiency with an emphasis on container transport. Alamoush et al. [5] offered a systematic review of ports' technical and operational measures to reduce GHG emissions and improve energy efficiency. They structured the identified measures into seven main categories and nineteen sub-categories. Barberi et al. [6] offered a comprehensive review of the recent interventions and technologies that can be adopted to mitigate emissions in ports and showed the correlation between emissions and port infrastructures. Alamoush et al. [7] adopted policy and management perspectives to identify and analyse policies and tools that port policymakers can use to accelerate the uptake of technical and operational measures in seaports. Wang et al. [8] conducted a systematic literature review on the various emission reduction measures in ports and summarised the effectiveness of these measures. It is stated that among the reviewed emission reduction measures applied to ships and ports, the operational measures can achieve an abatement average potential ranging from 20% to 50%, whereas energy measures could have an abatement potential of over 80%. Alamoush et al. [9] conducted a literature review on port decarbonisation focusing on the concept of port decarbonisation, the barriers that hinder progress, the pathways to implement decarbonisation measures, and the solutions to mitigate the barriers.

The above review papers have provided very good overviews of the emission reduction measures in ports from different angles or with different emphases. Most of them are primarily based on articles in academic databases. There is a lack of discussions on case studies, industrial practices, and pathways towards net zero in a broader context. Since seaports are hubs that connect to not only transport sectors but also other industrial sectors, we believe there is a need for research to build a broad strategic model to guide seaports towards net zero from the system viewpoint. This paper tries to fill this research gap by conducting a comprehensive literature review including multiple case studies of seaports and taking the system perspective to examine seaport decarbonisation in view of the bigger picture. More specifically, the objectives include the following: (i) categorise the emission sources at seaports according to different criteria for a better understanding; (ii) review and categorise emission reduction solution measures at seaports into a set of structured matrices; (iii) take representative ports in the UK and international context as case studies to discuss their decarbonisation practices and journeys to net zero; (iv) propose a time-phased roadmap of seaport decarbonisation towards net zero and discuss the challenges of its implementation.

The rest of the paper is organised as follows. In Section 2, we categorise the emission sources at seaports into groups according to different criteria, e.g., functionality, emission scope types, and geographic locations. In Section 3, we review the relevant emission reduction measures at seaports and classify them into a set of structured matrices according to the emission source categories, in which emission reduction measures are grouped into six categories. In Section 4, we present six case studies selected from the UK ports and three case studies from the international context, and discuss their emission reduction practices and pathways towards net zero. We then propose a time-phased roadmap of seaport decarbonisation to net zero in Section 5, and discuss the challenges and research opportunities of its implementation in Section 6. Finally, conclusions are drawn in Section 7.

The research process can be illustrated in the methodological framework, as shown in Figure 1.

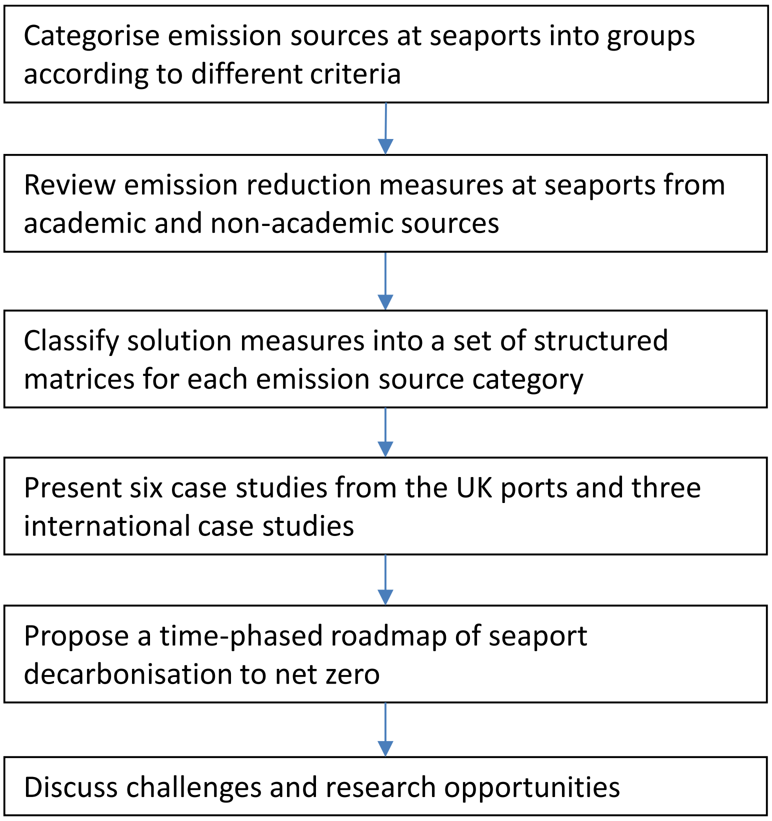

Figure 1. Methodological framework.

2. Emission Sources at Seaports

Seaports are regarded as transport hubs that link seaborne transport by vessels to inland transport by trucks, trains, and barges. Cargo and passengers are loaded onto and discharged from vessels at seaports with the destinations and origins at inland locations. Many seaports have been developed as logistic hubs, where different companies are co-located to perform various logistics activities and value-added services including transportation, warehousing, sorting, processing, and distribution of goods for national and international trade. For example, according to a survey study by the property consultancy Knight Frank (www.maritimegateway.com, accessed on 24 September 2023), which assessed 41 UK ports using 13 factors, the Port of Liverpool is the top port-centric logistics hub in the UK. Further, some ports have been developing as energy hubs in the transition of decarbonisation by producing, transporting, importing/exporting, storing, converting, distributing, and trading alternative fuels and energy.

According to IMO [10], port emission sources are classified into two types: stationary-type sources and mobile-type sources. This classification is mainly based on the emission source's functionality and relationship to the cargo. Stationary sources include offices, warehouses, storage yards, quayside facilities, gate facilities, rail terminal facilities, buildings, parking spaces, manufacturing plants, industry plants, power plants, electrical grids, electric charging facilities, lighting, maintenance facilities, heating ventilation and air conditioning (HVAC) systems, etc. These stationary sources are not directly related to cargo movements, but may be associated with or support cargo or person mobility. Mobile sources include seagoing vessels, support vessels (e.g., tugs, push-boats, tenders, fireboats, pilot boats, police boats), cargo handling equipment, heavy-duty vehicles, light-duty vehicles, locomotives, etc. Table 1 summarises the seaport emission sources from the functionality perspective.

Table 1. Seaport emission source categorisation from a functionality perspective (based on [10]).

Emission Source Type	Specific Emission Sources
Mobile type	Seagoing vessels; support vessels; cargo handling equipment; heavy-duty vehicles; light-duty vehicles; locomotives
Stationary type	Offices; warehouse; storage facilities; quayside, gate, rail terminal facilities; electrical grid facility; electric charging facilities; buildings; parking spaces; manufacturing, industrial, power plants; lighting; maintenance facilities; heating ventilation and air conditioning

Focusing on mobile-type emission sources, the Port Authority of New York and New Jersey has published several annual air emission inventories from the emission source categories including cargo handling equipment, heavy-duty trucks, rail locomotives, ocean-going vessels, and harbour craft (tugs, tow boats, and push-boats). Table 2 gives the GHG emissions by different source categories in tonnes/year at the Port of New York and New Jersey in 2006 and in 2021, where CO_2e represents carbon dioxide equivalents [11]. The percentages indicate the emission shares by each category in that year. It can be observed that heavy-duty trucks and ocean-going vessels were the top two emission categories and had similar shares of emissions in 2006, but the category of heavy-duty trucks was significantly higher than other categories in 2021, which accounted for 49% of the total emissions. Nevertheless, the categories of ocean-going vessels and cargo handling equipment were also significant, with more than 20% share of the total GHG emissions each for both years. The implication is that the estimation of the emission inventories from different categories could shed light on the prioritisation of emission source categories for decarbonisation.

Table 2. Port GHG emissions by source category (tonnes/year) in 2006–2021 in Port of New York and New Jersey (based on [11]).

Source Category	CO_2e in 2006	CO_2e in 2021
Cargo handling equipment	154,184 (23.78%)	166,170 (20.16%)
Heavy-duty trucks	224,050 (34.56%)	403,806 (48.99%)
Rail locomotives	14,710 (2.27%)	27,691 (3.36%)
Ocean-going vessels	221,638 (34.19%)	191,104 (23.19%)
Harbour craft	33,703 (5.20%)	35,475 (4.3%)
Total	648,284 (100%)	824,245 (100%)

Another classification of emission sources is based on the reporting organisation's responsibility. The GHG Protocol set up the internationally accepted GHG accounting and reporting standards for business [12]. According to a company's organisational boundary regarding the operations under its control, GHG emissions are classified into three scopes. Scope 1 refers to the direct emissions generated onsite by the reporting company from owned or controlled sources, e.g., emissions from combustion in owned or controlled equipment, vehicles, boilers, furnaces, and production processes. Scope 2 accounts for the indirect GHG emissions from the generation of the purchased energy consumed by the reporting company, e.g., the emissions occurring at the facilities where the purchased electricity is generated. The definitions of scopes 1 and 2 ensure that the GHG emissions will not be double-counted in the same scope. Scope 3 accounts for all other indirect emissions that occur in the value chains of the reporting company, e.g., leased assets, employee commuting, business travel, waste generated in operations, upstream activities (such as extraction and production of purchased materials, transportation and distribution of purchased products, fuel, and energy-related activities), and downstream activities (such as transport and distribution of sold products, processing of sold products, use of sold products and services, end-of-life treatment of sold products) [12].

The classification of three GHG emission scopes provides a useful view on which emission sources are under the control of the reporting company and which emission sources are not directly controllable but may be influenced. In the context of seaports, the GHG emission sources could be mapped into three scopes, as shown in Table 3.

Table 3. Seaport emission source categorisation from emission scope perspective.

Scope	Emission Source Description
Scope 1 Sources	Fossil fuels used in port-owned vehicles (light-duty vehicles, support vessels) and employee vehicles for port business; Fossil fuels used in port-owned equipment such as cranes, folk lifts, diesel generators for electricity generation; Fossil natural gas used in port-owned buildings;
Scope 2 Sources	Purchased electricity used by the port-owned buildings and equipment such as cranes, pumps, charging stations, reefer containers, machineries in workshop and for building air conditioning, lighting, and other uses; Purchased steam used in port-owned buildings;
Scope 3 Sources	Energy used by port tenants (logistics companies, industries), seagoing vessels, external heavy-duty trucks, rail locomotives, cargo handling equipment that is not controlled by port, waste transport and disposal, employee business travel by air, and port employees commuting to and from work.

A couple of points are worth noting. Firstly, seaports could involve a wide range of different stakeholders and different seaports have different geographical and operational boundaries, which makes it very difficult for the seaport to influence the scope 3 emission sources. The classification of the emission sources in Table 3 is more suitable for operating ports (where the port authority owns and operates the maritime terminal facilities and equipment, or a terminal operator leases the land and develops and operates the port). It requires some adjustments to the scope 1 and 2 emission sources for landlord ports (where the port authority owns the port and terminal operators operate the port facilities).

Secondly, the assessment of the emission inventories in seaports may be extended to some hinterland sources such as roadways, freeways, highways, urban residential areas, factories, and service facilities. In particular, from the system perspective, the port may act as an energy hub that connects to offshore windfarms at sea and supplies energy to hinterland industrial sectors. The implication is that the scope 3 sources could be much broader, more complicated, and difficult to decarbonise.

Naturally, a seaport has its geographical boundary. It is therefore convenient to classify the port emission sources from the geographical location perspective into four categories: seaside, quayside, and yardside, landside interface, and landside industry and support facility, as shown in Table 4.

Table 4. Seaport emission source categorisation from geographical location perspective.

Geographical Location	Emissions Sources
Seaside	Seagoing vessels; support vessels such as tugs, push-boats, tenders, fireboats, pilot boats, police boats;
Quayside and yardside	Cargo handling equipment; quayside facility, storage facility; heavy-duty vehicles; light-duty vehicles; reefer charging;
Landside interface	Gate system; rail terminals; heavy-duty vehicles; light-duty vehicles; locomotives; cargo handling equipment;
Landside industry and support facility	Offices; electrical grid; warehouses; cargo handling equipment; buildings; parking spaces; lighting; maintenance facility; manufacturing, industrial, power plants; heating ventilation and air conditioning.

The usefulness of the categorisation in Table 4 is that it gives a clear indication of where the emissions are generated; as a result, more focused solution measures can be identified to reduce the emissions. We will use this categorisation in the next section when presenting the emission reduction measures in structured matrices. It should be noted that different types of cargo handling equipment may be used at different port geographical locations, e.g., ship-to-shore crane at quayside, yard crane at yardside, rail-mounted gantry crane at rail terminals in the landside interface, and fork lifts at the warehouses in the landside support facilities.

3. Emission Reduction Measures at Ports

A seaport may consist of several terminals, which specialize in handling different types of freight commodities, e.g., containers, dry bulks, tanks, and Ro-Ro. Ports and terminals are equipped with various material handling equipment and facilities for loading/unloading, storing and maintaining the freights, and serving vessels, trucks, and trains. Port emission reduction solutions may be classified into the following six structured categories.

1. Operational measures, which focus on improving operational efficiency in the port system to reduce fuel/energy consumption and better utilise energies;
2. Technical measures, which focus on improving energy efficiency of the vehicles and equipment through upgrading, retrofitting, or replacing existing machinery, vehicles, equipment, and engines, and adopting carbon capture systems (CCS);
3. Fuel and energy measures, which focus on adopting cleaner alternative fuels and energies such as biofuels, hydrogen, electricity, solar power, and wind energy;
4. Infrastructural measures, which focus on the changes of port infrastructure and facilities to support emission reductions, e.g., port/terminal redesign and expansion for modal shift by increasing the use of rail services and barge services, cold ironing to provide shore power to vessels, and installing new electrical infrastructure to support equipment electrification;
5. Digitalisation measures, which focus on the applications of digital technologies to automate processes, collate reliable data, and implement artificial intelligence to support operational and technical measures;
6. Policy and collaboration measures, which focus on relevant legal regulations, incentive programs, financial investment, insurance policies, and cross-function, cross-company, and cross-sector collaborations that would impose, accelerate, and facilitate the adoptions of the solutions in other categories.

The solution measures in the first three categories are more fundamental and have a direct impact on emission reduction at ports, whereas the solution measures in the last three categories are more like enablers and facilitators that support the development and implementation of the solution measures in the first three categories. Nevertheless, some solution measures cut across different categories or may be classified into multiple categories. In the following, we provide a more detailed discussion on how these solution measures could be used to decarbonise the emission sources in each emission source category according to the geographical location: seaside, quayside and yardside, landside interface, landside industry, and support facility. It should be pointed out that there are some correlations among these geographical locations regarding emission reduction measures, e.g., some measures cut across two or more locations, so the effectiveness of the measures in one location may be affected by the measures in other locations.

3.1. Seaside

Emissions from the seaside are mainly from seagoing vessels and support vessels (e.g., tugs, push-boats, tenders, fireboats, pilot boats, police boats). In many seaports, seagoing vessels are the main source of port emissions, which can account for up to 69% depending on the port characteristics [13]. Seaside vessel activities occur in five traffic areas: sailing in the area close to port, anchorage area, port basin, manoeuvring, and berthing [14]. GHG emissions are generated by a vessel's main and auxiliary engines in the first four traffic areas, whereas during the berthing period, the main engine is switched off and only the auxiliary engines are used. We summarise the relevant solution measures, including the cases and effects in Table 5, and explain these measures below.

The operational measures to reduce vessel emissions at port areas include the following: slowing ship speed, just-in-time arrival, reducing port time, and training ship crew and port pilots. Slowing down the vessel speed is an effective way to reduce fuel consumption and therefore emissions; this measure has been widely adopted and documented, especially in the circumstances of vessel overcapacity in order to cut vessel fuel consumption cost. Slowing speed from 18–25 knots to 12 knots near the port would reduce the main engine load factor from 80% to 10% [15]. Vessel just-in-time arrival is also termed virtual arrival, which refers to the practice of the vessel slowing down in anticipation of the congestion and waiting at the next port of call. Jia et al. [16] evaluated 5066 voyages by 483 very large crude carriers between 44 countries and estimated the emissions could be reduced by 7% to 19% if the just-in-time arrival measure were adopted. It is well-known that vessels spend a significant amount of time at ports. Johnson and Styhre [17] conducted a case study of a dry bulk carrier and reported that more than 40% of the vessel time was spent at ports and half of the time at ports was unproductive. They stated that even if only one to four hours of port time per port call could be reduced, the vessel energy usage would be reduced by 2–8%. Paulauskas et al. [18] examined the influence of ships' crew and ports pilots' qualification on ship manoeuvring time. They reported that appropriate education and training could reduce ship manoeuvring time significantly and reduce emissions from ships up to 12.5%.

The technical measures to reduce emissions from vessels include the following: hull design (e.g., shape, material, coating), propulsion system (e.g., hybrid power, machinery, waste heat recovery), onshore power, and carbon capture and storage. Optimising the vessel dimensions and form may achieve 2–30% reduction in CO_2, and the use of lightweight materials could reduce CO_2 emission by 0.1–22% [19]. The adoption of hybrid electric auxiliary power and propulsion can reduce CO_2 emission by 2–45%; the use of waste heat recovery may achieve 1–20% CO_2 reduction [19]. Onshore power is also called cold-ironing. When vessels are docked at port, the vessel's diesel-fuelled auxiliary engines will provide power to maintain essential vessel functions such as lights, heating, and cooling. Onshore power refers to the process of providing electrical power from the shore supply to the docked vessel so that the vessel's auxiliary engines can be turned off. This practice can reduce CO_2 emissions by over 30% [15]. Carbon capture and storage (CCS) is the process of capturing CO_2 from emissions and then permanently storing them deep underground or utilising captured carbon to create other products. The Japanese shipping giant Mitsubishi Shipbuilding has developed a ship-based carbon capture system that can reduce ship emissions by up to 90% (www.potterclarkson.com, accessed on 10 December 2023). The EverLoNG project installed a ship-based carbon capture system on an LNG-powered LNG carrier, which achieved a 70% reduction in CO_2 emissions from the vessel (www.ukpandi.com, accessed on 10 December 2023).

The fuel and energy measures seek to use alternative cleaner fuels or energies to power vessels, which has more fundamental impact on the shipping industry and the vessel GHG emissions. According to DNV, 99.39% of world vessel fleet in operation are still using conventional fuels, with 0.48%, 0.10%, 0.03%, and 0.01% of ships in operation using LNG, LPG, methanol, and hydrogen, respectively (https://afi.dnv.com, accessed on 10 December 2023). LNG and LPG are low-carbon fossil fuels which can reduce CO_2 emissions by up to 20%, but they are regarded as transition fuels for ships. Biofuel is regarded as a renewable energy source; it can be derived from microbial, plant, or animal materials. Biofuels include bio-ethanol, bio-methanol, biodiesel, and straight vegetable oil. It can reduce GHG emissions in shipping by 25% to 100% [20]. However, there is a concern over the availability of biofuels because their supply will not be adequate to power the entire global marine fleet [20]. E-fuels are produced from renewable electricity and take either gas or liquid form. Examples of e-fuels include E-LNG, E-diesel, E-ammonia, E-methanol, and hydrogen. E-fuels can achieve 90-100% CO_2 reduction and will play an important role as ship fuels from a long-term perspective [21]. Full electric vessels are powered by battery and enable zero carbon emission. It is attractive to decarbonise ferries, tugs, pleasure boats, and inland waterway vessels that are sailing for short distances (www.wartsila.com, accessed on 10 December 2023).

The infrastructure measures are needed to support emission reduction from vessels. For example, port-side infrastructure must be in place to supply electricity to vessels to implement onshore power solutions [15]; charging facilities are required to support battery-powered vessels; and relevant infrastructure should be installed to offload and process the captured CO_2 under the CCS solution. Ports also need to construct infrastructural facilities to store and supply alternative fuels when vessels require refuelling.

The digitalisation measures at seaside include the applications of digital technologies to improve vessel operational activities, e.g., automated mooring systems can reduce ship manoeuvring time significantly [22]; the use of mobile satellite communication enables seamless connectivity between vessels and port operators; the use of machine learning and artificial intelligence such as Metocean Data Analysis by the company Sinay can simulate and predict weather patterns to improve vessel operations (https://sinay.ai, accessed on 10 December 2023).

The policy and collaboration measures related to seaside activities include regulations, incentive schemes, and collaborative agreements to enforce or facilitate emission reductions from vessels. IMO has issued several mandatary measures such as Energy Efficiency Design Index (EEDI), Energy Efficiency eXisting ship Index (EEXI), Carbon Intensity Indicator (CII), and Ship Energy Efficiency Management Plan (SEEMP) to specify the energy efficiency of the vessels, the carbon intensity in ship operations, and ship management plan to meet CII requirements (www.imo.org, accessed on 10 December 2023). However, these regulations are mainly applied to the vessels above 400 gross tonnage (GT). From January 2024, the EU's Emissions Trading System (EU ETS) will be extended to CO_2 emissions from all ships over 5000 GT entering EU ports (climate.ec.europa.eu, accessed on 10 December 2023). At the port level, individual ports have initiated incentive schemes, such as the Green Flag Program at Los Angeles and Long Beach, to give a 15-25% reduction in port fees if vessels reduce their speed to a certain level near the ports, and the Green Passports Scheme at multiple European ports, to give up to a 10% reduction in port fees to vessels meeting the Environmental Ship Index (ESI) threshold. Ports may collaboratively encourage vessels to adopt cleaner fuels, e.g., the World Ports Climate Action Program issued by 12 major ports across the world (www.hellenicshippingnews.com, accessed on 10 December 2023).

Table 5. Categorised solution measures to reduce port seaside emissions.

Measures	Cases and Effect	References
Operational		
Slowing ship speed	Container ships at Los Angeles and Long Beach; engine load factor reduced from 80% to 10%.	[15]
Just-in-time arrival	483 very large crude carriers; 7–19% emission reduction	[16]; bluevisby.com (accessed on 10 December 2023)
Reducing port time	Dry bulk ships in North and Baltic seas; 2–8% energy reduction	[17]
Training ship crew and port pilots	Tanker vessel at Klaipeda port; 12.5% emission reduction from ship manoeuvres	[18]
Technical		
Hull design, e.g., shape, material, coating	Various vessels; 1–30% CO_2 reduction	[19]
Propulsion system, e.g., hybrid power, machinery, waste heat recovery	Various vessels; 1–45% CO_2 reduction	[19]
Onshore power	Many ports including Gothenburg; Seattle; Vancouver; Antwerp; Southampton; Port of Koper; 30% emission reduction	[15,23]

Table 5. *Cont.*

Measures	Cases and Effect	References
Carbon capture and storage	LNG carrier; Mitsubishi Shipbuilding; 70–90% CO_2 reduction	www.ukpandi.com; www.potterclarkson.com (accessed on 10 December 2023)
Fuel and energy		
LNG	Various vessels; 15–20% CO_2 reduction	[24]
LPG	Very large gas carriers; 17% CO_2 reduction	[21]
Wind-assisted propulsion systems Nuclear-powered ship	Fruit juice tanker by Bound4Blue; 10% CO_2 reduction Icebreaker; Cargo ships; be carbon neutral	[25] [26]
Biodiesel	Various vessels; 25–100% GHG reduction	[20,27]
E-LNG	MSC Cruises; 98% CO_2 reduction	[21]; maritime-executive.com (accessed on 10 December 2023)
E-Diesel	Ferries; 90–99% CO_2 reduction	[21]; www.mtu-solutions.com (accessed on 10 December 2023)
E-Ammonia	Under development; 98% CO_2 reduction	[21]; www.zerocarbonshipping.com (accessed on 10 December 2023)
E-Methanol	Containership; 99% CO_2 reduction	[21,28]
Hydrogen; Battery	Ferries; tugs; 100% CO_2 reduction	[21,29]; www.wartsila.com (accessed on 10 December 2023)
Infrastructural		
Port infrastructure to supply electricity	Gothenburg; Seattle; Vancouver; Antwerp; Southampton; support onshore power- and battery-powered vessels	[15]; www.wartsila.com (accessed on 10 December 2023)
Port infrastructure to handle captured CO_2	Immingham in UK; support carbon capture storage and utilisation	www.ukpandi.com (accessed on 10 December 2023)
Bunkering facilities	Many major ports; support refuelling alternative fuels	[30]; bunkerpay.co.uk; maritimefairtrade.org (accessed on 10 December 2023)
Digitalisation		
Automated mooring systems	Port of Santander; reduce CO_2 emission by 76%	[15,22]
Mobile satellite communication	Inmarsat; Ensure seamless connectivity across the globe	https://sinay.ai (accessed on 10 December 2023)
Metocean Data Analysis	Sinay; Simulate and understand weather patterns	https://sinay.ai (accessed on 10 December 2023)
Policy & collaboration		
EEDI; EEXI	All ships above 400 gross tonnage; One-time certification on vessel energy efficiency	www.imo.org (accessed on 10 December 2023)
CII	All ships above 5000 GT; Annual requirement to calculate ship's carbon intensity indicator	www.imo.org (accessed on 10 December 2023)
SEEMP	All ships above 5000 GT; Ship management plan to meet CII requirements	www.imo.org (accessed on 10 December 2023)
EU ETS	All ships above 5000 GT entering EU ports; Define maximum GHG emission	climate.ec.europa.eu (accessed on 10 December 2023)
Green Flag Program	Los Angeles; Long Beach; 15–25% port fee reduction for reducing vessel speed	[15]
Green Passports Scheme up to 10% port fee reduction	Amsterdam; Hamburg; Rotterdam; Antwerp; Bremen; Le Havre; Meet Environmental Ship Index threshold	[15]
World Ports Climate Action Program	A total of 12 major ports across the world; Accelerate alternative fuels uptake	hellenicshippingnews.com (accessed on 10 December 2023)
Port green incentives	A total of 28 of the 100 world's largest ports; Incentive for environmentally friendly ships	[31]

3.2. Quayside and Yardside

The main emission sources at port quayside and yardside are the cargo handling equipment and facilities, such as quay cranes, yard cranes, internal moving vehicles, and reefer plugin charges. Cranes and vehicles traditionally use diesel fuels, whereas reefer plugin charges consume a significant amount of electricity. We present the relevant solution measures to mitigate GHG in quayside and yardside areas from six solution categories below and summarise them in Table 6.

The operational measures at quayside and yardside include berth allocation planning, quay crane assignment and scheduling, cargo loading and unloading, vessel stowage planning, internal moving vehicle scheduling, yard storage management, yard crane scheduling, container reshuffling/relocation, workforce scheduling, and coordination of equipment operations between quayside. The improved efficiency and productivity of quayside and yardside cargo handling equipment implies the reduction in fuel consumption and emissions. The vast majority of the studies on port operation optimisation belong to this category. A few survey papers, e.g., [32–34], have reviewed the literature on the applications of operation research techniques to optimise the port logistics processes, including ship stowage planning, yard storage and space allocation, crane scheduling, and internal moving vehicle scheduling. Acciaro et al. [35] analysed two European ports, Hamburg and Genoa, and stated that an appropriate energy management system could coordinate and match port energy need and supply so that substantial energy efficiency can be achieved. Lam et al. [36] simulated the energy consumption for container movements including unloading from vessels, inbound movements, RMG movements at yard, outbound movements, and loading onto vessel. An energy management system is presented to use renewable energy production by solar cells to reduce the peak energy demand. Zhang et al. [37] presented a unified framework to integrate the seaside/yard operations and the port energy system management for energy efficiency considering onshore power supply and microgrid.

The technical measures at quayside and yardside include replacing and repowering older and dirtier diesel engines in ports, which was initiated by the US Environmental Protection Agency [38]. The Port of Koper deployed nine electrified quay cranes [23]. Rubber Tired Gantries (RTGs) could be modified to save energy consumption by utilising the regenerative power from the gravitational potential energy released when a container is lowered [39]. Converting traditional RTGs to electric RTGs has been applied in many ports and can achieve up to 64% GHG reduction [40].

Fuel and energy measures: A terminal operator in the port of Hong Kong was trialling the use of hydrotreated vegetable oil (HVO) in three types of cargo handling equipment: RTG crane, reach stacker, and empty stacker from October 2023 (www.portstrategy.com, accessed on 15 December 2023). Several UK ports have also deployed HVO as the drop-in fuels for port cargo handling equipment. In July 2023, RWE, Mitsui, and the Port of Tilbury formed a partnership to initiate a project to investigate green hydrogen for port equipment by switching from fossil fuels to hydrogen (www.forthports.co.uk accessed on 15 December 2023).

Infrastructural measures: When the Port of Koper purchased nine electrified quay cranes, seven electrified RTGs, and three new RMGs in 2017, there was an infrastructure requirement of the 20 kV electrical network [23]. The use of low-carbon alternative fuels (such as HVO) for port equipment may require the rebuilding of fuel storage and distribution infrastructure [41]. The deployment of hydrogen equipment and its derivatives at port also requires building infrastructure to safely store and transport molecular hydrogen. Due to the continuous workloads, green vehicles (either electric or fuel cell) at quayside and yardside may have to visit the stations frequently [42]; this requires the installation of infrastructural stations for energy charging and refuelling. Another infrastructure measure is to re-design port layouts and facilities so that in-port travel distances can be minimised [23] and the efficiency can be improved.

Digitalisation measures: Digitalisation measures such as machine learning and artificial intelligence have been examined to improve port operations. For example, researchers have turned to data analytics to predict the vessel arrival reliability to support terminal operators in better managing quayside resources such as berths, quay cranes, and human resources (e.g., [43]). Predictive data analytics have also been applied in the container yard to predict the container dwell time of import containers (e.g., [44]). Such predictive information is useful to reduce truck waiting time and container reshuffling in the container yard. Feng et al. [45] developed a data-enabled smart stacking strategy, where customer information of the import containers is utilised when containers are stored at container yards so that the number of container reshufflings can be minimised. The idea is motivated by the Import Free Flow program implemented at the Port of Los Angeles.

Policy and collaboration measures: Port investment, such as infrastructure and facilities, may require compliance with legislation and national requirements [23]. The US EPA provided the Diesel Emission Reduction Act (DERA) grants to support seaports to retrofit the existing cargo handling equipment with emission reduction devices, or repower the dredge with new auxiliary and main engines. The new engines can reduce GHG emissions by 40% [46]. Within the World Ports Climate Action Program (https://sustainableworldports.org/wpcap, accessed on 15 December 2023), Working Group 5 was founded in 2019 with the aim of accelerating efforts to decarbonise the cargo handling facilities in ports by sharing up-to-date information on the applications of zero-emission terminal cargo handling equipment (including RMG, RTG, quay crane, yard truck, and container lifts). Kim et al. [47] examined the effect of a horizontal collaborative scenario by consolidating five independent container terminals in Busan New Port to pool the resources and reduce vessel waiting times.

3.3. Landside Interface

The port landside interface refers to the connecting areas between inland transport and port/terminal. External trucks access the port via gates, whereas trains access the port via seaport rail terminals. Therefore, the decarbonisation in the landside interface focuses on trucks, trains, associated equipment, and facilities. The relevant solution measures to mitigate GHG in landside interface areas for six solution categories are discussed below and summarized in Table 7.

Operational measures: The efficiency of gate operations can be improved through a variety of strategic, tactical, and operational planning measures including gate layout design, vehicle booking systems (i.e., truck appointment systems), extended gate hours, automated gate systems, optimising vehicle use and loading, and empty equipment (vehicle or container) logistics ([1,48,49]; www.epa.gov, accessed on 20 December 2023). For example, appropriately controlling truck arrivals can reduce congestion and emissions at the gates [48]. Extended gate hours can reduce peak period activity and avoid road congestion and long waiting times at ports. Empty container repositioning and empty vehicle runs not only incur costs but also generate emissions and congestion. Minimising empty container repositioning and optimising vehicle use and loading are effective measures to cut costs and reduce emissions [49]. The efficiency of rail service operations can be improved through rail terminal layout design, rail service slot scheduling, wagon shunting, container pre-staging, and equipment coordination. Xie and Song [50] optimised the container prestaging and dynamic discharging/loading at seaport rail terminals under uncertainty and showed that appropriate pre-staging can reduce the expected cost and avoid the misses of import containers that are designated to the trains.

Technical measures: Most American seaports have initiated replacement/retrofit programs for diesel and gasoline vehicles with hybrid or alternative fuel-powered vehicles [46]. Hutchison Ports introduced Westwell's Q-Trucks in Thailand's Laem Chabang Port in 2020, and then rolled the system out in the UK by deploying 100 autonomous electric trucks in Felixstowe port in 2023. The electric trucks can increase the operational efficiency and consistency and contribute to decarbonising port operations (www.eadt.co.uk, accessed on 20 December 2023). In several US ports, such as New York/New Jersey, Corpus Christi, and Long Beach, locomotives are retrofitted to decrease diesel emissions [46].

Table 6. Categorised solution measures to reduce emissions at quayside and yardside.

Measures	**Cases and Effect**	**References**
Operational		
Berth allocation planning, quay crane assignment and scheduling, cargo loading and unloading, vessel stowage planning, internal moving vehicle scheduling	Quayside at most ports and terminals; Operational efficiency	[32–34]
Yard storage management, yard crane scheduling, container reshuffling/relocation, workforce scheduling, coordination of equipment operations between quayside and yardside	Yardside at most ports and terminals; Operational efficiency	[32–34]
Energy management system	Hamburg; Genoa; Singapore; Energy efficiency	[35,36]
Integrated operations and energy systems	Yangshan Port in Shanghai; Energy efficiency	[37]
Technical		
Replacing and repowering older, dirtier engines in ports	US port; Energy efficiency	[38]
Electrify ships to shore gantry cranes	Port of Koper	[23]
RTG with regenerative power	Port of Tokyo; 40% emission reduction	[39]
Electric RTG; lithium battery hybrid RTGs;	Port of Tokyo; Port of Busan; Port of Shanghai; 64% GHG reduction	[39,40]
Fuel and energy		
Hydrotreated Vegetable Oil (HVO)	Hong Kong; Liverpool; up to 90% CO_2 reduction	www.crownoil.co.uk; www.portstrategy.com; (accessed on 15 December 2023)
Hydrogen	Port of Tilbury; Port of Los Angeles; many other ports	[42]; www.forthports.co.uk (accessed on 15 December 2023)
Infrastructural		
Electricity network	Port of Koper; To power electrified equipment	[23]
Rebuild storage and distribution infrastructure for new fuels and hydrogen	Many ports in Europe and US	[41]; www.forthports.co.uk (accessed on 15 December 2023)
Electric vehicle charging stations	Shanghai Yangshan port	[42]
Fuel cell vehicle refuelling	Port of Los Angeles	[42]
Re-designing port layouts and facilities	Port of Koper; Reduce in-port travel distances	[23]
Digitalisation		
Predict vessel arrival lateness	Mediterranean container terminal; quayside resource management	[43]
Predict container dwell time	Container terminal in the Middle East; reduce yard congestion	[44]
Customer information-based smart stacking	Port of Los Angeles; Import free-flow to reduce reshuffling and waiting times	[45]
Policy and collaboration		
Legislation and national requirements	Port of Koper; facilitate long-term investment	[23]
Diesel Emission Reduction Act grant	US ports, e.g., Port of Portland; Repower cargo handling equipment and dredge	[46]
World Ports Climate Action Program	Long Beach, Los Angeles, New York, Valencia, Vancouver, Yokohama; Decarbonise port equipment	sustainableworldports.org (accessed on 15 December 2023)
Container terminals collaboration	Busan New Port; Reduce vessel waiting time	[47]

Fuel and energy measures: Truck electrification with batteries has been applied in many countries. However, it is only feasible for trucks for short-distance transportation due to the relatively low energy density of the current battery technologies [51]. The Port of Houston started a pilot program to use hydrogen-powered trucks to transport 20-foot containers in December 2022. It is noted that the hydrogen fuel cells are larger than traditional engines, which led to smaller carry capacity compared to diesel-powered trucks (www.houstonchronicle.com, accessed on 20 December 2023). Houston is one of the largest producers of hydrogen in the US. It is expected that hydrogen can help decarbonise the shipping and trucking sectors.

Infrastructural measures: Brittlebank [38] reported that Siemens' eHighway system aimed to electrify selected highway lanes to supply external trucks with electric power near the Ports of Los Angeles and Long Beach via a catenary system. The Port of Gothenburg in Sweden expanded a double-track rail line in 2020 to increase rail service capacity and prompt modal shifts of cargo from road to rail [52]. The Port of Barcelona promoted a railway line to transport automotive components and new cars between the port facilities and the inland factory plant [52].

Digitalisation measures: In July 2023, Hamburger Hafen und Logistik AG (HHLA) deployed a digital solution at Hamburg to allow truckers to access its terminals in a more efficient way; this solution used a passify app to replace the existing truck card (www.portstrategy.com, accessed on 20 December 2023). As a result, the waiting time of external trucks at the port has been reduced. Two companies, driveMybox and IBEXUS, formed a partnership in November 2023, aiming at developing a secure method to store and validate emission data for container trucks by utilising blockchain technology and a digital container tracking platform (www.portstrategy.com, accessed on 20 December 2023). Predictive models such as deep belief net and support vector machine have been used to predict external truck arrivals, which can improve the terminal efficiency [53]. The Port of Antwerp initiated the Intermodal Solution and Connectivity Platform, which is an online tool designed to inform users about transport options to and from the port of Antwerp. As a result, a better synchronisation between port stakeholders and a smoother connectivity between the port and the hinterland can be achieved [52].

Policy and collaboration measures: Taiwan set up an emission standard regulation for diesel vehicles in 2013, under which all heavy-duty diesel vehicles must pass the test of the A5 standard to obtain a one-year pass to access seaports [54]. California's air regulator issued a new rule in 2023 that trucks bought for use in the state's ports and rail yards must be zero-emission (e.g., electric model powered by batteries or hydrogen fuel cells) from 2024, and every California drayage vehicle must be a zero-emission vehicle by 2035 (www.wired.com, accessed on 20 December 2023). The modal shifting policies can take international, national, and local perspectives. For example, internationally, the EU White Paper on Transport provided a roadmap towards a resource-efficient transport system and cut CO_2 emissions, including modal shifts, with the goals of shifting 30% of road freight to rail or water transport by 2030 (eur-lex.europa.eu, accessed on 20 December 2023). Nationally, the French Government initiated projects to promote modal shifts for the freight from the Port of Marseille-Fos to the region (www.marseille-port.fr, accessed on 20 December 2023). Locally, the Port of Rotterdam has included modal split obligations in concession contracts with container terminals since 2015 in order to promote modal shift to less polluting modes of transportation [55].

3.4. Landside Industry and Support Facility

Seaports not only act as an interface connecting seaborne transport to inland transport, but they often also accommodate multiple industrial sectors (e.g., logistics, manufacturing, energy industry, oil refineries, chemical industry) and are equipped with various supporting facilities and systems (e.g., electrical grid, warehouses, buildings, parking spaces, lighting, maintenance facility, heating ventilation and air conditioning). For example, in the port of Rotterdam, there are more than 120 industrial companies and a strong petrochemical cluster (www.portofrotterdam.com, accessed on 5 January 2024). We classify the relevant solution measures to mitigate GHG in landside industry and support facilities into six solution measure categories and summarise them in Table 8.

Table 7. Categorised solution measures to reduce emissions at port landside interface.

Measures	Cases and Effect	References
Operational		
Gate layout design, Vehicle booking systems, Extended gate hours, Automated gate systems, Vehicle use and loading, Empty equipment logistics	Many ports in China, Europe, and US; Improve efficiency of gate operations	[1,48,49]; www.epa.gov (accessed on 20 December 2023)
Rail terminal layout design, Rail service slot scheduling, Wagon shunting, Container pre-staging, Loading/unloading trains	Felixstowe in the UK; Container port in Italy; Improve efficiency of rail terminal operations	[1,50,56]
Technical		
Replacement/retrofit program	Most American seaports	[46]
Electric trucks	Laem Chabang Port; Felixstowe	www.eadt.co.uk (accessed on 20 December 2023)
Retrofitted locomotives	Ports of New York/New Jersey, Corpus Christi and Long Beach; decrease diesel emissions	[46]
Fuel and energy		
Battery	Road transport in many countries	[51]
Hydrogen	Port of Houston	www.houstonchronicle.com (accessed on 20 December 2023)
Infrastructural		
Electrified roadways	Los Angeles and Long Beach	[38]
Modal shift	Port of Gothenburg; Barcelona	[52]
Digitalisation		
Digital solution for truck access	Hamburg	www.portstrategy.com (accessed on 20 December 2023)
Blockchain technology	driveMybox and IBEXUS	www.portstrategy.com (accessed on 20 December 2023)
Predict truck arrival or delay	Jinzhou Port; increase port efficiency	[53]
Antwerp Intermodal Solution	Port of Antwerp	[52]
Policy and collaboration		
Vehicle emission standards	Taichung Port	[54]
Rule by California's air regulator	California drayage vehicle	[57]
Modal shift policies at international, national, local levels	European ports	[52,55]

Operational measures: Tsai et al. [54] presented a port self-management framework to reduce GHG emissions in Taichung Port, taking the port system perspective. The geographic locations and boundary of the self-management area include a heavy industry region (power plant and steel plant), export-processing region, and harbour area. The emission reduction actions include a vessel speed reduction program, using high-performance lamps, energy-saving programs for offices, vehicle emission standard enforcement, automated vehicle inspection systems, enforced emission reduction for nonmarine industries, deploying wind and solar power, and LNG cold energy power development. Manolis et al. [58] proposed a distributed demand response application to improve voltage regulation in the electricity distribution network in a port city. They used a multi-agent system to achieve efficient power management by controlling the reefers' energy consumption according to the voltage in the network. This essentially levels the energy consumption and mitigates peak and valley. It showed that active power management systems could lead to greener and sustainable ports. The port of Singapore developed the digitalPORT system to provide a one-stop platform for port call transactions and regulatory clearance for better operational efficiency [30].

Technical measures in port landside industry and support facilities include energy-saving actions in office design, improving emission standards for equipment and industries, installation of monitoring sensors, upgrading and replacing equipment and facilities, and the use of natural ventilation and hybrid hydraulic drive systems [39,54].

Fuel and energy measures associated with port landside industry and support facilities are closely related to the generation and utilisation of renewable energy. Renewable energy will play a critical role in decarbonising seaports and other industrial sectors. Seaports are well-positioned for power generation from renewable sources such as onshore wind, offshore wind, waves, tide differentials, geothermal energy, and solar panels [35,59]. In that sense, seaports could be developed into an energy hub. An energy hub may be defined as a geographical concentration area with high-energy demand and supply activities, where energy-intense industries, power generation, distribution, and related activities and projects are co-located [35,60].

Infrastructural measures are required to ensure power availability and meet the requirements from port operations, typically from the national grid [35]. Renewable energy generated from wind, solar panels, and harbour waste at port can be provided through a direct current microgrid to support the electricity needs for port operations. Here, microgrids refer to the decentralised electrical grids that combine clusters of loads and parallel distributed generation systems in a local area [61].

Digitalisation measures: The smart grid is an emerging concept based on smart meters and digital technologies to supply electricity to port electricity users via two-way digital communication. The smart grid allows for near-real-time monitoring, analysis, control, and communication within the electricity supply chain from generation and distribution to consumption in order to improve energy efficiency and reduce costs [60,62]. In October 2023, Nokia and EGC deployed a private wireless network at a Caribbean port to provide connectivity and enable digital solutions (www.portstrategy.com, accessed on 5 January 2024). The concept of a smart port aims to utilise smart technologies and digitisation to achieve port sustainability considering economy, climate, and people simultaneously. The port of Antwerp developed a digital platform to support innovation and collaborations across start-ups, scale-ups, accelerators, investment funds, government, and knowledge institutions (www.portofantwerpbruges.com, accessed on 5 January 2024). The port of Singapore initiated the Maritime Data Hub, which acts as a one-stop data repository and centralised data exchange platform in order to enable the integration of Singapore with the global trade ecosystem [30].

In terms of policy and collaboration measures, Taiwan Environmental Protection Agency (EPA) established a set of regulations and counselling methods to enforce the new manufacturers entering the port area or existing industries in the port area to meet low-carbon requirements [54]. The Port of Long Beach initiated a community program to mitigate port-related air pollution. The program provided grants to support renewable energy, replace traditional equipment, and use energy-efficient lighting. Moreover, the Port of Long Beach also launched an energy policy to collaborate with port tenants, utilities, city departments, industry stakeholders, labour unions, and the Port of Los Angeles in order to achieve a more sustainable and resilient supply of energy and match the increasing power demand at the port [46]. The Port Community System (PCS) can be regarded as a collaboration measure. It is defined as an open electronic collaborative platform that connects ports' various stakeholders such as port operators, customs agencies, ocean carriers, logistics companies, and freight forwarders to enable operational data exchange and consolidation within the port network, which can lead to quicker decisions and streamlined operations. For example, Dubai's PCS helped avoid 12.7 million physical visits of logistics service providers at the port and save over 1.7 million kg CO_2 (www.worldbank.org, accessed on 5 January 2024). International Association of Ports and Harbours (IAPH) is a non-governmental organisation (NGO) representing over 170 ports in 84 countries. One of its aims is to act as the industry reference for sharing best practices, such as innovations in energy transition, emission reduction measures at ports, and ship-to-shore interfaces (www.iaphworldports.org, accessed on 5 January 2024).

To provide a clearer academic landscape on the predominant themes and methodologies in the current research, we summarise the reviewed studies on port decarbonisation in Table 9 by six solution measure categories.

Table 8. Categorised solution measures to reduce emissions at landside industry.

Measures	Cases and Effect	References
Operational		
Port self-management framework	Taichung Port; Emission reduction across port geographic locations	[54]
Distributed energy management	Voltage regulation via multi-agent system; Be greener and sustainable ports	[58]
digitalPORT	Singapore; one-stop platform for port call transactions and regulatory clearance	[30]
Technical		
Full wall panels in office design; motion sensors; natural ventilation	Taichung port; Singapore; Save energy	[39,54]
Use of hybrid hydraulic drive systems	Singapore; Reduce fuel consumption by 20%	[39]
Fuel and energy		
Wind	Rotterdam; Kitakyushu in Japan	[35]
Waves	Port Kembla in Australia; Mutriku in Spain	[59]
Tide differentials	Dover in UK, Digby in Canada, Ribadeo in Spain	[63]
Geothermal energy	Hamburg	[35]
Solar panels/farms	Tokyo Ohi Terminal; Port of San Diego; Milford Haven	[35,60,62]
Infrastructural		
National grid	Ensure power availability for port electricity need	[35]
Microgrids	Port of Chennai	[61]
Digitalisation		
Smart grids	Milford Heaven	[62,64]
Private wireless network	Caribbean port	www.portstrategy.com (accessed on 5 January 2024)
Smart port	Port of Antwerp-Bruges	www.portofantwerpbruges.com (accessed on 5 January 2024)
Maritime Data Hub	Port of Singapore	[30]
Policy and collaboration		
Regulation by Taiwan Environmental Protection Agency	Taichung Port; Equipment certified by Taiwan EPA and emission reduction for nonmarine industries	[54]
Community programs; Energy policy	Ports of Long Beach; To support renewable energy and collaboration	[46]
Port Community Systems	Many ports, e.g., Dubai, Djibouti; Port of Koper; facilitate information sharing	[65]; www.worldbank.org (accessed on 5 January 2024)
International Association of Ports and Harbors	Global alliance of over 170 ports; facilitate sharing best practices	www.iaphworldports.org (accessed on 5 January 2024)

Table 9. Summary of studies by solution measure categories for port decarbonisation.

Measure Category	References
Operational measures	[1,15–18,30,32–37,48–50,54,56,58]; bluevisby.com; www.epa.gov (accessed during 10 December 2023–5 January 2024)
Technical measures	[15,19,23,38–40,46,54]; www.ukpandi.com; www.potterclarkson.com; www.eadt.co.uk (accessed during 10 December 2023–5 January 2024)
Fuel and energy measures	[20,21,24–29,35,42,51,59,60,62,63]; maritime-executive.com; www.mtu-solutions.com; www.zerocarbonshipping.com; www.wartsila.com; www.crownoil.co.uk; www.portstrategy.com; www.forthports.co.uk; www.houstonchronicle.com (accessed during 10 December 2023–5 January 2024)
Infrastructural measures	[15,23,30,35,38,41,42,52,61]; www.wartsila.com; www.ukpandi.com; bunkerpay.co.uk; maritimefairtrade.org; www.forthports.co.uk (accessed during 10 December 2023–5 January 2024)
Digitalisation measures	[15,22,30,43–45,52,53,62,64]; https://sinay.ai; www.portstrategy.com; www.portofantwerpbruges.com (accessed during 10 December 2023–5 January 2024)
Policy and collaboration measures	[15,23,31,46,47,52,54,55,57,65]; www.imo.org; climate.ec.europa.eu; hellenicshippingnews.com; www.worldbank.org; sustainableworldports.org; www.iaphworldports.org (accessed during 10 December 2023–5 January 2024)

4. Case Studies

The previous section provides a wide range of specific solution measures to mitigate GHG emissions in seaports. However, it does not offer sufficient insight into the pathways towards net zero. Case studies can be useful to obtain in-depth knowledge of how individual seaports are moving towards net zero. The UK government published "Maritime 2050" and "Clean Maritime Plan", which set out its ambition to achieve clean maritime growth with a transition to zero emissions. The UK aims to be a world leader in the zero-emission maritime sector. Most major ports in the UK have committed to achieving net-zero carbon emissions from its operations by 2040 or earlier. In this section, we mainly take the representative ports in the UK as case studies to discuss their decarbonisation practices and pathways towards net zero. The selected case ports are all large ports scattered around the UK coastline, including the Port of Felixstowe (located in the southeast of England), Port of London (located in the UK's capital), Port of Immingham (located in the northeast of England), Port of Milford Haven (located in Wales, in the west of the UK), Port of Liverpool (located in the northwest of England), and Port of Southampton (located in the south of England). Moreover, we also present three international case studies using the ports of Singapore, Los Angeles, and Rotterdam to represent Asia, America, and Europe. This may provide a comparison of decarbonisation measures and targets across different geographical and regulatory contexts and offer a more globally applicable insight.

4.1. Port of Felixstowe

The Port of Felixstowe (www.portoffelixstowe.co.uk, accessed on 18 November 2023) is the largest container port in the UK. The port is owned and operated by Hutchison Ports UK. It handles over 4 million TEUs (twenty-foot equivalent units) each year. In terms of tonnage, the Port of Felixstowe moved over 22.20 million tonnes in 2022.

Hutchison Ports has set targets to achieve global net zero emissions by 2050, and achieve net zero of scope 1 and scope 2 emissions by 2035 for three of its UK ports: Port of Felixstowe, Harwich International, and London Thamesport. Decarbonisation measures at the Port of Felixstowe include the following:

- **Operational measures**: The Port of Felixstowe has been involved in various research projects to pursue optimisation for quayside operations, yardside operations, vehicle booking system, and rail terminal operations.
- **Electric cargo handling equipment**: In 2020, they implemented eight remote control semi-automated electric RTGs to replace conventional RTGs; in 2021, they ordered 48 battery-powered terminal tractors and 17 zero-emission remote-controlled electric RTG cranes to replace existing diesel-powered cargo handling equipment. The report in 2021 indicated that the carbon footprint had been reduced by 30% since 2015 through a range of measures including the first phase of the programme to phase out diesel-powered yard cranes. In 2023, the port ordered 100 battery-powered autonomous Q-Trucks. By 2030, the port will replace 216 diesel-powered internal tractors and 32 of 74 diesel-powered RTGs, targeting a further 20% reduction in CO_2.
- **Hydrogen-powered port equipment**: In 2021, Ryse Hydrogen initiated a project to supply the Port of Felixstowe with green hydrogen for its prototype port trucks.
- **Green hydrogen**: In 2022, ScottishPower, with Hutchison Ports, was planning to invest GBP 150 million to build a green hydrogen plant to bring in 100 megawatts of power by 2026 to supply hydrogen to the vehicles and machinery used by the port. It will also have the potential to be used for the production of green ammonia or ethanol.
- **Rail infrastructure**: In 2019, the Strategic Freight Network and Hutchinson Ports UK invested GBP 60.4 million to complete a new rail line connected to the Port of Felixstowe, which has the potential for an increase from 33 to 47 freight train services a day in each direction. Each additional train would take the equivalent of up to 76 lorries off the roads; currently, about 30% of containers are moved by rail services at Felixstowe.

- **Electric infrastructure**: In 2022, the port started a 3-year project to upgrade the existing 11,000-volt electricity network to supply power to electric gantry cranes, electric yard cranes, and charging stations for battery-powered tractor units. In 2023, the port commissioned the setup of two new 11 kV high-voltage substations, which will primarily serve its conventional electric tractor fleet.
- **Digital technologies**: In 2022, the port became the 5G testbeds under a government funding project to deploy 5G technology and the Internet of Things (IoT). The project aims to make use of the real-time data from the IoT sensors and 5G network to detect anomalies in quay cranes and yard cranes to improve preventive maintenance. The port was also involved in a research project in 2022 to apply machine learning techniques to improve container storage allocation between quayside and yardside operations.
- **Green energy transition levy**: From 2022, each import-laden container through the port of Felixstowe is charged GBP 8.75 to the customs declarant (clearing agent) to contribute to the port's decarbonisation program.

4.2. Port of London

The Port of London (www.pla.co.uk, accessed on 18 November 2023) is the largest port in the UK in terms of cargo tonnage, moving 54.88 million tonnes in 2022. The London Port can handle all types of cargo, with the most common goods including containers, bulk cargoes, and breakbulk cargoes. The port is located on the River Thames and operated by the Port of London Authority. The River Thames is home to the UK's largest fleet of inland vessels. The Port of London has invested heavily in infrastructure and facilities in recent years, including the development of new container terminals, the creation of new logistics parks and distribution centres, and the upgrading of existing facilities.

The Port of London Authority (PLA) has committed to achieving net zero carbon emissions from its operations by 2040, with an interim target of halving its carbon emissions relative to the 2014 baseline by 2025. In the Port of London, the vast majority of carbon emissions are from vessels performing essential duties, including cargo transporting, pilot transfers, river patrols, and channel and mooring maintenance. Decarbonisation measures at the port of London are centred on the fleet of vessels, including the following:

- **Operational measures**: Applied to all vessels for energy efficiency.
- **Vehicle replacement**: By 2021, deployed some electric vehicles and hybrid vehicles; by 2025, switching road vehicles to electric and all pilot taxis to be lower-emission vehicles.
- **Retrofitting existing vessels**: 2020–2030, trial stage of retrofitting low-carbon fuel or modified internal combustion engine with biofuel; 2030–2050, adoption stage.
- **Electrify frequent-stop passenger vessels**: 2020–2030, trial stage of battery electric or fuel cell electric; 2030–2050, adoption stage.
- **Non-frequent-stop passenger vessels**: 2020–2030, internal combustion engine stage V with diesel; 2030–2040, internal combustion engine stage V (or above) with low-carbon fuel; 2035–2050, fuel cell electric.
- **Tugs**: 2020–2030, internal combustion engine stage V with diesel; 2025–2040, diesel electric with low-carbon fuel; 2035–2050, fuel cell electric.
- **Freight vessels**: 2020–2030, internal combustion engine stage V with diesel; 2025–2050, battery electric; 2030–2050, fuel cell electric.
- **Service and workboats**: 2020–2030, internal combustion engine stage V with diesel; 2030–2050, internal combustion engine stage V (or above) with low-carbon fuel; battery electric; fuel cell electric.
- **Hydrogen highway**: In 2021, a three-year GBP 2.1 million programme was initiated to establish a national hydrogen highway network to support the development of clean maritime technology. The programme includes the demonstration of alternative power and fuel such as fuel cell technologies; offshore hydrogen generation; business case and economic model; and autonomous ship and mooring systems.

- **Infrastructure**: By 2021, install solar PV panels on roofs at two sites, and used lower-energy lighting; by 2025, install biofuel tanks at PLA riverside locations to accommodate a phased switch; install a new sub-station at Denton Wharf base to cope with increased electrical demand from the vessels and vehicles.
- **Low-carbon fuel infrastructure**: 2020–2030, first refuelling to serve trials; 2030–2040, roll out refuelling infrastructure to serve existing vessel fleet.
- **Electric charging infrastructure**: 2020–2025, feasibility study for vessel charging; 2025–2040, roll out charging infrastructure.
- **Hydrogen infrastructure**: 2020–2030, feasibility study on hydrogen refuelling; 2025–2050, roll out hydrogen refuelling stations.

4.3. Port of Immingham

The Port of Immingham (www.abports.co.uk/locations/immingham, accessed on 18 November 2023) is the second largest port in the UK in terms of tonnage, owned and operated by Associated British Ports (ABP). The Port of Immingham moved over 50.17 million tonnes in 2022 covering various types of goods, including dry bulks, containers, bulk energy, liquid bulk, project cargo, rail freight, and ferries, in addition to servicing offshore wind business. The port is a critical part of the supply chain for sustainable electricity generation and other energy production in the UK.

The Port of Immingham set 2040 as the target year to achieve net zero emissions from its own operations. The port is targeting emission reduction across its major plants and equipment types (equipment, vessels, dredgers, cranes, vehicles, etc.) to meet the scope 1 and scope 2 net zero emission target. ABP has reduced scope 1 and 2 emissions by 38% between 2014 and 2021. Decarbonisation measures at the Port of Immingham include the following:

- **Electric cargo handling equipment**: In 2020, ABP deployed GBP 7 million electric RTG cranes as part of a GBP 33 million investment; in 2022, 14 electric forklifts were deployed at the Port of Immingham.
- **Hydrotreated Vegetable Oil (HVO)**: In 2022, four HVO reach stackers were used to replace older diesel equipment which had reached the end of its usable life.
- **Hydrogen truck**: In 2023, a hydrogen-fuelled truck was used in the port to cut GHG emissions.
- **Green hydrogen**: In 2021, a feasibility project was conducted to investigate the production of 20 MW of green hydrogen for use at the Port of Immingham by 2025.
- **Renewable energy**: In 2020, ABP completed the UK's largest rooftop solar array at the Port of Hull near Immingham. In 2023, the Ports of Grimsby and Immingham initiated the onshore wind projects for a generation capacity potentially up to 36 MW. Plans are being developed for up to four turbines at Grimsby (up to 24 MW) and at least two at Immingham (up to 12 MW).
- **Infrastructure**: In 2022, electric charging for vehicles was rolled out for colleagues and guests. In 2023, ABP installed a mobile hydrogen filling station to fuel the vehicle.
- **Carbon capture and storage**: In 2022, plans were announced to develop a CO_2 terminal to serve as a hub for the collection of CO_2 emissions from industrial businesses around the country. Its first CO_2 capture is expected in early 2027. It would not only decarbonise the maritime sector but also the Immingham landside industries, which is the most carbon-intensive industrial cluster in the UK.
- **Green certificate**: In 2021, ABP gained ISO 14,001 Environmental Management Certification.

4.4. Port of Milford Haven

The Port of Milford Haven (www.mhpa.co.uk, accessed on 25 November 2023) is the busiest port in Wales, handling over 38.90 million tonnes of cargo in 2022. It is the largest energy port in the UK (handling 30% of total UK gas demand) and its South Hook LNG terminal is the largest LNG terminal in the continent Europe. In 2020, 85% of gas consumption in Wales came through the Milford Haven port.

In 2021, the Welsh Government approved a net zero target for 2050 with interim targets of 63% reduction by 2030 and 89% reduction by 2040 from 990 level. The Port of Milford Haven is the first port facility in the UK to pledge to the green port work standards. Decarbonisation measures at the Port of Milford Haven include the following:

- **Electric vehicle**: In 2021, seven new electric commercial vehicles were in service at the port.
- **Renewable energy supply**: In 2019, the port switched its energy to a renewable energy tariff, indicating that all the electricity usage comes from renewable sources.
- **Renewable energy production**: In 2021, RWE launched the Pembroke Net Zero Centre to maximise the potential of hydrogen, floating offshore wind, and carbon capture to help decarbonise industries in Wales. In 2023, a major hydrogen fuel generation scheme, which could make up to five tonnes of the gas a day at the former Puma Energy site in Milford Haven, was submitted to county planners.
- **Infrastructure**: By 2019, the port had invested in solar panels, LED lighting, heat pumps, insulation, and smart energy innovations to minimise carbon emissions. In 2022, the Port of Milford Haven started the construction of a new supersize slipway and new workboat pontoons at Pembroke Port, as part of the GBP 60 million Pembroke Dock Marine project. The infrastructure will enhance the Port's operations and maintenance capabilities for the floating offshore wind industry.
- **Welsh and UK Governments support**: Expand South Wales' grid capacity by 10 GW by 2030; implement a fast-tracked consenting regime; incentivise the production and use of low-carbon fuels; back the Skills Accelerator and Supply Chain Accelerator programmes.

4.5. Port of Liverpool

The Port of Liverpool (www.peelports.com/port-locations/liverpool, accessed on 25 November 2023), operated by Peel Ports, is a key trading and logistics hub with strong links to North America and Europe. The Port of Liverpool moved 33.62 million tonnes of cargo in 2022. It handles a variety of cargo types including containers, bulk cargoes, and roll-on/roll-off (RoRo) cargoes. The port also accommodates over 60 cruise ships each year. In 2016, the GBP 400 million investment deep-water container terminal, Liverpool2, was completed, which enables the port to handle some of the largest vessels in the world; meanwhile, a GBP 100 million custom-built biomass import terminal was completed at Gladstone Dock in the Port of Liverpool in 2016. The port also has large bulk warehousing facilities with multimodal connectivity.

The Peel Ports Group has committed to becoming a net zero port operator by 2040 and achieving 67% reduction in fuel consumption by 2030. In October 2023, Lloyds List reported that Peel Ports group has reduced scope 1 and 2 emissions across its port operations by 32% against its 2020. A range of solution measures have been taken or planned at the Port of Liverpool, including the following:

- **Operational measures**: Dockside electric cranes work on renewable power, and the applied software ensures container movements are optimised to save energy. A vehicle booking system is adopted on the landside automated gate interface; it promotes reconfiguring the movement of goods into and across the UK to transport goods closer to their end destination with fewer emissions.
- **Replace diesel equipment**: In 2020 was first use of electric vehicles across all ports in the Peel Ports group; in 2021, Peel Ports started trialling the use of electric power for plant machinery. By 2022, 45% of Peel Ports' plant equipment fleet was moved to Hydrotreated Vegetable Oil (HVO), and 29% to electric. By powering freight carrying vehicles with greener fuels, Peel Ports has reduced landside carbon emissions by 70%.
- **Hydrogen powered trucks**: From 2021, Peel Ports were exploring the use of hydrogen to power their larger trucks.
- **Green electricity**: By 2025, Peel Ports intends to implement a green electric use scheme, which has an emissions factor of half the grid average.

- **Fuels and energy**: By 2035, Peel Ports intends to replace all gas usage and transition to electric or lower-carbon fuel sources.
- **Modal shift**: Peel Ports are increasing the number of rail connections and multimodal services across their ports to reduce road miles and emissions.
- **Infrastructure**: In 2020, lighting across the ports underwent transition to LED; in 2021, Peel Ports invested GBP 500,000 in electric charging infrastructure for new vehicles and conducted trials of greener fuels (such as hydrogen and electric alternatives) for plant equipment. For ships idle in docks, Peel Ports is planning to enable ships to plug into the ports' electric supply. In the last 10 years, Peel Ports group has invested over GBP 1 billion on sustainable infrastructure.
- **Support offshore and onshore wind**: Peel Ports supports the changing energy markets with both offshore and onshore wind sites available across its various locations.
- **Collaboration measures**: From 2021, Peel Ports requires their supply chain partners to sign sustainability codes that align with their carbon emission values; Peel Ports group has created an Innovation Forum involving universities, entrepreneurs, consultants, and start-ups to tackle the challenges of emission reduction.

4.6. Port of Southampton

The Port of Southampton (www.abports.co.uk/locations/southampton, accessed on 25 November 2023) is the UK's largest vehicle handling port (over 900,0000 vehicles per year), owned by Associated British Ports (ABP). Southampton is a hub for passengers and a diversity of cargos, including automotive, containers, dry bulks, liquid bulks, bulk energy, and ferries. It carried over 31.28 million tonnes of cargo in 2022. The port is also home to the UK's largest refinery—Fawley. The five-berth Southampton Container Terminal is operated by DP World. The annual throughput of containers at Southampton is about 2 million TEUs.

ABP has committed to reach net zero by 2040. DP World aims to be a carbon-neutral business by 2040 and to achieve net zero carbon emissions by 2050 across its entire global network. DP World's container terminal at Southampton reported a 55% reduction in net carbon emissions from its fleet and facilities in 2022. Decarbonisation measures having been taken or planned at the Port of Southampton include the following:

- **Operational measures**: Adopted vehicle booking system and traffic management system to streamline the arrival of HGVs in the container terminal and their movements around the port; initiated ongoing 'no idling' campaign to encourage drivers to switch off engines when vehicles are not moving or working to cut emissions at the port.
- **Equipment replacement**: From 2018, replaced its forklift trucks with the newest, most efficient models at Southampton Container Terminal; started to replace the straddle carrier fleet with newer more efficient models.
- **Electric vehicle fleet**: From 2018, introduced electric vehicles to transport staff; by 2023, 100% electric fleet for small vans and cars; 90% of HGVs at the container terminal have efficient Euro VI engines.
- **Hydrotreated Vegetable Oil (HVO)**: In 2021, DP World trialled HVO by using the fuel in its forklift trucks, reefer generators, and straddle carriers; by April 2022, DP World's Southampton container terminal completely eliminated fossil diesel from its operations and transitioned to HVO.
- **Renewable energy**: In 2023, on-port solar generation grew to 4 MW; around half of Southampton port operations are powered by on-port solar; maximise solar energy schemes within the port estate to reduce carbon footprint.
- **Hydrogen hub**: From 2021, investigated opportunities to decarbonise local industries and transport, and created a centre of excellence for hydrogen production and distribution on the south coast through carbon capture and hydrogen-based technologies; working with Fawley Refinery to build hydrogen capacity.
- **Rail Infrastructure**: Worked with Network Rail to extend rail capacity into the Port of Southampton; in 2023, the GBP 17 million project to expand the rail terminal at the

Port of Southampton completed its second phase. Currently, over 30% of containers are arriving or leaving the port on trains through four dedicated rail terminals.

- **Electric Infrastructure**: Installed electric charging points for cruise passenger vehicles; from 2023, will roll out electric charging for HGVs at the container terminal.
- **Fuel Station Infrastructure**: Explore the installation of a GTL fuel station for commercial and on-dock vehicles.
- **Facility infrastructure**: In 2017, installed monitors at locations across the port to monitor air quality in and around the port; in 2021, provided shore power connectivity in the new Horizon cruise terminal; installed large areas of solar arrays on the roofs of the warehouses and terminals; installed low-energy LED lighting; commissioned research into feasibility options for Solar Roads; growing shore power facilities.
- **Digital Tool for real-time visibility:** DP World launched a digital tool called "Where's my container" in 2012, which provides customers and cargo owners with visibility of the status of their containers through the container terminals to enable relevant stakeholders to optimise their operations and avoid delays.
- **Incentive Modal Shift Scheme**: Under this incentive scheme, customers will receive a GBP 70 (GBP 10) incentive if their import-laden containers are moved by rail to a railhead within (beyond) 140 miles of Southampton Container Terminal.
- **Port Consultative Committee**: Bring together members of the port community and external stakeholders quarterly to promote best practice.
- **Sustainable Transport Options**: Promote the My Journey sustainable transport initiative to the wider port community.

4.7. Port of Singapore

The Port of Singapore (www.mpa.gov.sg, accessed on 4 February 2024) is among the top two busiest ports in the worlds according to cargo tonnage handled. It is the world's largest transhipment port, and the world's fifth largest container port. The port terminals aim to reduce absolute emissions by at least 60% by 2030 from 2005 levels, and achieve net zero emissions by 2050. The committed and planned decarbonisation efforts include the following [30]:

- **Operational measures**: From 2019, developed digitalPORT, which provides a one-stop platform for port call transactions and regulatory clearance for operational efficiency; the JIT Planning and Coordination Platform can facilitate direct berthing on arrivals and on-time departures to enhance ship turnaround and reduce ship emissions. Moreover, the port plans to seek energy optimisation from 2025.
- **Electrify cargo handling equipment**: From 2015, adopted new electric automated RMG cranes; during 2019–2027, replace diesel RTG cranes with electric RTG cranes; in 2021, adopted battery AGVs; during 2023–2025, adopt electric prime movers; during 2025–2030, electrify port equipment (AGVs, quay cranes);
- **Low-carbon fuel for prime movers**: In 2021, adopted LNG-fuelled prime movers to replace diesel-fuelled prime movers; during 2025–2030, will adopt energy-efficient grab dredger; biofuels for domestic harbour crafts.
- **Renewable energy**: 2025–2030, solar energy; 2025–2050, hydrogen prime movers and green electricity; by 2050, harbour craft will be powered by alternative energy solutions such as electrification and net-zero fuels.
- **Infrastructure**: 2023–2030, support pilots for electric harbour craft and charging infrastructure; for international shipping, support the supply of biofuels (e.g., biomethanol, bio-LNG) as well as hydrogen derivatives (e.g., ammonia, e-methanol, liquefied hydrogen).
- **Digitalisation**: From 2019, developed Singapore Maritime Data Hub, which acts as a one-stop data repository and centralised data exchange platform in order to enable the integration of Maritime Singapore with the global trade ecosystem; will improve cyber security intelligence through early detection and quick response to cyber security threats; from 2025, will adopt smart grids.

- **Incentives and collaboration**: The digitalPORT tool promotes cross-sector collaboration among value-chain partners; decarbonise supply chain through efficiency gain; support technical development and incentivise the adoption and uptake of electric harbour craft and low-carbon fuels for seagoing vessels.

4.8. Port of Los Angeles

The Port of Los Angeles (www.portoflosangeles.org, accessed on 4 February 2024) is the largest container port in the US, located on the west coast. The port handles a variety of cargo including container, automobile, breakbulk, and dry and liquid bulk. The Port of Los Angeles has been focusing on establishing a "zero emissions pathway" for cargo movements from ship to terminal and to final destination. It set targets to achieve zero emissions from cargo handling equipment by 2030 and from trucks by 2035. Meanwhile, the port aims to help develop technologies to reduce carbon emissions from ships, harbour craft, and trains to move toward a carbon-free port. The relevant decarbonisation activities include the following:

- **Electrify cargo handling equipment:** Electric terminal tractor development and demonstration in 2009; capacity plug-in hybrid electric terminal tractor and hybrid yard tractor development and demonstration in 2010; lithium-ion battery demonstration in 2011–2012; in 2020, demonstrated two zero-emission battery electric top handlers and three battery electric yard tractors.
- **Hydrogen vehicles**: In 2021–2022, demonstrated 10 hydrogen fuel cell class 8 trucks.
- **Infrastructure to supply electricity**: The Shore Power Program supported vessels to plug into the electrical grid in the port; in 2020, installed charging infrastructure and smart charging system for charging cargo handling equipment; constructed necessary electrical infrastructure to deliver electricity power to all cargo handling equipment.
- **Infrastructure for hydrogen**: In 2022, built two heavy-duty hydrogen fuelling stations in Ontario and Wilmington.
- **Technology**: The Ports' Technology Advancement Program (TAP) provides continuous support (e.g., funding, guidance, testbed, demonstration) to test clean technologies and associated infrastructure in a real-world environment in and around the port.
- **Policy and incentive**: the OffPeak program was launched by PierPASS in 2005 to incentivise the truckers to use off-peak shifts, which can reduce cargo-related congestion in the surrounding areas of the ports of Los Angeles and Long Beach, and reduce truck waiting time and emissions at ports.
- **Policies and collaboration**: Adopted the Clean Air Action Plan (CAAP) in 2006 and updated it in 2010 and 2017, which set up the "zero emissions pathway" for cargo movements throughout the port. The CAAP puts in place a few specific port emission control measures, e.g., the Clean Truck Program introduces progressively strict standards on the external trucks to access the port; the Vessel Speed Reduction Program offers financial incentives to encourage vessels to slow down their sailing speed near the port; the CAAP also initiates the concept of cooperation among port stakeholders, including port authorities, terminal operators, ocean carriers, truckers, shippers, national and regional regulatory bodies, and local communities.

4.9. Port of Rotterdam

The Port of Rotterdam (www.portofrotterdam.com, accessed on 4 February 2024) is the largest seaport in Europe in terms of cargo tonnage. Its terminals have direct connections to deep sea and feeder, short sea, and RoRo, handling various cargo such as containers, dry bulk, liquid bulk, breakbulk, and LNG. The port of Rotterdam is also Europe's largest bunkering port for ships supplying transitional fuels and alternative low-carbon fuels.

The port is committed to accelerating sustainability. In the period of 2016–2022, the port achieved a CO_2 reduction of 67%. The future targets are to reduce scope 1 and scope 2 emissions by 75% in 2025 and 90% in 2030 compared to 2019 levels. The long-term target is to achieve carbon neutrality in 2050. The committed and planned measures to reduce emissions include the following:

- **Operational measures**: Conducted three green-corridor projects to seek port call optimisation; showed 14% CO_2 emission reduction by utilising just-in-time vessel arrivals.
- **Retrofitting existing vessels**: In 2018, eight vessels were switched from conventional diesel to 100% HVO fuel; in 2025, seven vessels will be switched from conventional diesel to cleaner 30% HVO fuel; in 2025–2035, will gradually replace the vessel fleet to be 100% HVO and zero-emission vessels.
- **Electrify vehicles**: During 2018–2021, 75% personal lease vehicles were transitioned to be fully electric; 25% of business lease vehicle were fully electric; during 2021–2025, passenger car fleet will be fully electric; during 2025–2030, will achieve fully zero-emission vehicle fleet.
- **Shore power supply**: During 2023–2025, will conduct four case studies to prepare Onshore Power Supply systems (OPS) at four major terminals in the port of Rotterdam.
- **Alternative fuels:** Will put the first zero-emission vessels into service from 2025; during 2028–2029, first zero-emission dredging work through the use of cleaner fuels such as bio-LNG, HVO, hydrogen, and methanol.
- **Infrastructure**: During 2026–2027, will redevelop new multifunctional housing only using renewable energy; replace heating oil with gas or climate-neutral energy; install onshore power systems to provide 35 MW of power for container ships, liquid bulk, and cruise ships by 2025.
- **Infrastructure to supply alternative fuels for vessels**: Scale up the supply of alternative bunker fuels including ammonia, electric shipping, LNG, biofuels, hydrogen, and methanol.
- **Digitalisation measures**: From 2019, test and implement digitalisation of logistics processes, including digital tools such as PortXchange, Navigate, Routescanner, and Nextlogic to enable sharing real-time data among stakeholders, including port authorities, terminal operators, shipping companies, and agents during a port call.
- **Policies and incentives on employee travels**: From 2018 and 2021, new policies on employee commuting and business travel (including flights) to reduce CO_2 emissions, e.g., effective incentives for the use of bicycle and public transport, air travel using sustainable aviation fuels.
- **Policies and collaborations with partners**: Policy and incentive schemes are initiated, such as vessel speed limits, and Environmental Ship Index-based green passport. From 2019, sign green energy contracts with suppliers to reduce scope 2 emissions from purchased electricity and district heating; from 2019, be a participant in the national partnership under the Green Deal on Maritime and Inland Shipping and Ports, which aims to reduce greenhouse gases from shipping; be a leader in the international partnership under the World Ports Climate Action Program, which focuses on port management to reduce CO_2 from shipping; be a participant in an international knowledge network under the Getting to Zero Coalition, which aims to demonstrate the first zero-emission seagoing vessels from 2030.

It is worth noting that the decarbonisation measures presented in the above case studies are not exhaustive. In particular, operational measures to improve efficiency and reduce emissions are often not explicitly described in the reports and newsletters.

5. A Roadmap to Decarbonise Seaports

The case studies in the previous section have different characteristics, e.g., the Port of Felixstowe is mainly a container port; the Port of Milford Haven is mainly an energy port; the Port of London's vast majority of carbon emissions are from various types of vessels; the ports of Singapore and Rotterdam are large transshipment ports; the Port of Immingham, Port of Liverpool, Port of Southampton, and Port Los Angeles all handle a diversity of cargos. These case studies shed light on how the seaports are taking steps towards net zero. A few points can be drawn from these case studies:

- Most case ports have explicitly stated their aims to reach **net zero emissions** from their own operations (scope 1 and scope 2 sources) by 2040. This is more ambitious than IMO's target for net zero by 2050.
- Most case ports have been pursuing **operational measures** to improve efficiency and reduce fuel consumption.
- All case ports are implementing time-phased **technical measures** of equipment/vehicle replacement, e.g., replacing diesel with low-carbon fuels or electricity or hydrogen; the implementation process is carried out phase by phase considering the availability of fuel/energy supply, the supporting infrastructure, and the cost–benefit ratio.
- All case ports are committing to time-phased **infrastructural measures**, e.g., installing electric charging stations, increasing electricity supply capacity, installing energy-saving devices, expanding rail service capacity for modal shift, and building alternative fuel facilities.
- All case ports are pursuing time-phased **fuel and energy measures**, especially vehicle electrification and the exploration of the usage and production of low-carbon fuels such as hydrogen.
- Some case ports have tried **digitalisation measures** to improve operations and reduce emissions; however, it appears that the applications of digital technologies and artificial intelligence (AI) are still in the early stage, especially in the UK ports.
- Some case ports have initiated **policy and collaboration measures** to facilitate emission reduction; however, the scope and scale are still limited.

Based on the above case studies, the literature review, and our domain knowledge, we propose a generic roadmap for seaports to achieve net zero in Figure 2, in which important solution measures within each category are divided into three phases: 2025, 2030, and 2040.

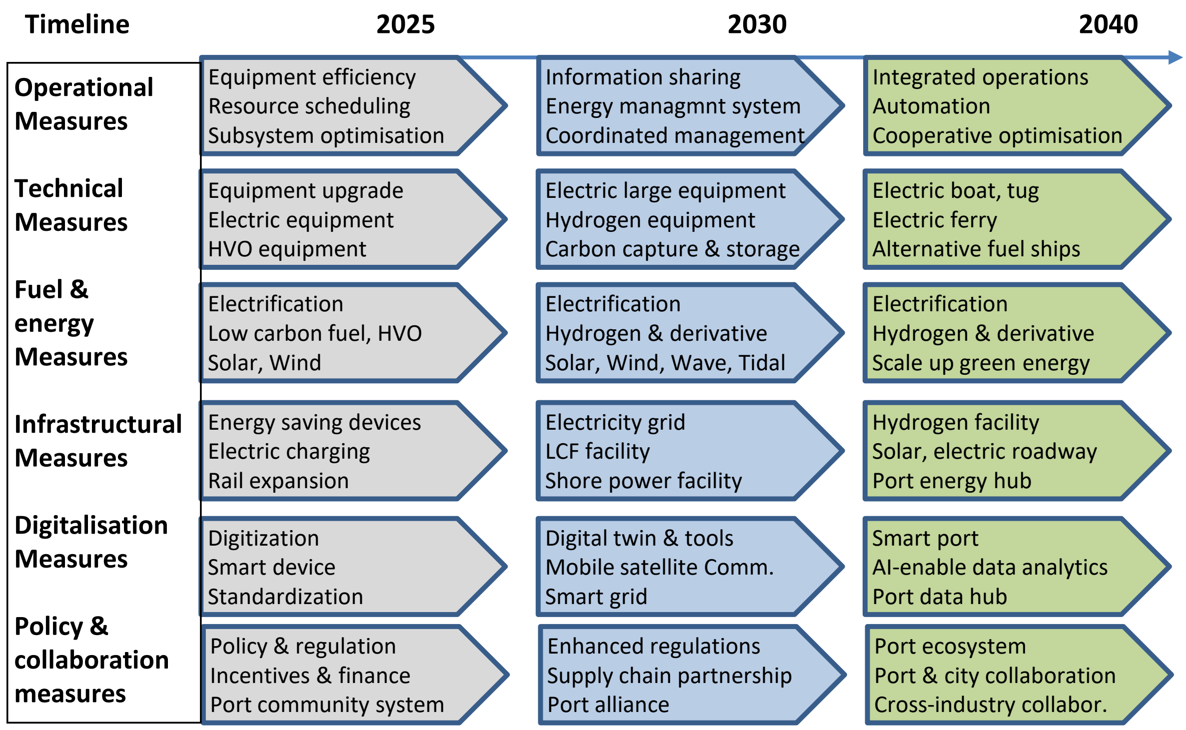

Figure 2. A roadmap of seaport decarbonisation to net zero with time-phased solution measures.

The timeline of the roadmap is divided into three phases. In the first phase up to 2025, operational measures mainly focus on equipment and resource and subsystem optimisation; stakeholders are largely working in silos due to the lack of data visibility and the challenge of interoperability. This is especially true in the maritime sector because of the rather conservative and risk-averse nature of the shipping industry [66]. Technical measures focus on upgrading or retrofitting the existing equipment to be more energy-efficient, and phasing in less energy-intensive electric equipment and HVO-powered equipment. From the fuel and energy perspective, electrification and low-carbon fuel are mainly applied to light-duty vehicles and equipment at this phase. The difficulty in electrifying energy-intensive equipment is due to the unavailability of electrical power supply and infrastructure. At this phase, ports have started the use of energy generated from solar panels and wind. Infrastructurally, energy-saving devices and measures have been deployed, such as LED lighting; electric charging stations are installed to support the equipment electrification. In addition, rail service capacity expansion has been carried out to facilitate the modal shift, for both logistics efficiency and emission reduction. Regarding digitalisation measures, some seaports have started the application of digital technologies, such as smart devices and smart sensors, to collect real-time data and digitise information to enable data-driven optimisation. Data standardization, including data formats and platforms, should be addressed to overcome the data incompatibility barrier. In terms of policy and collaboration measures, relevant policies and regulations at different levels (international, national, regional) are necessary to accelerate port decarbonisation. Incentive schemes and financial support should be strengthened globally. The port community system (PCS) has been used in many ports, but the collaboration between stakeholders through PCS should be improved along with the digitalisation measures.

In the second phase around 2030, operationally, it is expected that port-associated stakeholders will design mechanisms to achieve information sharing, develop energy management systems, and coordinate management across subsystems and across stakeholders for better operational performance. This will be supported by digitalisation measures such as digital twins/tools, mobile satellite communication, and the smart grid. For example, digital twins of quay cranes would enable optimising quay crane operations and shortening vessel berthing time. Technically, energy-intensive equipment such as gantry cranes will be electrified or powered by hydrogen. This is facilitated by the development of hydrogen technologies and more green energy generated from renewable sources such as solar, wind, wave, and tidal. In addition, it also requires the support of the relevant infrastructure, such as an electrical grid with sufficient power capacity, and renewable energy production facilities. Moreover, carbon capture and storage systems will be rolled out. At this phase, low-carbon fuel facilities and shore power facilities will be rolled out to support seaside vessel decarbonisation. In terms of policy and collaboration measures, stricter regulations and policies will come into force to enforce maritime decarbonisation. Large-scale financial investment and support is needed to enable the rollout of the fuel and energy measures and the infrastructural measures. Port operators will collaborate with supply chain partners vertically, and with other ports horizontally for better operations and energy management.

In the third phase around 2040, it is expected that more operational activities will be integrated, automated, and cooperatively optimised, enabled by digitalisation measures and collaboration measures. Technically, small or short-distance vessels such as boats, tugs, and ferries will be powered by either battery or fuel cells. Large ships are likely to be powered by alternative fuels such as hydrogen derivatives or equipped with a carbon capture storage system. Scaling up green energy/fuel production is essential to meet the huge demand from the maritime sector and other industrial sectors. Infrastructure measures include the rollout of renewable energy and hydrogen production, conversion, transport, and storage facilities. Moreover, electric or solar roadways could be constructed to decarbonise road transportation. Large ports can act as an energy hub to support the energy consumption by port operations, the shipping industry, and inland industries. Digitalisation measures include the wide adoption of the smart port concept and AI-enabled data analytics (predictive analytics and prescriptive analytics) to improve operational efficiency and optimise energy consumption. Ports can also be developed as a data hub that consolidates all-around data from various sources and connects to other industries. In terms of policy and collaboration measures, all the organisations within the port geographic boundary would share the same vision of net zero and work together as an ecosystem.

As ports are closely linked to the regional city, there is a need to establish a collaboration between the port and the city for decarbonisation. Noting that other industrial sectors (e.g., steel, cement, and chemical industries) are also required to decarbonise and ports are likely to be the energy hub to support their decarbonisation, it is therefore imperative that the maritime sector not seek decarbonisation alone. Cross-industry collaboration is needed to tackle the decarbonisation challenge from the system perspective.

6. Discussions and Research Opportunities

Although the proposed roadmap in Figure 2 is partially based on six case studies in the UK and three case studies in the international context, we believe it is generally applicable to other seaports in the world with some adjustments to the timeline and the solution measures, since different countries may have different targeted years for net zero and different ports have different characteristics. Moreover, the IMO's 2050 net zero target can be used as a reference point. A few insights can be drawn from the roadmap:

- The decarbonisation of seaports will take a time-phased approach as a progressive implementation process, especially for large seaports.
- The categories of operational measures, technical measures, and fuel and energy measures have a direct impact on port emission reduction, whereas the categories of infrastructure measures, digitalisation measures, and policy and collaboration measures will support and facilitate the development and deployment of the solution measures in the first three categories; life cycle assessment and value chain analysis should be performed to ensure that emissions and costs are evaluated appropriately.
- Operational measures are more readily available to apply in practice to reduce the fuel/energy consumption in port-associated activities. Advanced operational measures will be highly dependent on digitalisation measures and collaboration measures, because digitalisation and collaboration may revolutionise business processes, user behaviours, and relationships among port stakeholders; in addition, new business models and operational practices will emerge with the deployment of technical measures and fuel and energy measures.
- Technical measures will be highly dependent on infrastructure measures and fuel and energy measures. Without the availability of supporting infrastructure and sufficient low-carbon fuel and energy, it will be difficult to decarbonise energy-intensive landside equipment and vehicles and seaside vessels.
- Fuel and energy measures require the development, implementation, and scaling up of relevant technologies such as hydrogen production, conversion, storage, and transportation; on the other hand, they also require the collaborative efforts and commitment from associated stakeholders, including governments, and the enforcement from legal regulations in the policy and collaboration category.

Seaports have made good progress in reducing scope 1 and scope 2 emissions, as discussed in the case studies. However, it is often the scope 3 emissions that account for the largest share of emissions in the seaport geographical boundary. The roadmap covers all three scopes of emissions. There are a number of challenges and research opportunities in the process of implementing the roadmap.

Firstly, operational measures have a certain limit in terms of decarbonisation if fossil fuels are used. Therefore, operational measures alone are not able to achieve net zero. Nevertheless, operational measures are preferable at early stages because of the uncertainty in technical measures, alternative fuels, and regulatory measures in the maritime sector. Moreover, operational measures will continue playing an important role to decarbonise seaports at later stages along with the adoption of other measures. In particular, there is a huge opportunity for developing effective operational measures enabled by digitalisation and collaboration measures.

Secondly, there is a challenge of coordinating the implementation of technical measures, infrastructure measures, and energy measures. For example, the use of electric gantry cranes or shore power may cause overload of the port electricity network. At the

Port of Southampton, cruise ships plugged in to the National Grid only 71 times over two years from 2021, whereas every year, there are over 500 cruise ship visits to the port. One main reason is that "Each ship will use twice as much power as the rest of the port put together" and there is a need for substantially more electrical power supply at the port to accommodate more ships simultaneously (www.bbc.co.uk, accessed on 5 January 2024).

Thirdly, electrification and hydrogen-based fuels are essential to achieve net zero at seaports. Green hydrogen is produced via electrolysis, in which electricity is generated from renewable sources. Therefore, there is a big challenge in terms of generating sufficient electricity from renewable sources to meet the demand at seaports. According to DNV, the total electricity generating capacity for seaports could increase more than tenfold by 2050 (www.dnv.com, accessed on 5 January 2024). This is related to the issue of scaling up the production, storage, and distribution of green fuels. Liverpool City Region Combined Authority estimated that the hydrogen demand at the Port of Liverpool is 15 GWha. However, according to the British Energy Security Strategy, the low-carbon hydrogen production capacity in the UK by 2030 will only reach 10 GW (www.great.gov.uk, accessed on 5 January 2024). To fill the sizeable gap between demand and supply of green hydrogen is a worldwide challenge. One opportunity is to harness renewable sources on-site and near-site, as seaports are especially suitable for offshore and onshore wind energy and often have large capacity to install solar panels. On the other hand, renewable energies (e.g., solar, wind, wave, tidal) are often intermittent and variable in energy generation. There is a need to store the energy to match supply with demand over time. Currently, either batteries or hydrogen are viable solutions to store renewable energy. There are technological and logistics challenges in the management of green energy supply chains. Life cycle assessment and value chain analysis are needed for the fuel and energy solution measures.

Fourthly, in most seaports, seaside vessel activities are the primary sources of emissions. Vessel decarbonisation has been extensively discussed in recent years. Port infrastructure is essential to support vessel decarbonisation by providing logistics service of alternative fuels to various vessels. Meanwhile, port hinterland industries are also facing the decarbonisation requirements, which may require alternative fuels from overseas producers through seaports. Therefore, a significant challenge to seaports is which type of alternative fuel facility should be constructed and at what time in order to be an energy hub to support the wider demand for alternative fuels. This challenge is further complicated by the fact that shipping companies are undetermined on which alternative fuel will be used in the future.

Fifthly, digitalisation at seaports is still in its infancy. It faces both internal challenges, such as technical implementation for data collection and processing and technical skills and knowledge for data analytics, and external challenges, such as unwillingness to share information, technical difficulty of data compatibility, and concerns around cyber security and legal regulations. An incremental digitalisation approach is appropriate to tackle these challenges, e.g., starting with identifying the port's specific equipment or subsystem so that an easy-to-implement, low-risk digitalisation initiative can be developed with measurable cost–benefit ratio. In the long term, ports would be developed as data hubs.

Sixthly, the maritime industry is facing high uncertainty of legal regulations and the lack of collaboration across stakeholders. For example, IMO has delayed the introduction of a carbon tax or levy for shipping emissions several times. Clearly, high carbon tax on shipping emissions would decrease the cost–benefit ratio of alternative fuels and accelerate the maritime decarbonisation process. Another substantial challenge is the financial consideration, because many solution measures for port decarbonisation require huge financial investment. Some governments are more supportive, e.g., the UK has been one of the most mature hydrogen markets in the world and has committed to a pipeline of hydrogen production projects in six key industrial clusters across the country, totalling up to 18 GW (www.great.gov.uk, accessed on 5 January 2024). Collaboration opportunities along vertical supply chains and across horizontal supply chains require further progress. In this regard, insurance companies may have a role to play to facilitate the collaboration of port-associated stakeholders to make a joint commitment to the development of green fuels and infrastructure. In addition, topics such as the long-term socio-economic impacts of the port decarbonisation measures, the role of emerging technologies, and the comparative studies of policy and regulation effectiveness are understudied and deserve more research.

7. Conclusions

This paper focuses on seaport decarbonisation towards net zero, looking at a broad picture. Based on the literature, the emission sources at seaports are categorised according to different criteria. For example, according to the sources' functionality, they are broadly classified into two types, e.g., stationary and non-stationary types. According to their emission responsibility, they are classified into three categories: emission scopes 1, 2, and 3. According to their geographic locations at seaports, they are classified into four categories: seaside, quayside and yardside, landside interface, and landside industry and support facility. These categorisations from different criteria provide a better understanding of the emission sources, e.g., why the emissions occur, who has the direct/indirect control of the emissions, and where they occur.

Various emission reduction measures at seaports are identified through the literature review. We classify them into six structured categories: operational measures, technical measures, fuel and energy measures, infrastructure measures, digitalisation measures, and policy and collaboration measures. The first three categories have a direct impact on emission reduction, whereas the last three categories tend to support and facilitate the development and deployment of the solution measures in the first three categories. We present these solution measures as a set of two-dimensional matrices for each geographic location category. Six UK ports and three international ports are selected and their emission reduction practices and pathways towards net zero are discussed. Based on the case studies, literature review, and our domain knowledge, a time-phased roadmap of seaport decarbonisation to net zero is proposed, in which each emission reduction category is divided into three phases: 2025, 2030, and 2040, in a progressive process. The challenges and research opportunities of implementing the roadmap are discussed.

Seaports can play an important role in the IMO's shipping net zero target as well as the world's carbon net zero challenge. Seaports are not only acting as transport hubs and logistics hubs in their traditional roles but also can be developed as trading hubs (especially for those freeports), energy hubs, and data hubs in their emerging roles. The proposed strategic roadmap offers a guideline to seaports to implement emission reduction strategies and transition to net zero from the system perspective, even though seaports differ in many aspects. Broadly, it can also provide a blueprint for various industries, as well as local and national governments, to reduce emissions and transition to a cleaner energy future.

Further research could be conducted in the areas identified in the previous section on research opportunities. In addition, it is also interesting to examine theoretical frameworks that underpin port decarbonisation and barriers to solution measures. In this direction, economic theories related to investment in green technologies, social theories regarding community engagement and labour implications, and political theories associated with policy making and international cooperation could be explored.

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