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Review

Classification of Green Practices Implemented in Ports: The Application of Green Technologies, Tools, and Strategies

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Abstract: This study reviews and categorises ports' green initiatives to reduce their polluting emissions and improve their overall environmental performance. These categories facilitate comparisons between different practices and allow the identification of common trends and challenges. Through a systematic review that combines both academic and industry sources, green port practices including strategies, tools, infrastructures, and initiatives were identified. This methodology enhances the credibility and reliability of the findings by thoroughly reviewing the available literature and data. Overall, 380 records of green practices explored by ports and port-related stakeholders worldwide have been reviewed. The practices' main elements, characteristics, implementation challenges, and indicative environmental outcomes are highlighted. The results show that the most commonly discussed green solutions are driven mainly by the regulation requirements and ports' own interest to develop environmentally friendly operations, while at the same time remaining competitive in terms of sustainability in the port industry. Consequently, the most widely explored solutions include (i) Shore Side Electricity–Onshore Power Supply, (ii) alternative fuels, (iii) circular economy, and (iv) waste management.

Keywords: green seaports; green port practices; port performance; green port strategy; green practices classification

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1. Introduction

Ports inevitably generate anthropogenic emissions due to the ever-increasing volume of cargo handled, the diversification of the activities accommodated (modern ports, for example, can act as industrial hubs with a variety of activities such as energy production, distribution, and storage), and the dependence of land and seaside port activities on fossil fuels. To date, one of the main concerns of the port industry has been air emissions and GHG emissions associated with seaport operations. Port-related GHG emissions are usually reported on the basis of inventories, while the measurements conducted between different ports can vary considerably. For example, the emissions from ships at berth in the port of Rotterdam are estimated at 13.7 Mton CO_2, which is almost double the amount emitted by the port of Antwerp (7.4 Mton CO_2), which is ranked number one among the 10 most polluting European ports [1]. Although it is generally assumed that larger ports pollute more, there are examples of small ports that generate high pollution levels. For example, the port of Algeciras is listed as more polluting compared to bigger Spanish ports, such as the port of Barcelona and the port of Valencia. It is responsible for 3.3 million Mton CO_2, whereas the port of Piraeus follows behind with 2.7 Mton CO_2 [1]. Overall, the European ports are estimated to contribute about 210 Mton CO_2 per year, which accounts for 4.7% of the total CO_2 emissions in Europe [2].

In this context, increased pressure from regulators, customers, cargo owners, and other key port-related stakeholders to take action and reduce externalities through sustainable and cleaner operations has accelerated the quest for port sustainability. As a result, these forces are motivating and stimulating ports to move from a sole focus on economic development to a more resilient and sustainable approach. In other words, ports need to balance their commercial and economic growth with environmental and social sustainability in order to gain a competitive advantage and improve the quality of their services. In addition, the strong commitment to make the overall maritime sector greener and to meet the strict environmental targets imposed by the IMO [1], the European Green Deal [2], and other major policy initiatives inevitably leads to a commitment by ports to reduce their environmental footprint. Port authorities, terminal operators, and port users need to adapt their processes and operations to achieve the IMO decarbonization goals, as well as to comply with relevant legislation and meet specific port environmental criteria. In addition, development and upscaling of port infrastructures is required. There is an extensive list of international and European legislation dealing with all types of pollution with implications for ports. The new (2023) IMO strategy sets more ambitious targets, with the aim of accelerating the decarbonization of the maritime sector. Along the same line, the European Green Deal and the 'Fit for 55'/'FuelEU Maritime' package have focused on the elimination of air emissions and CO_2 by using alternative fuels in the maritime and port sectors. The Commission has adopted a Regulation on the use of renewable and low-carbon fuels in maritime transport [3]. In addition, the Alternative Fuels Infrastructure Regulation [4] 2023 requires Member States to ensure that by 1 January 2030, their TEN-T maritime ports, which have a minimum number of calls by the relevant categories of vessels, are able to meet at least 90% of the OPS requirements of container vessels and passenger ships (Article 9.1). In this context, several measures and strategies are implemented by port stakeholders with the aim to reduce environmental implications and improve their sustainability.

Previous studies have explored the role of ports towards the greening of the sector, providing a solid basis for green port activities, as well as a good overview of different groups and areas of implemented solutions [3]. In terms of decarbonization, much attention has been paid to the ship–port interface, focusing on technical and operational measures, such as provision of onshore power, alternative fuel bunkering, reduction of ship turnaround time, reduction of truck emissions, monitoring and modelling of air emissions [4–7], and various incentive schemes that ports apply to ensure ships' compliance with relevant environmental regulations and policies [8]. Relevant published research also reveals the process of converting ports to a smart, sustainable, and emission-free infrastructure highlighting the importance of information systems into ports' infrastructures and energy management measures [9]. The term "greening" of port operations, commonly discussed in the literature, lies within the wide range of actions and measures towards port environmental sustainability and resilience trying also to accomplish net-zero pollution over time [2,10,11].

The aim of this work is to examine the sustainability initiatives and green practices currently being discussed in the port industry, and implemented or planned to be implemented by ports, in order to align with their environmental sustainability commitments. In addition, an attempt is being made to systematise these practices and to develop a classification scheme based on their scope, while identifying trends and possible gaps in their implementation. In order to systematically categorise the green practices related to ports, a structured approach has been implemented, including the definition of categories based on the types of green initiatives and technologies used, the establishment of specific criteria based on the scale of impact, type of technology, stakeholder involvement, etc. It also includes data collection from multiple sources of information focusing on ports that have implemented or plan to implement these practices and data analysis to refine the categorisation and documentation of the categorisation. This categorisation provides clarity and a structured approach for the stakeholders to understand the range of the existing green activities and where their efforts fit within a broader context. It also allows port authorities to make more informed decisions about which green practices to implement based on their priorities and environmental objectives, as well as which ones can be used as a guide for researchers and technology developers to focus their innovation efforts within the established categories.

By consolidating a wide range of green port activities into a structured approach, this paper can act as a valuable guide to support stakeholders in the assessment and improvement of their environmental strategies. This will enable ports to review their efforts, compare themselves to industry standards, and plan future initiatives in a more informed manner. It may also influence policy development and encourage green technology innovation within the port sector.

2. Methods and Procedures

A review that combines both academic and industry sources has been undertaken as briefly discussed in Figure 1. The purpose was to identify published information on cases of implementation of green practices in ports. The main objective of this research is to provide insights into: (RQ1) How can green port-related actions be categorised systematically? and (RQ2) Are there trends and gaps in the efforts to make port operations greener?

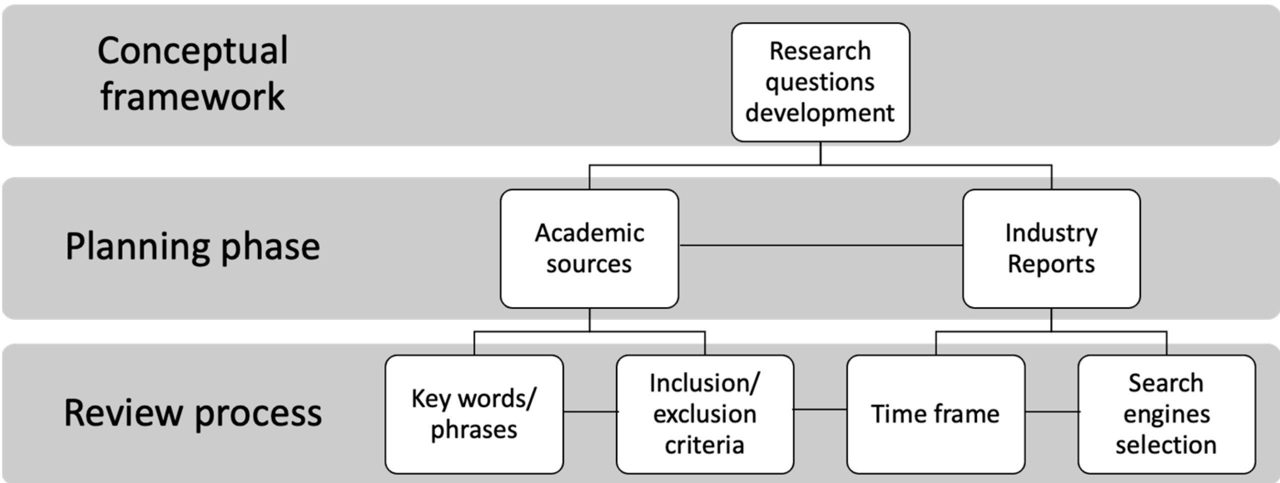

Figure 1. The outline of the research process (Source: own elaboration).

The review commenced with the planning phase, where the authors collected, analysed, and systematised the data and relevant information on the green actions currently being undertaken in ports with a view to their carbon neutral and zero-emission activities. As a first step, information was gathered on recent developments, trends, and priorities in the greening of the ports sector. The broad review revealed the issues that appear to be of high priority, and as such the most widely discussed in the trade and scientific literature. As a next step, the review was narrowed down with targeted key words and phrases that were used to identify cases of implementation of good practices in the port industry.

To obtain a representative list of the published literature and ensure that relevant studies are included, the authors defined a considerable number of keywords and phrases which are relevant to the research questions. The list of keywords and phrases were used for both the scientific review and the general web-based research, conducted through Google Scholar and an open Google search. This search provided access to the scientific literature and to reports, conference proceedings, government, and industry publications, as well as industry-specific databases, trade journals, and professional association websites.

The keywords used included the following: "Cold ironing" OR "Onshore Power Supply" OR "Shore Side Electricity", "Alternative fuels in ports", "Hydrogen in ports" OR "hydrogen production in seaports", "LNG in seaports", "bunkering alternative fuels in seaports", "Electricity in ports" OR "Electrified vessels and machinery", "Digital solutions in seaports", "Green policies in seaports", "Smart grid in seaports", "decarbonization in seaports", "Electric trucks in seaports", "Green policy in seaports", "Circular economy in ports", "Waste management in seaports", and "application of solar and wind farms in seaports".

As part of the research process demonstrated in Figure 1, the authors applied certain inclusion and exclusion criteria. Studies and articles that provided relevant information on implementation aspects of good practices, including information on benefits, critical areas, and challenges of green practices in relation to specific port cases were selected. Of these, studies and articles published in the last ten years, with a focus on publications in the last three years, were selected for review. Among the other sources, 60 scientific articles were included as the most recent and most relevant articles presenting cases of implementation of good practices in ports along with information on implementation outcomes.

The various sources of information were organised by type of publication, as shown in Figure 2. Overall, a total of 380 records of green port practices have been extracted from publications including both academic and practical sources. Several articles present multiple good practices and/or ports of application of these practices.

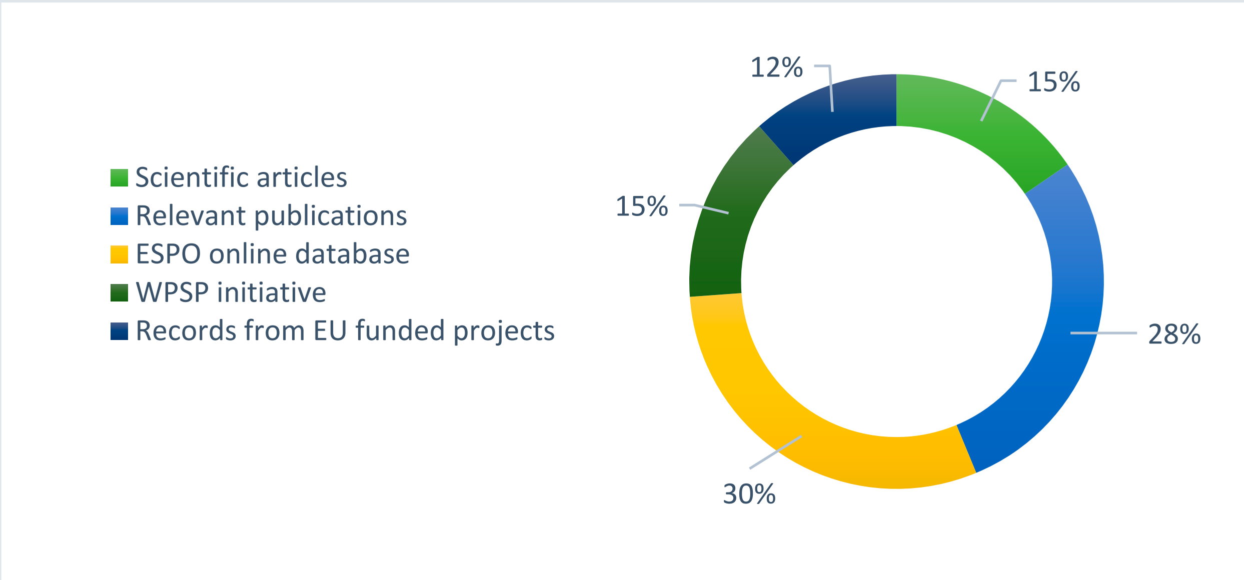

Figure 2. Share of the number of good practices by type of information source.

3. Results

From the perspective of their content and the description of green practices, the case study results are classified in 13 broad categories of green port practices as illustrated in Table 1. Specifically, Table 1 summarises the green port practices emphasising those that are most commonly discussed among publications, namely the provision of Shore Side Electricity–Onshore Power Supply, alternative fuels, circular economy, and waste management. Other green port practices include biodiversity protection, renewable energy production initiatives, green port policies and strategies, environmental quality monitoring actions, carbon management, and measures aimed at pollution prevention and response. Continuous monitoring of energy consumption in seaports is essential for controlling the escalating energy costs and the growing demand for fuel consumption. Therefore, several green practices related to energy efficiency are documented. In addition, aiming at maximising the efficiency in their operations, port authorities and port-related stakeholders are implementing digital tools and other automation solutions.

Table 1. Prevalent and other identified groups of green practices related to ports (Source: own elaboration).

	Green Port Practices	Short Description of Green Port Practices Content
Prevalent groups of green practices	Shore Side Electricity–Onshore Power Supply (SSE–OPS)	Implementation/commercialisation/knowledge transfer of SSE–OPS in ports, exploring the different characteristics and capacities of the systems, business models, and network planning, and cooperation for implementation/scale-up of the infrastructure
	Alternative fuels	Production/bunkering/charging (vessels, trucks) /transport network–corridor–supply chain planning of alternative fuels Alternative fuel supporting vessels and port terminal equipment
	Circular economy	Recycling and efficient (re)use of resources such as sediments from dredging operations, sea-storm water, and rain
	Waste management	Reduction, reception, recovery and use, management/treatment of plastic, water, heat, and raw material
Other green practices	Pollution prevention and response	Vessel emissions' capturing/water pollution prevention
	Renewable energy	Production/provision/conversion/use of wind, solar, and geothermal energy
	Energy efficiency	Infrastructure (terminal area, buildings)/equipment/energy systems
	Operational efficiency	Automation, 5G, IoT and AI, port call optimisation, port traffic management, port environmental conditions forecasting, and eco-driving
	Carbon management	Capture, storage, transport, monitoring, utilisation, and reporting
	Environmental quality monitoring	Air emissions, odour nuisances, water quality, and acoustic characterisations
	Award/certification/incentive schemes	Environmental awareness/environment, energy, integrated management/discounts, and priority handling
	Green policy and planning	Modal split, carbon-neutrality, zero-emission operations, and climate change adaptation
	Biodiversity protection	Port (re)development planning, port land uses, protection infrastructure, marine species management, and planting

3.1. Shore Side Electricity–Onshore Power Supply

A considerable number of green port practices reviewed focused on the economic and operational assessment of a planned Shore Side Electricity–Onshore Power Supply (SSE–OPS) facility in a specific port case or on the exploration of synergies and promotion of the adoption of cold ironing infrastructure. To address the specific requirements of each case, components that are commonly considered when studying the provision of shore side electricity in seaports are as follows: (i) the number and type of ships calling at the port; (ii) the cost of electricity production and distribution; (iii) the arrival interval of the ships; (iv) the existing or potential future installation of renewable energy facilities on the port site. In the context of scientific work, the above characteristics are often estimated for modelling purposes.

The Shore Side Electricity (SSE) deployment is currently being facilitated by EMSA Guidance that applies to Port Authorities Administrations (PAA) in EU ports [12]. The key regulatory framework and the technical requirements for SSE are commonly discussed in the literature, covering the main planning and operational elements. Targeting clean energy production, the SSE–OPS deployment is typically considered an integrated system with further installation components, such as micro-grid configurations, renewable energy production installations, smart grids, and virtual power plants applications at ports, which facilitate the balance between energy demand and supply in an energy-efficient way. However, it is highlighted that the scale of such applications and the components incorporated in each installation vary considerably between ports and highly depends on the available resources, energy demand at each terminal, and the type of vessels they are designed to accommodate [13,14]. In the case of a smart grid component for a SSE–OPS system in a seaport, the electricity distributed to the ships can be generated by local wind farms, solar panels, or conventional national grids (or in some cases a combination of the above) [15]. Smart grids are rather complex systems that provide a comprehensive platform that integrates various elements such as grid and sensor technologies, advanced smart meters, real-time monitoring systems, control tools, battery technologies, and communication technologies. However, the implementation of a microgrid in a seaport faces certain limitations. One of the most frequently discussed issues is the optimal sizing of batteries for microgrids. Although this has been extensively explored in the scientific literature, there is still a significant gap in the implementation process that needs to be investigated further [16]. Optimising the energy demand response through Energy Storage Systems (ESS) allows the port operator to dynamically decide the amount of energy needed for port operations to be procured from different electricity sources (e.g., ESS, RES, and conventional grid), while the remaining energy can be stored for the next use. As an emerging trend for ports, this method achieves significant cost savings for ports that have the ability to mitigate energy demand fluctuations during operational planning [17,18].

Previous research studies have successfully highlighted the positive environmental impact of using SSE–OPS in ports. Therefore, the analysis indicates that based on modelled emission savings, the provision of shore side electricity (provided that it is produced from renewable energy sources) can potentially save 65–82% of emitted CO_2, 75–97% of SO_2, 75–90% of NO_X, and over 95% of PM emissions in port areas (e.g., the port of Aalborg and the port of Heraklion) [19–21]. Depending on the stakeholder, the required investment expenditures might range for ship owners from USD 300,000 to 1–2 million per ship for retrofitting actions and for port operators the shoreside investment cost can range from USD 300,000 to 4 million per berth, depending on the scale of the application and the selected technical requirements [21]. Meanwhile, the payback period of the investment is highly associated with the type of vessels connected to shore side electricity (container/cruise ships, RoRo, etc.) and may vary considerably between four and six years [22]. The general consensus is that implementing SSE–OPS systems in ports should be combined with renewable energy production and provision of clean electricity to berthed vessels, which would consequently reduce emissions to the greatest extent. Results also indicatethat this technology is more economically attractive in North American and Northern European ports, where energy production costs are lower and national environmental policies are stricter [11]. In southern Europe, in areas such as the Adriatic, energy costs are relatively high, discouraging investment in cold ironing [13]. However, the remaining gaps of OPS implementation in a port can be broadly classified into the following aspects:

(a) High investment costs, as cold ironing is difficult to profitably implement with low ROI expectations [14,15]. In addition, while the implementation of OPS at berths can potentially lead to a reduction in pollution and an improvement in air quality, its effectiveness is highly dependent on the number of ships that are equipped to use OPS [16]. The benefits of installing OPS at berths may be negligible if the availability of ships capable of using OPS is limited. In this case, alternative green investments such as those on sustainable alternative fuels or speed reduction measures may be preferred.

(b) The long payback period is one of the main challenges when assessing the effectiveness of OPS installation in a port. Without government subsidies or incentives from non-governmental entities, it presents a significant financial challenge for ports [22].

(c) While OPS is an emerging technology in ports, the adoption rate remains relatively low as there is still a small percentage of ports globally that receive and deliver OPS to ships in port. The challenge is twofold and concerns the port authorities involved [14,17]. First, it is important to identify the terminal with the highest vessel traffic and long berthing times in order to make the installation more profitable, and then to explore the scaling-up of the OPS technology to other terminals. Another aspect includes port authorities often being faced with the challenge of reaching agreements with ship operators and providing them with financial incentives to retrofit ships and connect them to an OPS facility [12]. Consequently, under these conditions, ports are reluctant to invest in OPS facilities until a sufficient number of vessels can use them, and shipping companies are reluctant to retrofit their vessels until a sufficient number of ports offer shore side electricity facilities.

(d) Even though considerable steps forward have been made in the context of legislation and standardisation of SSE–OPS facilities in ports, there is a lot of work remaining to be accomplished. The international standardisation of voltage and frequency is a major barrier to the widespread adoption of cold ironing among ports [5,23]. This lack of compatibility is primarily due to differences in electrical parameters between different international ports and vessels, which do not have uniform voltage and frequency requirements. For example, while some ships operate on a 50 Hz frequency, others use a 60 Hz frequency.

3.2. Alternative Fuels

Ports and port-related stakeholders are exploring their capacity to produce and use alternative fuels in their operations in order to meet their carbon neutral targets. The green practices related to ports commonly refer to the alternative fuels production, bunkering or charging vessels and trucks, while exploring opportunities for new transport network or supply chain planning. Electricity, liquefied natural gas, hydrogen, ammonia, methanol, and fuel cells are all considered to be in the alternative fuels category.

The analysis shows that special attention is given to the implementation of green hydrogen (e.g., production, transport, and storage), mainly in the major port hubs (e.g., Amsterdam, Barcelona, Rotterdam, North Sea Port, Gothenburg, Antwerp, etc.) [24–26]. Their aim is to create hydrogen hubs in their units, develop hydrogen plants and/or storage stations and/or cooperate with other ports to facilitate transport, and plan relevant hydrogen supply chains. As ports move away from fossil fuels, the use of hydrogen can have multiple applications: (i) to replace heavy fuel oil directly in terminals and engines; (ii) to facilitate bunkering of port facilities and sustainable transport of cargo to the hinterland; (iii) to be used as a feedstock for the production of synthetic fuels for various types of vehicles. In terms of its production, port hydrogen is usually produced using non-fossil energy sources such as hydroelectric, solar, or wind power (or water electrolysis under certain circumstances) in order to achieve the elimination of emitted air pollutants (green hydrogen), since hydrogen itself only emits heat and water. On the other hand, the analysis shows the development of LNG bunkering terminals in the ports of Barcelona, Marseille, and Bilbao, whereas the port of Klaipeda is setting up a floating LNG import terminal to supply degassed LNG to the gas transmission system [27–29]. Ammonia produced from natural gas with carbon capture and storage in northern Norway will be shipped to Rotterdam under a signed MoU [30].

The complexity of a hydrogen production, storage, and delivery system in a port depends on the production method used (for example, green hydrogen from renewable energy sources), the type of application (whether the hydrogen is used for fuel cell vehicles), and the specific characteristics of the port [31,32]. A techno-economic analysis of hydrogen production in the port of Trieste has been carried out, considering on the one hand the demand for hydrogen fuel in the steel works of the port and on the other hand the case of fuelling a steel works and a hydrogen fuelling station in the port. The production costs in these two energy scenarios are estimated to be around 7.50 €/kg H_2 with hydrogen produced by the proposed hydrogen production plant [33]. The proposed system consists of the PV power plants, the electrical grid and energy management system component, the electrolyser, the LP compressor, and the hydrogen storage.

In the port of Wilhelmshaven, an electrolysis plant with a capacity of 70 MW is being built to combine offshore wind with hydrogen on a large scale [34], with the aim of supporting industries such as the chemical, steel, and transport sectors in their decarbonization efforts. The investment in the port of Bilbao is EUR 67 million and the e-fuel plant will have a production capacity of 8000 L/day, enabling the large-scale storage of renewable energy [35]. The production of all green hydrogen and renewable electricity from solar and onshore wind farms at the port of Shoreham will be used by heavy forklift trucks and lorries, saving up to 45,000 tonnes of CO_2 per year and reducing noise pollution [36].

From a technical perspective, the market offers scalable and replicable electrofuel plants using a process that mixes green hydrogen from sustainable electricity and water sources with captured biogenic carbon dioxide. Providers will be able to produce e-methanol, an electrofuel that achieves carbon neutrality, using this technology.

3.2.1. Alternative Fuel-Powered Port Terminal Equipment

The electrification of terminal equipment is a rather widely acknowledged practice that contributes to emissions reduction, lower fuel consumption, and lower maintenance costs for the terminals. Whether accomplished through retrofitting or replacing the current diesel-powered equipment at ports (forklifts, straddle-carriers, prime movers, lift trucks, terminal tractors, rubber-tired gantry cranes (RTGs), and mobile harbour cranes (MHCs)) with electric propulsion systems, this stands as an energy-efficient and cost-effective way to reduce emissions from cargo handling in port operations [37]. However, a critical point that needs to be raised is that the entirely electric equipment is considered emission free provided that the electricity is produced from renewable resources. The electric container handlers, which have built-in lithium-ion batteries, have a variety of charging options and can be adapted to each terminal's special technical requirements. The hybrid diesel-electric systems can nevertheless significantly reduce emissions for machinery that cannot be entirely electrified. While hybrid engines of machinery may not totally eliminate pollutants, they are able to significantly reduce exhausted emissions to air and GHG emissions when compared to the diesel-powered ones.

Alternative energy carriers such as ammonia, methanol, or hydrogen-fuelled equipment could serve as an alternative option; however, these technologies are currently less established for use in port and terminal equipment and have a lower level of technological maturity. It is essential, though, to take into consideration that there are cases of trucks and relevant terminal equipment that run on diesel and LNG with dual-fuel engines. For heavy-duty equipment or equipment with prolonged operational durations, low-to-zero carbon fuels such as hydrogen (used in conjunction with a fuel cell or engine) may be applied on a bigger scale in the near future, along with the application of batteries as an alternative option. The market also offers electric container handlers, which have built-in lithium-ion batteries with a variety of charging options that can also be equipped with hydrogen fuel cells for activities with higher power requirements and particularly demanding duty cycles. In this case, electricity and hydrogen are expected to provide integrated power solutions for energy consuming operations. The advantage of hydrogen use over electricity is that it provides easily accessible energy to operations with no requirement for a high-capacity electric charging infrastructure (in cases that the power demands of a fleet will exceed the grid capacity) [38].

In view of the constant global efforts in implementing electrically powered terminal equipment in ports, the benefits of the retrofitting and replacement actions are primarily the reduction in local emissions and noise. The electrification of terminal equipment also focuses on the reduction of the total footprint of port and terminal operations on surrounding communities and ecosystems [39]. Compared to the use of diesel-powered prime movers in terminals, the replacement and operation of electric ones is anticipated to significantly reduce carbon emissions. In the Guangzhou container terminal, for example, a reduction of over 50% is reported. The demonstration of energy-efficient port equipment indicates that in the near future, the terminal will accomplish substantial reductions in CO_2 emissions [40]. In order to develop a zero-emission port, busier ports that have intensive port operations employ integrated low and zero-emission fuels and technology in their terminals. The Vancouver Fraser Port Authority is currently exploring such efforts to completely eliminate all emissions associated with port activity. For example, battery-electric terminal tractors, a hydrogen-powered crane, and 100% renewable diesel on a terminal locomotive are being tested in the port [41].

3.2.2. Alternative Fuel-Powered Supporting Vessels

To promote greener operations in port areas, much of the emphasis has been placed on the greening of the port fleet, which includes tugs, dredgers, support vessels, etc. Operators frequently take part in “green” projects aimed at replacing or modifying the currently operating port supporting vessels. There are several types of alternative propulsion systems that are designed for and employed in tugboats, such as diesel-electric and diesel-hydraulic as alternatives to direct diesel-mechanical propulsion, pure gas (LNG), or dual-fuel and fully electric powered by batteries.

The selection of a propulsion system while designing a vessel is performed based on particular systems’ capacity to produce the power required to accomplish the anticipated maximum service speed. However, along with the maximum service speed, the maximum bollard pull is also taken into consideration while building tugboats. Robust diesel engines are frequently selected as the primary generator of power in maritime propulsion systems. Nevertheless, it is crucial to take into account that marine diesel engines run most efficiently between 70% and 85% of their nominal load. While numerous existing vessels are able to utilise that, it can be detrimental for tugboats, as well as for short-distance vessels or those with low load profiles [42]. Under these circumstances, in some port cases it may be worthwhile to explore the use of non-fossil fuels with low fuel consumption or hybrid propulsion systems that include an alternative power source such as electricity. The hybrid (electric-diesel) powered vessels gain increasing attention [43]. As an example, two firefighting diesel-electric hybrid vessels have been recently introduced at the port of Hamburg [44].

In recent years, the use of electricity, other alternative power sources, and non-fossil alternative fuels in supporting vessels has remained relatively low. However, there are a number of ongoing projects related to the use of alternative-powered vessels. These consist of electric passenger boats and ferries equipped with batteries for fully electric propulsion in short-distance routes as well as the use of batteries in conjunction with diesel or gas combustion engines for hybrid propulsion in long-distance routes. Nearly half of the fleet in the port of Algeciras has been replaced with hybrid or electric vehicles, together with the essential charging infrastructure required to support vessel operations [45]. A completely emission-free workboat in the port of Bergen, powered only by batteries, carries out a variety of activities, including port facility maintenance, boat towing, personnel transportation, rescue operations, and reacting to oil spills [46].

3.3. Circular Economy

Building on the circular economy principles, port-related stakeholders promote the design and use of products necessary for their activities that are produced with secondary materials as input, reusing waste as raw materials. As an example, the port of Nakskov has found a way to apply the concept of circular economy to the port's main equipment, the red beacons, which fade over time in the sunlight and need to be replaced. The port has therefore developed a method of grinding and repainting the beacons so that they can be reused rather than discarded [47]. Another example from Taipei Port also shows that reusing recycled materials to construct port fencing can save about TWD 560 million (USD 17.5 million), significantly reducing the consumption of environmental resources [48]. Major EU port hubs, such as the port of Rotterdam and the port of Antwerp establish dedicated strategic programs such as the "Upcycle Factory project" and the "88-hectare NextGen District", respectively, aiming at becoming circular economy hubs in Europe [49,50]. The circular economy strategies of the major port hubs of Antwerp, Rotterdam, Amsterdam, and Hamburg share the common approach of phasing out fossil fuels and rely on the use of renewable energy, systematic improvement of energy efficiency, and improvement of waste management. However, there are smaller ports that face challenges in terms of the lack of available resources needed to transform port operations from a linear to a circular model and to integrate port expansion plans with urban planning [47].

A port operation that is considered critical in terms of the circular economy strategy in a seaport is the dredging operation performed in the seaside. The well-established concept of the "building with nature" approach in dredging operations is directly linked to the circular economy principles and facilitates the removal of sediments in a port respecting the local ecosystem [51]. Depending on the type of dredging activity (capital, maintenance, remedial) and the level of contamination of dredged material, the port can benefit from recycled construction materials, reusing them in port development activities. As an example, the port of Sevilla has recovered a 275-m-long stretch that was achieved through the deposit of 62,000 m^3 of sand extracted during maintenance dredging of the navigation channel [52].

However, there are also issues that ports often face when developing the circular economy model. For example, the circular supply chain in the port of Szczecin faces challenges related to employees' internal resistance to change (also due to lack of awareness), insufficient traceability of used materials from port-related stakeholders, lack of coordination and information sharing, and uncertainty of return flows and higher transport costs [53,54].

3.4. Waste Management

The reduction of port waste as well as the reception, recovery, general management and treatment of plastic, materials, water, hazardous substances, and other types of waste are the main topics discussed in the port literature. Efforts are being made by the waste management operators (encouraged by the port managing bodies and shipping companies as clients) for the production and trading of alternative fuels, processing the waste and using the appropriate recycling and treatment methods. Apart from the mandatory construction of port reception facilities according to the MARPOL convention, waste management can be extended to additional treatment plants with a diversification of the treated wastes and processing methods [55].

In this context, initiatives or campaigns for port employees in Spanish ports (namely, the ports of Algeciras, Valencia and Barcelona) have restricted the use of single-use plastic bottles [56]. To facilitate the elimination of single-use plastics in the port, they also provide water dispensers on the port premises. On the other hand, the North Sea port is investing in "advanced" or "chemical" recycling processes for the plastic waste generated within the port [57]. Similarly, the port of Vigo is developing a comprehensive management system for waste generated mainly by fishing activities (e.g., food plastics, polystyrene boxes, discarded fishing gear, and marine debris) [58]. The port of Barcelona is also an example of the port authorities' active participation in reducing the generated waste from their port premises, implementing an initiative of installing 30 water dispensers, leading to a saving of 118,680 plastic water bottles per year, with the aim of consolidating and expanding this system, even avoiding the implementation of reuse or recycling processes. The recycling plant at the North Sea port will process around 55,000 tonnes of mixed plastic waste per year, which is equivalent to the plastic packaging waste generated by around 1.7 million EU citizens per year.

The green practices related to waste reception, processing, and treatment in ports require, in some cases, a short time of implementation (0–2 years) according to port authorities and waste management operators. Innovative solutions that use the waste generated (the use of different types of waste such as slop oil, solvents, solid waste as fuel, and fats) for the production of alternative fuels and the construction of new facilities within the port area have moderate implementation costs. The waste valorisation may also be transferable and applicable in many port cases under certain circumstances regarding the available resources [59].

3.5. Other "Green" Port Practices

3.5.1. Green Policy and Planning

Green development in ports is an urgent task and is usually based on a comprehensive green policy and planning, foreseeing strategies of modal split, carbon neutrality, zero-emission operations, and adaptation to climate change. Ports set out their approach and commitment to various environmental and operational port-related issues in their official port strategies, master plans, and/or the policy frameworks they develop. Carbon neutrality with zero emissions and climate change are the most commonly identified issues with different targets among ports, along with actions related to ocean acidification and flood risk management. For example, Flinders Port Holdings (FPH) in Australia's climate change adaptation strategy identifies environmental risks and opportunities. The Port of Baku Climate Strategy 2035 and Action Plan mentions the development of a green port and logistics centre by adhering to international standards, while the port of Helsinki incentivises customers and stakeholders in its own carbon neutrality work [60–63].

3.5.2. Environmental Quality Monitoring/Pollution Prevention and Response

Moreover, the environmental quality monitoring undertaken by ports is among the most promising "green" practices for positive results in emissions exhaust mitigation and include air emissions monitoring, water quality, acoustic emissions, and odour nuisance examination using smart sensors and digital platforms. Furthermore, technologies such as drones and autonomous robots are often used by ports to facilitate pollution prevention, monitoring, and detection. Smart sensors are being installed in the Ghent-Terneuzen canal to monitor air and water quality in real time, so that potential environmental problems can be identified and addressed [64].

3.5.3. Carbon Management

Gradually, the stricter standards towards carbon neutral port operations impose emerging trends in carbon management. Among them, the carbon capture, storage, transport, monitoring, utilisation, and reporting has attracted a lot of attention from companies and relevant research organisations worldwide due to the increase in carbon prices (from less than EUR 25/t at the beginning of 2020 to more than EUR 80/t at the beginning of December 2021 in Europe). It should be noted, however, that although it is a promising technology, Carbon Capture, Utilisation, and Storage has not yet developed into a profitable business model. As such, even though it has been identified as promising action for eliminating the carbon related emissions in ports, it has not been given much attention [65,66].

3.5.4. Renewable Energy and Energy Efficiency

Renewable energy production has gained much attention in the port industry. Offshore wind farm installations serve as key enablers for ports towards their green transition and facilitate greener port-related operations reducing or even eliminating emissions to air. Remarkable efforts have been made, including deprived communities in the Solomon ports, where an amount of USD 100,000 has been allocated for community projects that promote and incentivise the use of renewable energy sources and reduce greenhouse gas emissions in communities across the country [67]. Soon after the installation of the four wind turbines in the port of Hirtshals in 2019 (installed without any public subsidy), the port was able to generate a positive power curve, with electricity production exceeding consumption by 50% at certain times [68]. The largest solar energy project in the North Sea port is contributing to the development of sustainable energy in Zeeland with the construction of a 60 MW solar farm in Valuepark Terneuzen [69]. The solar farm will be able to generate solar energy for more than 14,000 households and is expected to produce more than 56 million KWh per year, resulting in a reduction of 22,600 tonnes of CO_2 per year.

3.5.5. Biodiversity Protection

Adverse effects of port activity on the local ecosystems highlight the emerging need for biodiversity protection actions. Measures to protect the local flora and fauna, including those aimed at increasing wildlife around ports or existing nearby nature conservation areas, usually include a variety of measures such as (re)planting or re-establishment of sensitive seagrass or grassland species, restoration of marine ecosystems, promotion of awareness of ecosystem conservation in port areas, reduction of carbon emissions through CO_2 sequestration techniques, and so on. Spanish ports in particular seem to be investing heavily in relevant projects and scientific studies in order to be fully aware of the advances and risks of ecological development. For example, the restoration project of the breakwater in the port of Tarifa aims to preserve the port infrastructure and the overall integrity of the port [70,71].

3.5.6. Operational Efficiency

Special attention has also been given to automation in port operations 5G, IoT, and AI technologies for port call optimisation and port traffic management. These technologies have remarkable results in enhancing port environmental conditions forecasting. Therefore, the operational efficiency is a cross-cutting type of action that ports usually invest in. Intelligent systems, such as the Dynamic Under Keel Clearance System at the port of Saqr, aim to optimise the use of existing port capacity, improve the decision-making process for dredging, and increase the efficiency of the port. Similarly, PortXchange is a digital collaboration platform that allows shipping lines, port authorities, terminals and agents to plan, execute, and monitor all port call activities related to the Algeciras port in real time [72,73]. Notably, the adoption of digital solutions is having a significant impact on the maritime industry and global supply chains, as they have been heavily researched and adopted in recent years, replacing the conventional way of operating the port. Compared to ports with traditional methods of data collection and monitoring of their operations, green ports with the capacity to adopt digital solutions have a comparative advantage. A higher level of digitalisation is not only correlated with cost reduction, but also leads to a reduction in energy consumption, increasing the overall operational efficiency and sustainability of port operations; therefore, ports can improve their overall environmental performance [74]. In addition, the adoption of digital innovation sharing (DIS) in maritime supply chains, which includes blockchain, cloud-based, and other platforms, provides several opportunities and improved performance outcomes in port operations, as well as reveals key enablers and barriers. Visibility, optimisation, resilience, market sensing, customer relationship management, and integration were identified as key capabilities of these systems, which aim to improve the overall operational, financial, sustainability, safety and security, and marketing performance. However, the cost of implementing DIS, lack of human resources and knowledge, conservatism, scalability and infrastructure, lack of regulatory framework, and stakeholder support can become barriers for ports [75]. In order to achieve digitalisation as part of the green transition in ports, a wide range of skills and capabilities are required. The expertise in digital technologies and understanding the environmental regulations and sustainability principles are essential skills for port authorities. However, the exchange of expertise and best practices among port professionals to facilitate the adoption of digitalisation can be achieved through training and capacity building programs, using knowledge sharing platforms, and collaboration with technology partners in order to foster skills transfer in the port industry.

3.5.7. Award/Certification/Incentive Schemes

In order to promote sustainable and efficient operations, incentive and certification schemes for ports are being developed. These programmes often reward ports for implementing green actions, such as the reduction of air emissions, improving energy efficiency, and managing waste effectively. Certification schemes, such as EcoPorts certification, recognise ports that meet high standards of environmental management. Incentives can include financial and regulatory benefits or public recognition, encouraging ports to adopt innovative technologies and practices that reduce their environmental impact.

4. Conclusions

This study contributes to the existing literature by analysing and synthesising information and data on the greening efforts of ports towards their decarbonization and zero-emission port operations. The approach of collecting and synthesising information from the scientific literature, trade journals, and reports from organisations and initiatives related to ports has resulted in a holistic approach to the main characteristics, perspectives, trends, and gaps as well as the state-of-practice of greening of ports worldwide. From a scientific point of view, the specific characteristics of technological developments are usually studied and demonstrated, while several different tools and methodologies are developed to assess their potential or actual application in specific port cases. On the other hand, professional journals dedicated to the port and shipping industry provide insights and news on the evolution of the implementation of green measures in ports, in some cases with concrete numerical results on their environmental performance.

The work presented in this paper reveals that there are measures that have been widely discussed, researched, and implemented by port authorities and port users, such as the provision of SSE–OPS, the production and use of sustainable alternative fuels, effective and environmentally friendly waste management, as well as the application of other green practices such as the deployment of carbon management and storage, innovation support, investment in start-ups, pollution prevention, etc. However, seaports often face legislative, economic, and technical impediments during the design and implementation process that need to be properly addressed.

It is recognised that the regulatory framework at European and international levels, which imposes strict environmental requirements, the need for pollution prevention and emissions elimination, along with the desire to remain competitive in the port industry, are the main drivers for ports to be proactive in their environmental sustainability and to explore their capacity to implement green practices. For example, it will be mandatory for TEN-T ports to provide Shore Side Electricity–Onshore Power Supply to the berthed vessels (containers and passenger ships) from 2030 on, according to the Alternative Fuel Infrastructure Regulation (AFIR) [76]. It is also important that the strict framework for deployment of the Onshore Power Supply is accompanied by an obligation to use this infrastructure. However, there are still some uncertainties related to the obligation of ship owners and operators to retrofit or renew their vessel fleet in order to be able to receive shore side electricity. In addition, there will be major technical challenges in terms of compatibility between the ship- and the shore-based infrastructure provided, in terms of voltage and frequency levels, as different levels of energy capacity are required from the ship and so far, there are no specific global requirements. Similarly, from a financial perspective, ports' investments in green solutions often require subsidies, as their financial resources are usually limited for large green projects, which should be economically viable based on the ROI. For most of the investments in green port practices, the pillars of regulatory, economic, and technical barriers also apply.

The findings of this study underline the importance of tailoring green projects and practices to the specific characteristics of individual ports. Larger ports, due to their size and complexity, may focus on implementing comprehensive holistic initiatives that address multiple facets of their operations simultaneously. Small and medium-sized ports, on the other hand, may succeed by adopting targeted green practices that fit their capacity and operational context.

In addition, this study provides a basis for future research efforts, particularly in exploring the characteristics of ports vis-à-vis the specifics of the various solutions. Examining the circumstances under which ports can successfully adopt and integrate sustainable initiatives will contribute to a more comprehensive and holistic understanding of the challenges and opportunities associated with greening efforts in the port industry. It also provides a basis for ongoing discussion and collaboration between port-related stakeholders, researchers, and policy makers in the context of a rapidly evolving global focus on environmental sustainability. By building on the findings of this study, the port industry can continue to make progress towards achieving zero-emission and carbon-neutral operations, ensuring a more sustainable and resilient future for maritime activities worldwide.

A perspective that can be adopted and further explored in future studies is the managerial insights into the implementation of green practices. Based on the findings of this study, integrated management approaches to effectively implement and optimise green practices in ports to reduce polluting emissions, enhance environmental performance, and foster long-term sustainability within the port industry are briefly described. First, strategic alignment with regulatory requirements not only ensures compliance, but also enhances the port's reputation against its competitors while minimising regulatory risks. Second, investments in green infrastructures and solutions according to the specific environmental needs and financial capacity of the port, such as the exploration of alternative fuels, electrification, etc., contribute to the overall environmental performance. Likewise, integrating circular economy principles into port operations can significantly reduce waste generation and promote reuse and recycling initiatives. Regarding the tracking of effectiveness of these green actions, port managers should implement continuous monitoring, improve the mechanisms, and assess the environmental outcomes of the interventions.

Although the study sheds light on green practices implemented by ports, on issues and challenges facing the port industry, as well as on benefits of these implementations, it does not present an exhaustive, thorough review. Future work could undertake a scientific review for the purpose of assessing methodologies, experimental design, and sample size, to present the status of the scientific literature more thoroughly. Furthermore, a bibliometric analysis could be performed to identify research trends and research priorities pertaining to the greening of ports. The outcomes of such an analysis, along with the findings regarding challenges and impediments presented in this paper, could provide useful insights on future research and development priorities in the greening of the port sector. In addition, while the use of industry sources of information contributes to the collection of up-to-date and practical information, there may be a potential bias towards industry perspectives. These sources raise questions about the reliability and objectivity of the data collected, as they may not be subject to the same level of peer review as academic publications.

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Abbreviations

The following abbreviations are used in this manuscript:

AFIR	Alternative Fuel Infrastructure Regulation
AI	Artificial Intelligence
CO_2	Carbon Dioxide
EMSA	European Maritime Safety Agency
ESS	Energy Supply System
EUR	Euro
GHG	Greenhouse Gases
H_2	Hydrogen
IMO	International Maritime Organisation
IoT	Internet of Things
KWh	Kilowatt-hour
LNG	Liquified Natural Gas
MHCs	Mobile Harbor Cranes
Mton	Metric ton
MW	Mega Watt
NO_X	Nitrogen Oxides
PM	Particulate Matter
RES	Renewable Energy Sources
ROI	Return on Investment
RQ	Research Question
RTGs	Rubber-Tired Gantry Cranes
SO_2	Sulphur Oxides
SSE–OPS	Shore Side Electricity–Onshore Power Supply
TEN-T	Trans European Transport Network

Notes

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