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Review

How to Achieve Comprehensive Carbon Emission Reduction in Ports? A Systematic Review

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Abstract: Under the mounting pressure to make changes to become more environmentally friendly and sustainable, port authorities have been exploring effective solutions to reduce CO_2 emissions. In this regard, alternative fuels, innovative technology, and optimization strategies are key pathways for ports to transition toward a low-carbon pattern. In this review work, the current development status and characteristics of renewable and clean energy in ports were meticulously analyzed. The CO_2 emission reduction effects and limitations of port microgrids, carbon capture, and other technological operations were thoroughly examined. Lastly, the emission reduction optimization strategies ports could adopt under different scenarios were evaluated. The research findings showed that (1) combining the characteristics of the port and quantifying the properties of different renewable energy sources and low-carbon fuels is extremely necessary to select suitable alternative energy sources for port development; (2) technological advancements, multi-party interests, and policy impacts were the primary factors influencing the development of emission reduction technology methods; and (3) the coordinated optimization of multiple objectives in cross-scenarios was the main direction for ports to achieve sustainable development. This study provides theoretical guidance to ports that are transitioning to a greener pattern, as well as pointing out future research directions and development spaces for researchers.

Keywords: green port; carbon emission reduction; alternative energy sources; technological measures; optimization strategies

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1. Introduction

Approximately 10 billion tons of cargo, accounting for over 80% of global commodity trade by volume, is transported annually through maritime transportation [1]. Indeed, a significant amount of cargo requires extensive handling and transfer operations during transit. The ports, as logistics hubs for major shipping routes, require quay cranes (QCs), yard cranes (YCs), and yard trucks to carry out loading and unloading operations of goods. During this process, ship auxiliary engines, various working equipment, and other port-related activities in the port can generate substantial CO_2 emissions [2]. These emissions have been proven not only to pollute the environment of port cities but also to pose serious health risks to nearby residents, leading to reduced life expectancy [3]. Furthermore, they contribute to global climate change and are a significant cause of damage to the Earth's ecosystems [4]. The concern for the future sustainability of the planet has also prompted action in the field of maritime transport and the shipping industry. The International Maritime Organization has set a target for a 50% greenhouse gas reduction in emissions from the shipping industry by 2050 compared to 2008 levels [5]. Ports such as Shanghai Port, Hong Kong Port, and Singapore Port have also developed detailed CO_2 reduction strategies, including the collection of exhaust gases and the use of clean energy [6]. Against this backdrop, ports face significant pressure to reduce CO_2 emissions and transition towards a sustainable pattern.

Bound by the environmental quality requirements, ports operators are motivated to explore effective solutions. Firstly, the utilization of eco-friendly fuels has received significant attention from governments and port authorities. For example, the European Council has approved a plan to increase the share of renewable energy consumption by 27% by 2030 [7]. Moreover, studies have shown that the implementation of technologies to manage the utilization of energy can achieve an average CO_2 emission reduction percentage of 25–70% [8]. Several ports, such as the Port of Los Angeles in the United States, have already implemented microgrids to optimize energy utilization and minimize energy costs. Meanwhile, numerous sustainability and green port studies have emphasized that optimization strategies can significantly enhance energy efficiency by providing the same services with reduced energy consumption, thereby leading to CO_2 reduction. The emission reduction potential of these optimization strategies has been estimated to range from 30% to 50% [8].

In recent years, there have been several reviews on how to reduce port CO_2 emissions through various methods. Among these studies, Hoang et al. [9] specifically examined the utilization of renewable energy and alternative fuels in ports. The importance of the collaborative adoption of clean energy sources by both ports and ships to reduce CO_2 emissions was stressed. Moreover, Alamoush et al. [10], centered on the technological measures to port decarbonization in developed countries, particularly considered the potential for emission reduction, cost, and complexity of each technical measure. In addition, Iris et al. [11] reviewed the key pathways for ports to transition to low-carbon port patterns, including alternative fuels, innovative technologies, and equipment energy efficiency. Wang et al. [12] reviewed the estimation method of port carbon emissions and concluded that port carbon emission reduction strategies involve aspects such as operation optimization, scheduling, equipment modification, and energy management. Sivakumar et al. [13] emphasized the importance of collaborative efforts involving key stakeholders, including logistics providers, terminal operators, liner shipping companies, and other relevant parties. However, few existing reviews combined the characteristics and development plans of ports when analyzing different alternative energy sources. There is also a lack of systematic research on ship–shore emission reduction technologies. What is more, there are still limited literature reviews that discuss in detail the integration of port equipment operation plans with energy conservation and emission reduction measures. Therefore, large gaps still exist in sustainable operations to reduce port CO_2 emissions.

In this paper, the "port" refers to a comprehensive entity that includes both the ship-side and shore-side areas where vessels interact with land-based facilities. It is an integrated interface facilitating the handling, transshipment, and cargo exchange between ships and the adjacent land infrastructure. Ports and maritime operators have the potential to implement various measures to reduce greenhouse gas emissions within port areas. These measures can be categorized into several key strategies: renewable energy sources, low-carbon fuels, technological approaches, and optimization strategies based on previous literature reviews [9–12]. This article conducts an in-depth analysis of the recent literature, providing a more comprehensive summary. Firstly, an analysis is conducted on the characteristics and current development status of each type of renewable energy source available for ports. Then, the feasibility, effectiveness, and implications of adopting various low-carbon fuel options in port operations are investigated and evaluated. Third, the technological measures in this study are holistic and broad, covering both the port-side and the ship–port interface. Finally, this review provides a comprehensive and detailed description of optimization strategies, which summarize how port equipment can be coordinated in different scenarios to optimize operational plans, effectively achieving the goal of decarbonizing ports. The motivation for this study is to summarize and assess the feasibility, effectiveness, advantages, and limitations of various methods for ports' green development. These aspects serve as a comprehensive perspective for port policymakers, shipping companies, and maritime regulatory agencies in developing a sustainable and climate-friendly port industry. Also, research gaps and future research directions for researchers in related fields are presented.

The article is organized into eight sections, in which Section 1 introduces the research gap in the field of study and clarifies the necessity of this review. Section 2 presents the methods for data collection and selection. Section 3 summarizes the characteristics and development prospects of different alternative clean energy sources in ports. Section 4 discusses the characteristics and future trends of low-carbon fuels. Section 5 focuses on the emission reduction technologies for port equipment and ships at berth. Section 6 discusses energy optimization strategies in different scenarios aimed at reducing CO_2 emissions and energy costs. Section 7 identifies research gaps and provides insights for port policymakers while also indicating research directions for scholars. Section 8 presents the main conclusions and points out the directions for ports' efforts in the path towards greener development.

2. Methodology

2.1. Literature Search

This study is a literature review on methods to reduce CO_2 emissions in ports. To analyze the most recent research status and identify directions for further investigation, relevant publications pertaining to this topic from the past seven years will be meticulously selected and analyzed. Therefore, this study began with a literature search in databases such as Scopus, Web of Science, and Google Scholar. Based on previous research [9–12], some keywords such as "green port", "zero carbon port", "zero emissions ports", "renewable energy source", "alternative fuels", "emission reduction measures", "energy management technologies", "emissions reduction strategy", and "port decarbonization strategy" were combined for the literature search.

Building upon the insights from previous studies [9–11], multiple attempts and modifications were made to establish the following search criteria: TS = ("green port" OR "clean port" OR "zero carbon port" OR "zero emissions ports" OR "environmentally friendly ports") AND ("renewable energy source" OR "clean fuels" OR "alternative fuels" OR "renewable energy technologies") AND ("emission reduction measures" OR "technical and operational measures" OR "energy management technologies") AND ("emissions reduction strategy" OR "energy efficiency measures" OR "energy saving measures" OR "port decarbonization strategy"). EndNote was used to remove duplicates and review articles, resulting in 286 articles related to the research topic as initial samples.

It was possible that the initial samples may have included papers unrelated to the research topic. We used the literature screening method of Wang et al. [12]. The titles, abstracts, and keywords of the 286 articles were read and screened to exclude papers that were not relevant to green and low-carbon ports. After the initial screening, 162 papers were excluded, leaving 124 papers for further analysis.

To ensure a comprehensive literature search, the snowballing strategy was incorporated in addition to keyword-based searches. The initial set of 124 papers obtained in the previous step served as a starting point for snowballing. Within these initial papers, relevant references cited within them were examined, along with papers that cited the initial papers. This process resulted in the identification of an additional 21 papers that met the inclusion criteria. Overall, a total of 145 relevant papers were selected for this study.

Our study closely aligns with the work presented in reference [11]. However, there are three notable distinctions between our research and the referenced study. Firstly, our research provides a more intricate analysis of the distinctive characteristics pertaining to renewable energy and clean fuels, as well as the requisite conditions for their successful implementation and development within port settings. Secondly, we present a more detailed categorization of scheduling operations that specifically incorporate considerations of CO_2 emissions. Third, we limit our analysis to the literature published within the past seven years, ensuring that our review encompasses the most up-to-date research in the field. As a result, the articles selected for inclusion in our study may exhibit some variation compared to [11].

2.2. Literature Analysis

In order to summarize the latest research status of low-carbon ports, we conducted an analysis of the annual publication trends of the 145 articles related to "reducing carbon emissions in ports" over the past seven years, as shown in Figure 1. It is evident that the academic community's enthusiasm for research on this topic has been consistently high, as the number of publications increases each year. For example, around 15 articles were published in 2018 and 2019, while the number of articles published in 2022 and 2023 exceeded 30, nearly doubling the quantity. Currently, research on emission reduction in ports is showing an upward trend. It is important to note that the scope of our analysis is limited to articles published within the last seven years. However, due to the limited number of publications available at the beginning of 2024, the collection of papers directly relevant to the research topic of this article is relatively small.

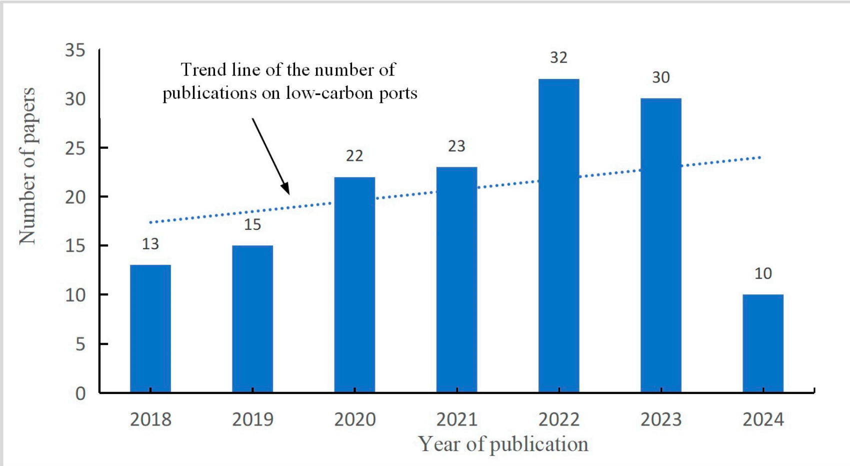

Figure 1. Research publications on green ports over the past seven years.

After the analysis of the annual publication trends, the 145 selected literature articles were further categorized based on various emission reduction methods in ports, mainly about the use of renewable energy sources, alternative fuels, technological approaches, and optimization strategies. There were 24 articles related to renewable energy sources, 30 articles related to alternative fuels, 55 articles related to technological approaches, and 36 articles related to optimization strategies. It is evident that renewables and low-carbon fuels continue to hold significant promise in the context of ports. The increasing focus on the use of technical means and technological transformation of port equipment can be observed as ports undergo the process of low carbonization. This indicates a growing recognition of the importance of incorporating advanced technologies to achieve environmental sustainability in port operations. Furthermore, numerous scholars are actively examining how to integrate equipment operation plans with emission reduction targets, aiming to achieve a mutually beneficial outcome.

3. Renewable Energy Sources

Renewable energy sources in ports primarily include offshore wind power (OWP), solar photovoltaic (PV) power, bioenergy, and tidal energy. These sources can effectively mitigate CO_2 emissions at the source and are considered the optimal alternative pathway due to their replenishable nature [14]. Moreover, they are recognized for their long-term investment value. The widespread deployment of renewable energy has currently expedited the progress of clean energy systems while considerably lowering fuel expenses [15].

3.1. Offshore Wind Power

Offshore wind power (OWP) has attracted significant attention from port managers due to its enormous energy production potential, high cleanliness, and mature technology. It has been widely applied worldwide [16]. Denmark, for example, derives 15% of its electricity from offshore wind power [17]. The European Union has established specific targets for OWP capacity, aiming for at least 60 gigawatts (GW) by 2030 and 300 GW by 2050 [18]. The U.S. West Coast is increasing its OWP projects and is expected to deploy commercial-scale floating offshore wind projects in California, Oregon, Hawaii, and other locations.

Abundant evidence has demonstrated that OWP can significantly reduce carbon emissions from ports and bring substantial benefits to port operations. Sadek et al. [19] discussed a new system combining OWP and fuel cells for energy supply in the Alexandria Port in Egypt. This system can reduce CO_2 emissions by 80,441 tons annually and generate a profit of 3.85–22.31% on electricity bills from electricity sales, helping alleviate the government's carbon emissions and electricity burden. Similarly, OWP and floating solar power could meet the shore-side electricity demand of the Port of Cartagena in Spain, resulting in a reduction of over 10,000 tons of CO_2 emissions annually [1]. Furthermore, to reduce the port's reliance on conventional power sources, Raileanu et al. [20] predicted wind speeds in the Port of Constanta in Romania and demonstrated that the port's electricity demand could be met with 385 turbines with a rated power of 8 MW each.

The selection of wind farm sites is dependent on factors such as wind speeds, geological structures, and transmission network conditions [21]. For instance, the proposed construction of an offshore wind farm in the Port of Aveiro, Portugal, was not approved due to insufficient wind resources [22]. Moreover, upfront investments and regular maintenance are also crucial factors. Through evaluating the influence of the distance between the offshore wind farm and the port on electricity generation and cable costs, Martinez et al. [23] identified the optimal locations for the wind farm, effectively minimizing the port's investment in offshore wind power infrastructure. In order to maximize the associated benefits, it is imperative to strategically determine the optimal location for wind farms based on the aforementioned factors.

3.2. Solar PV Power

The proximity of ports to the sea or rivers enables the cooling of floating solar power plants, enhancing the efficiency of their steam thermodynamic cycles, thereby increasing electricity generation. The unique natural conditions contribute to the widespread application of floating solar plants in ports [24]. By 2020, the global capacity of floating solar panels reached 3 GW. The Jurong Port of Singapore has achieved 350 MWh of solar power generation [25].

To meet the load demand and maximize significant economic benefits, it is vital to consider factors including economic feasibility, energy reliability, and environmental impact to determine the optimal configuration of PV systems [26]. For instance, Colarossi et al. [27] proposed a scheme integrating PV systems and energy storage systems (ESSs) to supply power in the Ancona Port in Italy, taking the operational costs and the scale of PV systems into consideration. In this context, a significant reduction of 87.4% in CO_2 emissions could be achieved. Furthermore, Elnajjar et al. [28] evaluated the solar potential of the Jebel Ali Port in the United Arab Emirates and found that applying solar PV systems in the port could reduce total costs by 10% and levelized energy costs by 5.20%.

Despite the significant potential of solar energy in the port industry, there are still major challenges to address. Solar PV power is highly intermittent, as it generates electricity only during daylight hours and is significantly influenced by weather and seasons. To ensure the stability of port electricity supply, ports typically incorporate corresponding ESSs when developing floating solar panels [27]. Moreover, extreme weather conditions in coastal areas, such as strong winds, waves, water currents, and corrosive saltwater, could affect the efficiency and lifespan of PV modules. Thus, ports need additional measures to cope with these conditions and further improve system efficiency [29].

3.3. Biofuels

Biofuels (methanol, ethanol) are favored by port managers as they serve as potential alternative fuel sources with lower carbon emissions compared to traditional fossil fuels. The Port of Rotterdam emerged as an early adopter to develop biofuels, which made it a major hub for the import and export of such fuels [30]. In addition, the United States, India, China, and Europe are the largest biofuel markets. Biofuels can be effectively integrated with renewable energy, such as solar PV. El-Amary et al. [31] conducted a simulation of the application of biofuels and solar PV in the Damietta Port in Egypt, revealing that a significant reduction in CO_2 emissions can be achieved under different strategies.

The advancement in biofuels in port settings entails notable economic benefits and promising prospects [32]. Specifically, the utilization of port waste as a feedstock for biofuel production, resulting in the generation of bio-methane and other biofuels, presents a viable solution for vessels engaged in fixed-route operations, including inland, coastal, and short-haul shipping. In this context, the necessity for infrastructure construction in ports can be diminished, leading to substantial cost-effectiveness [33]. However, different types of biofuels vary widely in emissions, costs, and utility, making it difficult to select one type of fuel for a particular application. As a result, research on biofuels largely remains confined to laboratory settings, yet it holds significant potential for practical applications.

3.4. Tidal Energy

Tidal energy, generated by the natural rise and fall of tides, can be effectively harnessed in locations with significant tidal range differentials [34]. Over the past few decades, many countries have recognized the tremendous potential of tidal energy in improving their energy infrastructure. The world's two largest tidal power stations are the Sihwa Lake Tidal Power Station in South Korea, with a capacity of 254 MW, and the Rance Tidal Power Station in France, with a capacity of 240 MW. In addition, the MeyGen tidal energy project in Scotland, with its four turbines, could deliver more than 35 GWh of electricity to the grid between 2018 and 2020. After the deployment of 61 underwater turbines, it will have a total capacity of 398 MW, making it the largest tidal stream power station in the world [34].

A positive correlation has been observed between the advancement in wave energy and the profitability of developers, particularly pertaining to the emerging trend of integrating wave energy with other renewable energy sources.

Tidal energy is an infinite and sustainable source of power that can effectively reduce the reliance on fossil fuels in coastal areas, making it a promising option [35]. However, the production of reliable and cost-effective energy sources remains a challenge due to the current technological immaturity. The high upfront investment and operational costs are considered major limitations to its development. Thus, tidal energy remains the largest untapped renewable resource [34].

Table 1 summarizes the advantages, development challenges, and applied ports for the four mentioned renewable energy sources.

Table 1. Current development of renewable energy sources.

Energy Type	Advantages	Development Challenges	Port Applications	References
Wind Power	1. Enormous energy production potential; 2. Highly clean energy; 3. Mature technology.	1. Wind speed, geological structure, and transmission network conditions need to be met for wind farm locations; 2. High initial investment for construction; 3. Regular maintenance is required.	Danish ports, the Port of Alexandria, Gothenburg Port in Sweden, Genoa Port in Italy, and Tianjin Port in China	[16–23]

Table 1. *Cont.*

Energy Type	Advantages	Development Challenges	Port Applications	References
Photovoltaic	1. The efficiency of photovoltaic power generation is high; 2. Can bring significant economic benefits; 3. Highly clean energy.	1. Electricity can only be generated during the day; 2. Efficiency is influenced by weather and season; 3. The lifespan of PV modules is affected by extreme weather conditions.	Long Beach Port in the USA, Jurong Port in Singapore, Port of Zeebrugge in Belgium, Gothenburg Port in Sweden, Port of Marseille in France, and Auckland Port in New Zealand	[24–29]
Biofuels	1. It has a smaller carbon footprint than traditional fossil fuels; 2. Could greatly reduce the construction of port energy-related infrastructure; 3. Blending with other fuels can further reduce carbon emissions.	1. Significant differences exist in emissions, costs, and applicability; 2. Inherent risks in development.	Port of Rotterdam, Helsinki Port in Finland, and Genoa Port in Italy	[30–33]
Tidal Energy	1. Infinite and sustainable energy source; 2. Can reduce coastal areas' demand for fossil fuels.	1. Not matured in terms of technology; 2. Tidal energy conversion efficiency is still at a low level; 3. High initial investment and operating costs.	South Korea, Scotland, tidal barrages in France, and Gladstone Port in Australia	[34,35]

4. Low-Carbon Fuels

Low-carbon fuels mainly include liquefied natural gas (LNG), hydrogen, ammonia (NH_3), and liquefied petroleum gas (LPG). These sources emit fewer greenhouse gases compared to traditional fossil fuels. However, the high usage costs and immature technologies are barriers to development. Nonetheless, they can serve as substitutes for conventional fossil fuels within smaller scopes [15].

4.1. Liquefied Natural Gas

Liquefied natural gas (LNG) is one of the most popular and cleanest options for ships. It has approximately half the density of conventional heavy fuel oil but has a higher calorific value of about 20%, resulting in a reduction of approximately 25% in CO_2 emissions [36]. Some shipping companies, such as Germany's Hapag-Lloyd and China Ocean Shipping Group, have purchased dual-fuel ships capable of burning both fossil fuels and LNG in response to emission reduction policies [37]. However, the application of LNG to the shipping industry is still in its early stages, and the total number of LNG-powered vessels remains relatively low. In addition, LNG can also be the fuel for port equipment, such as tractors, which is a substantial advantage in terms of environmental protection [38].

On the one hand, a large number of ports worldwide have started investing in LNG bunkering infrastructure, which not only ensured the operation of the rapidly growing number of LNG-powered vessels but also enhanced the competitiveness of the ports themselves. For instance, Europe has taken the lead in exploring the application of LNG in the shipping industry, with approximately 50 bunkering stations already in operation and 13 under construction [39]. Similarly, countries such as Singapore, South Korea, China, and the United States are actively promoting the construction of LNG bunkering stations in ports [40]. On the other hand, LNG-powered vessels select specific ports to refuel during their voyage based on certain criteria. In this aspect, the safety of port facilities and services are the priority aspects for most shipping companies when using LNG bunkering ports [41]. The price of LNG refueling, port service fees, and vessel turnaround time are determining factors that would influence the vessel's choice [42]. In these years, ports located at critical nodes in maritime networks have the opportunity to seize the LNG bunkering market. The development trend of LNG-powered vessels and the refueling requirements of different types of ships are essentially more valuable in most cases, as they affect the overall layout of the port. Moreover, the pros and cons of different refueling methods, including truck-to-ship, shore-to-ship, and ship-to-ship operations, are also key factors. Based on these assessments, appropriate refueling positions and methods should be selected for the establishment of LNG bunkering stations [43].

4.2. Hydrogen

Hydrogen, as a carbon-free fuel, is widely recognized as a clean energy source with the potential to power ship engines and port equipment. Its significant advantage lies in its lower emissions, which has led to its official inclusion in the strategies of prominent economic entities such as the United Kingdom, the United States, Japan, and the European Union [44]. Furthermore, hydrogen has emerged as a promising solution for storing renewable energy sources like PV solar and wind power. It exhibits the capability for large-scale seasonal energy storage and can be efficiently converted back to electricity using electrochemical devices [45]. Consequently, numerous ports around the world, such as Qingdao Port in China, Yokohama Port in Japan, Auckland Port in New Zealand, Antwerp Port in Belgium, Rotterdam Port in the Netherlands, and Los Angeles Port in the United States, have taken proactive measures by establishing hydrogen production centers or related facilities [46]. These efforts are aimed at facilitating energy upgrades within the port and fostering energy trading activities.

Hydrogen has enormous potential to significantly reduce emissions compared to various other energy sources. For instance, the substitution of natural-gas-derived syngas with green hydrogen can lead to a remarkable reduction of up to 88% in CO_2 emissions [47]. Moreover, the direct application of hydrogen in conjunction with electric arc furnaces has the capacity to achieve emission reductions of approximately 35% [47]. When utilized as a viable fuel source for ship engines, the utilization of hydrogen as a dual fuel in combination with heavy fuel oil in ocean-going tankers can potentially yield a carbon emission reduction of around 40% [48]. Additionally, the supply of hydrogen to a refueling station serving 20 vehicles has the potential to result in an annual reduction of 153 tons of CO_2 emissions, as demonstrated by research conducted on a hydrogen production and storage system in an Italian port [49].

In addition to reducing waste emissions, hydrogen provides a significant economic advantage for ports. In a comparative techno-economic analysis conducted in [50], the study compared a hybrid renewable energy power plant combined with a hydrogen energy storage system to the implementation of the cold-ironing technique. The findings indicated that a 3.33% reduction in levelized energy costs could be achieved through large-scale infrastructure. In the cold-ironing scenarios, the reduction reached 4% [50]. Similarly, according to Vichos et al. [51], by utilizing a hydrogen storage system to store surplus energy, the levelized energy cost was reduced by 8.41% and 2.20% in the presence and absence of cold ironing, respectively.

However, the development of hydrogen at ports also poses a challenge for the risk management of the port authority. The high permeability, low boiling point, and rapid burning rate of hydrogen could lead to metal cracking and material expansion and contraction, which is even more dangerous. This necessitates strict storage and handling requirements, thereby increasing the complexity of port layout [52]. Moreover, given the diverse state of hydrogen and the need for different technological approaches, ports must continuously enhance their facilities and service standards. In the future, the competitiveness of hydrogen is expected to strengthen due to continuous innovation in hydrogen production technologies and advancements in management systems [53].

4.3. Ammonia

Ammonia (NH_3) is a chemical compound with a pungent odor that can serve as a fuel. It can also be transformed to and from hydrogen given the appropriate conditions. Moreover, during the combustion process, NH_3 primarily yields water and nitrogen, making it a significant contributor to the reduction in carbon dioxide emissions when substituted for conventional fuels [54]. Consequently, NH_3 demonstrates substantial potential as a fuel for internal combustion engines or fuel cells, thereby enhancing the environmental carbon footprint of global shipping.

Several ports are currently directing their efforts towards the development of NH_3 infrastructure. For instance, the Port of Rotterdam is in the process of constructing a green ammonia terminal [55]. Similarly, ports such as Port Hedland, Bunbury, and Townsville have initiated plans for green NH_3 plants. Liu et al. [56] conducted a study on the synthesis of ammonia following hydrogen production through water electrolysis. They employed distributionally robust optimization methods to optimize the scheduling of the energy system of Tianjin Port, using real data from the port. This approach has resulted in increased flexibility and improved economic efficiency. However, the cost of constructing NH_3 terminals and establishing NH_3 storage facilities is a significant barrier that restricts the expansion of NH_3 as a sustainable maritime fuel, resulting in currently only a limited number of NH_3 terminals in port areas [57]. According to Balci et al. [58], their investigation on green ammonia revealed that the most significant factors influencing its utilization are stakeholder support, carbon taxes, public awareness, and the number of early adopters. Furthermore, the high toxicity of NH_3 to humans and marine organisms necessitates stringent safety standards for its use. Comprehensive laws and regulations enforced by the government are required to address the technical challenges associated with NH_3 and ensure its safe implementation [55].

4.4. Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is a byproduct of petroleum known for its high calorific value, ease of transportation, stable pressure, and simple storage. These properties make it a versatile and flexible fuel option. As a result, it is considered a viable alternative to traditional fossil fuels for marine engines and vehicles, providing significant pollution reduction benefits [59]. However, it is important to note that unlike LNG, which is supplied through external pipelines in ports, most LPG is delivered as fuel through on-site storage tanks, introducing additional risks in the use of this fuel [60].

There is evidence that LPG is changing fuel usage in the shipping industry. For example, the LPG trade holds a significant share of the global clean energy consumption market and has been growing in recent years. Europe, the United States, China, and India have been identified as major consumers of LPG, and their consumption is projected to continue growing in the near future [61]. The increasing adoption of LPG has unfortunately been accompanied by catastrophic accidents resulting from the improper handling of the fuel tanks or operational errors. This poses significant challenges for port managers and hinders further widespread development of LPG. Therefore, it is imperative for ports to prioritize the safety of liquefied petroleum gas tank trailers to prevent large-scale leaks and destructive explosions [61].

Table 2 summarizes the characteristics of the four low-carbon fuels mentioned above and their applications in ports.

Table 2. Current development of low-carbon fuels.

Energy Type	Advantages	Development Challenges	Port Applications	References
Liquefied natural gas (LNG)	1. Helps ships achieve emission reduction targets. 2. Can enhance the competitiveness of the ports.	1. Various refueling methods affect the overall layout of the port. 2. Higher requirements for safety in port facilities and services.	German shipping company Hapag-Lloyd and China Ocean Shipping Group	[36–43]
Hydrogen	1. Widely recognized as a clean fuel. 2. Assists nearby factories in emission reduction.	1. Chemical properties of hydrogen increase the complexity of overall port layout. 2. Limited technological advancement in hydrogen production. 3. Current management regulations regarding hydrogen are incomplete.	Qingdao Port in China, Port of Yokohama in Japan, Auckland Port in New Zealand, Port of Antwerp in Belgium, Port of Rotterdam in the Netherlands, and Port of Los Angeles and Long Beach Port in the USA	[44–53]

Table 2. *Cont.*

Energy Type	Advantages	Development Challenges	Port Applications	References
Ammonia (NH3)	1. Has good advantages in handling and storage. 2. Can serve as a medium for hydrogen storage and transportation. 3. Ammonia primarily produces water and nitrogen during combustion, making it highly clean.	1. Both construction of ammonia terminals and storage are very expensive. 2. Ammonia is highly toxic to humans and marine organisms. 3. Current laws and regulations regarding ammonia still need improvement.	Port of Halden, Port of Bonifacio, and Port of Townsville are already planning green ammonia plants	[54–58]
Liquefied petroleum gas (LPG)	1. A clean and low-carbon energy source. 2. Used as an alternative fuel for internal combustion engines and vehicles.	1. Transportation of LPG in tank trailers carries certain risks. 2. Large-scale release of LPG can cause destructive explosions.	Europe, United States, China, and India are the countries and regions with the highest usage of LPG	[59–61]

5. Technological Approaches

Using technological methods to manage energy systems and control waste gas emissions in ports is an efficient strategy to achieve environmentally friendly ports. Both the port-side and the ship–port interface are considered in this paper. Technologies such as port microgrids and energy storage systems facilitate the optimal utilization of diverse energy sources, resulting in lower greenhouse gas emissions. In addition, the use of cold-ironing technologies can supply electricity to the ships during their berthing period, while the implementation of scrubbers and carbon capture technologies at the exhausts of the ships' engines can effectively minimize emissions in the port area, ensuring a clean port environment [62]. Furthermore, digital transformation can accelerate the information exchange speed in maritime supply chains, ports, and vessels, thereby enhancing cargo handling efficiency and reducing port carbon emissions [63].

5.1. Microgrid

With the gradual adoption of renewable energy source in ports, along with technological advancements in systems such as cold ironing, QCs, reefers, electrical trucks, and other loads, traditional energy management methods were unable to effectively address the volatility and intermittency of renewable energy sources nor could they coordinate the energy consumption of equipment clusters [11]. Therefore, there is an urgent need for technological breakthroughs in energy management in ports. Establishing microgrids at ports is an effective approach. By monitoring and controlling the distributed power sources, loads, and connecting devices within the port area, it is possible to achieve the coordinated management of energy supply and consumption, ensuring that the power demands of loads are met under any circumstances [64]. The composition of a microgrid is illustrated in Figure 2. Additionally, the use of microgrids can enhance the energy efficiency of equipment, reduce peak-to-valley differences in energy consumption, and thereby achieve the goal of lowering energy costs in ports [65].

In recent years, there has been a growing focus on the development of microgrids in port areas, with numerous ports already implementing or in the process of implementing microgrids [11]. For instance, the Antwerp Port in Belgium has successfully established a microgrid that incorporates photovoltaics, wind power, and cold ironing. Similarly, the Port of Los Angeles in 2016 completed a microgrid consisting of 1 MW of photovoltaics, 2.6 MWh of lithium batteries, charging stations for electric yard trucks, and cold ironing. In 2021, the Port of Long Beach commissioned a microgrid that includes 300 kW of photovoltaics, a 670 kWh battery storage system, charging stations for electric yard trucks, and local loads. Additionally, the Rotterdam microgrid in the Netherlands is planned to utilize onshore wind energy and offshore photovoltaics in the near future [66].

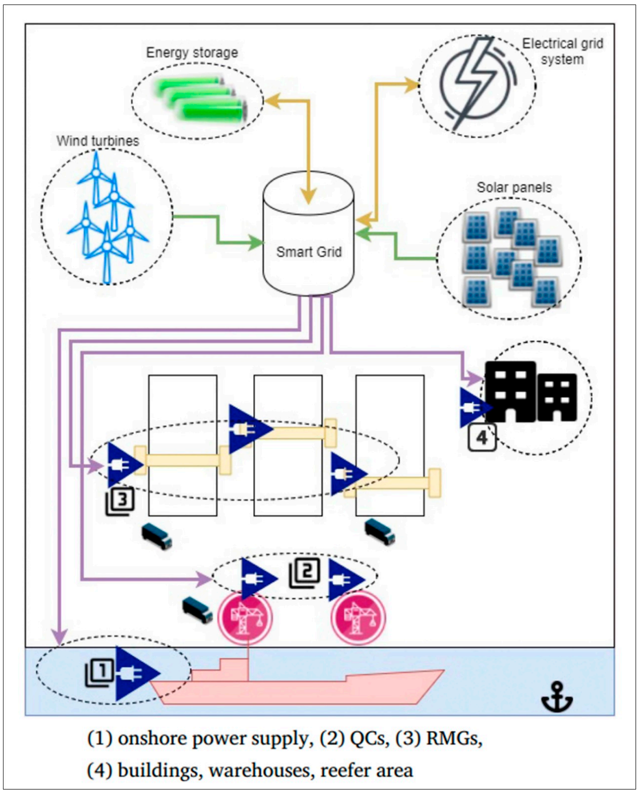

Figure 2. Overview of possible harbor microgrid facilities [11].

The operational efficiency of port microgrids has been assessed by many scholars. Molavi et al. [30] introduced a systematic framework that integrates a set of intelligent port indices into the planning process of microgrids. Through conducting comprehensive assessments across key domains such as operations, environment, energy, and security and implementing focused initiatives, port operations can achieve considerable enhancements in productivity, sustainability, and reliability. The uncertainty associated with renewable energy sources in port microgrids was addressed in [67]. This study integrated berth allocation problems and port operation schedules to enhance the independence and system efficiency of microgrids. In order to effectively manage and ensure the stable operation of microgrids, Pham et al. [68] modeled the energy storage units and DC bus and formulated economic constraints to describe the power and energy balance within the microgrid.

Despite the increasing number of publications on port microgrids, the implementation of microgrids in ports poses several challenges [11]. One of these challenges is the integration of energy consuming devices, such as reefers and cold ironing, into microgrid systems. In addition, berth allocation problems and the scheduling of port cranes need to be addressed. These factors contribute to the complexity of deploying microgrids in port areas [69]. Moreover, power demand from loads in port microgrids exhibits significant randomness and fluctuations, which places higher demands on the voltage and frequency control of the microgrid. Inadequate adjustment of the energy system to accommodate fluctuating load demand can lead to the deterioration of the power quality of the microgrid. In more severe instances, this can result in grid outages and safety incidents [30].

5.2. Energy Storage Systems

Energy storage systems (ESSs) are crucial components of port microgrids, with batteries, supercapacitors, and flywheels being common types. Lead–acid batteries are the most widely used type in ports due to their versatility in size and design, allowing for customization to suit a variety of situations. This enhances energy utilization efficiency and benefits both power generation and consumption in ports [70]. Lead–acid batteries have found wide application in prominent ports worldwide, including the Port of Los Angeles and the Port of Long Beach in the United States, the Port of Alexandria in Egypt, the Port of Singapore, and the Port of Tianjin in China [30].

The implementation of large-scale ESSs on the energy supply side of the port provides numerous advantages. Firstly, ESSs enable the optimal utilization of renewable energy sources by mitigating their variability and unpredictability, resulting in reduced wind and solar curtailment [71]. Secondly, ESSs can capitalize on price differentials to store energy and engage in arbitrage opportunities [72]. For instance, by optimizing the energy requirements of port cranes through ESSs, significant cost reductions can be achieved [73]. Lastly, ESSs serve as a short-term emergency power source for ports and other facilities, improving the overall power quality [73]. A study conducted at the Port of Jurong in Singapore identified the optimal configurations of ESSs and photovoltaic systems to minimize line congestion and mitigate significant transmission losses [74].

The small-capacity ESS on the energy consuming side of the port enables the integration of unused energy, facilitating efficient energy storage and feedback into the grid. For example, electric-powered rubber-tired gantry cranes can capture and store a portion of the energy generated during container lifting and transportation using supercapacitors or lithium batteries. Most studies focus on leveraging ESSs to enhance the efficiency of gantry cranes. For example, the impact of storage system component sizing on the overall efficiency of crane systems was examined in [75]. Similarly, Alasali et al. [76] investigated the integration of an ESS in rubber-tired gantry cranes, developing an optimal control strategy to regulate the energy storage device's flow rate. The impact of high demand fluctuations was mitigated, and peak demand was reduced through the implementation of this strategy. Additionally, energy recovery is also possible for forklifts in ports. Ceraolo et al. [77] studied a rechargeable ESS model of a diesel–lithium battery hybrid forklift, demonstrating that approximately 38% of fuel can be saved by harnessing and utilizing the significant amount of regenerative energy produced during the frequent stops and start-ups during forklift operations.

The primary barriers to the advancement in ESSs in ports are initial investment and technological advances. ESSs of various materials and sizes present significant disparities in cost, technical safety, environmental impact, lifespan, and power regulation. To reduce the overall cost of ports and balance renewable energy source generation, the appropriate scale and installation location of ESSs should be determined considering the actual requirements of the port [78].

5.3. Cold Ironing

Cold ironing refers to the utilization of shore-based electrical power instead of auxiliary engines when ships are docked. It provides the necessary electricity for various functions such as pumps, ventilation, lighting, communication, and other facilities, thereby reducing emissions in ports [79]. Cold ironing has reached a high level of maturity and is widely adopted in ports worldwide. Since 2010, cold ironing has been included in port modernization plans in European countries such as Belgium, Norway, and Finland. As of 2017, over 10 ports in the United States had implemented cold-ironing systems for different vessel types, offering both high- and low-voltage options [80]. Moreover, the Chinese Ministry of Transport has actively promoted cold ironing in Chinese ports, resulting in cold-ironing facilities being installed at approximately 7500 berths nationwide by the end of 2021 [81].

The implementation of cold ironing involves the collaboration of ship owners, ports, and governments. Ship owners play a pivotal role in deciding whether to utilize cold ironing. On the one hand, it offers advantages in reducing the required amount of refueling compared to ship fuel inventory planning and berth scheduling [82]. On the other hand, ship owners face significant costs to retrofit their vessels to comply with cold-ironing connection requirements, resulting in a lengthy recovery period to offset retrofitting expenses through the price difference between cold ironing and fuel [83]. For ports, the diverse range of vessel types berthing at ports and their varying requirements for cold-ironing frequency, voltage, and power pose challenges in developing port infrastructure for cold ironing and impede its progress [84]. The government acts as a bridge between ship owners and ports, promoting cold-ironing development through subsidies. Xu et al. [85] and Song et al. [86] employed game theory to examine the relationship between these stakeholders, highlighting the crucial role of government incentive measures in shaping the policy costs and social benefits of cold-ironing systems. Furthermore, the impact of government subsidies on cold-ironing prices and investments in projects was compared in [87]. The optimal investment scale and price for cold ironing to maximize net profits were determined. Similarly, Luo et al. [88] investigated three policies related to the use of cold ironing, namely subsidies, carbon taxes, and promotion of shippers' green awareness. They examined the strategies employed by shipping operators to balance their utilization of sustainable practices under these different policy scenarios and provided recommendations. Additionally, the implementation of cold-ironing projects for bulk carriers, tankers, and general cargo ships also yields socio-economic benefits, with the pricing of cold ironing being a significant factor influencing economic returns [89]. Karapidakis et al. [90] investigated the energy requirements of cold ironing during ship berthing at the Port of Iraklio, emphasizing the contribution of renewable energy and shore power to the port environment.

Indeed, apart from the interests of various stakeholders, the successful application of cold ironing in ports is closely tied to technological advancements. Cold-ironing implementation continues to face challenges related to security risks, technical complexities associated with frequency, and regulatory oversight. From a technical point of view, it is crucial to take into account the power requirements and operational plans of different types of vessels, the uncertainties surrounding berthing schedules, and the unpredictability of local energy sources. These aspects are key to ensuring the seamless functioning of cold ironing and should be the focus of future efforts [91].

5.4. Carbon Capture

Carbon capture has been considered as a mid-term solution for reducing carbon dioxide emissions before the widespread use of clean energy sources [92]. Among the various carbon capture technologies, solvent-based CO_2 capture has emerged as the most mature and well-established approach. The principle involves the use of an absorbent to adsorb or dissolve CO_2 from a high concentration point source into the corresponding medium. It has been used in industries such as coal-fired power plants, oil refineries, petrochemical companies, and cement plants.

Several studies have assessed the viability of deploying carbon capture technology in port environments. Notably, Shan et al. [93] and Song et al. [94] conducted simulations of a low-carbon port microgrid incorporating carbon capture and storage technologies. An energy management model integrated with carbon trading was developed to optimize coordination between port microgrids and carbon capture plants to achieve low carbon emissions and cost-effectiveness. Experiments showed that the proposed approach can effectively achieve the economical, low-carbon, and reliable operation of port microgrids [92]. In a related context, the port energy consumption was extended, and a novel multi-objective energy management model was introduced in [95]. The results highlighted the significance of carbon capture and storage systems to control CO_2 emissions and provided valuable insights into optimizing the overall energy system within seaports [96].

Carbon capture technology serves as a viable alternative to achieve compliance with ship emissions and as an effective tool to assist ports in their carbon reduction efforts. Nevertheless, during its application, various challenges related to absorbents need to be addressed, and the stability of impurities in the absorbents must be ensured. The high operating costs hinder its large-scale deployment in the power industry, but it still holds great potential for future development [97].

5.5. Digital Technologies

Currently, blockchain and cloud platforms are increasingly being used in shipping supply chains and ports [98]. These digital technologies facilitate the establishment of effective connections and information sharing among different entities, such as shipping companies, ports and terminals, customs, and shippers [99]. By utilizing these technologies, it becomes possible to effectively monitor the entire operational process in ports, improve communication efficiency, and expedite operational procedures. As a result, unnecessary transportation, warehousing, and inventory in ports can be reduced, leading to a significant decrease in energy consumption and carbon emissions [100].

In port seaside areas, digital technology enables the design of port layouts and related infrastructure to minimize ship travel distances and optimize vessel speeds during port entry and exit, thereby reducing carbon emissions from ships within ports [101]. Additionally, by integrating digital technology with ship travel data and weather conditions, timely adjustments can be made to port operations, minimizing economic losses and environmental pollution resulting from adverse weather conditions [102]. Furthermore, digital technology facilitates the comprehensive monitoring of ship statuses in ports, which is essential for waste discharge and marine pollution control [103].

In port land areas and yard areas, container cranes are major contributors to greenhouse gas emissions. Leveraging digital technology allows for the real-time monitoring of crane operations and energy consumption, enabling adjustments to operational intervals for improved energy efficiency [104]. Remote monitoring and management of automated guided vehicles has also been made possible, enabling real-time monitoring of their operating status and energy consumption. This fosters collaboration between automated guided vehicles and other port equipment, optimizing cargo handling processes and reducing energy waste and carbon emissions [105]. Moreover, digital technology provides comprehensive insights into the availability of empty containers at port facilities and the status of terminal vehicle operations, facilitating the optimization of truck arrival times at port gates and reducing waiting times outside yard gates, thereby mitigating greenhouse gas emissions resulting from truck congestion [106].

Undoubtedly, digital technology has immense potential in facilitating the development of green ports. However, the process of digitalization in port infrastructure faces significant challenges. A primary challenge pertains to the high costs associated with infrastructure development, necessitating careful cost–benefit analysis by port management authorities and operators [107]. Additionally, effectively managing, analyzing, and utilizing diverse data forms a crucial focal point. This entails the integrated application of data collection techniques, big data analytics, and artificial intelligence [108]. Overcoming these challenges enables ports to achieve enhanced efficiency and environmental sustainability [109].

6. Optimization Strategies for Port Emission Reduction

Optimization strategies for port emission reduction have attracted a lot of attention from scholars and port managers. Currently, there are four prominent forms of emission reduction strategies. First, it is crucial to consider energy consumption when optimizing operation planning. By striking a balance between operational efficiency and energy savings, the objective of reducing carbon emissions can be effectively achieved. Second, energy efficiency would be enhanced by reducing the peak energy requirements of the devices, thus accomplishing the same task with reduced energy consumption and contributing to green ports. The third approach involves incorporating operational planning that responds to time-of-use electricity pricing from the utility grid. This strategy aims to minimize the likelihood of increased greenhouse gas emissions resulting from power plant adjustments while also reducing energy costs for the port. Lastly, carbon taxes are important when formulating operational plans, as the penalties associated with carbon emissions incentivize ports to reduce their carbon footprint [110].

6.1. Operation Optimization Based on Energy Awareness

There is a wide range of equipment in ports, including cold ironing, QCs, YCs, reefers, and electric internal trucks (EITs). Each piece of equipment has a different level of energy consumption in different operating states. For example, when the simultaneous utilization of the quay cranes increases, the productivity of each crane inevitably decreases, leading to a higher energy demand to complete the same task. Moreover, when multiple devices need to collaborate to accomplish a task, improper coordination increases the waiting times and results in additional energy consumption [110]. To effectively reduce carbon emissions in ports, current research primarily focuses on optimizing the operational efficiency of individual equipment and a group of equipment working in synchrony. The main objective is to enhance the overall efficiency of equipment operations while simultaneously reducing energy consumption.

In container terminals, QCs, YCs, and EITs are responsible for the loading, unloading, and transportation of containers within the port, rendering them the primary electricity consumers and having substantial potential for energy savings [111]. However, the operational efficiency of these pieces of equipment does not increase linearly with the increasing numbers; instead, it tends to decrease. A dynamic approach was proposed in [112] to handle variations in the working quantity of QCs and YCs. Many scholars have demonstrated that this approach can ensure optimal work efficiency and lower operating costs. EITs play a crucial role in the horizontal transportation of containers within ports. The operational efficiency of these trucks is influenced by factors such as yard occupancy and QC queuing times. To mitigate emissions resulting from deceleration, EIT arrival modes can be adjusted to minimize waiting times [113]. Building upon this concept, Karakas et al. [114] achieved a harmonious balance between operational efficiency and environmental considerations. By optimizing the efficiency of yard trucks from 27.8% to 42.8%, they successfully reduced CO_2 emissions by 1.70% to 2.30%.

By establishing close collaboration with systems like QCs, YCs, cold ironing, and EITs, which possess inherent coordination capabilities, it becomes feasible to achieve a green and low-carbon economy while simultaneously ensuring the overall efficiency of the container handling system [115]. Based on this, the system consisting of external container trucks, QCs, YCs, and EITs in a U-shaped automated container terminal was optimized to effectively address conflicts between transportation equipment. The results showed that total energy consumption could be reduced by 0.03–14.15% [116]. Furthermore, various loads, such as cold ironing, QCs, YCs, and reefers, were integrated and studied within a thermal–electric energy network [117]. The research successfully validated the potential of flexible logistics loads in enhancing the energy efficiency of ports and minimizing overall energy consumption.

6.2. Operation Optimization Based on Energy Efficiency

Incomplete energy utilization during periods of increased energy demand results in reduced energy efficiency, which necessitates increased energy consumption for similar operations. Research data indicated that peak electricity usage represents around 25–30% of monthly electricity costs [11]. Ports have the ability to adjust their operational schedules for adaptable loads such as QCs, YCs, EITs, and reefers. By strategically managing the timing and amount of energy consumption within a specified timeframe, it becomes feasible to alleviate peak energy demand and consequently lower greenhouse gas emissions.

There is a positive correlation between the reduction in energy peaks in the QCs and the CO_2 emissions. To reduce carbon emissions, a limitation on the maximum number of operating cranes was imposed in [118]. In this way, approximately six quay cranes can result in a 50% reduction in peak costs. It is important to note that the impact of such measures on the efficiency of container ship loading and unloading is negligible, with an increase of less than half a minute per hour. Moreover, Tang et al. [119] introduced a comprehensive approach that entails restricting both the number of cranes and their maximum energy consumption. This strategy not only mitigated power peaks but also mitigated energy demand fluctuations, thus ensuring the stability of the grid. In the case of double-trolley QCs integrated with energy storage technology, a simple delay of 21 s in one cycle for each trolley start time can significantly reduce the maximum power peak of the crane set from 10.22 to 5.84 MW, as demonstrated in [120].

Besides QCs, EITs also contribute to peak energy consumption due to their charging requirements. Strategies such as shifting the charging time to off-peak periods can effectively mitigate the peak energy demand [121]. To address this issue, a two-stage stochastic programming model was presented and optimized in [122]. By accounting for uncertainties in truck arrival times and charging station availability, a reduction in peak energy demand was successfully achieved while simultaneously increasing the charging infrastructure utilization [123].

6.3. Operation Optimization Based on Price-Responsive Strategies

The electrification of port equipment has transformed container terminals into electricity-intensive consumers, heavily dependent on the utility grid. The implementation of time-of-use electricity pricing policies has had a notable influence on the electricity expenses incurred by container terminals [123]. Consequently, this development creates an opportunity to investigate operational planning strategies under time-of-use electricity pricing schemes. Such strategies could minimize electricity costs and carbon emissions associated with container terminal operations [124].

In the framework of time-of-use electricity pricing, decisionmakers tend to make a trade-off between operational efficiency and electricity costs, which can be achieved by adjusting equipment tasks in response to fluctuating electricity prices. For instance, in ports where multiple energy sources such as electricity, heat, and gas are utilized, load demand can be strategically managed based on time-of-use electricity pricing. By harmonizing energy supply and demand and taking into account the electricity price characteristics, energy-intensive operations can be strategically shifted to periods of lower electricity prices. This approach could maximize the potential for energy arbitrage [125,126]. Another commonly employed approach is to schedule internal truck arrivals during non-peak electricity price periods. The practice has been observed in container terminals located in ports such as Los Angeles, Long Beach, and Qingdao. By aligning the arrival of internal trucks with non-peak electricity price periods, container terminals can take advantage of lower electricity rates, further optimizing their cost-efficiency [127].

Time-of-use electricity pricing significantly affects the integrated operations planning of the port. The impact of time-of-use electricity pricing on berth allocation was investigated in [128]. This study considered factors such as shore power costs, departure delays, and vessel emission costs, thereby expanding the scope of berth allocation problems and promoting the development of green ports and green shipping. Additionally, to enhance port electricity usage management and emission control, Qiu et al. [129] focused on various factors including electric vessel scheduling and the profitability of shore power services to explore how time-of-use electricity pricing influences shore power services. Furthermore, to minimize energy costs and vessel tardiness rates, Chargui et al. [130] examined the joint scheduling problem of berth allocation and quay crane assignment under time-of-use electricity pricing, leading to significant operational cost savings for the port. Building upon these studies, Chen et al. [131] conducted joint optimization of berth allocation, scheduling of QCs and YCs, and assignment of external trucks based on time-of-use electricity pricing. The result showed that the formulated integrated operational plans could minimize electricity costs for the port.

6.4. Operation Optimization Based on Carbon Tax

The Marine Environment Protection Committee of the International Maritime Organization (IMO) has put forward a proposal for the implementation of long-term carbon emission taxation for ports. The carbon tax is a pollution tax based on the principle of negative externality economy, which imposes a fee on the production, sale, or use of fossil fuels based on the amount of carbon emitted by them [132]. If a carbon tax is enforced, the carbon emissions directly or indirectly generated by port cargo handling equipment will be subject to taxation [133]. Consequently, this will lead to increased operational costs for ports, thereby incentivizing port operators to actively reduce carbon emissions voluntarily [134].

The incorporation of a carbon tax within the port industry must be correlated with the specific operational dynamics of the port, which are influenced by various factors including container throughput, energy consumption per throughput, the number of berths, and the overall value of foreign trade imports and exports [135,136]. To effectively regulate greenhouse gas emissions in ports, it is essential to monitor the carbon emissions of ships within ports and strengthen market-based environmental regulatory policies [137,138]. The implementation of a carbon tax policy has been proven to significantly reduce carbon emissions and is a crucial tool in emission reduction efforts [139]. However, it is important to mention that excessively stringent environmental regulatory policies may hinder the economic benefits of ports [140]. Some academics argued that governments should focus on taxing shipping companies rather than ports to achieve maximum carbon reductions. This perspective suggested that placing the responsibility of carbon taxation on shipping companies, as the primary contributors to maritime emissions, would yield more substantial emission reductions [141]. Therefore, government agencies and port authorities should develop reasonable and effective carbon tax regulations to strike a balance between environmental objectives and economic considerations [141].

Indeed, the examination of the impact of carbon tax policies on integrated port operations, including berth allocation, has attracted many researchers. Wang et al. [142]. conducted a study on the joint optimization of berth allocation and quay crane assignment in ports based on two different carbon emission taxation policies: a unified tax rate and a tiered tax rate, inspired by the electricity tax rate implemented in Germany. The results of the experiment revealed that imposing carbon emission taxes on ports can effectively reduce carbon emissions but may have a negative impact on the service efficiency level of ports [143,144]. In addition, Lin et al. [144] expanded their study to include yard space allocation alongside berth allocation. Their findings further confirmed that efficient resource allocation, coupled with the implementation of carbon tax policies, can contribute to the reduction in carbon emissions in the vicinity of ports. Xu et al. [145] developed an optimization model for the scheduling of continuous berths and quay crane operations, with a specific focus on considering the carbon emission cost. They incorporated the carbon emission cost of ships, terminal operating costs, and time costs incurred by ships at ports into their analysis.

These studies demonstrated the importance of considering carbon tax policies in the optimization of various operational aspects of ports to achieve both environmental objectives and operational efficiency.

7. Discussion

The systematic review of emission reduction measures in the previous sections identified what has been done and what remains to be done. Future research directions for mainstream content and optimization perspectives can be derived based on the research gaps identified in previous studies, as illustrated in Figure 3. The optimization of measures to reduce carbon emissions in ports can be achieved through four key aspects: the development of renewable energy sources, the utilization of low-carbon fuels, the application of technological approaches, and the adoption of optimization strategies. The dashed arrows in Figure 3 indicate the research gaps, while the dashed arrowheads indicate future research directions. Subsequent discussions will delve into these points in detail.

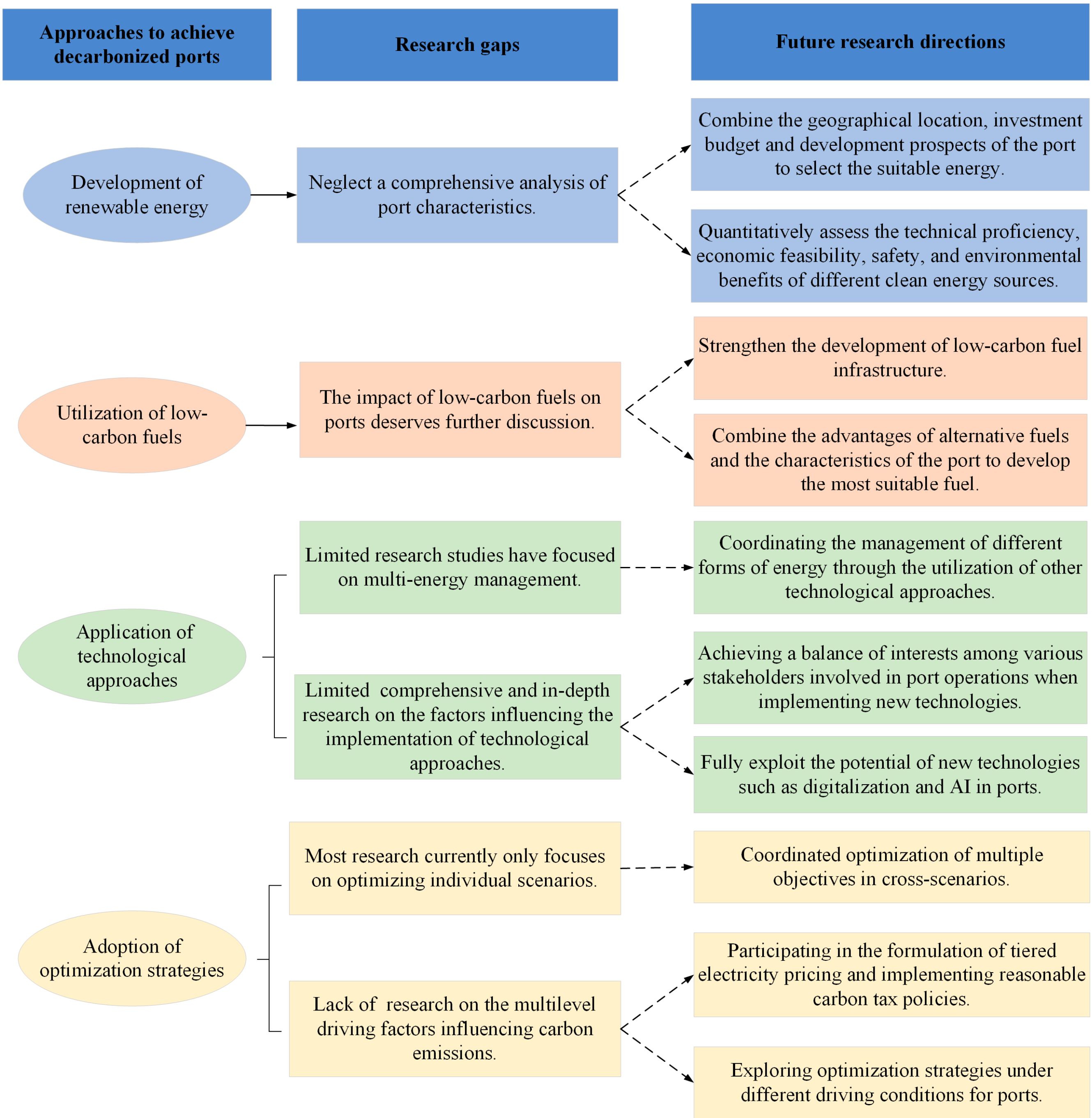

Figure 3. Future research directions for port emission reduction.

(1) Research on the selection of renewable energy sources suitable for ports.

Previous studies have often neglected port-specific factors, thus limiting their practical application to real-world port contexts. To overcome this limitation and support the selection of suitable renewable energy options, two key aspects should be considered. On the one hand, port-specific factors, including geographical location, investment budget, and the development prospects of individual ports, should be taken into account. On the other hand, quantitative assessments should be conducted to assess the technical proficiency, economic viability, safety, and environmental benefits associated with various clean energy options. Future research efforts could integrate these two aspects to identify the most appropriate renewable energy source that aligns with the specific development requirements of each port. Moreover, only a limited number of ports currently have the necessary infrastructure and layout to produce, transport, and store such fuels. Future investigations into alternative fuels for ships should also include an examination of the actual development of bunkering infrastructure at ports along shipping routes.

(2) Research on the utilization of low-carbon fuels.

Further discussion is warranted regarding the impact of implementing low-carbon fuels in ports. Promising fuels such as hydrogen and ammonia possess special characteristics, necessitating specific requirements throughout their production, transportation, storage, and utilization processes. Consequently, this imposes novel demands on safety regulations, propulsion technology, and port facility layout. Moreover, the cost of LNG and LPG plays a pivotal role in influencing their development. Stakeholder support, carbon taxes, public awareness, and utilization volume are key determinants for the adoption of these low-carbon fuels. When selecting a low-carbon fuel for advancement, ports should holistically consider multiple factors.

(3) Research on the application of emission reduction technological approaches.

The utilization of various technologies such as microgrids, ESSs, cold ironing, carbon capture, and scrubbers is influenced by diverse aspects including complex energy management technologies and conflicting stakeholder interests, as well as port regulatory policies. While the current technological approach in ports is primarily focused on electricity, there is a growing need for the integrated development of multiple energy sources, including cold, heat, electricity, and gas, which add to the complexity of energy management. Therefore, the future research direction lies in the efficient management of various forms of energy through advanced technological means and methods. The utilization of onshore power is related with complex relationships among ship owners, ports, and governments. Strategies aimed at reducing emissions should take into account the shared interests of these stakeholders and establish fair pricing for cold-ironing usage. Currently, there is limited scholarly literature on the implications of deploying novel technologies within port environments. Prior to the implementation of such technologies, it is essential to strike a balance between the benefits they offer to port stakeholders and the mitigation of potential conflicts among them. Furthermore, through the integration of digitalization and artificial intelligence in port operations, ports can uncover the untapped potential of these emerging technologies and leverage data derived from diverse sources to optimize port management practices and curtail carbon emissions.

(4) Research on emission reduction optimization strategies.

In the absence of technical modifications or additional investments, ports should prioritize operational optimization strategies. These strategies consist of energy-efficient equipment scheduling, peak energy reduction, time-of-use electricity price-responsive strategies, and carbon-tax-responsive strategies. These measures can effectively achieve emission reductions and efficiency improvements. While current studies focus on optimizing a single objective in a specific scenario, it is important to note that the four scenarios mentioned in Section 6 can coexist. Therefore, from the perspective of the coordinated development of port energy and logistics, future research should employ advanced algorithms to simultaneously optimize multiple objectives including energy efficiency, carbon emissions, energy costs, and carbon taxation across different scenarios. Additionally, there is a lack of existing research on the multilevel driving factors influencing carbon emissions. Future researchers could explore underlying reasons for port carbon emissions, such as participating in the formulation of tiered electricity pricing and implementing reasonable carbon tax policies. They can also explore optimization strategies under different driving conditions, providing greater incentives for ports to embrace sustainability.

8. Conclusions

Ports are currently undergoing a crucial transition towards greener practices, making the reduction in emissions a significant research focus for scholars and practitioners. Researchers and practitioners are actively investigating ways to achieve emission reductions. However, existing review studies in the field of clean ports have overlooked the integration of port characteristics and development plans when selecting targeted energy sources. Additionally, the presented reduction technologies are incomplete, and there is a lack of comprehensive summaries regarding optimization strategies for reducing CO_2 emissions. Therefore, this study aims to address these gaps by conducting a comprehensive and systematic review of 145 research papers on CO_2 reduction methods. The review focuses on analyzing the current implementation status of alternative energy sources, technological solutions, and CO_2 reduction strategies in ports. This study identifies research gaps, provides directions for future research, and presents the following findings.

Firstly, it is essential to consider the suitability and development prospects of different renewable energy sources based on the geographical location of ports. Offshore wind power, for example, is advantageous in ports with high wind speeds, while offshore PV is affected by port weather and seasonality. Biofuels and tidal energy, although used in some ports, have untapped potential due to technical and cost constraints. These renewables vary in terms of technical proficiency, economic feasibility, safety, and environmental benefits. Therefore, a comprehensive assessment of these factors is necessary when implementing renewable energy in ports. Researchers can provide quantifiable analysis to assist port managers in making informed decisions. Secondly, various low-carbon fuels have development potential, but they differ in cost, safety considerations, and port infrastructure requirements. LNG is currently widely used as a low-carbon fuel, but its cost can still be reduced further. Hydrogen and ammonia, as cleaner fuels, have strict requirements for port layout and safety. As future advancements address technical barriers and reduce costs, these fuels are expected to be more widely adopted. Additionally, the high cost of liquefied petroleum gas hinders its development. Third, the adoption of technologies related to port facilities and equipment, as well as port and vessel operations, holds significant potential for decarbonizing ports. Technologies such as microgrids, energy storage systems, cold ironing, carbon capture, and digitalization can support the green transition of ports. Port managers should introduce relevant technologies with the interests of different port stakeholders in mind. Furthermore, it is crucial to leverage these technologies effectively to manage port energy consumption and address CO_2 emissions. Finally, advanced optimization strategies have been identified as effective means to improve port operations planning, achieve energy savings, and minimize carbon emissions. Optimization approaches based on energy awareness, energy efficiency, price responsiveness, and carbon tax response can optimize port operations planning. It is important to consider multiple scenarios simultaneously and employ advanced algorithms to optimize multiple objectives concurrently. Future research should focus on the intersection of multiple scenarios and utilize advanced optimization techniques.

It is essential to emphasize that the methods proposed in this paper, encompassing alternative energy sources, technological solutions, and optimization measures, should not be regarded as standalone solutions for achieving low-carbon and energy-efficient ports. Ports should carefully analyze the economic, technical, and environmental aspects before selectively implementing these methods. This review could help port managers gain a deeper understanding of the available approaches to transitioning to a greener pattern. Furthermore, research gaps and research directions are presented for future studies.

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