

Review

Smart, Connected, and Sustainable: The Transformation of Maritime Ports Through Electrification, IoT, 5G, and Green Energy

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Abstract

In recent years, there has been a fast expansion in the usage of renewable energy sources (RESs) in power distribution systems. Numerous advantages result from this advancement, such as environmental friendliness, cost-effective power generation, easier maintenance, and energy sustainability and reliability. Reducing reliance on fossil fuels, which are of significant environmental concern, and increasing energy efficiency are two benefits of integrating RESs into maritime systems, such as port microgrids. As a result, ports are implementing several programs to increase energy efficiency using various RESs that are supported by power electronic converters. To highlight the most recent developments in seaport electrification and infrastructure, this work conducts a systematic review. It addresses important issues like energy efficiency enhancements, environmental concerns, the integration of renewable energy sources, the Internet of Things (IoT), and regulatory and legal compliance. The study also discusses technology strategies like digitization, electrification, onshore power supply systems, and port energy storage options. Operational tactics, including peak-shaving methods and energy-efficient operations, are also covered. Additionally, an infrastructure framework—which includes port microgrids and smart seaport microgrids—that is intended to enhance energy efficiency in contemporary ports is examined.

Keywords: smart/green ports; smart energy management; microgrids; digitalization; Internet of Things; energy efficiency; peak-shaving; 4G/5G



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1. Introduction

With more than 80% of the world's commodities being moved by sea, maritime transportation is at the heart of international trade. As a result, between 2018 and 2024, the energy consumption of maritime shipping, including port activities, increased by 10–15% [1]. This increased demand for energy has led to increased greenhouse gas (GHG) emissions, higher

energy costs, and increased levels of other pollutants. The 2023 International Maritime Organization (IMO) Strategy for the reduction of GHG emissions from ships states that roughly 3% of GHG emissions worldwide are caused by the shipping sector. Unless significant improvements are implemented, overall GHG emissions are predicted to increase significantly in the upcoming decades [2–4]. In addition, ports are severely strained because of rising energy costs; therefore, controlling energy use or increasing commerce is essential for reducing transportation costs. Similarly, the development of green ports improves operational efficiency and lowers hazardous gas emissions [5].

In the most general sense, energy efficiency refers to the use of techniques for reducing energy use while maintaining the same level of useful power. The primary goal of port authorities is to ensure that policies, technology, and the integration of RESs are validated and used to produce significant energy savings [6,7].

Due to growing pressure from regional and international rules (such as the EU's Energy Efficiency Directive/2012) to enhance environmental credibility, ports' role in addressing climate change has drawn a lot of attention [8,9]. Various mitigating strategies are suggested in this context, including limiting the idle hours of trucks, replacing outdated equipment with newer models, and switching to cleaner fuel [10]. At the same time, the European Council ranked energy efficiency as the third most important environmental objective for the EU maritime sector in 2020 [11]. Additionally, the maritime industry has been under tremendous pressure to improve energy efficiency [12] from international organizations like the IMO, the World Port Climate Initiative (WPCI), the Associations of Waterborne and Transport Infrastructure (PIANC), and the International Association of Ports and Harbors (IAPH). Furthermore, a port's energy efficiency and operational efficiency are strongly positively correlated. Energy efficiency is increased by lowering energy consumption using resources such as equipment and berths to improve operational efficiency [13]. Port energy efficiency is also greatly enhanced by technology innovations such as flywheels, converters, batteries, ultracapacitors, digitalization, electrification, onshore power supply (OPS), and smart energy management systems [14].

Five main phases are used in the literature to describe the evolution of ports [15]. According to the first phase, ports are only nodal sites that link land and sea transportation and provide fundamental services like fishing, rescue operations, logistics, and cruises [16]. To lessen their dependency on physical labor, ports started using simple infrastructure and equipment in the second phase. In the third stage, ports became hubs for cargo processing, complete with distribution centers, warehouses, and packaging [17]. Networked ports, which function under a single administration despite being physically distinct, were introduced in the fourth phase [18]. Modern, customer- and community-focused ports are represented by the fifth and current phase. With advancements like the Internet of Things (IoT), Radio-Frequency Identification (RFID), cloud and fog computing, robotics, and other cutting-edge technology, these ports are extremely competitive and technologically sophisticated. Modern ports are better equipped to handle the difficulties encountered by earlier generations thanks to these developments, which improved operational efficiency, customer management, and environmental impact reduction [19,20].

Many assessments of subjects including smart electrification, energy efficiency, sustainability, and seaport energy management can be found in the literature [17–20]. Nevertheless, some crucial elements are not considered in parallel, including energy and environmental challenges, technological approaches, operational strategies, the infrastructure of contemporary ports, and the use of emerging technologies like the Internet of Things. Therefore, this article considers the transition from conventional to greener ports and fills the current gap in research on infrastructure, energy efficiency measures, obstacles, and the uses of emerging technologies for smarter and more efficient ports. Investigating recent advance-

ments in these fields and giving the reader a comprehensive overview are the goals of this paper. We will clearly articulate that while the existing literature contains “many assessments of subjects including smart electrification, energy efficiency, sustainability, and seaport energy management,” no previous review has simultaneously integrated all the five critical dimensions that we examine here:

- Energy and environmental challenges (comprehensive scope);
- Technological approaches (including emerging technologies);
- Operational strategies (efficiency measures and practices);
- Modern port infrastructure (charging stations, microgrids, smart systems);
- Integration of emerging technologies (IoT, EMS, 5G).

Although the existing literature offers extensive insights into port energy management and sustainability, a closer analysis reveals that most reviews address these themes in isolation, lacking the comprehensive integration needed to guide real-world port transformation. For instance, studies such as those by Iris & Lam [7] and Sdoukopoulos et al. [21] focus primarily on energy efficiency and environmental pressures—particularly regulatory constraints from the IMO and EU—but fall short in integrating these with emerging technologies like IoT and AI that could enhance traditional energy systems. On the other hand, reviews about smart ports (Belmoukari et al., [16]; Li et al., [22]) explore digital technologies, including IoT, RFID, and automation, yet overlook their alignment with concrete energy efficiency practices such as peak-shaving, load balancing, and energy recovery. Infrastructure-focused research (e.g., Sadiq et al., [23]) examines physical systems like microgrids and shore power supply, but often neglects how these can be optimized through advanced operational strategies and technology integration. Similarly, reviews that concentrate on operational improvements (Alamoush et al., [14]; Lim et al., [24]) discuss energy-saving techniques and scheduling tools, but fail to consider how these can be supported or enhanced by smart infrastructure and technological solutions. The most critical gap across all of the literature in this field is the absence of a holistic framework that links environmental imperatives, emerging technologies, modern infrastructure, and operational strategies into a cohesive transformation model. As a result, port authorities lack the integrated guidance necessary to implement effective and sustainable energy transitions. Our study addresses this gap by proposing a unified perspective that connects all these dimensions, providing a more actionable and comprehensive foundation for smart green port development. In essence, this review transforms fragmented knowledge into actionable, integrated intelligence for practical port transformation. To better position our work within the existing body of research, Table 1 provides a comparative analysis of previous literature reviews and our own contribution, emphasizing the novelty and added value of our approach.

The remainder of this paper is structured as follows: Section 2 presents the research methodology. The difficulties facing contemporary ports are covered in Section 3, and in Section 4, methods, energy efficiency, and operational measures are explained. The infrastructure of contemporary ports, including charging stations, smart port microgrids, and port microgrids, is described in Section 5. Applications of emerging technologies in seaports are described in depth in Section 6. Section 7 presents an in-depth discussion addressing the challenges, economic and social impacts, lessons learned, and future work to be considered, while Section 8 concludes this review.

Table 1. A comparative overview between existing literature reviews and the present study.

Review Study	Energy and Environmental Challenges	Technological Approaches	Operational Strategies	Modern Port Infrastructure	Integration of Emerging Technologies	Simultaneous Integration
Iris & Lam (2019) [7]	✓	✓	✓	✗	✗	✗
Xiao et al. (2024) [9]	✓	✓	✗	✗	✓	✗
Alamouch et al. (2020) [14]	✓	✓	✓	✗	✗	✗
Belmoukari et al. (2023) [16]	✗	✓	✗	✓	✓	✗
Sadiq et al. (2021) [23]	✓	✓	✗	✓	✗	✗
Sdoukopoulos et al. (2019) [21]	✓	✓	✓	✗	✗	✗
Lim et al. (2019) [24]	✓	✗	✓	✗	✗	✗
Zhang et al. (2024) [25]	✓	✗	✗	✓	✓	✗
Li et al. (2023) [22]	✗	✓	✗	✓	✓	✗
This Review	✓	✓	✓	✓	✓	✓

2. Research Methodology

This systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and transparency. A comprehensive search strategy was developed using relevant keywords like “green port,” “smart microgrids,” “advanced port infrastructure,” “modern port technologies,” “future ports,” “digitalization”, “smart energy management”, and “electrified ports”. The researchers investigated major bibliographic databases like Scopus, Web of Science, Google Scholar, and Compindex to find peer-reviewed papers with Boolean operators.

In certain instances, relevant material from conference proceedings was also included in the list of peer-reviewed articles. A few technical publications from magazine journals and national news were also included in the list of references for further research. The authors reviewed more than 296 papers, primarily journal articles, to carry out an in-depth evaluation of decarbonization strategies and modernization pathways for the contemporary seaports sector. A rigorous quality appraisal was performed using adapted CASP (Critical Appraisal Skills Program) criteria, emphasizing methodological robustness, data reliability, and the relevance of findings. This process resulted in the final inclusion of 206 publications for in-depth analysis. Each selected study was evaluated using a modified quality assessment framework based on methodological rigor, data quality, relevance, empirical evidence, and transparency (clear reporting of methods, limitations, and findings).

The concepts and conclusions of this review are primarily derived from a thorough analysis of these publications. Studies carried out in the last ten years make up most of the review. Here, two things are involved. First, the authors intended to focus on the most recent findings to determine the present state of the field. Second, concerns about sustainability—specifically, the impact of climate change—have pushed the maritime sector to become more efficient, resulting in a surge of research over the last decade. This system-

atic review involved analysis of publicly available research publications and did not require ethical approval. All sources were properly cited and attributed according to academic standards. The review methodology was designed to minimize bias and ensure fair representation of diverse perspectives and findings in the port transformation literature. Figure 1 presents the PRISMA flow diagram illustrating the systematic selection process from initial identification through to the final inclusion of studies in the comprehensive analysis.

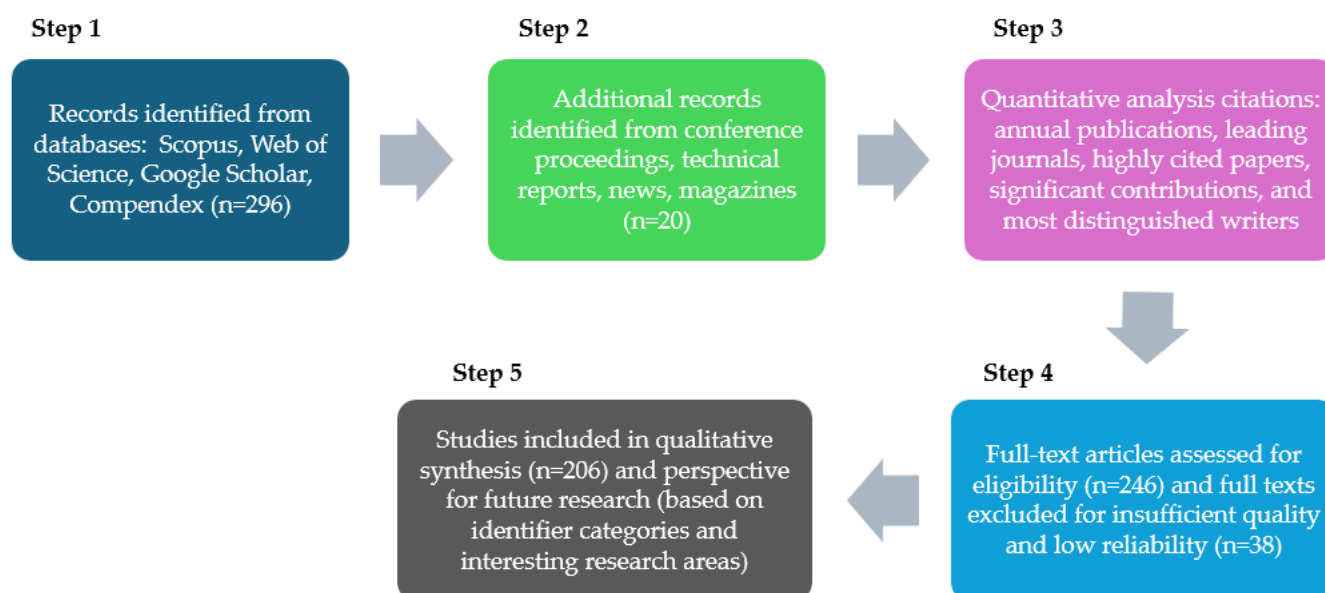


Figure 1. The approach taken in this study.

3. The Challenges That Modern Ports Face

Environmental issues, energy efficiency improvements, the integration of renewable energy, legislative and regulatory laws, power and grid reliability, infrastructure complexity, and rising energy consumption are some of the difficulties that ports face [26]. The following is a description of the main issues affecting ports.

3.1. Environmental Issues

Important environmental issues that ports must deal with include garbage, air pollution, noise pollution, vessel congestion, and CO₂ emissions [23]. The maritime sector is accountable for 2.2%, 15%, and 6% of CO₂, NO_x, and SO_x production, respectively [27]. Implementing environmental measures and managing the external consequences of port operations are crucial for addressing the problem of global climate change and enhancing ports' perceived greenness. Numerous regional and global studies have been conducted to address the impacts of climate change on ports [28]. International studies include IMO, WPCI, PIANC, and IAPH, while regional studies include the European Sea Ports Organization, the EU project, and the Green Effect project. Many ports throughout the world are making significant efforts to mitigate the negative effects of GHG emissions to address these issues. Shanghai and the Port of Tianjin have changed their regulations to require onshore power supply (OPS) to be installed at all new terminals to achieve this [29]. Likewise, the ports of Hamburg, Helsinki, and Antwerp are all adopting stringent measures to lessen their negative effects on the environment. For example, the Hamburg government has made the decision to phase out coal-based energy sources and increase renewable energy to lower CO₂ emissions [30]. Additionally, by implementing the Carbon-Neutral Helsinki Action Plan 2035, the Port of Helsinki has pledged to become completely carbon-free through the primary initiatives of energy efficiency and renewable energy [31]. Surprisingly, the

port has also made the decision to reduce energy use by installing LED lighting, updating its heating system, and installing a solar system in the port area by 2035 [32].

In a similar vein, the Port of Antwerp has mandated the building of tugboats propelled by hydrogen and methanol to lower air pollutants within the port. These tugboats have been in service since the end of 2021 [33]. Similarly, the Port of Singapore has provided 25% tax reductions for ships utilizing alternative technology to lower greenhouse gas emissions [34]. Notably, Singapore's port administration has also made a large investment in greening ports and associated technology, totaling around USD 70 million. Strict measures are also being taken by the European Union (EU) to lower greenhouse gas emissions at ports, especially when ships are hoteling. European ports have provided 20–50% subsidies for OPS utilization and set a 2025 deadline for OPS adoption [35]. Additionally, the ports of Seattle, Tacoma, and Vancouver have agreed to cut back on diesel generators by 75% [36]. On the other hand, the constant noise produced by auxiliary engines that run on diesel is viewed as being harmful to people's health. The main source of noise in ports is thought to be the auxiliary engines that are utilized to provide energy for docked ships. To reduce noise, the Port of Helsinki has implemented adaptive measures, specifically prohibiting vessels from using auxiliary engines to generate energy when moored [37]. However, shipping congestion is another problem that ports around the world face, frequently brought on by poor maintenance of port handling machinery [38]. Section 3 discusses several crucial technology strategies to address these problems.

3.2. Legislative and Regulatory

Various ports may adhere to distinct regulations based on their local, geographic, political, and economic contexts. To make their domain more ecologically friendly, the four top ports in the world—Singapore, Rotterdam, Shanghai, and Antwerp—have modified their fees, tracking, and measurement procedures. There are two types of pricing policies: incentive pricing and penalty pricing [39]. All the ports have implemented incentives or incentive pricing for good behavior and penalties for bad behavior as a means of enhancing environmental performance in the maritime industry. In a similar vein, a widely utilized instrument in all ports is the monitoring and measurement of air and water quality. To identify the baseline year and gather and monitor emissions data over time, a carbon footprint monitoring project has been launched by the Port of Singapore [40]. Similarly, a group of top ports from around the world launched the World Port Climate Action Plan as a global effort to address the emissions issues facing the port industry. These harbors include the ports of Long Beach, Los Angeles, Le Havre, Barcelona, Hamburg, New Jersey and New York, Rotterdam and Amsterdam, Gothenburg, and Antwerp [21]. To increase energy efficiency, the Port of Los Angeles has also created an energy management strategy program.

An effective instrument for accomplishing energy reduction objectives is ISO 50001, which was introduced in 2011 and uses the Plan–Do–Check–Act (PDCA) methodology [24]:

- Plan: Create an action plan, goals, and performance metrics after establishing an energy baseline through audits.
- Do: Put certain technological or operational measures into action.
- Verify: Keep an eye on operations and procedures that affect energy performance.
- Act: Take calculated actions to guarantee ongoing progress.

A methodical, data-driven methodology, strong commitment, and accreditation resources are needed to implement ISO 50001 [41]. It has been implemented in the ports of Felixstowe (2013) and Antwerp (2015), with a few more, such as those of Hambourg and Valencia, following suit. The PDCA principles are shared by ISO 50001 and EN 16001 (2009) [42], although there are some significant differences between the two standards.

Three new concepts, for instance, have been added by ISO 50001 [43]. The first one relates to the core function of top management, which oversees establishing operational tasks, energy policies, goals to be met, and resource allocations. Therefore, the energy management team must be established in accordance with ISO 50001 with the assistance of top management. The second concept relates to the Plan phase, which placed an emphasis on conducting more energy reviews to establish a reliable baseline that enables monitoring of energy performance. This idea relates to the Do phase, where ISO-50001 uses operational and technology measures to highlight the conceptualization processes. Nonetheless, EN-16001 presents certain distinct aspects that are not addressed in ISO-50001:

- Cost savings related to potential upgrades for the consumption of energy savings in their entity.
- Priority scales for energy factors that facilitate the identification of those that require more thorough analysis.
- Identification of which of the company's staff members may exhibit higher energy usage behavior.

3.3. Improved Energy Efficiency

Ports rely heavily on energy sources such as electricity and diesel fuel to operate [44]. Ports must effectively manage their energy needs. Electrifying port infrastructure leads to more automation, improved energy efficiency, lower energy costs, and reduced greenhouse gas emissions [45]. Port electrification requires increased power consumption to compensate for the energy gap created by engines powered by diesel. Greater electrical demand may not be satisfied by local networks or microgrids, requiring upgrades to electrical substations and greater power production. These consumers necessitate efficient energy management and flexible power infrastructure. The energy management system should be evaluated. Port energy efficiency involves implementing practical and technological steps to reduce energy consumption and use renewable energy. This reduces GHG emissions, which are directly proportional to fuel burning [46]. A seaport's energy consumption can be divided into necessary and wasteful energy. Hence, energy waste should be reduced.

In 2023, energy efficiency was listed second among the EU's environmental priorities, following air pollution and climate change [47]. Modern ports face the following hurdles in enhancing their energy efficiency [48]:

- Ensuring reliable energy supply;
- Implementing cutting-edge communication systems;
- Ensuring environmental sustainability;
- Addressing grid stability and power quality issues;
- Controlling energy expenses.

To address these difficulties, modern ports should introduce RESs and incorporate new communication technologies like the Internet of Things and big data. Energy resilience can be achieved through decentralized networks that integrate electric power systems. Integrated power system technologies combine data and technology for reliable, cost-effective, and promising solutions.

3.4. Integrating Renewable Energy Sources

Energy for port activities might come from renewable sources, clean fuels, or the national grid. Energy can be generated in the vicinity of the port. As the global energy demand rises, traditional energy sources like fossil fuels are causing environmental difficulties. The integration of renewable energy sources like wind and solar power poses challenges for grid management due to fluctuating power supply, unlike conventional energy sources. However, their implementation is seeing rapid growth due to their ben-

eficial ecological effects and financial viability [49]. Renewable energy is generated from the Earth's replenished resources, including solar, hydroelectric, wind, geothermal, and biomass-based energy [50]. One of the most significant obstacles in integrating renewable energy is these systems' tendency to cause low inertia. This occurs when the seaport's grid is not connected to a rigid grid with a sufficient capacity of synchronous power plants. Low inertia is the primary cause of grid instability.

Several solutions have been proposed in the literature to address this issue by changing feedback control systems, including virtual inertia management and virtual impedance management [51,52]. Another difficulty is over-generation, which occurs when PVs or wind turbines provide more electricity than seaports require. As a result, fuel-based generators are disconnected, and excess energy is stored in a storage facility [53]. Ports rely heavily on renewable energy sources, particularly wind turbines (e.g., Kitakyushu, Rotterdam in Japan) and waves (e.g., Port of Kembla in Australia) [54]. Furthermore, solar panels might be put on the rooftops of warehouses in the port area. Examples include the administrative buildings at the Port of San Diego and the OHI terminal in Tokyo. However, these forms of infrastructure may not be suited for large-scale solar energy extraction [55,56]. In [57], the integration of solar panels, wind turbines, and energy storage systems is briefly addressed. The advantages of integrated energy include the following:

- Improved land utilization;
- Reduced project development costs;
- Cost-effective distribution evacuation;
- Supplementary production of energy;
- Cost-sharing for operations and maintenance.

Reference [58] investigated the usage of renewable energy at the Damietta Port in Egypt. The research showed that the incorporation of renewable sources, such as offshore wind and hydrogen fuel cells, is much less expensive than traditional energy solutions. Another study [59] found that solar photovoltaic (PV) leasing programs in Singapore, especially at Jurong Port, proved useful and attractive for port purposes. In a similar way, the harbor city of Hamburg has installed rooftop PV systems on massive storage facilities owned by the Hamburg Port Authority. In Germany, the government has sponsored many big renewable energy initiatives to improve port energy infrastructure. The German government has spent EUR 18.9 billion euros on RESs, including onshore and offshore wind, to meet port energy needs [60].

Wind energy is effectively deployed in several ports, including those of Kitayjush, Hamburg, Rotterdam, Zeebrugge, and Venice. Genoa plans to deploy wind energy to reduce CO₂ emissions in the coming years. Similarly, solar energy is used for heating water at the Port of Hamburg's offices [61]. The World Power Climate Initiative is promoting the use of liquefied natural gas (LNG) in the maritime industry, and ports such as those of Venice, Genoa, Rijeka, Antwerp, San Diego, and Tokyo have responded to this initiative. The provision of LNG in harbor regions contribute to the natural expansion of ports, where trade is already taking place. However, there are still issues with shipping facilities and bunker placement optimization. Using LNG in port regions can significantly reduce SO₂, NO_x, and PM levels [62,63]. Additionally, [64] and [25] investigate the usage of biofuels in harbor areas. Table 2 identifies key practical issues affecting ports.

Table 2. The main practical issues affecting maritime ports, according to [65–68].

Main Practical Issues	Description
Renewable energy integration	World maritime ports are reducing their reliance on fossil fuels and increasing their use of RESs. To achieve this objective, they are attempting to facilitate renewable energy integration with an energy storage system without updating existing infrastructure.
Energy storage capacity	Energy storage systems (ESSs) are critical, particularly during blackouts, since throughout the period of transition between the grid and generators, all data centers are temporarily powered by ESSs. As a result, ports are focused on developing affordable monitoring solutions for ESSs that will indicate when the battery needs to be replaced in the event of a malfunction. This method can reduce the need for battery replacements while also increasing the security of services.
Carbon footprint	Emissions of greenhouse gases are one of the most difficult concerns facing global ports. Many ports throughout the world are working to reduce their carbon footprints. The Marseille Port has launched a prototype of an eco-calculator to estimate the carbon footprint of every shipping container in transit. In a similar vein, the Port of Antwerp launched a hydrogen-powered tugboat as part of its aim of turning carbon neutral. Hydrotug boats employ a dual fuel hybrid engine which mostly runs on hydrogen, resulting in reduced CO ₂ emissions surrounding the facility.
Container flow	Shipping firms also encounter container flow issues because of growing port congestion, with trucks coming to a halt if there is a problem with the port cranes. CMA CGM Shipping firm is attempting to enhance container movement using real-time data analytics to improve its supply chain in partnership with Mistral AI.
Port orientation	Port orientations additionally pose a concern for modern ports due to larger fleet sizes. Problems arise from a mix of traffic, which includes public transportation and tourist automobiles. These difficulties can be solved using novel digital technologies, including applications and digital signs, which are particularly useful for cruise ships and passenger ferries.
Trailer collection	Several ports have developed a Radio-Frequency Identification (RFID) system to assist truckers in locating their docks via their cell phones. The interaction between the run management system and the RFID tag shown on the vehicle's trailer is an obstacle. The goal of this service is to expedite traffic flow in the port region.

4. Technologies and Energy Efficiency Strategies

This section covers control strategies, technologies, and operational measurements for improving energy efficiency. The literature reports several energy management strategies, including multi-agent systems (MASs), integrated power supply systems, and correction of power factors. This study discusses the use of MASs along with combined power supply techniques for efficient energy management in maritime ports.

4.1. MAS-Based Energy Management

Figure 2 illustrates the notion of controlling port energy demand using multi-agent systems. The figure depicts both the time sequence and the communication signals generated by each agent. Port agents are classified into three distinct categories: local agents, cluster agents, and aggregation agents [69]. Local agents represent single-component power systems, cluster agents indicate aggregate feedback, and aggregation agents connect actions coming from supervised clusters. The operations of each sort of agent are well defined.

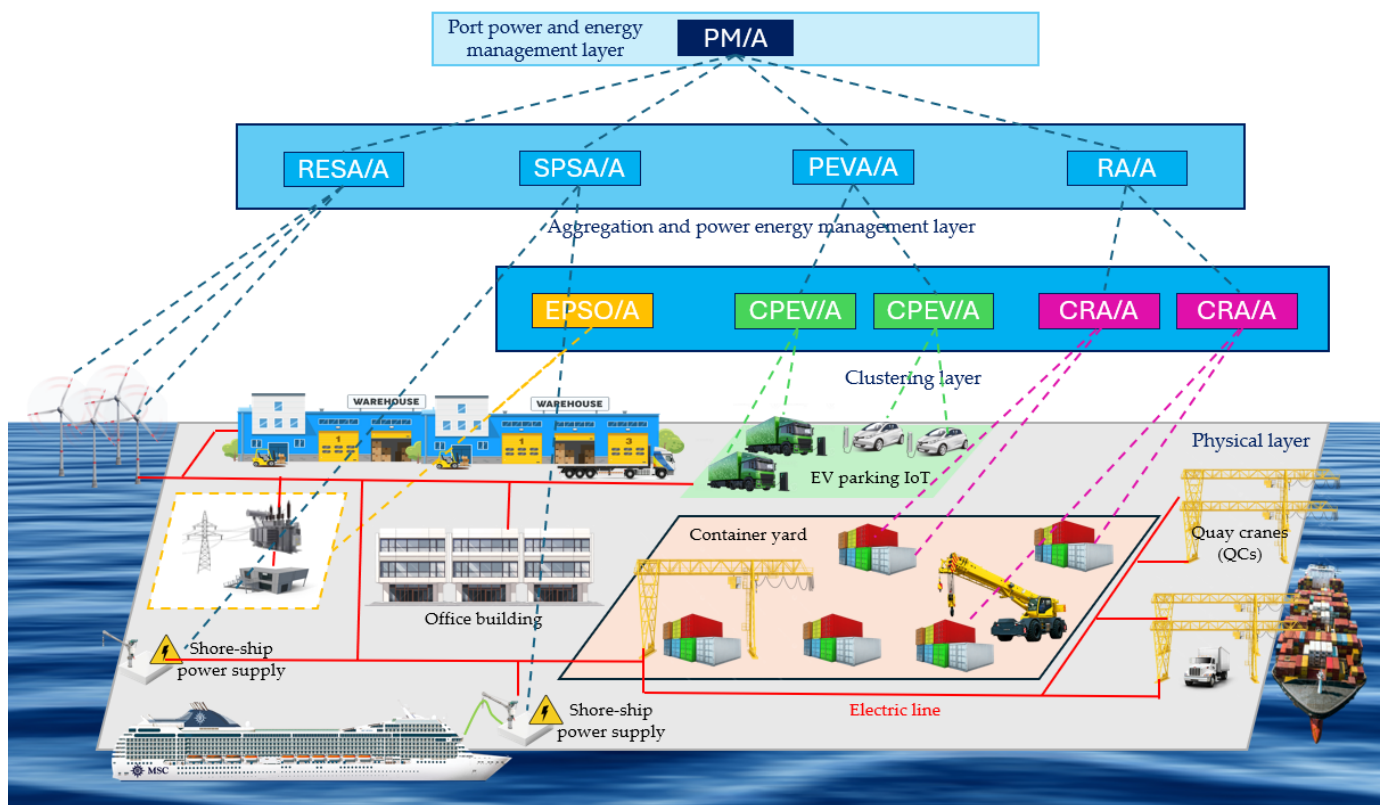


Figure 2. The conceptual organizational framework of an MAS-based real-time management system for significant ports [70].

The Port Manager Agent (PM/A) has higher levels of control. It collects energy signals from both local and cluster agents [71]. The PM/A is in charge of meeting energy demands for port operations and adjusting power usage during off-peak hours [72]. The PM/A receives demand for energy forecasts from cluster agents and optimizes power rates based on port load profiles. The port manager's technique involves adjusting the demand for energy during low pricing periods and peak-shaving during exceptionally busy periods [73]. The PEV Aggregation Agents (PEV/A), Reefer Aggregation Agents (RA/A), Renewable Energy Sources Aggregator Agent (RESA/A), and Shore Power Supply Agents (SPS/A) are all one step behind the PM/A in the organizational hierarchy. They serve as information services by combining demand for energy profiles from all the PEV and Reefer clusters under their supervision. Additionally, they distribute the marginal flexibility acquired by the PM/A to all cluster agents. The Reefer Area (R/A), Electric Power System Operator Agent (EPSO/A), and Plugged-in Electric Vehicle Agent (CPEV/A) are accountable for modeling services under their supervision. They estimate reefers and PEVs' ability to adjust their power needs based on port requirements. The computed flexibility and variations in power demand are relayed to the CPEV/As and CR/As. A cluster of Plugged-in Agents (CPEV/A) and Reefer Agents (CR) sit ahead of the agents designated for every PEV and reefer. These clusters, positioned at medium- and low-voltage transformers, only power PEVs and reefers. Agents typically aggregate PEV and request responses and send them to pertinent upstream agents. The PM/A implements CPEV/A and CR/A forward rates for monitored PEVs and reefers. Additionally, restriction signals are sent by specific cluster agents in the case of technical infractions, such as when the supplied power rises above the nominal transformer capacity [74]. The concept of MASs has been used to optimize the location of charging stations for electric vehicles in Valencia, Spain [75].

4.2. Electrification

Ports have distinct docking and unloading areas, such as the quayside and landside. Various machinery for handling cargo is employed to perform additional port activities [76]. Containers are handled at the quayside using quay cranes (QCs) and ship-to-shore (STS). The machinery found on the landside/yard side varies according to the port structure [77]. Ports use machines such as rail mounted gantry cranes (RMGs), rubber-tired gantry cranes (RTGs), automated guided vehicles (AGVs), and yard tractors (YTs) to carry out their operations (Figure 3). Containers are typically transported horizontally using YTs and AGVs, while piled with RMGs and RTGs [78].

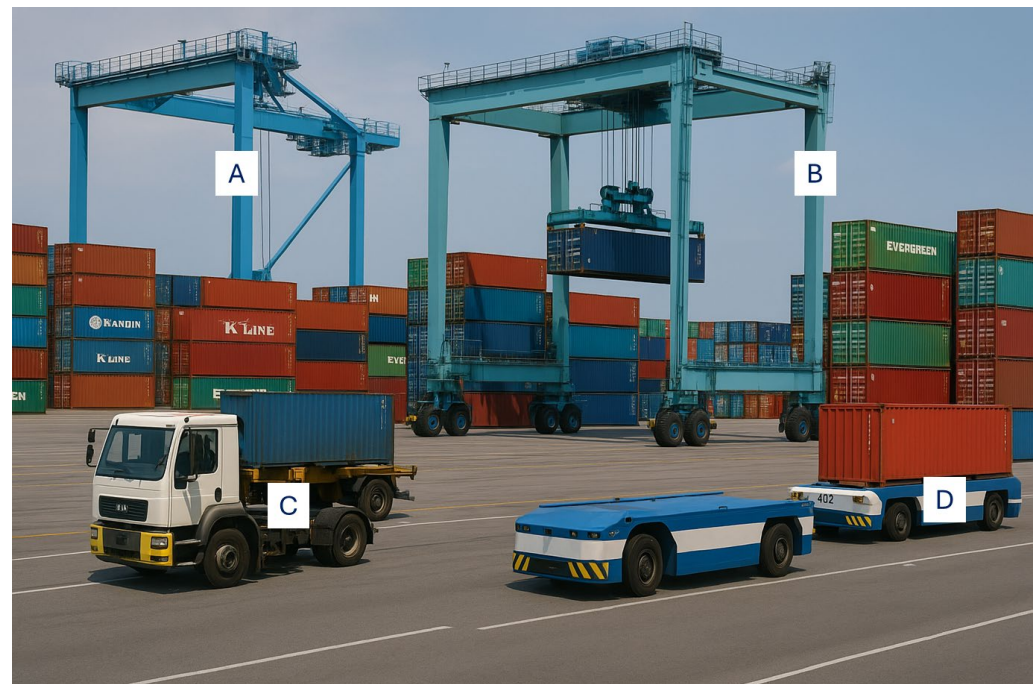


Figure 3. Illustration of container terminal operations with port logistics equipment: (A) RMG; (B) RTG; (C) YT; (D) AGV.

Yang and Lin [79] analyzed the environmental impact and energy efficiency of four types of cargo-handling machinery in the Port of Kaohsiung in Taiwan: tire transporters, automatic rails, rails, and electric tires. This study found that tire transporters and automatic rails have lower GHG emissions and higher energy efficiency. QCs may use shuttles to reduce operating time. Compared to traditional QCs, these novel designs provide greater flexibility and efficiency. AGVs in horizontal port operations have improved efficiency, safety, and reliability. AGVs can be supplied by batteries, diesel engines, or hybrids. For the use of B-AGVs, it is recommended to perform electrical charging of the batteries during periods of low demand. Table 3 compares the net present cost (NPC) of AGVs and different types of B-AGVs, indicating that B-AGVs are more profitable than AGVs [80]. Yard cranes (YCs) are typically divided into RMG and RTG cranes. RTGs are manually operated with free mobility, but RMGs can be digitized or conventional. RMGs are also known as Automated Stacking Cranes [81]. Yang and Chang [82] conducted a comparison of RTGs and E-RTGs to assess energy savings and greenhouse gas emissions reductions. The study found that E-RTG cranes outperform traditional RTGs in terms of both energy reductions (86.60%), carbon dioxide emissions (67.79%), and overall performance. E-RTG cranes require 30% fewer repairs and maintenance expenditures compared to diesel-powered RTGs.

Table 3. Net present cost (NPC) comparison of AGV fleet configurations.

Fleet Configuration	Description	CapEx	OpEx	Infrastructure Cost	Battery Replacement Cost	NPC Summary
Diesel-powered AGV fleet	Conventional AGVs powered by diesel engines	Medium	High (fuel and maintenance)	Low	None	Highest NPC due to fuel emissions
Battery AGV fleet	Standard battery-powered AGVs with typical charging schedule	High	Low (electricity and maintenance)	Medium	Medium	Lower NPC than diesel AGVs
Battery AGV fleet (minimum vehicle-to-battery ratio)	Fewer batteries than AGVs, batteries swapped/120tator efficiently	Medium–High	Low	High (for swap stations)	High (due to faster cycling)	Balanced NPC with efficient operations
Battery AGV fleet (controlled charging)	Charging scheduled for periods with off-peak electricity rates	High	Lowest (optimized energy use)	Medium	Medium	Lowest NPC due to energy cost savings

Table 3 offers a comprehensive comparison of the NPC across four different AGV fleet configurations, revealing important economic and operational insights that guide decision-making for port and industrial logistics applications.

Firstly, diesel-powered AGV fleets, despite having a moderate CapEx, incur significantly higher OpEx due to their fuel consumption and maintenance requirements. This results in them having the highest overall NPC among all the configurations. The implication here is clear: although diesel fleets may appear cost-effective initially, their long-term financial burden, exacerbated by fluctuating fuel prices and stricter environmental regulations, makes them less viable for sustainable port operations. This underscores a shift away from fossil-fuel-based logistics solutions in favor of cleaner alternatives.

In contrast, standard battery-powered AGV fleets exhibit higher upfront costs, driven by battery procurement and the installation of charging infrastructure. However, these costs are offset by lower operating expenses, mainly electricity costs and reduced maintenance demands. Consequently, this configuration presents a more favorable NPC, emphasizing the growing economic advantage of electrification. The implication is that ports investing in battery-powered AGVs can expect better long-term cost efficiency alongside environmental benefits.

Battery-powered fleets with a minimal vehicle-to-battery ratio represent an innovative operational model that reduces the total number of batteries required and enables rapid battery swapping. This configuration leads to medium-to-high CapEx and infrastructure costs—particularly for specialized swap stations—and increases battery replacement expenses due to accelerated cycling. Despite this, their improved operational efficiency helps to balance costs, demonstrating that intelligent battery management and logistics can significantly influence overall economic outcomes. This highlights the importance of enhancing operational strategies alongside technological choices when optimizing AGV fleets.

Finally, battery-powered fleets employing controlled charging strategies to utilize off-peak electricity rates achieve the lowest NPC, despite their higher initial investment levels. By scheduling charging during cheaper energy periods, operational expenses are minimized. This finding implies that integrating smart energy management practices, such as demand-side management and real-time scheduling, can substantially enhance the economic viability of electric AGV fleets.

Overall, Table 3 clearly shows that while battery-powered AGVs generally outperform diesel options in terms of both cost and environmental impact, the specific fleet configuration and energy management practices used critically shape their net cost. For ports aiming to optimize their sustainability and efficiency, the adoption of advanced battery management systems and smart charging protocols presents a promising pathway. Future research should focus on coupling these strategies with renewable energy integration and predictive maintenance technologies to further reduce the costs and environmental footprints of AGV operations.

4.3. Onshore Power Supply (OPS)

Shipping by sea is among the most fuel-efficient modes of transportation, accounting for over 90% of worldwide trade. The shipping industry accounts for 5–8% of world carbon dioxide emissions [83], prompting efforts to minimize GHG emissions and improve ecological sustainability through regulations. One example is the deployment of OPS in harbors [84]. OPS involves linking vessels to shore power during docking to provide electrical power for lighting, air conditioning, heating, and additional facilities. This is commonly used for cruise ships and ferryboats due to their extended stays at ports (up to 40%) and frequent ferrying requirements [85,86]. Onboard diesel-powered engines often create energy which is then replaced by liquified natural gas (LNG) or liquified petroleum gas (LPG) such as propane and butane. However, these systems contribute to the production of GHGs and unwanted noise [87].

Hitachi ABB Power supplies static frequency converters that can adjust a vessel's power supply to the required frequency. This is necessary because most ships operate at 60 Hz, while most land-based electrical grids use 50 Hz [88] (refer to Figure 4). Siemens created Germany's largest shore power system at Kiel Port (Germany), with 16 MV amps capable of serving two vessels consecutively with certified eco-power for the first time. This will decrease CO₂ emissions by over 8 Kilotons yearly [89]. OPS is mandated in different cities, such California, and is used in various seaports worldwide. Europe plans to implement OPS in all seaports by 2025 [90].

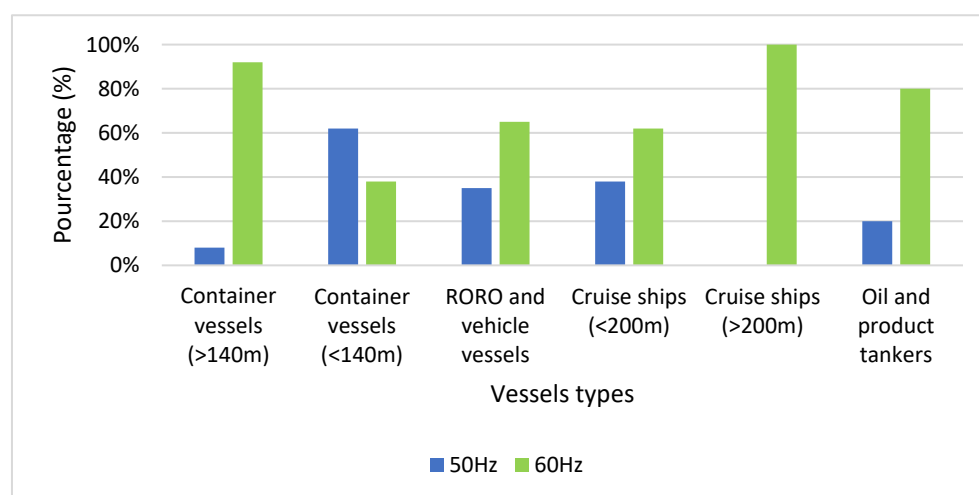


Figure 4. An illustration of the electrical frequency of various types of ships, according to [88].

T. Zis et al. [91] compared the efficacy of speed reduction diesel generators and OPS for seaport pollution reduction, indicating that OPS is more effective than speed reduction diesel generators, since speed reduction increases black carbon emissions. However, OPS reduces both black carbon and GHG emissions simultaneously. A financial comparison of OPS and marine diesel found that OPS benefits countries with diverse seaports and lower

energy prices than fossil fuels do [92]. Modern OPS systems have reduced CO₂ emissions from Norwegian, French, and United States cruise ship terminals by 99.5%, 85%, and 9.4%, correspondingly [93]. The Stena Line, among the world's leading ferry companies, improved its shore-to-ship power system with a wireless link built by ABB at the Stena Ro-Ro port in Hook of Holland [94]. Wartsila's wireless electrical charging approach offers benefits like increased safety, decreased maintenance, and faster charging times (Figure 5). This method eliminates the need for physical cable connections between the vessel and shore, which improves safety and allows for faster, more efficient charging. This concept involves using a frequency converter to convert a 50/60 Hz three-phase system into AC voltage through an output frequency in the range of kHz. The voltage generated powers a sensing coil device onshore and a receiver coil component onboard the vessel. High-frequency voltage is converted to DC voltage. Greater than 2 MW of electrical power may be exchanged between coils at distances ranging from 0.15 to 0.5 m for vessels that spend little time at the port [95].



Figure 5. The world's first automatic wireless induction charging system on Norled's hybrid ferry, developed by Wartsila [94]. Credit: Shippax.

According to [96], problems encountered in the implementation of shore power systems include high price tags for installation, varying ship needs (e.g., cables, interfaces, current, voltage frequency), system design specifications, and lack of defined global rules for OPS. From a regulatory and governance standpoint, implementation is complicated by the division of responsibilities among stakeholders (port authorities, shipowners, utility companies). The Port of Gothenburg successfully implemented OPS for RoRo and ferries by establishing clear collaboration frameworks and cost-sharing models with shipping lines and energy providers. However, in many ports—especially in developing regions—such cooperation is lacking, slowing OPS adoption.

Cost recovery models also present a challenge. OPS systems involve high CapEx, and ports must decide whether to absorb these costs, pass them to shipping companies, or rely on government subsidies. The Port of Rotterdam, for instance, managed to partially mitigate this issue through national green funding programs, but smaller ports often lack access to such support mechanisms, creating inequalities in global OPS deployment. These case studies highlight the fact that while OPS offers significant long-term environ-

tal benefits—especially in reducing Nox, Sox, and CO₂ emissions—the path to effective implementation requires overcoming technical integration issues, establishing supportive regulatory frameworks, and ensuring financial feasibility. Therefore, successful OPS deployment hinges not only on technological readiness, but also on multi-stakeholder coordination, standardization efforts, and policy incentives. Figure 6 shows different ships' electricity requirements.

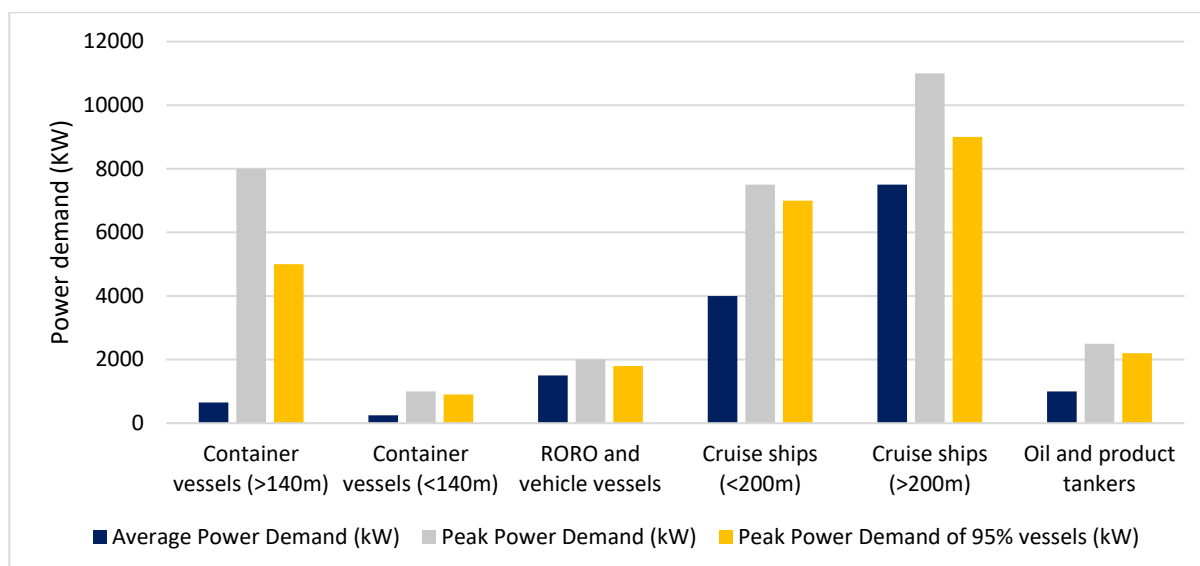


Figure 6. Power requirements of various types of vessels, according to [96].

4.4. Digitalization

The integration of digital innovations in smart ports is critical in addressing difficulties such as congestion at the port and orientation issues caused by the rising number of maritime vessels, trucks, and other types of infrastructure in seaports. Digital solutions can be used to monitor and gather information to improve seaport efficiency, both environmentally and operationally. Autonomous cars are increasingly being incorporated into current systems using digital technologies. This equipment includes AGVs, intelligent autonomous vehicles (IAVs), and QCs. Integrating AGVs into existing systems has various benefits, such as increasing production, decreasing energy use, lowering salaries, and improving human and natural environment security [97]. Wireless sensors and big data processing can minimize carbon footprints, operational costs, and system failures, and can improve data safety, warehouse efficiency, and smart energy control, as illustrated in Figure 7. In addition, digital technologies, such as IoT, can be used to monitor logistics and fuel consumption in smart ports. For transportation companies and port facilities to facilitate effective communication, they can employ digital information communication.

Figure 6 visually encapsulates the key performance dimensions influencing the deployment of smart technologies, including automated guided vehicle (AGV) systems, in modern ports. At the center of the image is a container terminal with digital overlays, symbolizing the integration of IoT, AI, and automation for enhanced operational efficiency. Surrounding this core are various icons representing critical evaluation criteria:

- **Operation cost:** Represented by the hand and dollar sign, this highlights the importance of cost-effectiveness, both in capital and operating expenditures. Smart port systems must balance investment with long-term financial returns.
- **Sustainability:** Denoted by the plant symbol, sustainability underscores the growing demand for environmentally friendly operations through reduced emissions, noise, and resource consumption.

- **Smart energy:** Indicated by the green energy leaf icon, this reflects the necessity of optimizing energy use, especially by shifting from diesel to electric systems and integrating renewable sources.
- **Carbon footprint:** The CO₂ footprint icon stresses the environmental imperative to reduce greenhouse gas emissions, aligning port operations with international climate targets.
- **Information security:** Highlighted by the shield and lock symbol, this acknowledges that increased digitalization requires robust cybersecurity frameworks to safeguard critical infrastructure.
- **Smart warehouse:** The mobile-device icon represents the deployment of digital tools and automated systems for real-time decision-making, improved asset utilization, and predictive maintenance.
- **System failure:** Illustrated by the warning symbol, this acknowledges the operational uncertainties associated with system complexity, technology integration, and supply chain disruptions.
- **High performance:** The colored gauge indicates the continuous need to monitor and enhance key performance indicators (KPIs) such as throughput, dwell time, and fleet utilization.



Figure 7. Automation of seaport terminals with advanced digital technologies.

This holistic visualization reinforces the idea that transforming ports into smart, sustainable, and economically viable hubs is a multi-dimensional challenge. Success depends not only on the adoption of advanced technologies, but also on aligning them with environmental goals, economic constraints, and operational resilience.

While the Port of Los Angeles has converted to digital information for all maritime industries, the ports of Hamburg (Germany) and Rotterdam (Netherlands) use IoT for maintenance and repair and 3D printing applications, while Singapore's seaport and the Port of Antwerp use cloud-based computing and large-scale data collection [22,98]. A study on the green performance of IAVs was conducted by [99]. These are a brand-new kind of automated guided vehicle with improved characteristics like autonomous pickup

and drop-off, 180-degree maneuverability, no requirements for a fixed track, and integrated sensor technology to identify nearby movement and stationary hazards. According to a pertinent study [100,101], autonomous lifting vehicles are better for the natural environment than AGVs. The process of automation involved in QCs is covered in [102]. Automated QCs can handle two or more twenty-foot comparable units at once, and come with two wagons. The automation of terminals is currently being integrated with numerous additional digital technologies, such as drones and robots, for the purpose of managing warehouses [91]. Only 1–2% of maritime terminals worldwide are currently completely automated, while 2–3% are semi-automated. Examples of these include the terminals in the ports of Melbourne (Victoria International Container Terminal), Los Angeles (TraPac terminal), Rotterdam (Maasvlakte II), and Tanger-Med (APM terminals). Therefore, it is anticipated that conventional ports will soon undergo complete digitization [103].

4.5. Energy Storage Systems (ESSs) in Seaports

Through the process of load management improvement, ESS integration promotes fuel-efficient operations, which decreases energy expenses and greenhouse gas emissions [104]. It ensures the integration and stabilization of sustainable energy production, either for storage or reinjection into the main grid, addressing the challenge of relying solely on green energy sources due to the intermittent and variable nature of local grid power supply. Fly-wheels, batteries, and supercapacitors are the most popular energy storage technologies. Installing ESSs on cargo handling machinery can reduce fuel usage by 20% to 50%. According to the research conducted in [105], ESSs for cargo handling equipment can reduce energy usage by about 57% when compared to traditional cargo vessels.

As maritime transport expands globally, hybrid cranes are being used more frequently [106]. With the use of energy storage devices, these common cranes have significant potential for recuperating energy during braking and hoist-down functioning. The recaptured energy can be recycled in two different ways. The surplus energy can be recycled using energy storage devices like flywheels, supercapacitors, or batteries, or it can be sent to the main power grid [107]. Similarly, integrating ESSs into RTGs for on-board energy storage provides several advantages, including lower fuel consumption and GHGs, as well as longer lifespans for engines due to a decrease in peak electrical demands.

4.6. Peak-Shaving

Electrified machines are increasingly used in ports due to their cost-effectiveness and efficiency. This causes significant electricity use during particular hours. Peak-shaving is a crucial operational method for reducing the peak energy use in port areas [108]. Figure 7 illustrates alternative approaches for leveling load profile curves. One way to move energy consumption from peak to off-peak times is through load shifting (Figure 8a), while the power sharing method uses stored energy when demand for energy is at its highest (Figure 8b). Finally, as shown in Figure 8c, load shedding involves turning off non-essential loads during busy times.

Reefer containers, QCs, and electrical equipment can all be maneuvered successfully with the use of these peak-shaving techniques [109]. Because the fluctuating tariff is based on peak power usage, this approach consequently lowers the variable cost of power consumption. A more expensive tariff may be responsible for between 25% and 30% of monthly energy expenses [110]. Because STS cranes are major energy consumers in ports, H. Geerlings et al. [109] proposed reducing the total number of QCs and simultaneously lifting containers, because synchronizing QCs reduces energy consumption at peak times.

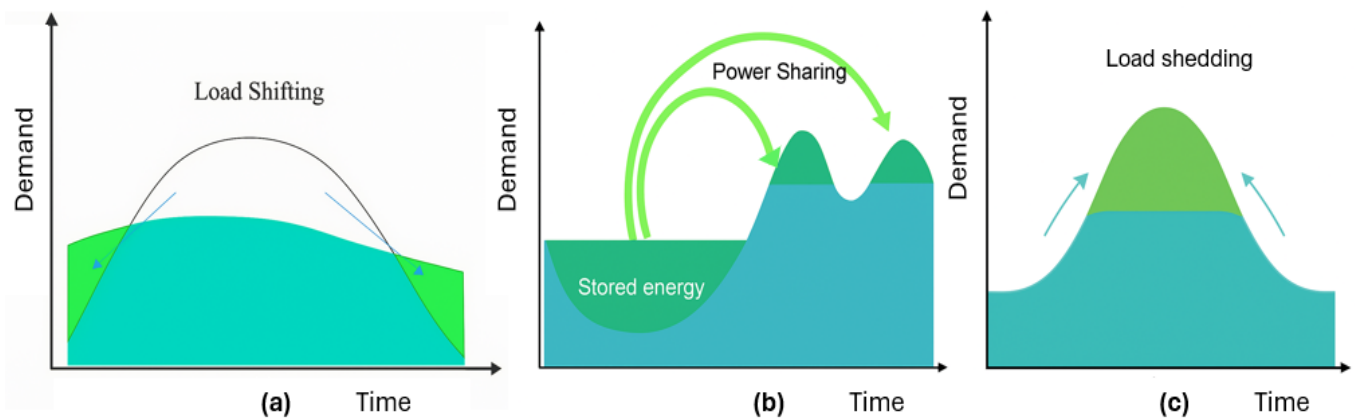


Figure 8. Techniques to reduce energy consumption using peak-shaving [108].

The implementation of the peak-shaving technique on QCs with twin lift and a pair hoist technology has been suggested in research papers [110,111]. Two of the primary technical and practical devices for peak-shaving are energy storage systems and the management of crane duty cycles. Delaying the start point by 21 s between both cranes significantly lowers the highest peak of group need and levels the whole load distribution curve. The above-mentioned energy-saving methods only cause a 2 min lag for each operation, resulting in significant time savings and a significant drop in power expenses. By lowering the peak energy consumption, these savings can be used during peak hours. According to one study, flywheels and ultracapacitors have respective life cycles of ten to twenty years, with a seven-year return on investment. Peak-shaving solutions are particularly beneficial for reducing the use of energy during peak hours, since reefer containers contribute between 30% and 45% of overall port energy use [112].

4.7. Energy-Aware Operational Management

The management of resources plays a major role in port operating efficiency [113]. The three primary sectors of container ports—yard side, quayside, and landside—are the focus of the current study's attention in relation to energy-conscious operations [114]. Energy optimization on the yard side concentrates on container transport planning and stacking, specifically tackling problems with machinery for handling and yard assignment. Studies have examined the energy consumption and scheduling of AGVs and Ycs using models designed to stabilize their energy consumption in tandem with QCs. By simulating both discrete events and dynamic conduct, hybrid automation techniques enable AGVs to decrease speed while consuming less energy and to operate for longer periods of time. For example, it can take about 65 kWh to load 90 containers [115].

Dual-cycle operations, in which machines execute both loading and unloading without emptied travel, offer greater power savings than single-cycle approaches, according to power-efficient planning for Ycs, Yts, and QCs. Additional research balances energy consumption with operational time by including energy concerns in crane deployment and berth management. QCs' energy usage is divided into two distinct groups: inactive (auxiliary, lighting) and operational (as well as moves) [116]. Energy efficiency is also enhanced by the employment of water-borne AGVs for inter-terminal cargo transit. Crane optimizers, yard optimizers, and truck schedulers are examples of advanced programs that are used in modernized ports to reduce pollution and energy consumption while increasing production and decreasing time wasted [117,118].

5. Modern Seaport Infrastructure

A seaport is a type of maritime infrastructure that accommodates individuals, supplies, and space. While current seaports are local points of intersection of several different worldwide supply chains, early seaports served as basic harbors. They are often distribution centers that connect public transport to the sea, rivers, air, canals, trains, and roads. The facilities that comprise modern seaports are the authors' primary concern here.

5.1. Seaport Microgrids

Regarding all aspects, a microgrid (MG) is a compact system situated close to the customer. Stated differently, an MG system is a low-voltage distribution network that is connected to modest generations [119]. The latter can be used with multiple sources in both connection-to-the-grid mode and island mode. Such sources can include hydropower stations, diesel-generating units, wind energy, solar energy, biomass energy, and marine energy. Occasionally, an ESS is added to improve efficiency and durability. An MG can offer excellent energy efficiency, lower line distortions, and lower connectivity costs. Additionally, MGs may contribute to improved power quality, lower emissions, lower investment costs, increased reliability, and less energy distribution loss [120].

A seaport microgrid generally refers to a localized, self-contained energy system within a port area. Its primary focus is on energy generation, distribution, and management at a smaller scale than the main grid, and it is often capable of operating autonomously (in island mode) or in connection to the grid. The main goals of a seaport microgrid include improving energy resilience, reducing emissions, enhancing power quality, and lowering operational costs within the port's energy system.

The significant expansion of maritime traffic has led to a significant rise in ecological concerns. The European Commission has recommended the use of shore-side electrification as a first step in addressing the negative environmental and health impacts of the maritime industry. In addition, port authorities need to support the idea of an entirely electric vessel. Numerous technical issues, such as variances in electrical supply demand, frequency levels, and voltage between the shore and shipside, continue to plague shore-side power projects. Therefore, the first step approaching future sustainable ports is the integration of microgrids into traditional port cities [121,122]. The idea of a seaport MG for port energy management is evaluated by Parise G. et al. [123]. Enhancing the supply, as well as the integration, of energy from renewable sources into the main electrical network is the aim of a port microgrid. Furthermore, the authors of [124] claim that the port zone is a special place where port managers can implement innovative energy management strategies to accomplish quality, dependability, and energy savings. A case study of two European ports is covered in [125], which examines how microgrid solutions have been effectively implemented at the ports of Hamburg in Germany and Genoa in Italy. Figure 9 depicts the layout of a seaport MG, in which the primary grid and a variety of RESs generate electricity that is sent to the seaport. Enhancing the operational behavior of seaport services is the main purpose of a seaport MG [126]. The growing integration of renewable energy sources (RESs) into MGs and microgrid clusters (MGCs) has led to heightened demand for advanced control techniques. In MGs and MGCs, multi-agent-based control techniques are highly advantageous for energy adjustment, frequency and voltage support, and attaining financial coordination [127]. Due to the features of power electronic conversion devices, MGs and MGCs are controlled differently from traditional power systems. In the interim, either in a grid-connected or isolated mode, the MG must strike an equilibrium between supply and demand to preserve voltage/frequency reliability. A hierarchical control method has been proposed as a successful strategy to handle these problems [128]. MGs' goal of increasing the resilience and dependability of crucial facilities, including

communications, sanitation, shipping, alimentary supplies, medical care, and disaster recovery infrastructure, has been a major driver of MGs' implementation and advancement in the USA [129,130].

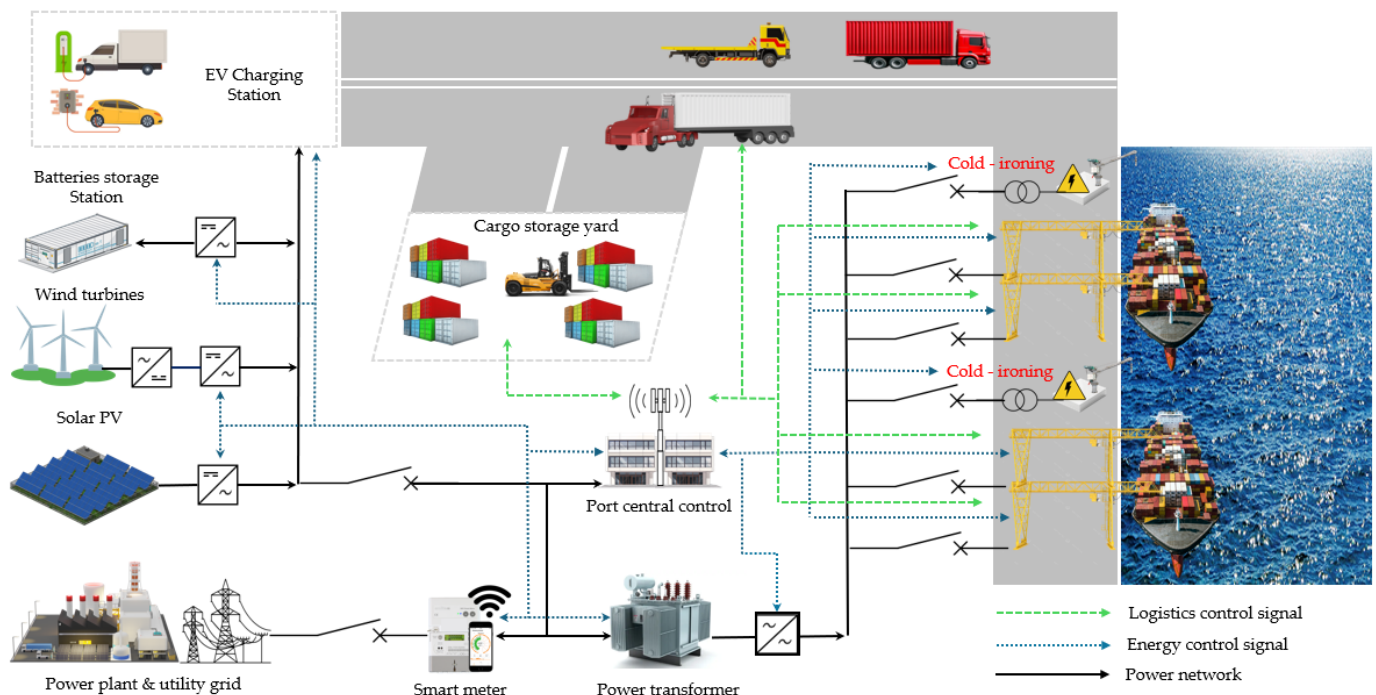


Figure 9. The configuration of a seaport microgrid integrating RESs [126].

To assist local populations, the USA has been investigating the viability of expanding MGs beyond vital infrastructure. MG development in Europe has faced challenges due to environmental issues and the introduction of renewable energy sources into the main electrical grid [130]. In addition to enabling local supply–demand balancing, MGs have the adaptability to incorporate intermittent distributed renewable energy into primary networks [131]. Financial development, sustainable development, environmental dependability, and energy safety are the main groups into which the potential advantages of MGs in seaports can be divided [132].

5.2. Smart Port Microgrids

A smart grid is an energy system that uses a variety of modern technologies, such as communication networks, to efficiently control and manage the generation and transmission of electricity. Smart port microgrids are built upon the seaport microgrid concept by embedding advanced information and communication technology (ICT), such as IoT sensors, real-time monitoring, and intelligent energy management systems. This transforms the microgrid into an integrated, responsive platform capable of dynamic energy balancing, predictive maintenance, and optimization of energy use across multiple port assets (e.g., cranes, warehouses, electric vehicles). It aligns with the broader vision of a “smart port”, where data-driven automation, connectivity, and sustainability converge to optimize both energy and operational efficiency. According to the European Regulatory Group for Electricity and Gas (ERGEG), a smart grid is an electrical network that may integrate the decisions and behavior of all users who are connected at a reasonable cost [133]. As a result, smart grids guarantee increased effectiveness, less power outages, and superior safety and reliability. Consumer-friendliness, self-healing, optimum asset usage, resilience to physical and cyberattacks, strong communication, sustainability, enhanced power safety, and increased efficiency and dependability are just a few of the characteristics that define

the concept of smart grids. Figure 10 shows an example of intelligent energy management (IEM) at a seaport's terminal. A vessel, dock cranes, a warehouse, a charging facility, and RMGs are the five required powers shown in this illustration. Smart communication gadgets are used to link these loads to the IEM platform. Public grid supply, wind farms, rooftop solar cells, and ESS are among the sources of power. Using suitable sophisticated monitoring techniques, the IEM system effectively controls the power through communication networks [134]. The planning process for port smart grids is thoroughly covered in [135], including the preliminary phases of energy balancing, machine load examination, smart grid benefits, and scenario assessment. These preliminary phases aid in the analysis of daily RES fluctuations, peak-shaving improvement, storage facility design, and pricing and financial management.

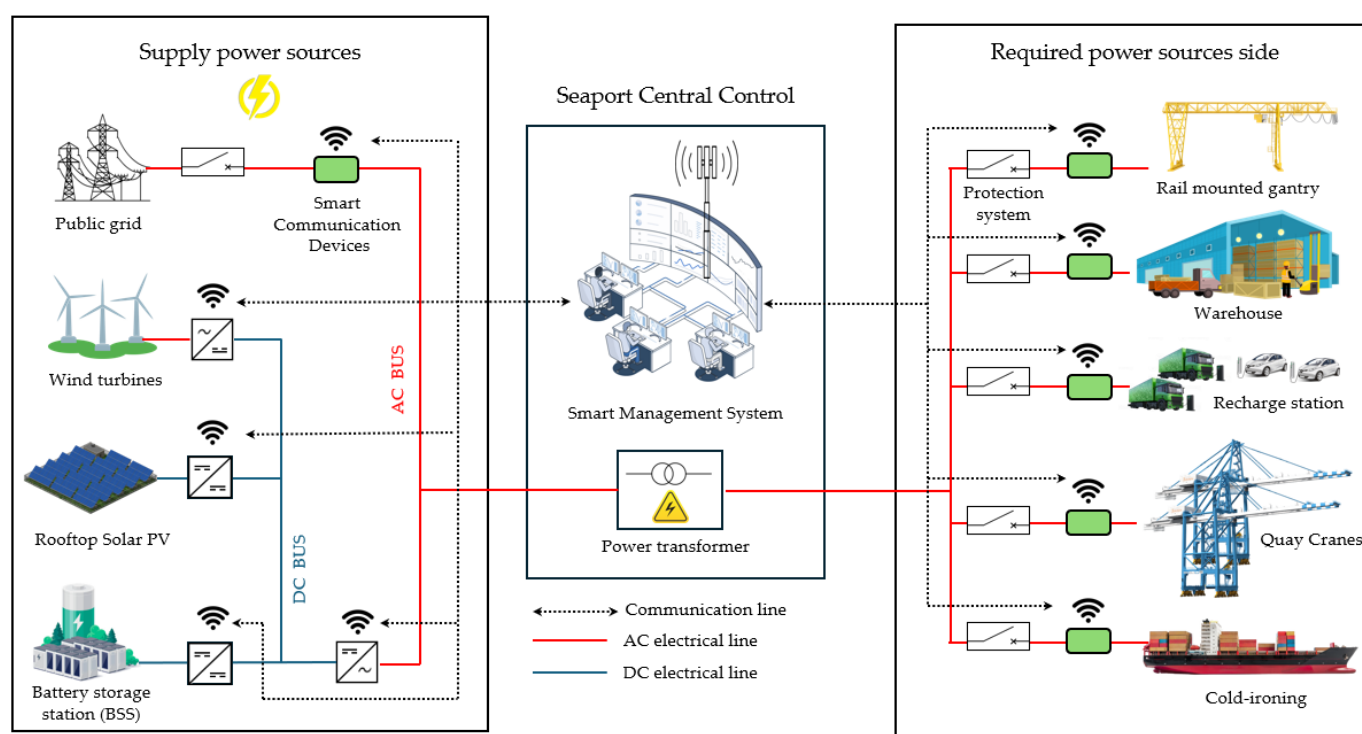


Figure 10. An example of a seaport's intelligent energy management [134].

MGs, although relatively small and capable of operating independently from the main public power system, play a crucial role in advancing the smart grid concept, which typically involves larger-scale utilities with extensive transmission and distribution infrastructure. According to the authors of [136], port sustainability involves port authorities working collaboratively and ethically with users to deliver services that are aligned with a strategy for socio-economic sustainable development. The concept of green or smart ports offers a pathway to achieving sustainable energy use in ports [137].

5.3. Charging Stations in Smart Seaports for Electrical Vehicles and Hybrid Ferry Vessels

Vessels and harbor managers are under pressure to constrain their impact on the environment within target ranges and use RESs, due to the strict emissions regulations established by the EU and the International Maritime Organization (IMO) [138]. To address the expansion of onshore electrical power and shore charging stations for vessels, port grids are moving onto RESs [139]. By employing sophisticated control techniques, these contemporary vessels contribute to a 10–35% reduction in GHG emissions and marine fuel usage. For regular battery recharging, these ships require charging facilities in the harbor sector. In addition, the port microgrid needs to be oriented to support shore

charging infrastructure, particularly for hybrid ferry vessels [140]. Figure 11 illustrates the fundamental schematic layout of DC fast-charger power circuits. It consists of two conversation levels with galvanic separation from three phases of AC/DC and DC/DC circuits. As the DC/DC levels offer galvanic isolation among the electrical grid and the EV and assist in incorporating parallel connectivity at the charger output levels, the AC/DC rectification level houses the power factor correction (PFC) loop, which guarantees that the power meets requirements.

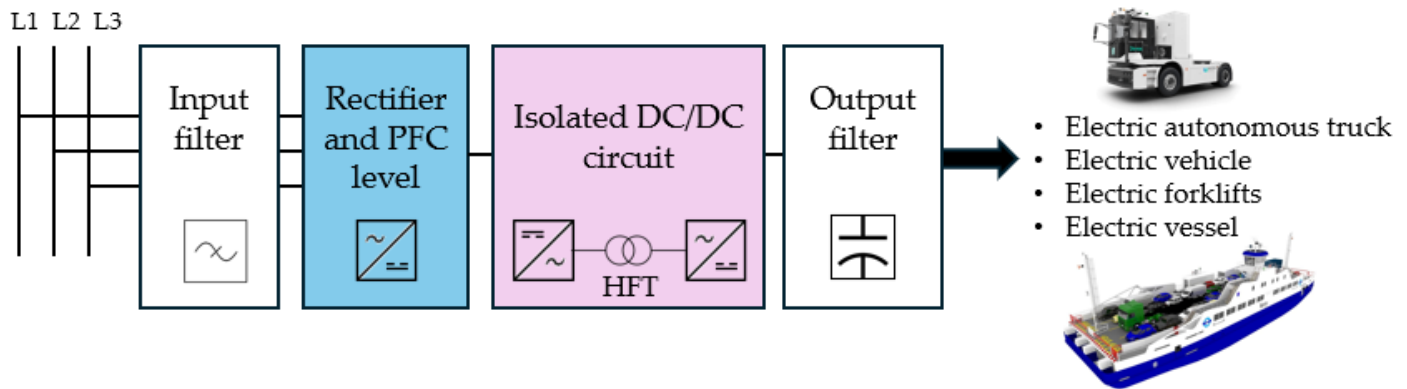


Figure 11. DC charger circuit layout in simplified configuration.

There are two primary types of battery charging: slow charging and fast charging. Both have distinct time domains for recharging batteries, typically eight hours or longer for the first type and one hour or less for the second type [141]. The most famous approach to zero emissions is the most recent advancement of port electrification. In addition to attempting to implement plug-in battery-powered ferry operations and the expansion of related facilities, many nations with lengthy coasts are currently aiming for significant emissions reductions in their port areas. For instance, Norway has taken significant steps and now generates about 98% of its electricity from renewable energy sources, primarily hydropower. In Norway, there are currently very significant industrial initiatives and governmental laws aimed at lowering national GHG emissions from sea traffic. Additionally, it is leading the way in ferry and other port infrastructure electrifications. As of early 2025, Norway operates approximately 100–102 battery-powered ferries and passenger boats [142]. An overview of some recent plugged-in battery-powered/fully electric vessels are listed in Table 4.

According to Table 4, the commissioning of battery-electric vessels spans from 2013 to 2023, clearly illustrating a decade-long evolution and accelerating momentum in maritime electrification. The surge in newbuilds during 2022–2023 signals not just a growing trend, but a strategic shift driven by global decarbonization targets (e.g., IMO 2030/2050), rapid advancements in battery technologies, and increasing pressure to transition toward zero-emissions shipping.

Notably, Norway emerges as a global frontrunner in this transition, with vessels like Festøya and Hinnøy—both large-capacity ships designed for passenger and RO-RO operations—demonstrating the country’s commitment to maritime sustainability. This leadership is no coincidence; it reflects a well-aligned national strategy backed by robust public policy, financial incentives, and an advanced shipbuilding industry that embraces clean energy innovations.

Table 4. A summary of the newest battery-electric vessels worldwide [143–150].

Vessel Name	IMO No.	Type	Year	Country	Battery Capacity	Manufacturer
Festoya	9863132	Hybrid passenger/RO-RO cargo ship	2020	Norway	1582 kW	Remontowa Shipbuilding SA, Gdansk
Hinnøy	9969766	RO-RO passenger ship	2023	Norway	4750 kW	Cemre Shipyard, Altinova
Elektra	9806328	Hybrid ferry	2017	Finland	1000 kW	Siemens, Munich
Tapana Catamaran	567000479	All-electric ferry	2020	Thailand	175–192 kW	Danfoss, Nordborg
Hallaig	9652832	Hybrid ferry	2013	United Kingdom	700 kW	Ferguson Shipbuilder, Glasgow
Sea Change	-	Electric hybrid passenger ferry	2023	United States	100 kW	All American Marine, Washington, DC
Elektra	-	Barge pusher	2022	Germany	2500 kW	Schiffswerft Hermann Barthel, Derben
FaehrBaer 2	4811480	Electric inland ferry	2022	Germany	252 kW	Formstaal GmbH & Co. KG, Stralsund

Battery capacity across the listed vessels varies widely, from as little as 100 kW (Sea Change, Minneapolis, MN, USA) to an impressive 4750 kW (Hinnøy, Norway). This disparity underscores the diversity of operational requirements, with higher capacities required for large RO-RO or cargo vessels to ensure adequate range, performance, and energy autonomy. It also reflects the scalability of battery-electric propulsion systems across multiple vessel classes and mission profiles, reinforcing their versatility as a cornerstone of next-generation maritime transport.

5.4. Hybrid Options for Modern Seaport Equipment

Fuel-electric and plug-in hybrids, along with diesel-hydraulic combinations, which use hydraulic energy to drive motor and wheel movements, are among the many hybrid alternatives available for port machinery [151]. The enhanced setup could reduce consumption by up to 330 kW during periods of peak demand in hybrid powertrains that use flywheels and ultracapacitors as their primary energy storage systems and energy sources [152].

Cranes are one of the main types of machinery in shipping terminals that are suitable candidates for retrofitting with electric hybrids. Since such machinery is electrically driven, it is possible to feed the energy generated by regenerative braking back into the grid, as demonstrated by the rail-mounted gantry cranes (RMGs) in the harbor of Vancouver [153]. In [154] and [155], it is reported that a QC's peak demand is approximately 1211 kW, and this may be lowered by up to 73%. Another investigation found that using ultracapacitors and supercapacitors can reduce the peak demand for energy storage and a bidirectional converter by 90% [156]. Similarly, there is also an opportunity to lower QCs' energy consumption by using a spreader tandem dual lift which can reduce QCs' energy consumption by allowing the lifting of multiple containers (e.g., two 20-foot or 40-foot containers) in

a single lift cycle [157]. Wei et al. [158] examined the consumption of hybrid RTGs and discovered that they might allow for savings of up to 70% on energy costs. In Figure 12, the main RTG combined with an ESS is shown. According to [159], installing a flywheel resulted in an energy consumption reduction of more than 30%.

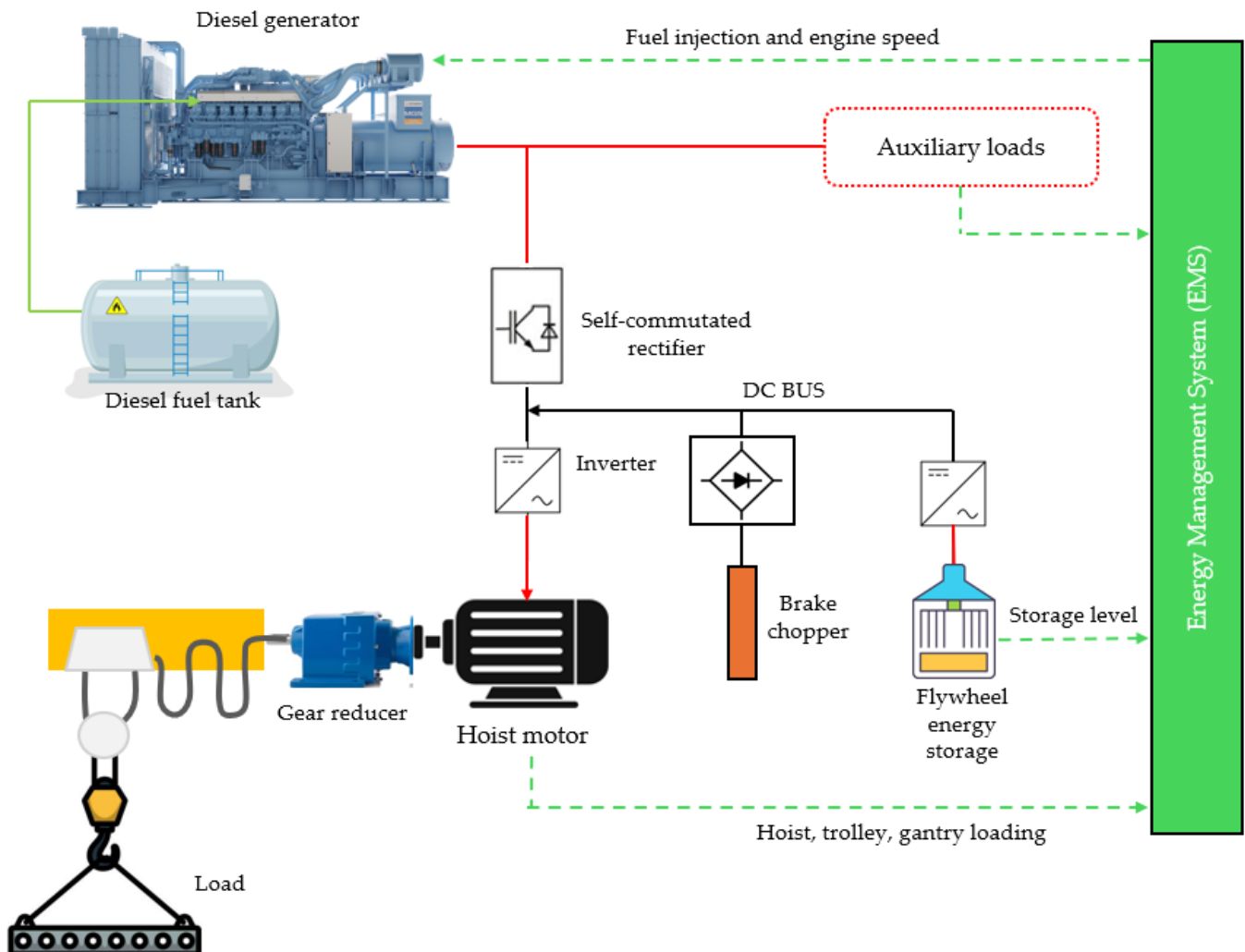


Figure 12. Diagram of hybridized energy flow of RTG with integrated ESS and EMS [159].

Energy savings of up to 35% were attained when the authors of [160] studied the arrangement of a flywheel structure combined with an undersized diesel engine to store energy for an RTG. Additional advantages were also noted, such as a longer generator lifespan, reduced noise levels, and faster system response times. Furthermore, it has been demonstrated that adding a generating source to supercapacitors—such as a diesel generator—could reduce energy consumption by up to 35%. Another study [161] found that using a flywheel in RTGs reduced initial electrical consumption by 38% when used in conjunction with a power management system that displayed variable runtime and unpredictable loads. Table 5 presents the impact of hybridization of port equipment in seaports [162–167].

Table 5. An overview of the impact of hybridizing in seaport equipment with and without an ESS [162–167].

Equipment Type	Hybridization Type	Energy Efficiency Gain	GHG Reduction	Key Advantages
Container crane (RTG)	Diesel–electric without ESS	25–30%	30%	Reduced fuel use, lower maintenance
Container crane (RTG)	Diesel–electric with ESS (Lithium-ion)	40–50%	50 to 60%	Energy recovery during braking and quiet operation
Terminal Tractor (Shunt truck, yard truck, etc.)	Hybrid without ESS	15–20%	20%	Electric startup assistance and torque support
Terminal Tractor (Shunt truck, yard truck, etc.)	Hybrid with ESS	30–40%	45%	Partial electric operation and better energy control
Straddle carrier	Hybrid without ESS	20%	25%	Reduced engine idling
Straddle carrier	Hybrid with ESS	35%	50%	Fast recharge, power boost capability
Reach Stacker (forklift designed for handling shipping containers)	Hybrid without ESS	18–25%	20 to 30%	Fuel consumption reduction
Reach Stacker	Hybrid with ESS	35–45%	50%	Energy regeneration during load-lowering

6. Modern Technologies in Leading Global Seaports

Traffic jams and port orientation are just two of the many difficulties brought by rising numbers and quantities of marine vessels, containers, and other equipment. There are several potential applications in seaports for the use of emerging technologies such as IoT, big data, artificial intelligence, and cloud computing. In this regard, smart seaports have surfaced, and they employ innovative technological approaches to boost productivity, enhance security, and promote environmental sustainability [168].

The idea behind a smart seaport is centered on using techniques and tactics to lessen environmental effects while simultaneously boosting ports' profits [169]. According to [170], a smart seaport is one that has been upgraded and furnished with modern technology. More specifically, a smart port is an automated port with devices that are linked to big data, cloud/fog computing, sophisticated sensors, and the Internet of Things (IoT). Several network and information technology (IT) facilities, including local area networks (LANs) and wide area networks (WANs), as well as other geolocation systems, support all these advancements. Table 6 lists a few international seaports that are engaged in smart port initiatives.

Table 6. International seaports that are engaged in smart port projects [68,171–177].

Continent	Country	Name of Seaport	Features
Africa	Morocco	Tanger Med	The port features a fully integrated digital platform for logistics, a Port Community System (PCS) connecting over 800 stakeholders, automated gates, IoT sensors, real-time cargo tracking, and digitized customs procedures—all with a strong emphasis on energy efficiency and emissions reduction. It was ranked among the world's top 25 container ports by UNCTAD in 2023.

Table 6. Cont.

Continent	Country	Name of Seaport	Features
	South Africa	Durban	The port is undergoing modernization through the implementation of automation systems, digital twin models, and smart scheduling tools. It also employs drone technology and automated cargo handling, with plans to introduce AI-driven logistics and predictive maintenance solutions.
America	USA	Long Beach	Nearly USD 185 million has been spent by the Port of Long Beach on the development of port infrastructure, particularly shore electricity.
	USA	Los Angeles	Implement real-time data analytics to integrate shipping data across the port eco-system to improve the efficiency of the supply chain.
Asia	China	Yanshan	The port has installed automated container handling facilities with bridge cranes, AGVs, and remotely operated RMGs.
	China	Tianjin	Improved incorporation of emerging technologies, including AI, 5G, and big data.
Europe	Germany	Hamburg	RES's shore power supply, real-time navigation tracking, and management of fleets using mobile GPS sensors.
	Netherland	Rotterdam	IoT is used to improve ship berthing conditions.
	Spain	Barcelona	Quantifications of freight environmental footprints and weather prediction systems.
	Belgium	Antwerp	Incorporation of digital sensors and cameras to guarantee proper ship berthing and preventive maintenance, as well as blockchain technology to increase security between rival parties for digital trade.
	France	Le Havre	Concentrates on several initiatives pertaining to air quality enhancement, traffic monitoring and coordination, energy management, and energy efficiency.

6.1. IoT Applications in Contemporary Seaports

For global economic development and prosperity, the marine industry has been essential. For instance, over 74% of European goods are shipped across the ocean. Sea traffic congestion, maneuverability issues, ineffective navigation systems, elevated pollutants, and ineffective ship-to-port communication networks have all been brought on by the swift growth of global maritime trade. Ports are attempting to use IoT technologies to address these problems. Things, systems, and objects are being moved from traditional to advanced technologies with the aid of IoT concepts [178]. As shown in Figure 13, smart devices have numerous specialized applications in seaports.

A cutting-edge tool for managing lines, truck appointment systems (TASs) are primarily utilized in a variety of industries, including truck inspections, medical care, border-crossing, and immigration centers. In contemporary ports, they are usually employed to control traffic and lessen congestion. Different European seaports, such as those in Haminakotka, Antwerp, Gothenburg, and Valencia, use TASs [180].

Other intriguing IoT applications are RTPORT and PORTMOD. PORT MOD serves as an eye-catching and engaging tool for container terminal operations. It is an independent Java application designed to solve container management problems. PORT MOD assists in locating problems and errors in crane operations, straddle carriers, container flow, and accurate machine pooling calculation during loading and unloading procedures. In addition, RTPORT is a 5G-enabled real-time management unit that facilitates intelligent

terminal operations. The main goal of the RTPORT unit is to use 5G networks to deliver a fully autonomous cargo port management solution. The use of device was evaluated for the first time in Italy at the Port of Livorno, where it was discovered that the effective use of RTPORT with 5G technology decreases ecological effects and contributes to energy efficiency via improved real-time cargo management amenities [181].

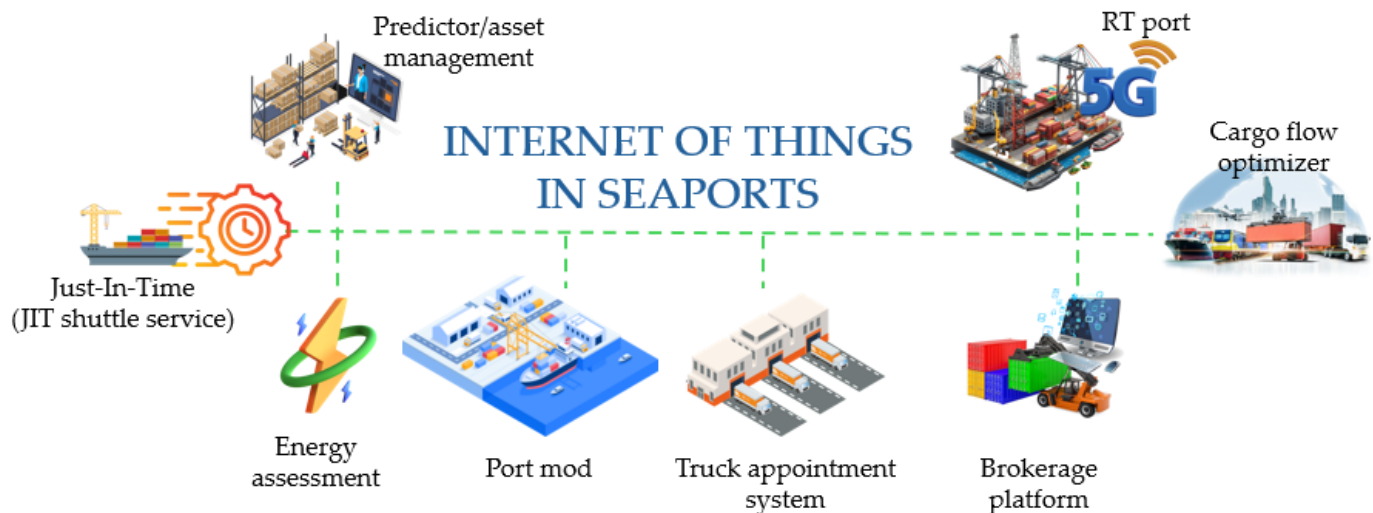


Figure 13. IoT applications in contemporary seaports [179].

An additional tool for optimizing shipping on rivers and lakes, railroads, and seas is a cargo flow optimizer. The creation of a description of the most effective routes for traveling from the hinterland to the harbor was made easier by the application of this technique in the harbor of Antwerp [182]. Improved cargo forecasting helps with terminal scheduling and management, which ultimately results in dependable and robust services. Port traffic congestion, lines, interruptions, and the presence of cargo and ships in ports are caused by an ongoing rise in the amount of container shipping and the number of vessels [183]. The harbor of Valencia has therefore launched a just-in-time (JIT) railway shuttle service called the Valencia Zaragoza rail line that expands railway services to address this significant difficulty.

Implementing JIT and rail transportation will lower operating costs, enhance railroad systems, shorten container stay times, and enhance port-to-port interactions in logistics chains. In addition, asset predictors and energy rating methodology are IoT tools that can be used for energy and asset management. The energy assessment methodology serves as a guide for lowering the ecological impacts of ports, and it is reasonably priced. It is being used in Greece at the Port of Piraeus to investigate how to integrate RESs with ESSs at an affordable price. An asset predictor is a machine learning and optimization tool for optimizing the utilization of port facilities [184]. Machine learning methods aid in the prediction of imbalanced classification issues.

Lastly, another exciting aspect that is currently being implemented in contemporary ports is brokerage platforms. These serve as intra-port asset exchange and lease marketplaces that run on the cloud [185]. One is currently being trialed in the Port of Antwerp. Marketplace services make it easier to make the best use of equipment in harbors, including wagons, chassis, cranes, and barges. Improved yard usage and less lengthy container transit at harbors are some of the outcomes of improved equipment and service management.

6.2. The Use of 5G Services in Contemporary Seaports

Ship navigation, port operations, and marine logistics are all being revolutionized by the introduction of fifth-generation (5G) mobile networks into seaport environments. Fifth-

generation networks offer a fundamental framework for next-generation port digitization, and are distinguished by their extremely low latency, high data throughput, and strong dependability [186]. Their implementation enables a wide range of innovative uses that improve safety, operational effectiveness, and real-time decision-making throughout the maritime industry.

Although 5G offers strong potential to improve efficiency, automation, and security in maritime harbors, its integration remains limited due to several obstacles [187]. The high cost of the required infrastructure (antennas, compatible equipment, IT systems), the complexity of its integration with existing technologies, the lack of interoperability standards among various port stakeholders, and regulatory constraints related to frequency allocation all hinder its adoption [188]. Moreover, the return on investment for 5G has not yet been clearly demonstrated, making port authorities cautious [189,190]. Some ports prefer to focus their resources on more urgent priorities, such as energy transition or cybersecurity [190]. Finally, 5G remains in the pilot testing phase in several major ports, which is delaying its widespread implementation on a global scale. While specific abandoned projects are not widely documented in the existing literature, many initiatives remain in the pilot or feasibility study phases. The Washington Maritime Blue 5G feasibility study exemplifies how projects often struggle to move beyond research phases due to funding and technical complexities. Table 7 presents the major ports that have adopted or piloted 5G, while Table 8 presents a technical comparison between the use of 4G and 5G in maritime ports.

Table 7. Ports that have piloted 5G facilities [191–197].

Port	Country	5G Applications/Initiatives
Rotterdam	The Netherlands	One of the most advanced ports; uses 5G for autonomous ship navigation, smart cameras, and IoT sensors.
Hamburg	Germany	Pilot zone with Deutsche Telekom; uses 5G for traffic control, augmented reality technology to assist in maintenance tasks, and IoT.
Antwerp	Belgium	Fifth generation-enabled drones, smart containers, and AI for logistics optimization.
Qingdao	China	Fully automated terminal using 5G for real-time crane and AGV (automated guided vehicle) control.
Tianjin	China	World’s first 5G smart terminal; fully automated container handling and digital twin systems.
Busan	South Korea	Testing 5G with KT Corporation for autonomous vehicles, AR inspection, and smart logistics.
Singapore	Singapore	Trialing 5G for smart yard management, predictive maintenance, and autonomous vehicles.
Livorno	Italy	EU-funded 5G pilot for safety systems, environmental monitoring, and real-time logistics data.
Barcelona	Spain	Uses 5G for remote crane control, port security, and smart environmental monitoring.
Felixstowe	United Kingdom	Implementing a 5G testbed project to boost cargo handling efficiency and real-time monitoring.

Table 8. Comparison between 4G and 5G in maritime ports [198–201].

Criterion	4G (LTE)	5G
Maximum data rate	~100 Mbps	Up to 10 Gbps
Average latency	30–50 ms	1–10 ms
Simultaneous connections	~10 k devices/km ²	>1 M devices/km ²
IoT support	Moderate	Excellent (massive IoT)
Geolocation accuracy	Meters	Centimeters
Robotics and automation	Limited (with possible latency)	Optimal (real-time control, fine synchronization)
Connection reliability	Good, but congestion possible	Very high, even in high-density environments
Security	Moderate	Enhanced
Initial investment cost	Low to moderate (existing infrastructure)	High (5G antennas, edge servers, new equipment)
Typical applications	GPS tracking, video surveillance, VoIP calls	Autonomous cranes, AGVs, digital twins
Return on investment (ROI)	Moderate (already deployed)	Long-term, depends on automation and use cases

6.3. The Socio-Economic Impact of 5G in Maritime Ports

The Port of the Future project has yielded numerous economic benefits, including reduced operational costs, fuel consumption, and machine working hours, as well as increased operation speeds [202]. Business case studies have quantified revenues for three 5G use cases—eMBB, automation of container handling (ACH) in container terminals, and augmented reality for construction projects—demonstrating their measurable ROI potential [203]. The Hamburg Port 5G pilot represents one of Europe’s most comprehensive maritime 5G implementations. The project has a funding volume of approximately EUR 2.3 million and will run until mid-2026. A transmitter installed at 150 m elevation on Hamburg’s television tower covers 8000 hectares of testing ground in the port area, offering mobile connectivity with unprecedented reliability, safety, and speed [204].

Key socio-economic outcomes from these pilot projects include enhanced worker safety through real-time monitoring systems, the creation of high-skilled technical roles requiring advanced digital competencies, and the attraction of technology partnerships that generate regional economic multiplier effects. The Hamburg project has particularly demonstrated how maintenance procedures can be improved using data glasses for engineers and connected sensors, while fostering workforce development in emerging maritime technologies.

The socio-economic potential of this technology extends beyond individual ports. Fifth-generation technology is estimated to add USD 1.3 trillion to global GDP by 2030, with increased efficiencies and productivity adding value across sectors [205]. For manufacturing industries connected to ports, annual savings enabled by 5G through real-time monitoring and control amount to EUR 27 million for one factory, with the technology’s global value potential reaching EUR 360 million annually.

While these pilot projects demonstrate promising economic returns and social benefits, successful 5G adoption in maritime ports ultimately depends on overcoming implementation barriers such as high infrastructure costs, regulatory complexities, and the need for sustained public–private partnerships to realize the technology’s transformative potential.

6.4. Job Displacement and Workforce Transformation

The automation enabled by 5G technology presents a complex socio-economic challenge regarding employment. While pilot projects like Hamburg’s 5G-MoNArch have demonstrated job transformation rather than outright elimination, creating new technical roles in digital monitoring, data analysis, and advanced equipment maintenance, their broader implications warrant careful consideration. Current automated port facilities provide concrete evidence of employment impacts. A 2022 report by the Economic Roundtable found that automation eliminated 572 full-time roles across two terminals at the ports

of Long Beach and Los Angeles in 2020 and 2021, representing nearly 5% of roughly 13,000 job. The Port of Rotterdam faces similar challenges, with projections indicating that increasing automation could lead to a 25% reduction in job numbers in a port that employs around 192,000 people, making up 19% of the entire workforce in the Rotterdam Rijnmond region [203,206]. Currently, 27% of global dock work is automated, a figure predicted to increase to 85% by 2040 [206,207]. However, these reductions are often offset by increased demand for technicians, IT specialists, and remote operation center personnel, with traditional longshoremen roles evolving into equipment supervisors that manage multiple automated systems simultaneously.

6.5. Real-World 5G Deployments in Modern Ports and Lessons Learned

In recent years, 5G technology has evolved from pilot initiatives to fully operational deployments in several major international ports. A notable example is the Port of Antwerp (Zeebrugge), which has implemented a private standalone (SA) 5G network in partnership with Orange and CityMesh. This network spans approximately 150 km² and supports a wide range of advanced applications. These include real-time guidance of automated tugboats via high-definition video streaming, deployment of drones for safety and environmental monitoring, augmented reality (AR) inspections in high-risk areas, and autonomous forklift operations. The system demonstrates ultra-low latency—measured at below 1 millisecond—enabling seamless remote control and coordination of port logistics and safety infrastructure.

Similarly, the Port of Hamburg's Container Terminal hosts the federally funded "PROCON-5G" initiative (EUR 2.3 million), which provides a high-performance, provider-independent network to support automation in equipment maintenance and mobile terminal operations. This project illustrates the critical role of flexible 5G infrastructure in enabling scalable digital transformation. In Asia, the Port of Tianjin (Terminal C) has entered commercial-scale operation since October 2021 by integrating 5G with Level 4 autonomous driving technologies developed by Huawei. Its operations include 76 driverless trucks guided by the BeiDou navigation system and remotely operated quay cranes capable of handling ~39 TEU/hour. Reported gains include a ~20% reduction in container energy use, 90% alignment precision on the first attempt, a 55% increase in traffic efficiency via vehicle–cloud coordination, and an overall ~30% cost reduction. The shift has also reduced staffing requirements by approximately 60%, while achieving zero-carbon operations in a terminal handling over 20 million TEU annually. These examples collectively demonstrate the tangible performance, scalability, and environmental benefits of commercial 5G adoption in modern seaports.

Lessons learned across these deployments highlight key enablers and challenges: high-speed, ultra-reliable connectivity is essential for latency-sensitive applications such as real-time crane control and coordinated autonomous fleets [208–210]. However, interoperability with legacy port infrastructure remains a barrier, underscoring the need for open standards and modular system design. Economic viability appears to be closely linked to strong public–private partnerships, as demonstrated in Antwerp and Hamburg, where funding mechanisms and joint testing platforms have been instrumental [211]. Finally, the Port of Tianjin illustrates the critical importance of workforce transition planning. Large-scale staff reductions have been accompanied by targeted retraining programs, enabling a shift toward highly skilled roles in system supervision and remote operation [212]. These insights emphasize that successful 5G integration depends not only on technological readiness, but also on governance, inclusiveness, and long-term adaptability.

7. Discussion

7.1. Significant Achievements and Technological Progress

This comprehensive review demonstrates substantial progress in maritime port transformation across multiple technological domains. The literature reveals impressive quantifiable benefits from individual technology implementations: electrified RTGs with ESSs achieving 40–50% energy efficiency improvements and 50–60% GHG reductions, battery-powered AGVs demonstrating superior NPC compared to diesel alternatives, and 5G pilots like Hamburg’s EUR 2.3 million project covering 8000 hectares and providing measurable operational improvements. These achievements represent concrete evidence that the technological foundations for port transformation are not only feasible, but increasingly economically viable.

The diversity of global implementation cases—from Norway’s 100+ battery-powered ferries to Singapore’s comprehensive renewable energy integration, and from Hamburg’s advanced 5G pilots to Rotterdam’s successful IoT applications—demonstrates the universal applicability and adaptability of these technologies across different operational contexts, regulatory environments, and economic conditions. This geographic diversity validates the robustness of the transformation approach, while highlighting successful adaptation strategies for various port configurations.

7.2. Emerging Synergetic Opportunities and Integration Potential

While acknowledging implementation challenges, the literature reveals promising synergistic opportunities that emerge from the convergence of electrification, IoT, 5G, and renewable energy integration. The MAS-based energy management systems described in the review demonstrate how intelligent coordination between renewable energy sources, energy storage systems, and electrified port equipment can achieve optimization levels that are impossible to attain with standalone technologies. The Port of Hamburg’s integration of 5G networks with IoT sensors for predictive maintenance, and the Port of Barcelona’s combination of environmental monitoring with smart energy management, illustrate the multiplicative benefits of integrated approaches.

The review identifies several successful integration examples that challenge the perception of purely fragmented implementation. Ports like Antwerp’s, which combines hydrogen-powered tugboats, digital sensors, and blockchain technology, or Singapore’s, which integrates renewable energy systems with smart yard management and predictive maintenance, demonstrate that comprehensive transformation is not only possible, but already underway in leading facilities.

7.3. Integration Gaps and Implementation Challenges

The literature review reveals a significant disconnect between the theoretical potential of integrated port transformation and the reality of fragmented, technology-specific implementations. While electrification, IoT, 5G, and renewable energy sources are extensively studied as individual solutions, the reviewed studies demonstrate limited evidence of comprehensive, simultaneous deployment across these four technological domains. Most ports implement these technologies in isolation—Hamburg focuses on 5G pilots, and Singapore emphasizes renewable energy integration, while Los Angeles prioritizes electrification—suggesting a lack of holistic transformation strategies. This fragmented approach represents a critical gap in current research and practice. The synergistic benefits of simultaneous deployment remain largely theoretical, with limited empirical evidence demonstrating how these technologies interact operationally. For instance, while the literature extensively discusses the potential of 5G for real-time energy management and IoT applications for the optimization of renewable energy integration, few studies provide concrete evidence of

ports successfully combining all four technologies to achieve multiplicative, rather than additive, benefits.

7.4. Economic Validation and Investment Challenges

Hamburg's 5G pilot, Singapore's renewable energy investments totaling USD 70 million, and Germany's EUR 18.9 billion investment in renewable energy sources for port applications demonstrate significant institutional confidence in transformation technologies. The quantified benefits—annual savings of EUR 27 million for manufacturing facilities through 5G-enabled monitoring, energy cost reductions of up to 70% through hybrid RTGs, and operational cost reductions through optimized container handling—provide compelling evidence of economic benefits. However, the literature also reveals legitimate concerns about economic scalability and risk management. While 5G technology promises to add USD 1.3 trillion to global GDP by 2030, port authorities remain cautious due to high infrastructure costs and uncertain short-term returns. This reflects prudent financial management rather than technological skepticism, highlighting the need for more comprehensive business models that account for both direct operational benefits and indirect economic multiplier effects.

7.5. Social Transformation and Workforce Development Opportunities

While automation has eliminated specific job categories—572 roles in the ports of Long Beach and Los Angeles—evidence also demonstrates job evolution and the creation of new technical positions. Hamburg's 5G pilot has generated highly skilled technical roles in digital monitoring, data analysis, and advanced equipment maintenance, while projects across multiple ports have created demand for renewable energy technicians, IoT specialists, and automated systems operators.

The documentation of workforce development programs in leading ports provides valuable models for managing social transition. Rotterdam's early stakeholder engagement, retraining initiatives, and partnerships with labor unions represent proactive approaches to workforce transformation that minimize social disruption while maintaining operational efficiency gains. These examples challenge overly pessimistic projections about employment displacement and highlight the potential for managed transition strategies. Nevertheless, the literature acknowledges that communities that are heavily dependent on traditional port employment face genuine transition challenges requiring coordinated policy responses and social support systems. The projection of an increase in dock work automation from 27% to 85% by 2040 represents a significant transformation that requires comprehensive planning and community-centered implementation strategies.

7.6. Regulatory and Standardization Vacuum

This study reveals a significant regulatory and standardization vacuum that threatens the scalability of port transformation initiatives. While acknowledging that "radio frequency allocation varies from country to country, creating uncertainty in the 5G network operator landscape," studies fail to propose concrete solutions for harmonizing international standards and regulatory frameworks. This regulatory uncertainty extends beyond 5G to encompass all four technological domains. The lack of standardized protocols for IoT device integration, inconsistent renewable energy certification processes, and varying electrification safety standards creates barriers to technology transfer and international best practice dissemination. The literature's focus on individual port success stories obscures the systemic regulatory challenges that limit widespread transformation adoption.

7.7. Future Research Imperatives

Based on these identified gaps and contradictions, future research should prioritize several critical areas. First, comprehensive longitudinal studies should be conducted to examine the long-term performance and integration challenges of simultaneous technology deployment across multiple ports of varying sizes and geographic locations. Second, detailed social impact assessments should be carried out that extend beyond immediate employment effects to encompass community resilience, skills development pathways, and regional economic adaptation strategies.

Third, standardized frameworks should be developed for evaluating the true total cost of ownership for integrated port transformation initiatives, including hidden costs such as cybersecurity infrastructure, continuous training programs, and technology upgrade cycles. Finally, research focusing on smaller and developing-region ports should be conducted to ensure that transformation strategies remain inclusive and globally applicable, rather than limited to technologically advanced facilities.

The current literature provides a solid foundation for understanding individual technology benefits, but falls short of addressing the complex, interconnected challenges of comprehensive port transformation. Addressing these gaps is essential for ensuring that the transition toward smart, sustainable ports delivers on its promises while minimizing unintended social and economic consequences.

8. Conclusions

The seaport sector emits greenhouse gases and uses a lot of energy to operate. Because of their unique characteristics, the problems of reducing greenhouse gases emissions and preventing global warming are not unique to any particular port. Furthermore, there are no worldwide standards for port carbon reduction. This article has discussed several issues, energy-saving techniques, contemporary infrastructure, and the use of emerging technology in modern seaports.

First, a general overview of seaport difficulties was given. Next, standard methods and energy-saving strategies were introduced. New developments in technology, including digitization, offshore power system, electrification, and energy storage system applications, were also covered in detail. It has been noted that using energy storage systems to supply electricity during peak hours is becoming increasingly important.

The review has identified compelling evidence of technological convergence, where the integration of multiple transformation technologies yields multiplicative rather than merely additive benefits. MAS-based energy management systems effectively coordinate renewable energy sources, energy storage systems, and electrified port equipment to achieve optimization levels that are impossible to attain with standalone implementations. The Port of Hamburg's integration of 5G networks with IoT sensors, Barcelona's combination of environmental monitoring with smart energy management, and Antwerp's integration of hydrogen-powered systems with digital technologies exemplify the synergistic potential of comprehensive transformation approaches.

Proper legislative regulations offer a promising means to increase efficiency and reduce the carbon footprint of the port industry, but their practical application is currently limited. In a similar vein, the integration of emerging technologies such as cloud computing, big data, and the Internet of Things into contemporary ports' infrastructure (smart microgrids) can significantly lower greenhouse gas emissions and increase energy efficiency. Furthermore, the presence of energy management systems plays a key role in enhancing the performance and efficiency of both electrical and hybrid power systems. These systems can help to balance electrical supply and demand, especially when dealing with fluctuating

renewable energy sources and consumption on the user side. Improving energy efficiency not only helps to reduce greenhouse gas emissions, but also brings economic benefits.

While maritime ports globally have successfully integrated 4G technologies to optimize operational efficiency and performance metrics, the deployment of fifth-generation (5G) networks represents a more complex implementation challenge characterized by substantial capital requirements and advanced technical integration demands. Although 5G technology offers transformative potential through ultra-low-latency communication and unprecedented data throughput capabilities that could fundamentally revolutionize port operations, current adoption rates remain constrained by economic and infrastructural barriers, particularly in regions with limited financial resources or legacy system dependencies.

Concurrently, the social implications of technological transformation present a nuanced landscape of both challenges and opportunities that extend beyond traditional workforce displacement concerns. The documented emergence of highly skilled technical positions in digital monitoring, renewable energy management, and automated systems operation—as evidenced in leading transformation initiatives at the ports of Hamburg and Rotterdam—demonstrates the potential for strategic workforce evolution that elevates, rather than erodes, employment quality. This transition toward knowledge-intensive roles reflects a broader paradigm shift where technological advancement creates opportunities for professional development and career enhancement, provided that appropriate training frameworks and transition support mechanisms are implemented to facilitate this workforce transformation effectively.

We recommend that appropriate regulations be created and incentives be offered to encourage the procurement of smart technologies linked to increased port energy efficiency. Modern port terminal operations could greatly benefit from the use of ESSs and emerging technologies like IoT to increase energy efficiency. As technological advancements continue, windows of opportunity to maximize the potential for energy efficiency and carbon reduction will eventually come to fruition.

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