FEASIBILITY ANALYSIS FOR TRANSFORMATION OF PORT QASIM INTO A GREEN PORT

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Executive Summary

Ports are vital to global trade and economic growth, handling the majority of the world's cargo and serving as critical hubs for connectivity, employment, and development. At the same time, port operations contribute significantly to environmental degradation through emissions, waste generation, and habitat loss. With growing international commitments to net-zero emissions and sustainable development, ports are increasingly expected to transition toward greener and more resilient operations.

Port Qasim, Pakistan's second-largest port, manages nearly half of the country's maritime trade and plays a central role in the national economy. Despite this importance, it faces major environmental challenges, including outdated equipment, poor waste management, and heavy industrial discharges. Air quality monitoring in 2025 showed a sharp deterioration, with particulate matter levels reaching hazardous levels that exceed safe limits, posing risks to human health, ecosystems, and port efficiency. These issues highlight the urgent need for Port Qasim to adopt a structured strategy for sustainable transformation.

The proposed research seeks to identify the environmental challenges faced by Port Qasim, evaluate the potential of adopting green technologies, and analyze the regulatory frameworks and policy measures required for effective implementation. The study also aims to draw lessons from leading global ports that have successfully integrated renewable energy, smart technologies, and sustainable logistics, and provide recommendations for Port Qasim's green transformation. Using a mixed-methods approach, the research combines qualitative policy reviews and expert interviews with quantitative analysis of emissions, waste, and cargo data, as well as comparative case studies from advanced ports worldwide.

Findings from the best international practices highlight key strategies that Port Qasim can adopt. Integrating renewable energy systems such as solar and wind can significantly cut operational emissions while improving energy security. Electrifying cargo-handling equipment and vehicles would reduce reliance on diesel, improve efficiency, and cut air pollution.

Shore power, or cold ironing, would allow vessels to connect to the grid while at berth, eliminating the need to run auxiliary engines and thereby reducing harmful emissions. Advanced waste and water management facilities, including certified reception systems and waste-to-energy projects, would prevent marine pollution and protect surrounding ecosystems. Digital technologies such as AI, blockchain, and Internet of Things (IoT) systems could transform operations by optimizing scheduling, monitoring emissions in real time, and enhancing supply chain transparency. At the same time, ecological measures such as mangrove restoration, biodiversity monitoring, and coastal greenbelts would build natural resilience and strengthen environmental stewardship.

An evaluation of Port Qasim's current sustainability practices shows uneven progress. While some advances have been made in ecosystem restoration and digitalization, there remain significant gaps in renewable energy adoption, emissions monitoring, ballast water treatment, and compliance with international green certifications. Without a comprehensive Green Port Master Plan, progress will remain fragmented and reactive rather than strategic and forward-looking.

Transforming Port Qasim into a green port would deliver long-term benefits across economic, environmental, and social dimensions. Economically, it would enhance competitiveness, attract sustainable investments, and reduce operational costs. Environmentally, it would lower the port's carbon footprint, reduce pollution, and support fragile coastal ecosystems. Socially, it would improve the health and well-being of port communities while creating new opportunities in renewable energy, logistics, and environmental management.

In summary, Port Qasim is at a critical stage where aligning with global best practices and adopting innovative green technologies can ensure its sustainable future. By implementing renewable energy systems, smart logistics, digital monitoring, and effective waste management, and by strengthening policy alignment and stakeholder collaboration, Port Qasim can evolve into a model green port for the region. This transformation will not only safeguard the environment but also position Pakistan as a competitive and responsible player in global maritime trade.

Chapter 1

Research Proposal

1.1 Problem Statement

Over 80% of the world's cargo is handled by ports, which act as vital commercial hubs that promote regional connectivity, job creation, and economic growth (UNCTAD, 2024). Ports must adopt smart, robust, and environmentally friendly ways to limit environmental degradation as trade soars. Sustainability requires adherence to the International Maritime Organization's (IMO) net-zero targets, UN Sustainable Development Goals, and the MARPOL Annexes [1] [2]. According to UNCTAD's Review of Maritime Transport 2024 Enhancing port efficiency, embracing digitization, and incorporating low-carbon initiatives are essential for long-term resilience[3]. Carbon neutrality, energy efficiency, and climate resilience will be improved by integrating green technology, renewable energy, automation, and AI-driven logistics, establishing ports as significant future-ready economic hubs[4] [5] [6]; The second-largest port in Pakistan, Port Qasim, is vital to the nation's economy, as it handles more than 48.85% (MoMA year book 2022-2023) million metric tons of national cargo, including coal (16%), edible oil (08%), LNG (16%), and containerized cargo (29%) [7] [8]: Zhang *et al.,* 2021). Besides its economic contributions, it also contributes to environmental degradation due to GHG emissions, inapprprioate waste handling, outd ated infrastructure, and industrial zone wastewater discharge.

To improve sustainability, adherence to global frameworks including Pakistan's National Action Plan for Climate Change (Government of Pakistan, 2023), UNCTAD 2024 standards, and MARPOL Annex-VI is crucial. Emissions can be decreased and efficiency increased by switching to renewable energy sources, electric cargo handling equipment, and smart port technology. Setting the standard for sustainable port development, Shanghai Port, the busiest container port in the world, has effectively incorporated green projects including automated logistics and shore power [9] Port Qasim can set a benchmark for sustainable port development by adopting advanced green initiatives similar to Shanghai Port to meet good global practices standards & sustainable port operations.

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[2] https://www.bing.com/search?q=MArpol+annexs+of+IMO+2024&form=ANNTH1&refig=eafd5dbcd4674adfac19ebe38727551d&pc=U531

[3] Trade and Development Report 2024 | UN Trade and Development (UNCTAD)

[4] Abubakar, A. S. (2024). *Adopting Digital Technology to Drive Resource Efficiency in Manufacturing* (Doctoral dissertation).

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[7] Wang, B., & Zhang, L. (2021). Waste reception in Chinese mega ports. *Ocean & Coastal Management, 119*, 45–59.

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Port Qasim can reduce environmental damage, draw attention of Sustainability focused investors, and support global eco-friendly objectives like SDG-7 (Affordable and Clean Energy), SDG-9 (Industry, Innovation, and Infrastructure), SDG-13 (Climate action), and SDG-14 (Life Below Water)

By implementing above practices Operational emissions might be reduced by up to 40% by installing solar and wind power sources, modernizing solid & wastewater management systems, and digitizing logistics[10]. Financial collaborations with organizations such as the World Bank and the Green Climate Fund may also help the port become a regional leader in environmentally friendly port operations. A sustainable port will provide long-term economic and environmental advantages by lowering Pakistan's carbon footprint and increasing its trade competitiveness[11].

1.2 Research Objectives

a. To assess the current environmental challenges faced by Port Qasim and their impact on sustainability.

b. To evaluate effectiveness of adopting green technologies at Port Qasim.

c. To analyze operational, and environmental benefits of transforming Port Qasim into a green port.

d. To examine regulatory frameworks and policy measures that can support green port initiatives in Pakistan.

e. To explore the best global practices in green port development and provide recommendations for Port Qasim's sustainable transformation.

1.3 Research Questions

Primary Question

a. How can Port Qasim adopt sustainable practices to align with global environmental standards & enhance its economic and ecological resilience?

Secondary Questions

a. What are the key environmental challenges faced by Port Qasim, and how do they impact its sustainability efforts?

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[11] Abubakar, Ibrahim Damana, Shekwobagwu Paul Galadima, Abdulmalik M. Mustapha, Yusuf Ndagi Baba, and Araoye Olarinkoye Ajiboye. "Assessment of occupational of health and safety regulations in the Nigerian port environment." (2024).

b. How have global ports like Shanghai implemented green initiatives, and what lessons can Port Qasim learn from them?

c. What financial and technological strategies can Port Qasim employ to transform toward more sustainable and efficient port operations?

1.4 Methodology

This study adopts qualitative and quantitative research approach synthesizing the complementary strengths to yield a understanding of the research problem. By integrating these approaches, the investigation seeks to explain the intricate dynamics inherent in sustainable port development, with a particular emphasis on environmental sustainability and operational efficiency at Port Qasim. The methodology is structured as follows:

1.4.1 Qualitative Analysis

a. Review of government policies, port authority reports, and environmental regulations.

b. Interviews with maritime experts, PQA officials, and sustainability consultants.

1.4.2 Quantitative Analysis

a. Data collection of GHG emissions, solid waste, wastewaters production in Port Qasim jurisdiction.

b. Data collection on PQA's cargo handling capacity, and energy consumption.

1.4.3 Comparative Case Studies

a. Analysis of successful green port initiatives of Shanghai, Singapore, Rotterdam, Khalifa Port, and Port of Colombo.

b. Evaluation of China's and Europe's approaches to sustainable port development.

Chapter 2

Introduction & Literature Review

Ports play essential role in trade globally, managing approximately 80% of global goods trade by quantity[12]. As environmental issues and strict international rules and regulations, the maritime industry is crucially changing its approach to concentrate on developing ports sustainably. This shift is happening because of urgent need to reduce carbon emissions, improve the efficiency of port operations, and implement digital technology in port operations. As a result, ports around the globe are putting more investments in renewable energy, modern technologies, circular economic projects, and ways to adapt to climate change. Their goal is to reduce their environmental impact[13]. New studies show that major ports globally are executing, emission reduction strategies, building green infrastructure, and utilizing AI to improve efficiency with the United Nations' Sustainable Development Goals (SDGs) and the International Maritime Organization's (IMO) emission reduction goals[14] [15].

A significant trend in sustainable port development involves adopting environmentally friendly energy solutions. Ports are under intense pressure to switch to low carbon and renewable energy because shipping is responsible for 2-3% of the world's carbon dioxide emissions[16]. Major ports such as Rotterdam, Los Angeles, and Singapore are managing the way by innovative investments in solar farms, wind energy, and hydrogen powered systems to minimize their use of hydrocarbon fuels. For example, the Port of Rotterdam has built vast wind parks[17]. These don't just power port operations, they also provide electricity into the local grid. In the same way, numerous ports are organizing hydrogen power stations to promote zero emission shipping corridors [18]. Onshore power supply (OPS) technology is new advance idea picking up speed. Basically, it lets ships that are docked in a port plug into the regular Electricity network. This means they don't have to keep their noisy, polluting diesel engines running. It's a huge win because it slashes emissions, making the air in port cities much, much cleaner. Such ports as the Port of Gothenburg are on the edge; even

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[18] Committed to decarbonisation | Global Maritime Forum

there they provide a reason to make ships avail themselves of this electric energy when at the berth[19] [20].

Two examples of alternative energy solutions applied in ports considered to be Practical substitutes are bioenergy and geothermal energy. The Port of Stockholm's clean energy project, which converts organic waste into biofuels for terminal operations, is one example of this. This is a way of offering Alternative energy sources besides minimizing waste. Other than that, the integration of alternative systems to energy management in the port management also requires careful infrastructure development and planning. To make porting services reliable in terms of power supply to the local population and port management, ports are investing in the advanced power grids supply which can organize and distribute clean energy effectively.

Another method through which ports are enhancing energy efficiency besides sustainable energy is through energy efficient lighting systems[21]. An example is the Port of Antwerp, which has installed LED lighting systems all over its buildings, which has minimized the consumption of energy, but the operational transparency remains intact. It is also a good strategy in reducing emissions as well as decreasing the energy cost[22].

Simultaneously, the world is witnessing the transformations of the port management processes due to innovative technologies and technological integration. Examples of IOT systems are Vessel Traffic Service (VTS), sophisticated container management, blockchain, artificial intelligence (AI), and predictive maintenance processes[23]. By adopting AI-based platforms, ports can minimize energy bills, decrease the wait period of vessels, and enhance visibility of the supply chain[24]. The example of this change is the AI-driven congestion control systems in the Port of Singapore which enables to achieve efficiency in turnaround with minimal fuel consumption. Besides improving productivity, automated operations of the terminal with smart cranes also decrease the operating expenses. Besides, blockchain technology is being introduced to digital port

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platforms to increase the security of maritime logistics and streamline documentation processes[25] [26].

The use of digital innovations is not only effective in enhancing operational performance. Also, ports are applying data analytics to enhance sustainable operations and determine environmental effects[27]. An example is that it should do so to implement targeted interventions to reduce the effect of its resource consumption[28], the Port of Antwerp uses deep data analysis to monitor the energy spending and emissions. There is also the development of digital systems that assist the stakeholders like shipping companies, the port authorities, and the regulatory bodies to work together[29]. These platforms enhance coordination and communication by making sure that sustainability goals are aligned across the supply chain[30].

In addition to sustainable energy innovation, green port management is becoming more and more dependent on the framework of the circular economy. In order to minimize environmental degradation, ports are employing more closed-loop recycling processes, green dredging technologies, and waste-to-energy technology system[31]. To attain the 100 percent reuse or recycling of waste generated by ports by 2030, e.g., the Port of Los Angeles introduced the zero-waste initiatives. To minimize the amount of waste and resource use, other ports are exploring innovative strategies, such as the reclaimed water systems and products packaged in compostable materials[32] [33]. Focusing on those industrial ecology projects which enable recovery of energy in the waste streams the Belgian seaports have shown leadership in the embrace of the circular economic model[34]. These projects show that ports could implement more sustainable activities that embrace international environmental objectives instead of actual operational models.

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Another element of circularity initiative in ports is the reuse and recycling of materials of inactive ships[35]. The Port of Rotterdam has opened a ship recycling facility to ensure that there is safe disassembling of vessels, recovery of vessel materials and minimization of waste. Moreover, ports are building their infrastructure based on the ideas of the circular economy[36]. In an example, the Port of Hamburg is showing its commitment towards environmentally friendly building activities by building new buildings using recycling materials and designing buildings in an energy-efficient manner[37].

Climate resilience is another significant problem ports in the world are grappling with. The attention of global port infrastructure is threatened by the rise in sea level and the frequency of extreme weather events[38]. Studies indicate that over half of the large ports may face impacts of coastal flooding by 2050, which will cause huge loss of money[39]. Response measures include ports which are raised up, environmentally friendly breakwaters. The Port of Hamburg has heavily invested in green infrastructure projects and flood resistance structures to ensure uninterrupted business in case of extreme weather conditions[40] [41]. Likewise, to safeguard supply routes through natural disaster-related impacts, port management in Southeast Asia is incorporating climate adaptation approaches within their long term planning systems[42].

Another way of climate resilience strategy is the improvement of the natural environment in which ports are located[43] [44]. As an example, the Port of Rotterdam has embarked on a large-scale nature restoration project in order to conserve the coastal ecosystems and increase biodiversity. The strategy enhances the natural flood and storm defenses besides supporting the local wildlife[45]. Ports are also cooperating across territorial borders to share the best practices in climate change preparedness. The International Association of Ports and Harbors in a bid to enhance the preparation

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[45]VILAIN, BAPTISTE GABRIEL. "Floating Urban Structures as a Response to Rising Waters–A Case Study of Bordeaux."

of member ports to the challenges of climate change [46] has initiated a climate endurance program which provides technical support and information sharing[47].

The introduction of alternative fuels such as hydrogen, ammonia and liquefied natural gas (LNG) is also making the maritime industry shift toward more environmentally friendly shipping pathways[48]. To achieve the stringent emissions requirements of the IMO decarbonization agenda on shipping industries by 2050, ports are undertaking massive investments on low-emission fuel infrastructure[49]. Recent statistics of Global Maritime forum (2025) reveal that over 200 ports across the globe are initiating the construction of green hydrogen fueling stations to receive zero emission vessels[50] [51]. Recent statistics of Global Maritime forum (2025) reveal that over 200 ports across the globe are initiating the construction of green hydrogen fueling stations to receive zero emission vessels.

The switch to green shipping corridors will require a large investment in technology and infrastructure. Ports are also liaising well with shipping companies to establish compatible bunkering facilities and vessels. The collaboration of the Port of Los Angeles with major shipping lines to create hydrogen-powered ships is one of the steps to zero-emission shipping[52]. Moreover, green shipping corridors are to be established on the international level. To make sure that the world achieves the targets of reduction of emissions and at the same time maintain the optimization of world trade, the IMO has initiated projects to encourage the creation of green shipping routes across the world[53].

There should be collaboration among the different stakeholders including port authorities, shipping companies, local communities and policymakers, and also alignment with the world systems like SDGs to ensure sustainable port development[54]. Ports need to apply combined planning processes that prioritize conservation of the environment and foster economic growth through innovative solutions such as smart ecosystem and renewable energy areas[55]. Governments can also contribute a lot in making incentives towards sustainability through regulatory frameworks that encourage investments in clean technologies and improvements in infrastructure. The transition to more environmentally friendly operations in all ports of the world can be

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[52] Ports of Los Angeles and Shanghai Launch 'Green Shipping Corridor' to Reduce Emissions from One of the World's Busiest Trade Routes - Supply Chain Council of European Union | Scceu.org

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accelerated by tax incentives on renewable energy projects or subsidies on electrification projects, e.g.[56].

Education and training programs are also required to equip port workers with knowledge on how to supervise and maintain supportable technologies[57]. To make sure, that the port employees are ready to cope with the transition to green technologies in the productive way, the World Ports Sustainability Association (WPSA) offers training modules, which are focused on sustainable port operations[58]. Ports are also initiating community engagement programs so as to engage locals in environmental projects and to create awareness on the importance of sustainable practices. This plan fosters the feeling of collective responsibility and makes sustainability efforts work in the long term[59].

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Chapter 3

Component of Green Port

Green port transformation refers to the systematic integration of environmentally sustainable practices into port infrastructure, operations, and logistics to mitigate environmental degradation and support climate resilience[60]. Core to this transformation is the shift toward renewable energy integration such as solar, wind, wave, and tidal energy to power port operations. Additionally, the electrification of port equipment and vehicles helps reduce dependence on fossil fuels[61]. Recent studies show that floating solar PV systems installed in port basins can achieve 15% higher efficiency compared to land-based systems due to water surface cooling[62]. Offshore wind farms are also being piloted near port facilities, notably in Northern Europe and China, providing a stable renewable supply directly to smart micro grids that support port electrification needs.

One of the most impactful changes is the adoption of shore power (cold ironing), which enables vessels to plug into the local grid while at berth, significantly cutting emissions from auxiliary engines [63]. A 2023 European Commission report estimates that full implementation of shore power across EU ports could cut 6.5 million tonnes of CO_2 emissions annually and save nearly €1.3 billion in fuel costs[64]. In the Port of Los Angeles, shore power adoption alone led to a 95% reduction in NOx emissions during docking operations. These actions collectively reduce carbon dio xide (CO_2), sulfur oxide (SOx), and nitrogen oxide (NOx) emissions, helping ports comply with IMO and regional environmental regulations[65].

Equally important are advanced waste and water management systems that ensure proper disposal and treatment of ballast water, greywater, bilge, and solid waste, thus reducing marine pollution[66]. Ports such as Rotterdam and Singapore have implemented AI-controlled waste-to-energy conversion units, processing biodegradable waste into biofuels that contribute to local energy grids[67]. Recent innovations also include biomass gasification plants, as piloted in Italian and Turkish ports, which serve as part of circular economy ecosystems, transforming port-generated organic waste into thermal energy[68].

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[67] Artificial Intelligence in the port | Port of Rotterdam

Digitalization and smart port technologies also play a critical role by enabling real-time monitoring, predictive maintenance, automated scheduling, and optimized vessel traffic flow. IoT systems and digital twins simulate port energy usage and environmental performance to reduce emissions and energy waste[69]. In 2024, ports deploying smart energy management systems (SEMS) reported a 15–20% increase in energy efficiency and reduced blackout incidents[70]. Additionally, the integration of blockchain into supply chains enhances transparency and emission tracking from berth to hinterland.

Additional components include green logistics, which promotes the use of electric or hydrogen-powered freight vehicles, inland barges, and rail intramodality, substantially reducing road congestion and emissions[71]. The eco-design of terminals, such as the use of recycled low-carbon concrete, permeable pavements, and vertical green walls, contributes to passive temperature control and biodiversity enhancement[72]. Biodiversity preservation is addressed through the installation of artificial reefs, eco-quay walls, and marine sanctuaries, especially in ecologically sensitive coastal regions[73]. In the Port of Valencia, biodiversity interventions have led to a 30% increase in fish larvae density near green infrastructure zones[74].

Equally critical is stakeholder engagement to support collaborative governance and regulatory compliance[75]. Ports are increasingly structured as renewable energy communities where local businesses, shipping companies, and city authorities co-invest in green infrastructure and share clean energy[76]. These participatory frameworks enhance policy coordination, ensure fair distribution of green gains, and build resilience against climate shocks and economic fluctuations.

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[76] Njikatoufon, A. G. (2024). Renewable energy communities in port supply chains: Governance and innovation (PhD dissertation). University of Genoa.

3.1 Renewable Energy Integration (Solar, Wind, Wave)

The integration of renewable energy sources such as solar, wind, and wave into port operations has become a critical strategy to decarbonize maritime logistics and reduce port emissions[77]. The use of solar power is also prevalent because it is easy to scale and its cost is on the decline and photovoltaic-powered systems are being installed on rooftops of terminals and warehouses. Wind power, especially offshore developments close to coastal ports, is an important part of regional power systems as well as indirectly electrifying ports. Wave energy is still in its infancy, but it is a huge potential to coastal ports that are subjected to the activity of waves[78].

The Port of Los Angeles and Rotterdam are two of the most popular examples when solar and wind systems are hybridized to help ports autonomously produce power to power the facility[79]. The International Transport Forum (2022) states that port CO2 emissions can be reduced by up to 70% by 2040 in case of a broad adoption of renewable energy. Visual comparison of the renewable sources of emission reduction at ports is provided below.

Table 1: Estimated CO_2 Reduction and Implementation Cost for Renewable Energy Technologies at Ports (IRENA, 2023: ITF, 2022)

Energy Source	Average CO_2 Reduction Potential (Ports)	Implementation Cost (USD/kW)	Operational Maturity
Solar	25–30%	$1,200–1,500	High
Wind	35–40%	$1,500–2,000	Medium
Wave	10–15%	$2,500–3,000	Low

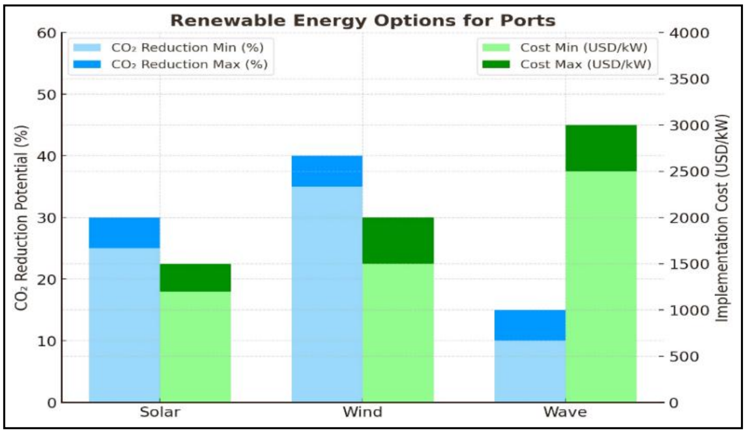

Figure 1: Estimated CO_2 Reduction and Implementation Cost for Renewable Energy Technologies at Ports (IRENA, 2023: ITF, 2022)

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[79] International Renewable Energy Agency (IRENA). (2023). Innovation outlook: Renewable energy solutions for ports. https://www.irena.org/publications/2023/Mar/Innovation-Outlook-Renewable-Energy-Solutions-for-Ports

3.2 Electrification of Port Machinery and Vehicles

Electrification of port machinery and apparatus such as cranes, trucks, and forklifts as well as Automated Guided Vehicles (AGVs) has become a pillar of green port strategies. Electrification will also have a substantial impact on air pollution, such as NOx and PM 2.5, energy efficiency, and a more simplified logistic system due to automation-capable systems[80]. Other ports such as Hamburg and Singapore have gone a long way in eliminating diesel-powered equipment by adopting battery-electric and hydrogen fuel cell technologies[81][82]. According to the data provided by the World Bank (2023), electrified cargo handling equipment can reduce energy consumption by 45% in comparison with traditional machines that use diesel. Also, lifecycle cost of electric cars is lowering as their maintenance and energy expenses reduce, enhancing sustainability in the long run.

Table 2: Emission Reductions and Payback Period for Electrified Port Equipment (UNCTAD, 2023: World Bank, 2023)

Equipment Type	Emission Reduction (%)	Average Cost Increase	Payback Period (Years)
Electric Cranes	40–60%	20%	3–5
Battery Trucks	50–70%	30%	4–6
Hydrogen AGVs	80%	50%	5–7

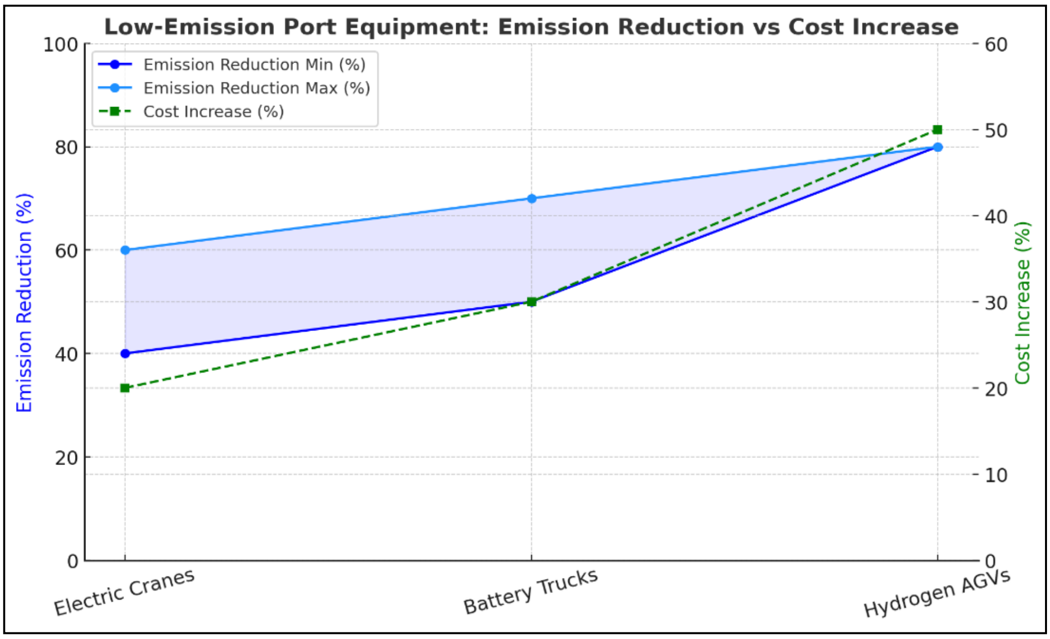

Figure 2: Emission Reductions and Payback Period for Electrified Port Equipment (UNCTAD, 2023: World Bank, 2023.

[80] Savolainen, Ville-Petteri. "TOWARDS GREENER CONTAINER TERMINAL." (2025).
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[82] Maritime Singapore Decarbonisation Efforts

3.3 Shore Power (Cold Ironing) for Vessels

Shore power, sometimes called cold ironing, enables docked vessels to be connected to the electrical grid rather than using diesel engines which has a major effect on emissions of NO_x, SO_2, CO_2, and particulate matter[83]. It is a solution that is becoming more and more widely used in large ports of Long Beach, Hamburg, and Shanghai. Cold ironing will have the environmentally positive effects of creating a less noisy and cleaner port environment and meets the IMO MARPOL Annex VI regulations on air pollution[84] [85]. A study commissioned in 2023 by the Port of Los Angeles found that the ship emissions during berth were decreased by 95 percent through shore power. First, costs of infrastructure are high averaging five to ten million dollars per berth, but the environmental and health benefits are rewarding. Also, the standardization has been hastened through international cooperation through the globally operating power supply partnership Onshore Power Supply Global Partnership[86].

Table 3: Impact of Shore Power Implementation in Selected Ports (IMO, 2023: Port of LA Annual Report, 2023)

Port	Emissions Reduced at Berth	Avg. Cost per Installation (USD)
Los Angeles	95%	$7 million
Rotterdam	85%	$6 million
Busan	90%	$5.5 million

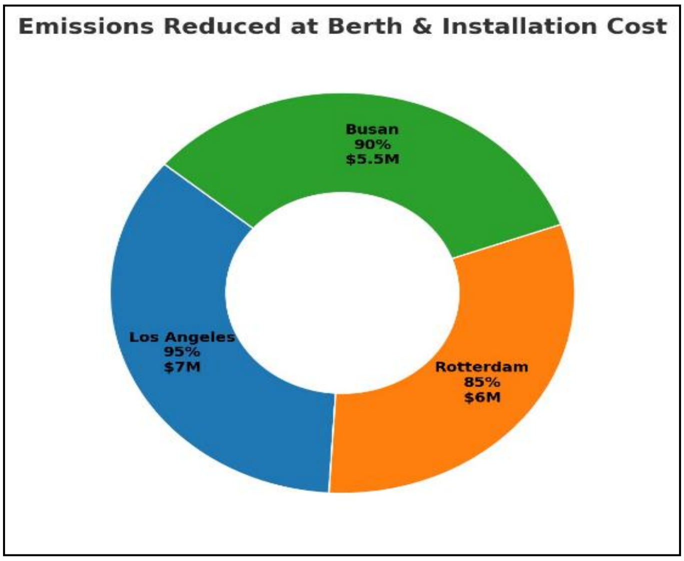

Figure 3: Impact of Shore Power Implementation in Selected Ports (IMO, 2023: Port of LA Annual Report, 2023)

[83] Ennis, Sean F., Constantinos Mammassis, Raphael N. Markellos, John M. Prousalidis, Anastasios Manos, George Loukos, and Neil Tracey. "Regulatory and Business Innovation in Uncharted Waters: Mandatory Cold-Ironing." *Available at SSRN 5287349* (2025).
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[86] Shore Power Technology Assessment at U.S. Ports | US EPA

3.4 Waste and Water Management Systems

Efficient port waste and wastewater management systems help protect marine ecosystems by treating oily bilge water, ballast discharge, and solid waste generated during loading/unloading[87]. Technologies such as oil-water separators, compactors, and biological treatment units are now integrated in green terminal operations[88]. These systems align with EU Directives on port reception facilities and the International Convention for the Prevention of Pollution from Ships (MARPOL)[89].

Ports like Antwerp and Singapore have adopted digital monitoring systems for tracking waste handling compliance, while mobile reception barges are used in constrained terminals. According to UNCTAD (2023), ports with advanced waste infrastructure report a 30–40% reduction in marine pollution incidents.

Table 4: Key Components and Benefits of Waste and Water Management Systems in Ports (European Commission, 2023; UNCTD Port Guidelines, 2023)

Component	Function	Impact
Bilge water treatment	Separates oil from water	Protects marine life
Digital waste tracking	Ensures regulatory compliance	Reduces illegal discharges
Compactor-based segregation	Efficient solid waste management	Cuts landfill disposal by 60%

3.5 Green Logistics and Sustainable Hinterland Connections

Green logistics focuses on decarbonizing freight transport by enhancing modal shifts to rail and inland waterways, using electric trucks, and integrating renewable-powered intermodal hubs[90]. Ports like Antwerp and Hamburg use inland barges and electric cargo trains to cut road congestion and emissions. According to the OECD (2022), shifting 30% of freight to rail or waterway reduces CO_2 by 25% per ton-km, additionally, green logistics incorporates real-time route optimization, green warehousing, and smart customs clearance to reduce environmental impact. EU's “Green Corridors” initiative supports transnational hinterland sustainability[91].

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[87] MICKIENE, Rima, Cătălin POPA, and Dinu ATODIRESEI. "MARINE ENVIRONMENT ISSUES IN PORT OPERATIONS."
[88] Erfani, Hadi, Nithar Ranjan Madhu, Sajjad Khodayari, Mohammad Amir Qureshi, Swetanshu, Pratichi Singh, and Sapana Jadoun. "Separation and removal of oil from water/wastewater in the oil industry: a review." *Environmental Technology Reviews* 13, no. 1 (2024): 325-343.
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[90] Prause, Gunnar. "Sustainable development of logistics clusters in green transport corridors." *Journal of Security and Sustainability Issues* 4, no. 1 (2014): 59-68.
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Table 5: Comparison of Emissions and Energy Efficiency across Hinterland Transport Modes (EU-Commission, 2023: Organization for Economic Co-operation and Development, 2022

Mode	CO_2 Emissions (g/ton-km)	Energy Efficiency (MJ/ton-km)
Road (Diesel Truck)	62	2.1
Rail (Electric Train)	22	0.8
Inland Barge	30	1.1

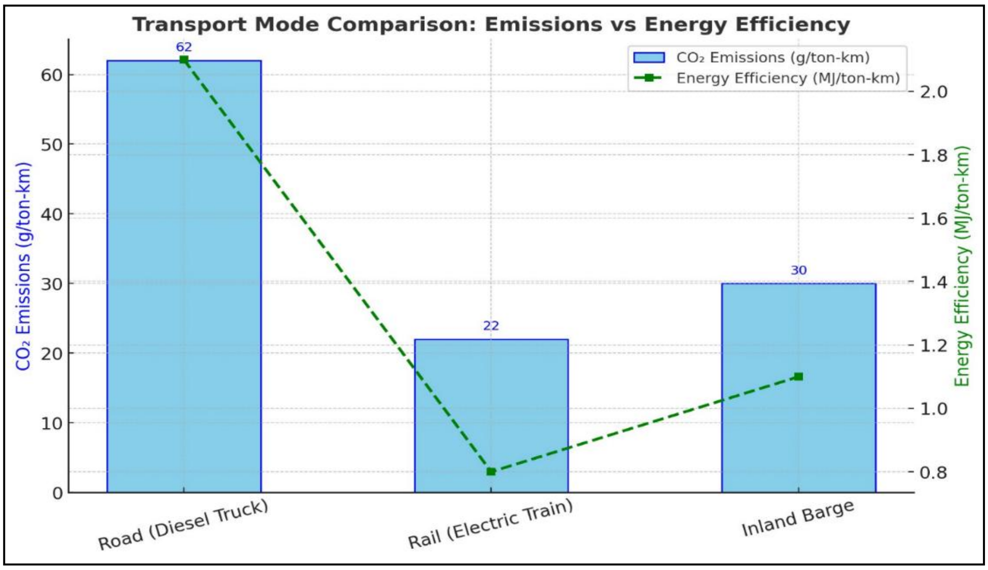


Figure 4: Comparison of Emissions and Energy Efficiency across Hinterland Transport Modes (EU-Commission, 2023: Organization for Economic Co-operation

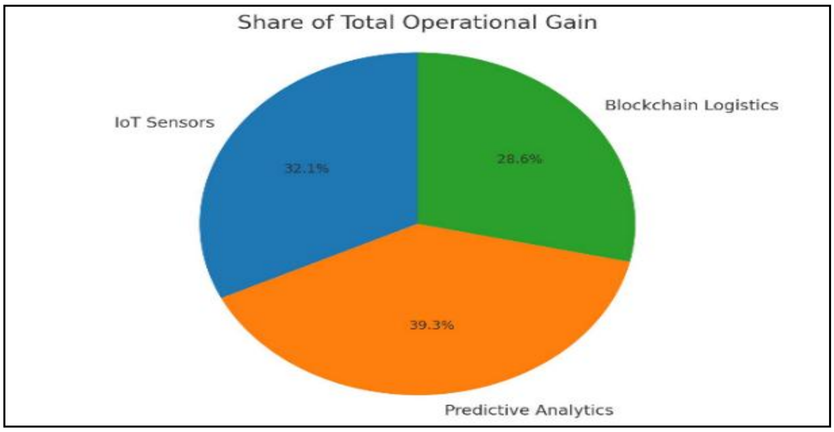
3.6 Smart Port Technologies and Digital Monitoring

Smart ports deploy AI, IoT, and blockchain to automate and monitor operations, enabling predictive maintenance, real-time emissions tracking, and improved energy efficiency. Systems like Digital Twin technology and Port Community systems (PCS) create a virtual model of port infrastructure for remote management and simulation-based planning. Ports such as Singapore and Rotterdam are global leaders in implementing smart solutions[92]. Digital sensors can monitor crane energy usage, predict equipment failure, and even optimize ship berth to reduce idling time. This digitalization contributes up to 20% energy savings and significant carbon footprint reduction. The chart below shows the benefits of digital integration.

Table 6: Operational and Environmental Benefits of Smart Port Technologies (World Economic Forum, 2023)

Technology	Operational Gain (%)	Emissions Reduction (%)
IoT Sensors	+18% efficiency	-12% CO_2 emissions
Predictive Analytics	+22% uptime	-15% maintenance waste
Blockchain Logistics	+16% cargo throughput	-10% fraud/error rates

[92] Annual Report 2023-2024 | World Economic Forum



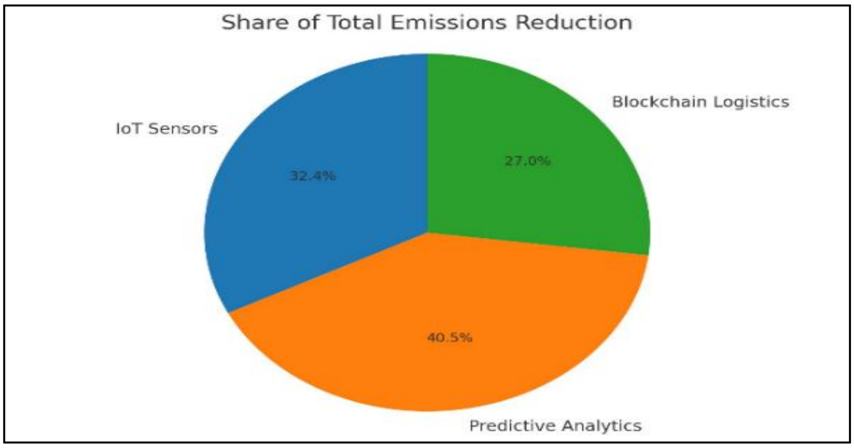


Figure 5: Operational and Environmental Benefits of Smart Port Technologies (World Economic Forum, 2023)

3.7 Biodiversity Protection and Habitat Conservation

Port development often threatens surrounding marine and terrestrial ecosystems. Biodiversity protection involves creating ecological buffer zones, restoring mangroves or wetlands, and conducting Environmental Impact Assessments (EIAs). Leading ports, like Singapore and Brisbane, have introduced eco-engineered seawalls, fish habitat modules, and sea grass transplantation to offset development impact[93]. Additionally, ports are collaborating with environmental NGOs and academic institutions for ongoing biodiversity monitoring and carbon sequestration assessments. Port of Seattle, for instance, reports a 60% increase in near shore biodiversity after installing bio-habitat piers. This helps meet both sustainability goals and stakeholder expectations[94].

93 Marine Stewardship Council. (2022). Port biodiversity programs and marine conservation. https://www.msc.org

94 Satır, Tanzer, and Neslihan Doğan-Sağlamtimur. "The protection of marine aquatic life: Green Port (EcoPort) model inspired by Green Port concept in selected ports from Turkey, Europe and the USA." *Periodicals of Engineering and Natural Sciences* 6, no. 1 (2018): 120-129.

Table 7: Sustainable Infrastructure Features in Green Terminal Design (World Bank, 2023); Port of Valencia, 2023).

Feature	Energy Savings (%)	CAPEX Increase	Typical ROI Period
Green Roofs & Passive Design	25–35%	10–15%	6–8 years
LED & Smart Lighting	40–60%	5–10%	3–5 years
HVAC Upgrades	20–30%	15%	4–6 years

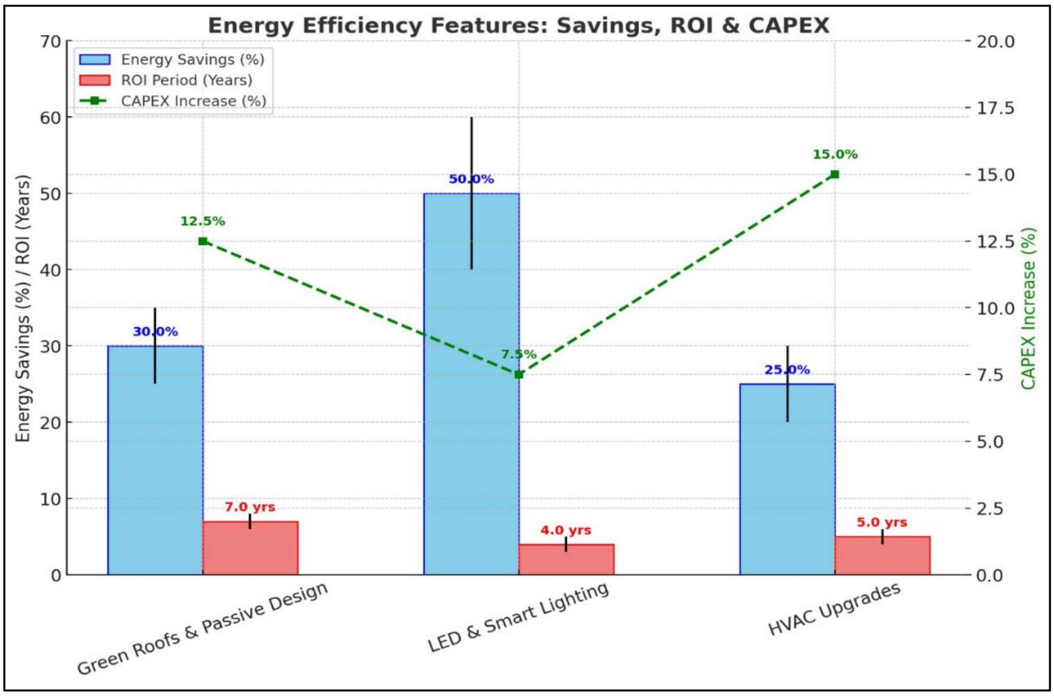


Figure 6: Sustainable Infrastructure Features in Green Terminal Design (World Bank, 2023); Port of Valencia, 2023)

3.8 Policy Frameworks and Environmental Regulations

Environmental sustainability in ports is governed by a web of international, regional, and national regulations. MARPOL Annexes, the EU Green Deal, and national emission control laws all guide green port practices. The IMO's 2023 revision of its greenhouse gas strategy includes net-zero shipping targets by 2050, influencing port authorities to decarbonize port operations and infrastructure. At a regional level, the EU's fit for 55 package mandates ports to provide shore power and monitor ship emissions under the EU Emissions Trading Scheme. These regulatory frameworks have catalyzed investments in green energy, cold ironing, and carbon footprint assessments[95].

[95] Ogola, Daniel Bekesuomowei, Laureta Yinlayefa Seifigha, Ifegha David Ogonoye, Blessing Uzoma, Andrew Abeku, and Famous Denhinbofa Egelu. "POLICY FRAMEWORK FOR BUILDING A GREEN PORT IN WARRI SEAPORT, NIGERIA." *INTERNATIONAL JOURNAL OF MARITIME AND INTERDISCIPLINARY REASEARCH (IJMIR)* 7, no. 3 (2025): 1-16.

Table 8: Eco-Engineering and Biodiversity Enhancement Measures in Ports[96].

Intervention Type	Ecological Impact	Cost Range (USD/m²)
Mangrove Restoration	+25% fish biomass	$20–50
Eco-Engineered Sea Walls	+30% invertebrate colonization	$60–80
Artificial Reefs & Modules	+40% biodiversity near port edge	$100–120

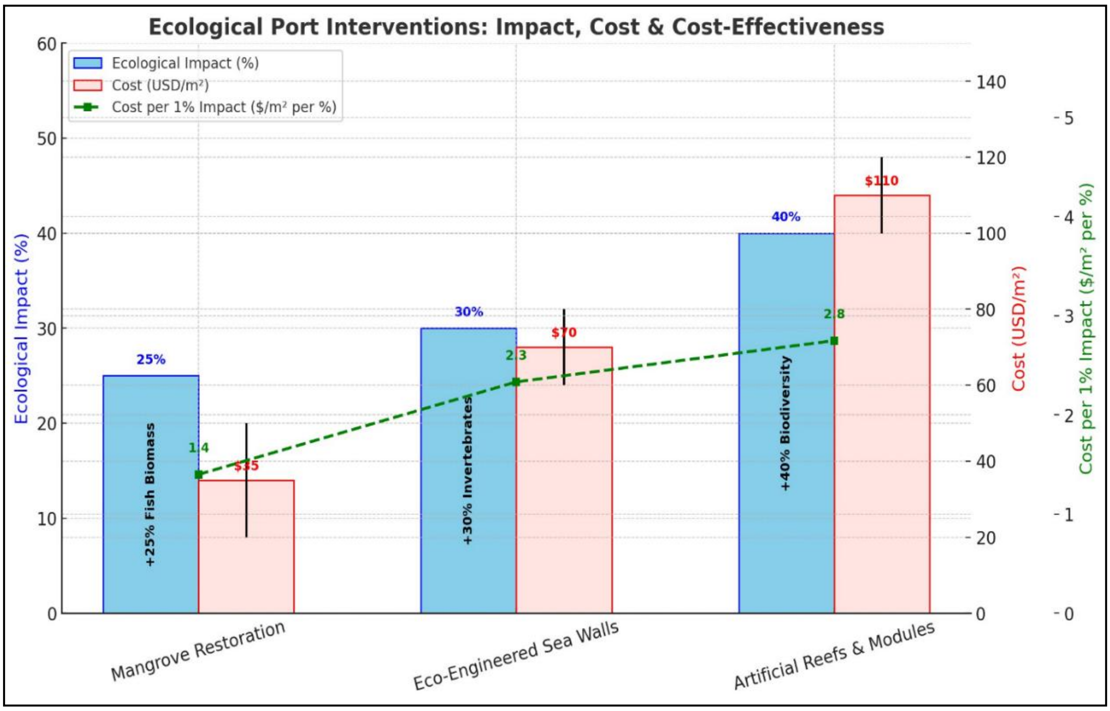


Figure 7: Eco-Engineering and Biodiversity Enhancement Measures in Ports

3.9 Stakeholder Collaboration and Capacity Building

Sustainable port transformation demands multi-stakeholder collaboration among port authorities, terminal operators, shipping lines, regulators, and civil society[97]. Collaborative platforms such as the World Ports Climate Action Program (WPCAP) and Clean Marine Fuels Alliance bring together actors to exchange technology, align policies, and fund green pilot projects[98] [99] [100]. Building capacity through training, green certification programs, and digital up-skilling ensures that personnel can manage new technologies and sustainability mandates effectively[101]. As an example, the Port of Gothenburg educates employees on the ISO 14001 and eco-efficiency management. Studies have

[96] Port of Seattle. (2023). Environmental dashboard and habitat enhancement projects. https://www.portseattle.org

[97] Satta, Giovanni, Francesco Vitellaro, Abdel Ganir Njikatoufon, and Marcello Risitano. "Green strategies in ports: a stakeholder management perspective." *Maritime Economics & Logistics* 27, no. 1 (2025): 96-122.

[98] Loza, Pedro, and Fernando Veloso-Gomes. "Literature review on incorporating climate change adaptation measures in the design of new ports and other maritime projects." *Sustainability* 15, no. 5 (2023): 4569.

[99] World-Ports-Climate-Action-Program-v1.0-final-A3-additional-signatures-20190403.pdf

[100] WPCAP Positioning Statement - 2023 and beyond.pdf

[101] Fonseca, Liliana, Rebecca Baugh, and Hannah Corbett. "Future-proofing the Regional Workforce: Policy and Practice in Low-carbon Skills Development." (2025).

indicated that collaborative governance can be used to fast-track project delivery by 30% and cut on compliance costs[102][103].

Table 9: Environmental Policies and Their Areas of Impact on Port Sustainability (IMO, 2023, EU Commission, 2023)

Regulation	Impact Area	Enforced By
IMO GHG Strategy 2023	CO_2, CH_4 emissions	International
EU Fit for 55 (Fuel EU Maritime)	Shore power, ETS	European Union
MARPOL Annex V	Waste & discharge control	Global (IMO)

[102] Osifo, Emmanuella Osagioduwa. "INTEGRATING COMPLIANCE AND COST CONTROL IN PUBLIC INFRASTRUCTURE AND AFFORDABLE HOUSING CONSTRUCTION CONTRACT MANAGEMENT."
[103] Huckstep, Sam, and Helen Dempster. "Meeting Skill Needs for the Global Green Transition." (2024).

Chapter 4

International Frameworks and Standards (MARPOL, SDGs, IMO NetZero Targets, UNEP)

The maritime industry contributes a lot to the global trade since over 80 percent of all the goods are shipped through the sea. Its impacts on the environment remain rather problematic, however, as it leads to the degradation of the ecosystem, greenhouse gas (GHG) emissions, and pollution of the ocean. Internationalization structures have become very instrumental in steering the process of sustainable maritime operations as the issue of environmental sustainability continues to be significant to the global population. The frameworks, which are important to develop green or sustainable ports, include the International Maritime Organization (IMO) Net-Zero Targets, the United Nations Sustainable Development Goals (UNSDGs), and the International Convention for the Prevention of Pollution of Ships (MARPOL). The aim of these ports is to enhance cost efficiency, minimize their environmental footprint, and provide long-term environmental and social benefits. This extended first copy discusses these structures, their role in the development of green ports and how they can be useful to the maritime stakeholders.

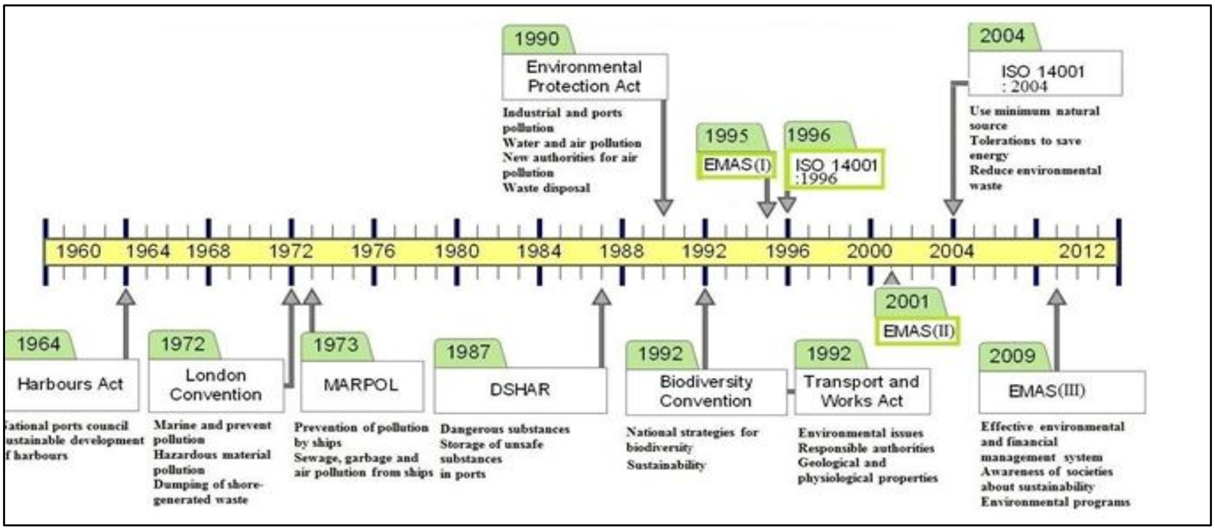


Figure 8: The historical path of green port legislation (Canbulat, 2014)

4.1 MARPOL: Preventing Marine Pollution

The International Convention on Prevention of Ship-related Marine Pollution (MARPOL) is one of the key international mechanisms used to fight against ship-based marine pollution. It has six annexes that deal with specific pollutants:

4.1.1 MARPOL ANNEX I

It is concerned with the prevention of pollution by ship oil. It sets specifications on how much oil is to be emitted to the ocean in the course of scheduled and impromptu operations. The necessity of oily water separators, oil discharge monitoring apparatus, and specific operating procedures aimed at preventing the occurrence of oil spills are important. To reduce the risk of pollution, Annex I similarly demands that oil tankers comply with high standards of design, including the use of double hulls, and keeping of an Oil Record Book.

4.1.2 MARPOL Annex II

It regulates the Noxious Liquid substances (NLS) pollution control that is carried out by mass. It outlines the way chemicals that are considered harmful to marine life should be handled, discharged, and held in safe ways. Every chemical tanker should comply with strict provisions contained in Annex II, including maintenance of Cargo Record Book, restrictions of discharges, and tank washing. Depending on their level of risk, the issues are classified into four categories of pollution (X, Y, Z, and OS) whereby the first category (Category X) is the most hazardous.

4.1.3 MARPOL Annex III

Guidelines on the prevention of pollution of packaged hazardous materials are contained in MARPOL Annex III. It includes materials that are shipped in portable tanks, containers and other types of packaging. To mitigate the risks caused to marine environments in relation to the occurrence of spills or accidents, Annex III will require these substances to be appropriately labeled, recorded, stashed and operated. It has provisions to safeguard the environment and the crew against the dangers involved in packaged dangerous good and emergency response information provisions.

4.1.4 MARPOL Annex IV

It concerns itself with ship sewage prevention. To reduce the environmental effects of sewage on marine environments, it establishes regulations on how it operates by collecting, treating and discharging sewage. Under certain conditions, Annex IV requires ships to install sewage remedies plants, contain sewage onboard or to discharge it offshore at defined distances. This annex also involves using a Sewage Pollution Prevention Certificate in order to ensure compliance. With such measures, the coastal and marine ecosystems are protected against harmful pathogens and pollutants caused by untreated sewage.

4.1.5 MARPOL Annex V

It sets regulations that prevent environmental pollution by ship waste. It prohibits the discharge of most of the waste and products to the ocean such as plastics which are also forbidden. Other types of waste can only be disposed of in specific conditions and at specific distances to shore, including food waste, paper, and metal. Ships are required to have Garbage Record Book and come up with Garbage Management Plan among other strict garbage management procedures. Due to Annex V, the adverse impacts of marine debris on wildlife and the ocean ecosystems are reduced.

4.1.6 MARPOL Annex VI

Its primary objective is to prevent air pollution from ships. It reduces ODS and is harmful to the emission of sulfur oxides (SOx), nitrogen oxides (NOx) and other toxic substances. Annex VI requires low-sulfur fuel, energy-depleting measures such as the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI). It has also developed ECAs that have stricter emission regulations, reducing the adverse impacts of air pollution of shipping on the environment and human health.

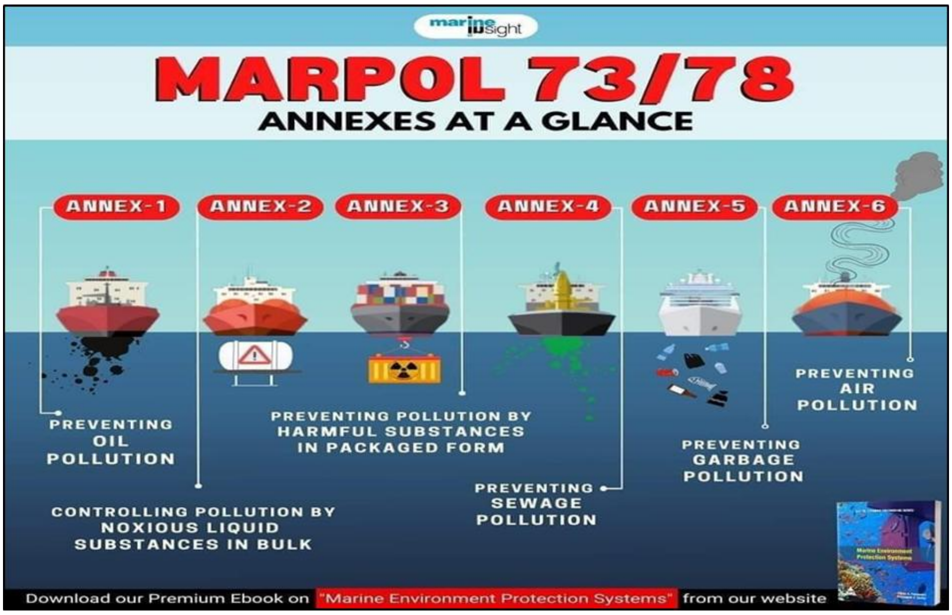


Figure 9: Understanding MARPOL Annexes 73/78

Among them, the Annex VI, about air pollution is core to the establishment of green ports. Annex VI provides strict regulation of the emissions of sulfur oxide (SOx) and nitrogen oxide (NOx) into the atmosphere by ships with the aim of enhancing air quality around ports and coasts. Emission Control Areas (ECAs) are primary ingredient of this strategy and involve stricter limits on the quantity of sulfur in fuel in specific regions. Having achieved up to 90 percent reduction in certain areas such as the North Sea and the Baltic Sea, these ECAs have been successful in ensuring that SOx emissions are reduced drastically. Moreover, reducing the amount of sulfur in fuel to 0.5% on a global scale, new global sulfur boundaries which became active in January 2020 also promote green port initiatives.

The introduction of Shore Power and Low-Sulfur Fuel Requirements are two important initiatives that are undertaken in ports throughout the world. To illustrate, the Mediterranean Sea Sulfur ECA, which would become effective in May 2025, will reinforce further actions of MARPOL to reduce the degradation of the air. Further, under MARPOL, shi ps are required to possess Garbage Management Plans (GMPs) and Shipboard Oil Pollution Emergency Plans (SOPEPs), which is maintained by port reception facilities which are supposed to manage ship waste. To comply with MARPOL requirements and ensure that vessels are adhering to the established pollution requirements, ports have to invest in such reception facilities and monitoring systems.

4.2 IMO Net-Zero Targets: Decarbonizing Maritime Activities

The Net-Zero Targets of the IMO are part of the international initiative in terms of the minimization of the carbon footprint of the maritime sector. The IMO has established a goal to have net-zero GHG emissions of international shipping by 2050. This goal belongs to the IMO First Strategy on GHG Reduction which was approved in 2018 and updated in 2023.

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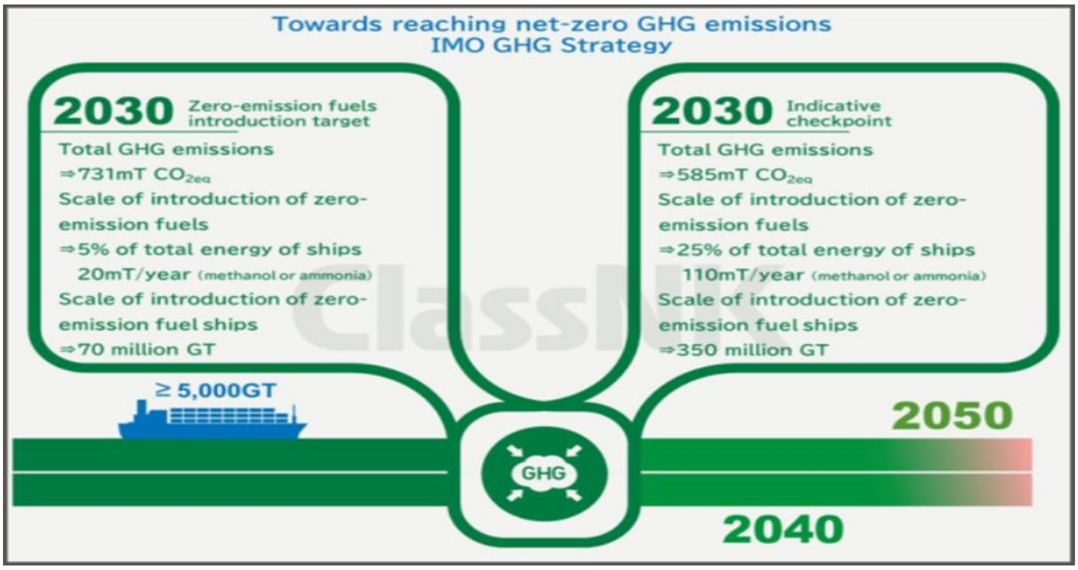

Figure 10: IMO GHG strategy source Class NK

The IMO has also outlined several key measures for achieving this ambitious goal:

Fuel Transition: The decarbonization of shipping industry depends on transition to low-carbon and zero-carbon fuels, such as hydrogen, ammonia and biofuels. The use of such potential fuels as ammonia and hydrogen as fuels in long haul shipping is also discussed as a possible way of reducing the GHG emissions significantly, when fuel cells or combustion engines are powered.

Economic Mechanisms: The IMO favours the idea of carbon pricing and other economic instruments to encourage the emission reduction throughout the maritime sector. One of the proposed strategies is the

International Carbon Pricing Mechanism (ICPM), which gives the ports the authority to charge ships according to their emissions.

Technological Innovation: Ship design, power system, and practices inventions are anticipated to contribute towards the meeting of the net zero objectives of the IMO. Reducing fuel consumption and emissions, new technologies, e.g., wind-energy propulsion, hull designs with reduced energy use, and renewable energy solutions are becoming increasingly popular.

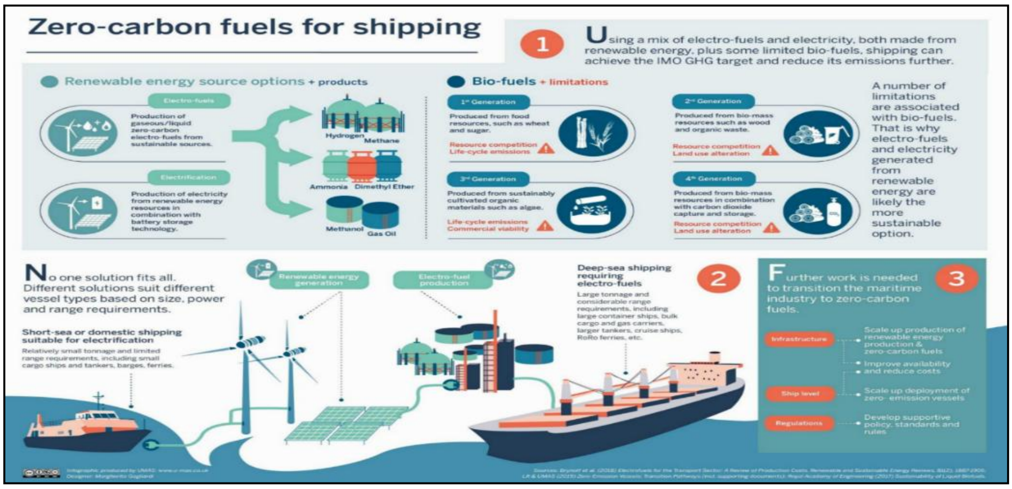

Figure 11: Achieving Shipping's Decarbonization by 2050

Also, the IMO is developing a new Chapter 5 under the MARPOL Annex VI, which will entail environmental compliance conditions of decarbonization and mitigation plans of emissions. It is believed that these steps will be completed by 2025, and hopefully, offer additional recommendations to port operators and shipping companies on how to achieve a net-zero. These targets in the context of green ports point out the necessity of ports to invest in infrastructure that facilitates the adoption of sustainable fuels, including ammonia and hydrogen bunkering supply ports.

4.3 Green Ports and Shore Power Infrastructure

Green ports can use the Execution of shore power technology as one of the main steps to reduce emissions of vessels during the time of berth. Power of the shore batteries enables the ships to switch off their engines but get connected to power supplied in the port to eliminate air pollution generated by combusting fuel during docking. Shore power is already operational in ports such as Long Beach (USA) and Rotterdam (Netherlands) and a lot of ports are in the process of providing the necessary infrastructure to enable shore power to work. Moreover, green ports are also applying resource efficient innovations to reduce energy consumption and improve port operations. The application of big data, the IOT, and automated technologies is part of Smart port technologies which reduce energy waste, enhance traffic flow, and support real-time emission tracking. These technologies will be able to help ports to manage energy resources in a more efficient way, minimizing their carbon footprint and maximizing the effectiveness of their operations.

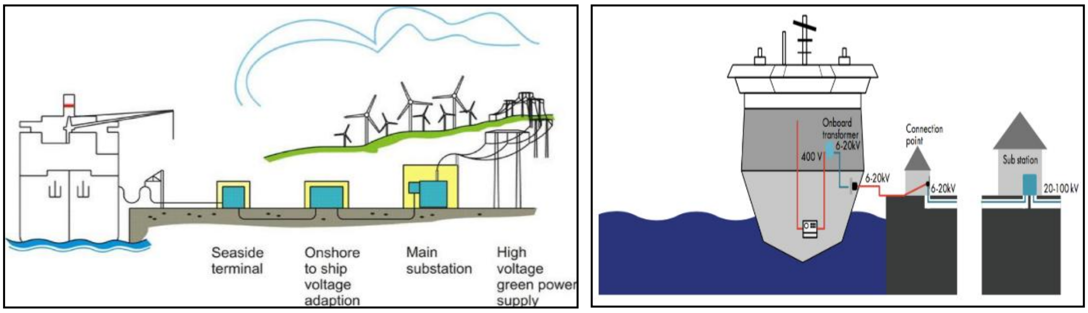

Figure 12: Onshore Power Infrastructure

4.4 SGD's and role of ports

Ports are significant to the global quest to achieve the SDGs and they are one of the most significant crossroads of trade and technology as well as sustainability. Ports have a special responsibility in terms of environmental, social and economic layers as they become the entry-gates to economies and influence the coastal ecosystem. Reducing air and water pollution (SDGs 3 and 6), adopting energy sources and digital technologies (SDGs 7 and 9) are gradually becoming a part of the core processes of ports. They are also used in creating urban resiliency and fair economic development (SDGs 8 and 11), and in the conservation of marine and terrestrial ecosystems (SDGs 14 and 15).

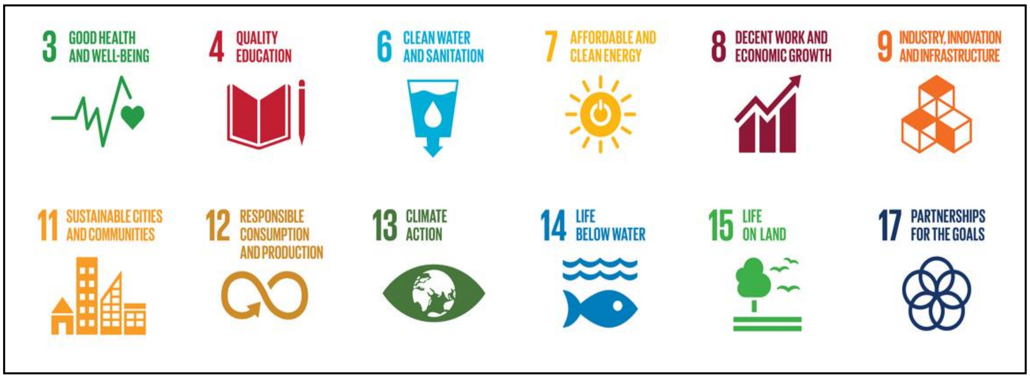

Figure 13: Green Ports and role of SDG's

Current port policies make a focus on circular economy methods, green logistics, and partnerships (SDGs 12 and 17), and port is not only a point of transportation but a force of sustainable development. Ports are also emerging as active participants in carrying out the 2030 Agenda of Sustainable Development through innovation, collaboration, and environmental responsibility.

Sustainable Development Goals (SDGs), which have realized their importance in achieving global sustainability goals. On the example of SDG 3: Good Health and Well-Being, when air and noise pollution at port facilities is decreased, it will positively influence the well-being of the workers and the community around them. It is also common practice to carry out routine health checks by many ports and invest in occupational health to protect their workers.

SDG 4 Quality Education, ports offer perpetual education, and technical training to their workers so that they have knowledge of digital systems, environmental supervision, and automation. Such efforts will ensure that the labor force is competent to embrace sustainable technology and practices. Ports can contribute to SDG 6: Clean Water and Sanitation, whereby advanced systems of wastewater treatment can be installed, stormwater runoff can be controlled, and toxins can be prevented from being released into the surrounding water bodies.

SDG 7 Affordable and Clean Energy, a number of ports are converting to renewable energy sources such as solar energy and wind power and constructing cold ironing machines to reduce the amount of emission at the dockyard. Such renewable energy programmes enhance energy conservation and environmental sustainability. Under SDG 8: Decent Work and Economic Growth, ports remain a vital place of employment and economic activity, and the focus on equitable labor standards, open hiring approval, and healthy working environments is particularly relevant to changing the port functions after the advent of technologies.

SDG 9 Industry, Innovation, and Infrastructure through the adoption of smart port systems and digital logistics platforms and AI-based monitoring. These improvements modernize the infrastructure and reduce the environmental impact of the port activities. At the same time, ports contribute to SDG 11: Sustainable Cities and Communities by applying urban planning interventions, including management of congestion, access to multimodal transportation, and green buffer areas to reduce visual and noise pollution.

Circular economy models, minimizing trash, and responsible buying approaches are also among SDG 12 Principles of responsibility under consumption and production at ports. Top ports are formulating decarbonization roadmaps, alternative fuels, including LNG or hydrogen, and electrifying port equipment to make a substantial reduction in greenhouse gas emissions to meet SDG 13: Climate Action.

In a bid to protect marine ecosystems, ports can play a role in SDG 14: Life Below Water by installing ballast water treatment systems, limiting the emission of oil and plastic material, and safeguarding threatened marine ecosystems. Likewise, SDG 15: Life on Land is reflected in such measures as reforestation, restoration of land close to port areas, and safeguarding the local biodiversity against the impact of industrial activity. Lastly, to ensure the realization of these sustainability goals, there should be collaboration as highlighted in SDG 17: Partnerships for the Goals. Ports are joining forces with governments, industry players, research institutions and NGOs to hasten green transformation. They share best practices, standardize sustainability, and report on sustainable progress together through such global programs as the World Ports Sustainability Program.

Chapter 5

Environmental Challenges in Port Operations

Sophisticated environmental problems are threatening ecological soundness, as well as financial efficiency in port operations worldwide[104]. However, ports pose severe environmental threats despite the fact that they spur economic growth[105]. The sudden growth of port activities, maritime traffic, and industrialization cause air pollution, contamination of water, destruction of habitats, waste disposal issues, and consequences of climate change[106].

Consequently, ports globally are experiencing more and more pressure applied on them by governments to become sustainable and reduce their environmental footprint[107]. It is stated that in recent research, most ports, especially in developing countries, remain behind with respect to investments in green infrastructure and sustainability in operations[108]. Although intelligent technologies and Environmental, Social, and Governance (ESG) models have become the key to reducing carbon footprints[109]. Also, systemic innovation in the management of waste, energy consumption, and partnership with the stakeholders is needed as ports transition to circular economy schemes encouraged by the policies of the European Green Deal[110] [111] [112] [113].

[104] Galvão, C. B., Robles, L. T., & Cutrim, S. S. (2025). Best practices in ESG: a benchmarking for Brazilian seaports sustainability journey. *Journal of Shipping and Trade*.
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[107] Delfin-Ortega, O. V. (2025). Technological gaps and sustainability in maritime transportation (2000–2023): An analysis using the SFA-based metafrontier approach. *Research Square*.
[108] Ali, S. S. S., Abd Razak, M. H., & Shukri, M. S. B. I. N. (2024). Magnitudes of carbon footprint in Port Klang towards Net Zero Port 2050 in Malaysia. *Journal of Engineering Science and Technology*.

[110] Andriamanantena, A. N., Mbena, J. Y., & Viala, C. (2025). Enabling circular economy transitions in ports: The role of innovation ecosystems in North Sea Port. *Journal of Environmental Management*.
[111] Georgeta, I. L. I. E. "The Impact of Global Environmental Objectives on Trade in Services." *EU Economy And Its Main Priorities* (2024).
[112] Sadiq, M., Su, C. L., Ali, Z., & Micallef, A. (2025). Roadmap to greener seaports: A bibliographic analysis. IEEE Transactions.
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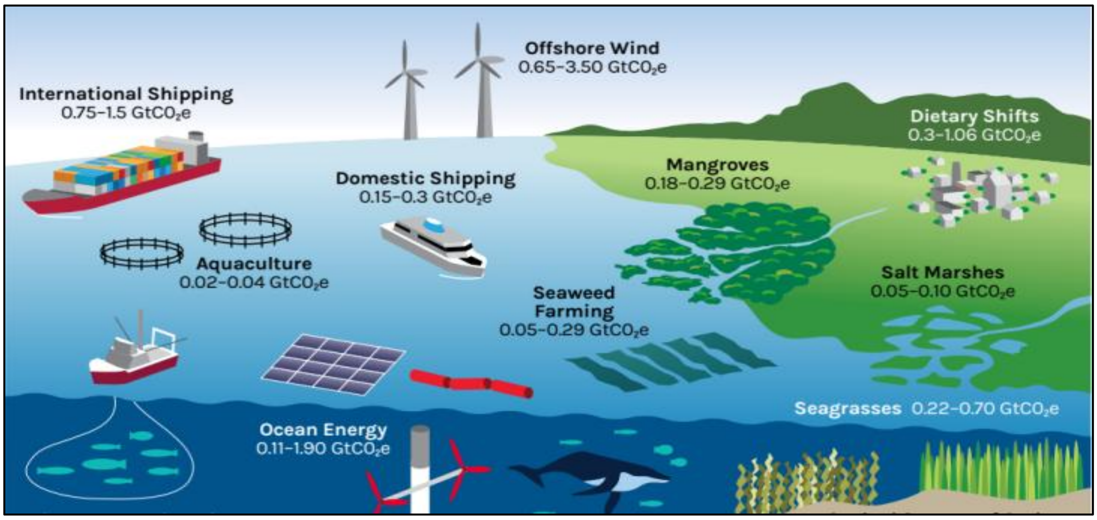

Figure 14: Port Environmental Impact: Source Global Maritime Hub

5.1 Air Pollution and Greenhouse Gas Emissions

One of the most pressing environmental challenges in port operations is air pollution caused by emissions from ships, cargo-handling equipment, and trucks[114]. Shipping contributes to approximately 2-3 percent of the total carbon dioxide emissions in the world, and in large port cities, vessel activities result in increased level of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) due to vessel operations[115] [116]. Also, the use of diesel powered port equipment leads to poor air quality that affects the health of the local communities. The ports all over the world are fighting this by implementing shore power (cold ironing), LNG fueling stations, and electrified cargo-handling equipment to reduce emissions.[117]. As an example, the Port of Rotterdam has made an investment in hydrogen-related fuel systems and onshore power supply to decrease its carbon footprint[118] [119]

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[114] Sun, Ruikai, Wessam Abouarghoub, Emrah Demir, and Andrew Potter. "A comprehensive analysis of strategies for reducing GHG emissions in maritime ports." *Marine Policy* 171 (2025): 106455.
[115] Sun, Ruikai, Wessam Abouarghoub, Emrah Demir, and Andrew Potter. "A comprehensive analysis of strategies for reducing GHG emissions in maritime ports." *Marine Policy* 171 (2025): 106455.
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[118] Crippa, Monica, Diego Guizzardi, Federico Pagani, Marcello Schiavina, Michele Melchiorri, Enrico Pisoni, Francesco Graziosi et al. "Insights into the spatial distribution of global, national, and subnational greenhouse gas emissions in the Emissions Database for Global Atmospheric Research (EDGAR v8. 0)." *Earth System Science Data* 16, no. 6 (2024): 2811-2830.
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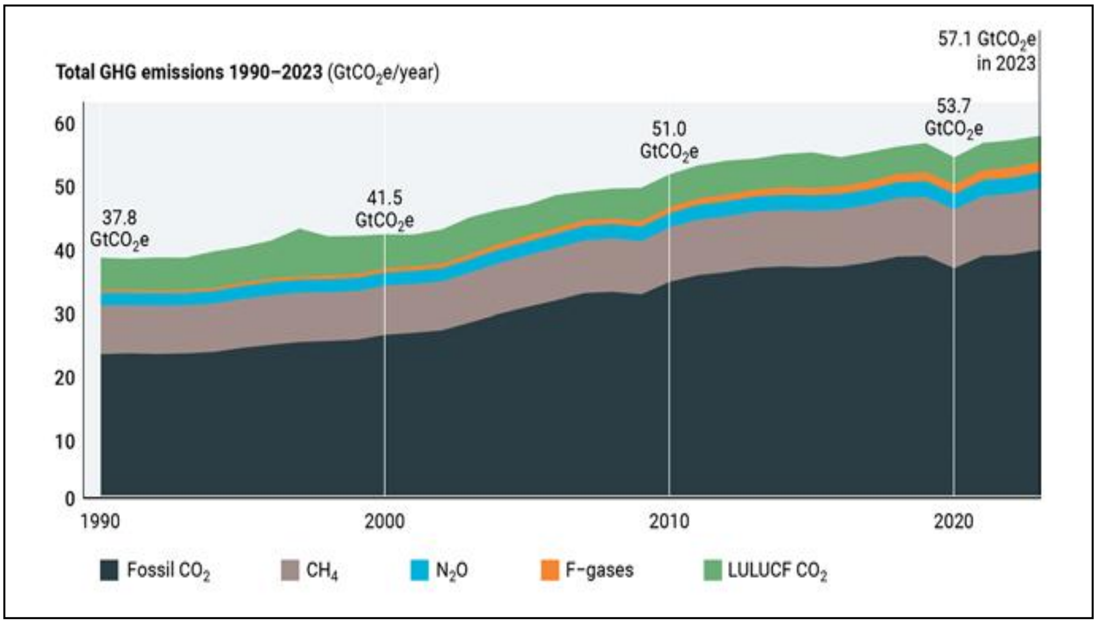

Figure 15: Total net anthropogenic GHG emissions 1990-2023

5.2 Water Pollution and Marine Ecosystem Degradation

The port activities that include oil spills, discharge of ballast water, and industrial runoffs are major factors that water pollution and loss of marine biodiversity[120]. Numerous ships empty the ballast water which has invasive species, which interferes with the local ecosystem and poses a threat to the native marine life. Besides, the chemical spills, dredging, and dumping of wastewater of port industries deteriorate the quality of water and destroy aquatic life[121]. In order to deal with this, ports are moving towards environmentally friendly dredging methods, ballast water treatment equipment and sophisticated spill-response devices. New policies such as the Ballast Water Management Convention by the IMO require a tighter regulation of the release of ballast water and this has ensured the safety of the marine ecosystems.

[120] Putri, Maulin Masyito, Prita Meilanitasari, Nindya Putri Prasodjo, and Dwi Sekar Arumjani. "Optimizing Ship Berthing Allocation Strategies at a Dry Bulk Fertilizer Terminal: A Simulation Approach Considering Material Handling Equipment Availability." *Jurnal Teknik Industri: Jurnal Keilmuan dan Aplikasi Teknik Industri* 27, no. 1 (2025): 77-92.

[121] Deng, Chenning, Yi Qian, Xiaocong Song, Minghui Xie, Huabo Duan, Peng Shen, and Qi Qiao. "Are electric vehicles really the optimal option for the transportation sector in China to approach pollution reduction and carbon neutrality goals?." *Journal of environmental management* 356 (2024): 120648.

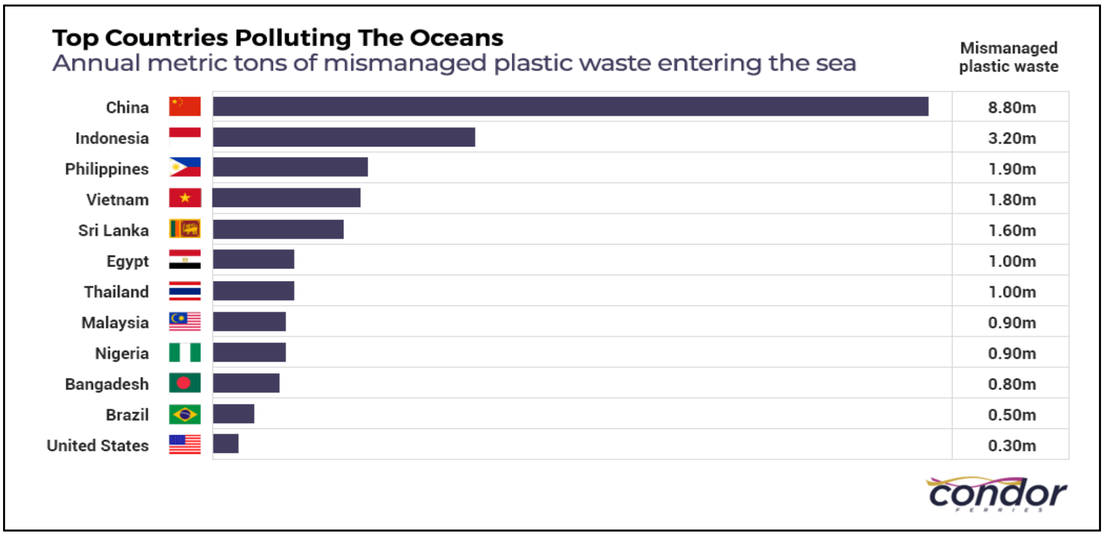

Figure 16: Global Dumping of waste by ships

5.3 Waste Management and Circular Economy Challenges

Ports produce huge volumes of waste such as plastics, hazardous materials, ship waste and oil residues. Another major problem is the fact that ship generated garbage is not properly disposed of and it frequently finds its way into the sea causing ecological harm in the long term[122]. The Port of Los Angeles adopted zero waste policy, which means that by 2030, the Port will send 100 percent of waste to be recycling or reuse centers. Equally, ports all over the globe are investing in their circular economies, turning organic waste into biofuels and publicizing waste-to-energy technologies. (Sirait et al., 2025).

[122] Putri, Maulin Masyito, Prita Meilanitasari, Nindya Putri Prasodjo, and Dwi Sekar Arumjani. "Optimizing Ship Berthing Allocation Strategies at a Dry Bulk Fertilizer Terminal: A Simulation Approach Considering Material Handling Equipment Availability." *Jurnal Teknik Industri: Jurnal Keilmuan dan Aplikasi Teknik Industri* 27, no. 1 (2025): 77-92.

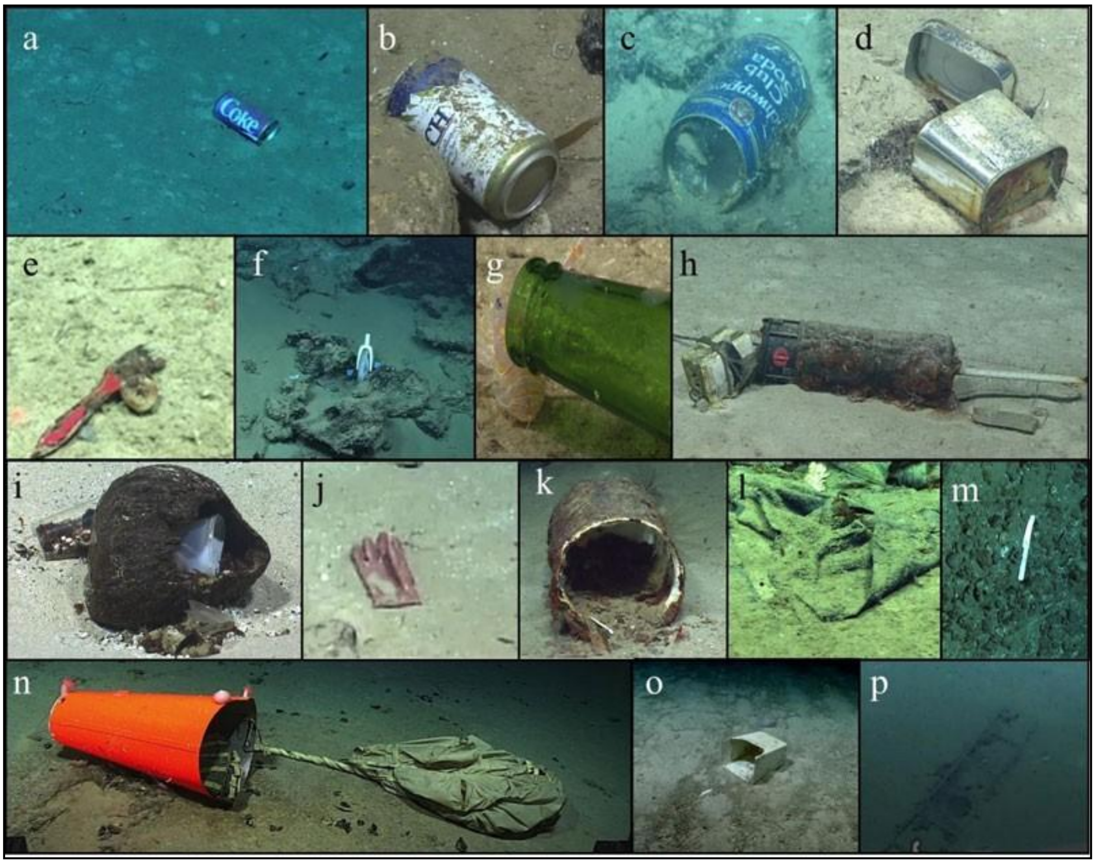

Figure 17: Researchers exploring deep waters of the tropical Atlantic and Caribbean found many pieces of marine debris between 2015 and 2022. Source: Fuller et al. 2024

5.4 Climate Change and Rising Sea Levels

The threat to port infrastructure posed by climate change is existential. Extreme weather conditions and rise in sea levels like hurricanes and typhoons threaten port resilience and efficiency in logistics[123]. Research indicates that more than half of the large ports will face flood risks in 2050 leading to disruption of operations and a loss in economy[124]. Ports in turn are responding by putting in place climate adaptation measures such as high port construction, floodwalls and natural based solutions to reduce climate effects. As an example, the Port of Hamburg has strengthened flood-resistance mechanisms to keep up with the extreme weather conditions[125].

123 Vaca-Cabrero, Javier, Nicoletta González-Cancelas, and Alberto Camarero-Orive. "Bayesian networks for assessing the sustainability of the Marine Renewable Energy sector in the Blue Economy of Spanish ports." *Sustainable Futures* 9 (2025): 100497.
124 Deng, Chenning, Yi Qian, Xiaocong Song, Minghui Xie, Huabo Duan, Peng Shen, and Qi Qiao. "Are electric vehicles really the optimal option for the transportation sector in China to approach pollution reduction and carbon neutrality goals?." *Journal of environmental management* 356 (2024): 120648.
125 Hanf, Franziska S., Felix Ament, Marita Boettcher, Finn Burgemeister, Lidia Gaslikova, Peter Hoffmann, Jörg Knieling et al. "Towards a socio-ecological system understanding of urban flood risk and barriers to climate change adaptation using causal loop diagrams." *International Journal of Urban Sustainable Development* 17, no. 1 (2025): 69-102.

Figure 18: Flooding of Hamburg port area surrounding

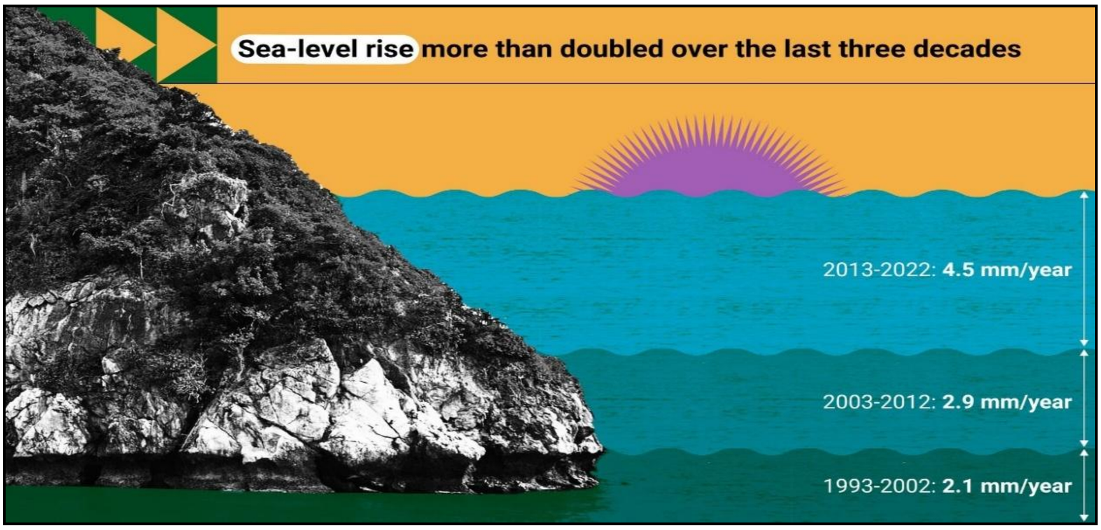

Figure 19: Sea level rise increase (UN Ocean impact, IPPC, 2025)

5.5 Sustainable Solutions and Future Outlook

In order to cope with environmental issues, ports are implementing digitalisation, AI-driven logistics, and integration of renewable energy. Sustainability is being enhanced by the move to smart ports, which have AI-driven emission monitoring, IoT-based energy tracking, and automated cargo handling[126]. In addition, ports are being converted into low-carbon logistics centres by investing in solar, wind, and hydrogen energy. The European Green Port Initiative is expected to achieve the goal of rendering all the large European ports carbon-neutral by 2050 establishing a global standard of sustainability[127].

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[126] Elhussieny, M. (2025). Challenges and opportunities for autonomous vessels in the era of the smart ports. ResearchGate.
[127] Theofanis, Sotirios. *Greening of European Sea Ports–Final report*. No. MI-01-24-002-EN-N. 2024.

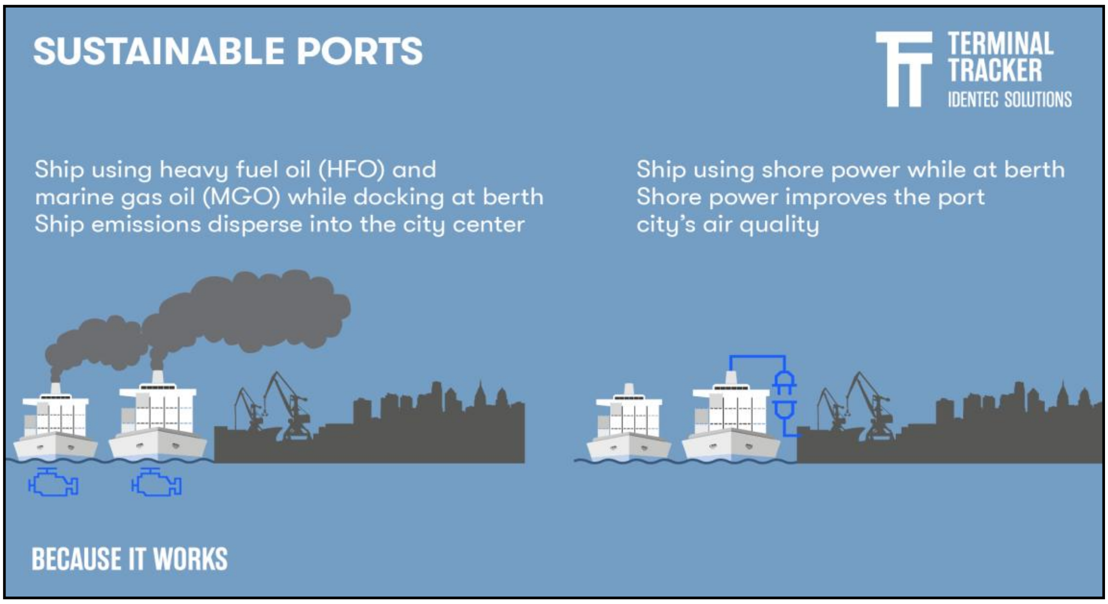

Figure 20: An outlook of sustainable adoption of port operations

Nature is multidimensional and no single solution exists to address the environmental issues that are faced in handling the port operations, which involve governmental involvement, and the involvement of the stakeholders in the industry[128]. Ports can reduce their environmental footprint by adopting low-emission technologies, climate-resilient infrastructure and circular economy models, which also guarantee operational efficiency in the long term. With the increased stringency in sustainability regulations, the future of the port operation is in the green innovations that create a balance in trade.

[128] Purvis, Beinn, and Dominique Bonet Fernandez. "Sustainability in global industrial shipping chains: a positivist perspective of international relations." *Management Research Quarterly* 1, no. 3 (2024): 12-22.

Chapter 6

Sustainable Port Operations and Green Technologies

Ports that are sustainable in terms of their port operations and involve green technology usually assume a planned approach that cuts across on six key fronts. These interconnected areas help ports to achieve environmental responsibility, operations efficiency and social inclusion. The aspects incorporated in the Port Sustainability Plan are the best practices in sustainable port development:

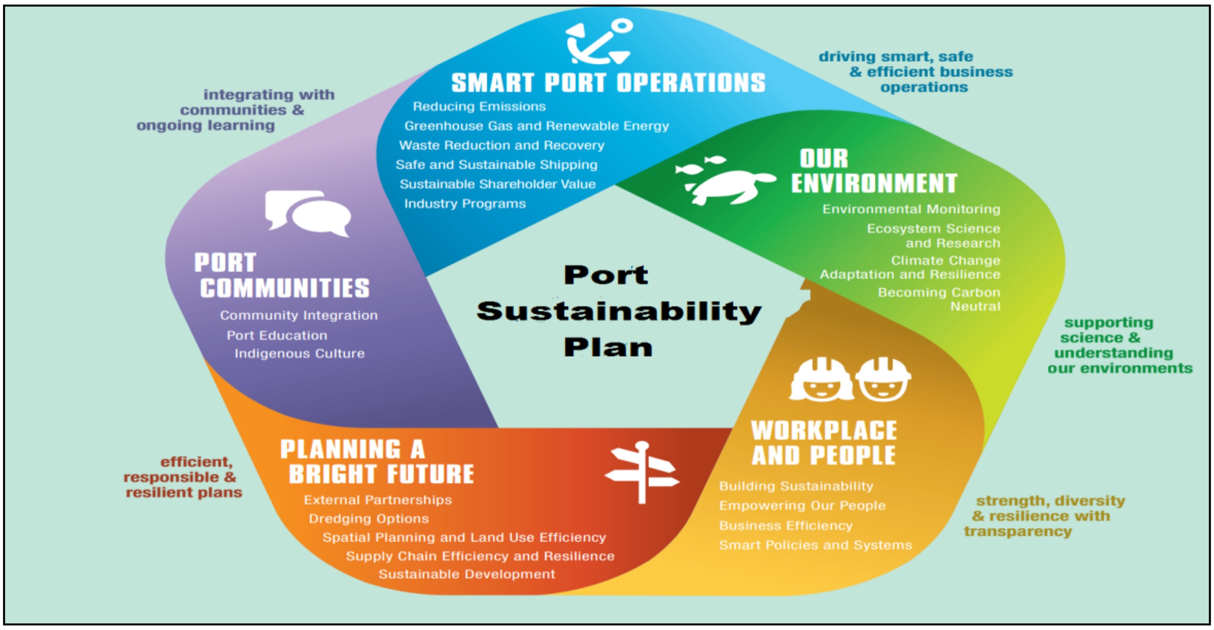

Figure 21: Energy-efficient and environmentally sustainable future ports of EU Source (www.docksthefuture.eu)

6.1 Smart Port Operations

Smart ports are also trying to minimize their impact on the environment by converting to low carbon energy sources such as solar and wind energy. They implement greenhouse gas cutting methods and promote waste minimization with the help of modern recovery and recycling technology. These ports also spend in sea technology that ensure safety and sustainability like energy boating and unmanned cargo technology. Moreover, they align with sustainability norms and standards across the industry, which ensure constant growth. This approach is integrative, and it enhances efficiency in operations and environmental responsibility.

6.2 Environment

Green ports also implement all-inclusive monitoring plans to determine the quality of air, water, and soil in the vicinities of ports. They endorse research on ecosystems in order to comprehend the coastal and aquatic biodiversity and implement adaptive climate strategies to protect port infrastructure against sea-level increase and excessive climate. Shoreline rehabilitation and tracking of emissions are among some of the steps taken to make ports carbon neutral.

Planning will enable ports to reduce the environmental risks by incorporating scientific information. Such an active approach renders the environmental custodianship entrenched in the governance of ports.

6.3 Workplace and People

Sustainable ports understand that they need a robust and competent workforce in order to be successful in the long-term. They focus on staff training, diversity, and inclusion and also on ensuring that health, safety, and well-being have been taken care of through inclusive programs. The employees should be empowered at every level, and this will help in innovation and owing of the sustainability aim. Also, intelligent HR policies and open decision-making models can be used to align workforce approaches with port modernization. It is human capital that leads to resiliency, flexibility, and sustainable leadership.

6.4 Planning a Bright Future

Forward-looking ports entail sustainability in master planning through interacting with external stakeholders, such as the local governments, environmental agencies, and industry partners. They invest in conscientious dredging practices to reduce the impact to ecology and use spatial planning practices in an effort to optimize land and water use. These ports utilize resilience in infrastructure design and develop their terminals in a future proof state to climate hazards. Long-term strategic planning will help the ports to develop sustainably without undermining the environmental and community interests. This is a planning model that will enhance stability of the supply chain.

6.5 Port Communities

Ports which place community first will generate mutual values because they will engage local communities in port related activities. They establish outreach initiatives, provide educational opportunities regarding the maritime operations, and respect the Indigenous knowledge systems in the planning processes. Establishing good relationships with the community would create a sense of trust and improvement in social license to operate. Such efforts also establish feedback mechanisms to make sure port projects are based on shared values. Social inclusion leads to harmonious operations of a company and local economic growth.

6.6 Port Governance

Successful sustainability implementation is based on good governance. Well governed ports have clear procedures, environmental compliance and flexible management. Its approach to decision-making is long-term and data-driven, as well as inclusive. The frameworks that guarantee sustainability goals are achieved consistently are the resilience planning, performance monitoring and accountability frameworks. Such governance practices establish stability in the institutions and establish the trust of the stakeholders in the port in its desire to achieve sustainable growth.

Chapter 7

Technological Strategies for Transformation

A coherent complex of technical solutions is required to make the traditional port turn into the resource-efficient, low-emission, and sustainable organization. Green Port Technologies (GPTs) are revolutionizing maritime operations worldwide and they comprise automation, artificial intelligence (AI), renewable energy systems, and shore-to-ship electrification. While the hydrogen bunkering project of the Port of Antwerp-Bruges will decrease 23,111 tonnes of CO 2 /year, the project is set to be completed only after a year[129], and the power plant on the shore of the Port of Goteburg is reducing at-berth emissions of nitrogen and sulfur oxides by up to 94%[130].

To transform a traditional port into a sustainable, low-emission, and resource-savvy organization, a solid set of technological interventions is needed. Ports globally have implemented innovations that vary in degree of automation and integration of AI to systems based on renewable energy and shore-to-ship electrification that are known as Green Port Technologies (GPTs). They are aimed at carbon cutback, logistic optimization, waste reduction, and safety and compliance[131]. AI-based vessel scheduling has helped to boost yearly CO_2 compared to 11,111 tonnes by 15 percent in the Port of Singapore, thereby enhancing Berth productivity[132]. In the year 2024, 51 GWh of clean energy generated by giant photovoltaic (PV) systems in Ningbo-Zhoushan Port in China offset around 35,111 tonnes of CO_2 [133]. These developments are enhancing operational efficiency, regulatory compliance, and resilience at the international port systems besides reducing the emissions when combined.

At Port Qasim, this transformation is still in its early stages. Nevertheless, the technological plan of greening the port can be informed by the proven interventions that have been implemented in more developed ports. Installation of cold ironing systems or shore power facilities where ships can be connected to the electrical grid in the port and switch off onboard diesel generators when in port is one of the steps. This minimizes emissions on ships of CO_2, NO_x and SO_x by as much as 91%, especially in ports where the grid power is clean or renewable. Xu et al. (2023) found that the cold ironing systems at the Port of Los Angeles reduced more than 61,111 tons of CO2 per year[134].

Besides electrifying the ships at the berth, the electrification of the terminal equipment such as rubber-tired gantry crane (RTG) and the strangle carrier and the forklift can radically cut down on the diesel consumption. Hybrid-electric RTGs such as those

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[129] Verma, P., Chang, Y. C., & Lim, S. (2025). Hydrogen as a maritime fuel: Transition pathways for ports. *Journal of Cleaner Production*, 456, 141297.
[130] Lindstad, E., Eskeland, G. S., & Rialland, A. (2024). Shore power's potential for emission reduction in European ports. *Transportation Research Part D: Transport and Environment*, 126, 103687.
[131] Ren, Y., Xie, T., & Ning, Z. (2024). Degradation, Ecological Restoration and Adaptive Management of Estuarine Wetlands under Intensifying Global Changes.
[132] Chow, K. Y., Tan, P. L., & Ng, A. K. Y. (2023). Artificial intelligence in port operations: Enhancing sustainability through optimized berth allocation. *Maritime Policy & Management*.
[133] Wang, Y., & Li, H. (2024). Renewable energy deployment in Chinese ports: Case study of Ningbo-Zhoushan Port. *Energy Reports*, 10, 2456–2468.
[134] Xu, Y., Huo, X., & Jordan, F. (2023). Smart Port Infrastructure for Climate Mitigation. Frontiers in Marine Science,

have been said to reduce emission by 41 percent and operation costs by 31 percent in ports in Southeast Asia such as Tanjung Pelepas and Ho Chi Minh City[135].

The other technology revolution is an energy-saving cargo routing system, which was motivated by Artificial Intelligence (AI) and Io) infrastructures. These logistics intelligence applications can help optimize the work of gates, trucks, and containers, minimizing unnecessary idling and congestion. The predictive maintenance presented by AI also guarantees port machinery to be running at optimal efficiency and minimizes the energy usage as well as down time of equipment. The example is the Port of Rotterdam which has documented a 25% reduction in logistics turnaround time with the implementation of AI systems.

Besides, by introducing Digital Twin technology, a virtual model of port infrastructure and logistics, planners can visualize energy consumption, water consumption, and greenhouse gas emissions and optimize them before introducing physical modifications. Such systems in combination with the blockchain of cargo documentation, enhance transparency and traceability and enhance environmental and economic performance.

Finally, the port has an opportunity to implement the Building Management Systems (BMS) in their administrative and logistics buildings, such as Heating, Ventilation, and Air Conditioning (HVAC) automation, intelligent lighting, and solar backup. These are relatively low-cost steps but high returns in terms of energy conservation[136]

Table 10: Technological Interventions for Green Port Transformation.

Technology	Function	Impact Area	CO_2 Reduction Potential
Cold Ironing (Shore Power)	Ships connect to shore electricity at berth	Air Quality, GHG Emissions	61–91% (during berthing)
Electric RTGs and Cranes	Replace diesel engines with electric motors	Equipment Emissions, Noise	31–41%
AI-Powered Logistics	Optimize truck movement and cargo routing	Congestion, Fuel Efficiency	15–25%
Digital Twin Simulation	Plan infrastructure in virtual environment	Energy & Emission Planning	Scenario-based
Blockchain Cargo Ledger	Track cargo origin, emissions, delays	Traceability, Customs Efficiency	Indirect benefit
BMS (Smart Buildings)	HVAC, lighting automation, energy optimization	Facility Operations	11–21%

7.1 Renewable Energy Integration

Integration of renewable energy technologies is one of the most promising and transformative strategies of sustainable port operations. In the case of Port Qasim that is situated in an area rich in solar irradiance and medium wind corridors, the transition to solar and wind energy has significant potential, not only in decarbonization, but also in operational cost and energy security.

[135] WMU. (2023). Green Port Strategies for South Asia: A Comparative Study.
[136] IEA. (2023). Global Port Energy Efficiency Report. International Energy Agency.

The renewables currently being applied in Port Qasim are in small scale rooftop solar installation by some individual terminal operators. These systems, which are mainly utilized to energize administrative buildings, are not adequate to counter the energy-consuming processes in the port like lighting, cranes, HVAC systems and logistics control towers. Nevertheless, the large land footprint of the port presents great potential to develop utility-scale solar farms in unused perimeters, roads to the access, and rooftops of warehouses. According to research conducted by the International Renewable Energy Agency (IRENA), even a 5 MW solar array would be able to counter almost 3,111-4,111 tonnes of CO_2 yearly, which would equal eliminating more than 851 vehicles per year off the road[137].

The policy aspects include the Alternative and Renewable Energy Policy (AREP) 2021, which has been introduced by the government of Pakistan, which encourages grid-connected solar and wind projects and incentives like no tax imports and exemption of custom duties on renewable energy equipment. Provided that Port Qasim Authority (PQA) collaborates with Independent Power Producers (IPPs), it may work out Power Purchase Agreements (PPAs) to consume electricity independently or net metering, particularly in the times of peak summer when the load of both cooling and lighting at the ports grows significantly.

Coastal wind power is another promising one besides solar PV. The Sindh coastal belt including the Korangi and Gharo wind corridors of Port Qasim has a wind speed ranging between 6.5-7.5 m/s, and this is the range which is suitable in wind turbines. Even installation of a small onshore wind cluster of 11 15 MW located close to the port would be able to complement daytime generation of solar and provide stable energy at night for an all-round hybrid renewable system.

Additionally, energy storage units, including lithium-ion battery banks or thermal energy storage (TES) units can be interconnected to equalize the mismatches between supply and demand and to limit the use of a backup diesel generator. PV, wind, and battery storage architecture can be customized to microgrids that provide the essential infrastructure of a port such as traffic control towers, emergency lighting systems, and security systems, to ensure that energy is supplied during grid outages or in case of a disaster[138].

Table 2 is based on IRENA (203) to come up with these estimates[139] and Pakistan Council of Renewable Energy Technologies (PCRET)[140] comparable wind and solar profiles field models. Renewable energy integration into the operations of Port Qasim would go a long way in enhancing its ability to meet Sustainable Development Goal 7 (Affordable and Clean Energy) and SDG 13

[137] IRENA. (2023). Renewables in Ports: Case Studies from Developing Countries. International Renewable Energy Agency.
[138] NEPRA. (2023). State of Industry Report – Wind Resource Mapping. National Electric Power Regulatory Authority, Pakistan.
[139] IRENA. (2023). Renewables in Ports: Case Studies from Developing Countries.
[140] PCRET. (2022). Solar Energy Mapping in Coastal Sindh: Technical Report. Pakistan Council of Renewable Energy Technologies.

(Climate Action) and meet Pakistan Nationally Determined Contributions (NDCs) to the Paris agreement[141].

Table 11: Renewable Potential and CO_2 Offset Estimates at Port Qasim.

Technology	Scale (MW)	Estimated CO_2 Offset (tons/year)	Recommended Use Cases
Solar PV	5–11 MW	3,111–6,111	Buildings, street lighting, RTG cranes
Wind Turbines	11–15 MW	7,111–8,511	24/7 base load, warehouse refrigeration
Hybrid System	21 MW + Storage	11,111–12,111	Full microgrid for terminal operations

7.2 Electrification of Cargo Handling Equipment

One of the largest changes that can be made to mitigate the air pollution, operational noise, and greenhouse gas emissions in ports is the electrification of Cargo Handling Equipment (CHE). The majority of CHE in the traditional port environment, like Port Qasim, is diesel-powered, with most of the products being RTGs, straddle carriers, forklifts, and reach stackers. This not only results in significant emissions of CO_2, NO_x, and particulate matter, but also contributes to increased operational costs and maintenance overhead due to the complex nature of internal combustion machinery.

Port Qasim's CHE fleet is largely outdated, with a majority of its terminal operators still relying on diesel-powered RTGs and yard tractors. These machines can consume up to 25–31 liters of diesel per operational hour, and collectively account for a substantial portion of the port's carbon emissions. According to Clarksons Research (2023)[142], modern ports that transitioned from diesel to electric RTGs reported CO_2 reductions of up to 61% per crane and operational cost savings of 25–31% over five years.

Globally, ports like Port of Long Beach, Jawaharlal Nehru Port (JNPT) in India, and Tanjung Pelepas Port in Malaysia have deployed hybrid-electric or fully electric CHE using lithium-ion batteries or ultra-capacitor systems. These upgrades were supported through green port financing schemes, carbon offset credits, and government-backed green bonds. Pakistan's State Bank Green Financing Scheme for Renewable Energy (2021) could serve a similar function in subsidizing the transition to electric port machinery[143].

Port Qasim can also adopt grid-connected RTGs, which operate via cable reels connected to the port's internal power supply. Alternatively, battery-powered mobile units with regenerative braking can be introduced for intermittent yard operations, thereby reducing peak electricity demand and fuel consumption.

[141] Government of Pakistan. (2020). Alternative and Renewable Energy Policy (AREP) 2020. Ministry of Energy.
[142] Clarksons Research. (2023). Global Port Equipment Emissions Outlook 2023–2027.
[143] JNPT. (2022). Environmental Performance and Electrification Strategy Report. Jawaharlal Nehru Port Authority.

Table 12: Diesel vs. Electric CHE Performance Metrics *(Source: IEA, 2023).*

CHE Type	Power Source	CO_2 Emissions (tons/year)	Fuel Cost/year	Maintenance Downtime
Diesel RTG	Diesel Engine	281–311	High	Moderate–High
Electric RTG	Shore Power Grid	111–121	Low	Low
Hybrid RTG	Battery + Grid	151–181	Medium	Low

Moreover, electrification must be coupled with training for port operators and maintenance staff, as the operational characteristics and safety protocols differ significantly between electric and diesel-based systems. Partnerships with vocational institutes and higher education (e.g., NUTECH, NED University) may be utilized in the program of workforce upskilling, which will result in a clear and secure shift.

It is also important to implement smart charging infrastructure to support the CHE that is battery-powered. With such systems, load balancing, inverters that can work with the sun and cloud-based monitoring dashboards can be installed to maximize energy consumption and extend battery life. The positive effects of electrification in the long run are not limited to the environment. They include:

a. Reduced noise pollution, improving occupational health.

b. Lower operating expenses over the equipment lifecycle.

c. Better compliance with international shipping partners, many of whom now require low-carbon terminals as part of ESG frameworks.

7.3 Smart Port Technologies and AI-Driven Logistics

Ports are becoming smart, interconnected logistics centers in the era of digital transformation, using data analytics, automation and AI to make operations more efficient, less emitting, and to improve real-time decision-making. In the case of Port Qasim, the implementation of smart port technologies provides a way out not just to sustainability, but also to economic competitiveness in the global supply chain that is increasingly becoming digital.

Some of the technologies that a smart port will combine include IoT sensors, AI-based traffic management, digital twins, blockchain cargo tracking, and predictive maintenance algorithms. These systems provide an environment that is full of data where the port operators can keep track of equipment performance, vessels, cargo flows, and environmental indicators real-time. As an example, AI-based berth scheduling has the potential to save 15-25% of vessel idle time, which leads to a decrease in ship-based GHG emissions[144].

Currently, Port Qasim does not have a centralized Port Community System (PCS), which is an online platform, whereby the shipping lines, terminal operators, customs authorities, and inland transport providers can smoothly

[144] Xu, Y., Huo, X., & Jordan, F. (2023). Smart Port Infrastructure for Climate Mitigation.

share information. A PCS would mean that a lot of paperwork is saved and also delays are minimized as well as container congestion, which contributes to the wasting of fuel and environmental degradation. According to the World Bank (2022)[145],and building ports which embraced PCS models achieved up to 41% decrease in cargo turnaround time and 21 percent decrease in port related emissions.

The use of digital twins which are virtual copies of physical port infrastructure and operations is another essential instrument. They allow simulating a potential scenario like a bottleneck at the gate, a malfunctioning crane or heavy wind and respond in advance before crises become overwhelming. Digital twins are employed in ports such as Antwerp, Singapore, and Rotterdam to model the patterns of energy consumption, optimize the traffic of trucks, and even control maritime traffic based on real-time weather data and AI modeling.

In the logistical optimization, it is already possible to implement machine learning algorithms in smart ports that can be used to control container stacking, predict cargo loads, and make predictions on terminal throughput. Such tools facilitate trade-off between import-export, less re-handling of containers, and synchronization of internal logistics with external rail and truck networks. In the case of Port Qasim, this optimization may help relieve the current congestion at the outer port roads significantly and simplify its accessibility to the M-9 Motorway and Karachi Circular Railway (KCR) route.

Blockchain technologies are also important in protection and optimization of cargo documentation. Smart contracts and tamper-proof cargo register help to eradicate fraud, maintain traceability and minimize the disputes, which are typical issues in the maritime customs environment in Pakistan. Digital trust has demonstrated strengthening port-customer relationships and also lower emissions by removing unnecessary physical procedures by initiatives like Trade Lens, a blockchain platform developed together with IBM and Maersk[146].

To implement it successfully, Port Qasim also needs to invest in digital infrastructure, such as fiber-optic backbone networks, edge computing nodes and cloud-based data centers. Moreover, the implementation of cybersecurity measures should also be enhanced to avoid cyber-attacks and ransomers on critical infrastructure, which is an increasing threat to ports globally.

Lastly, digital literacy of the workforce is required. Grassing smart port transformation is not just a technological issue, but also a human response to digital technology. Port authorities are thus advised to liaise with technical universities and maritime academies to come up with training modules on custom officers, crane operators, logistics managers and marine pilots.

Table 13: Smart Port Technologies and their Operational Impacts (Source: World Bank, Maersk & IBM).

Technology	Function	Primary Benefits	Emission Impact

[145] World Bank. (2022). Digitalization of Ports in Developing Countries: Operational Case Studies.

[146] Maersk & IBM. (2021). TradeLens Blockchain Case Implementation Reports.

Port Community System	Integrates all stakeholders digitally	Reduced delays, faster clearances	↓ Emissions from idle cargo
AI Berth Scheduling	Optimizes ship docking and cargo handling	Lower idle time, faster cargo flow	↓ GHG from berthed vessels
Digital Twin	Simulates port operations & infrastructure	Scenario planning, energy optimization	Indirect
IoT-Based Monitoring	Real-time data on equipment/fuel usage	Predictive maintenance, leak prevention	↓ Waste and losses
Blockchain Cargo Docs	Secure, paperless tracking system	Fraud reduction, cargo traceability	↓ Printing and admin emissions

7.4 Waste Management and Pollution Control Measures

Effective waste management and pollution control are critical pillars of sustainable port operations, particularly in ecologically sensitive coastal zones like Port Qasim, which borders mangrove ecosystems and the biologically diverse Korangi and Phitti Creek systems. However, Port Qasim currently lacks a comprehensive and institutionalized Environmental Management System (EMS) for dealing with the solid, liquid, and gaseous waste generated from port activities, ship operations, and the surrounding industrial zones. The primary sources of pollution at Port Qasim include:

a. Ship-generated waste, such as bilge water, sludge, sewage, and plastic waste.

b. Industrial effluents containing toxic heavy metals, dyes, and hydrocarbons.

c. Construction and dredging waste, which impacts sediment quality and aquatic life.

d. Unregulated solid waste, such as packaging, used oil containers, and domestic refuse from workers and visiting ships.

One of the biggest challenges is the lack of a centralized Port Reception Facility (PRF) that complies with MARPOL Annexes I, IV, and V, which regulate the reception of oil, sewage, and garbage from ships. Currently, most ships calling at Port Qasim rely on private waste contractors, many of whom operate informally and without sufficient oversight, leading to illegal dumping into creeks and open grounds. According to WWF-Pakistan (2022)[147], over 15% of the waste from ships and port terminals at Port Qasim is discharged without proper treatment or disposal, posing direct threats to marine biodiversity and human health.

In contrast, ports such as Singapore, Rotterdam, and Jawaharlal Nehru Port (India) have deployed automated waste segregation and tracking systems, ensuring that waste generated is collected, categorized (hazardous/non-

[147] WWF-Pakistan. (2022). Coastal Pollution Risk Assessment in Port Qasim Industrial Zone. Karachi: WWF Marine Programme.

hazardous), and treated or recycled appropriately. These ports integrate digital barcoding, waste manifest systems, and remote waste tank level sensors to minimize leakage, reduce pilferage, and ensure full compliance with environmental standards.

Port Qasim's pollution control efforts have been minimal, limited to intermittent oil spill drills and manual silt traps installed in a few terminals. There is no real-time environmental monitoring network or air and water quality dashboard accessible to regulators or stakeholders. As a result, there are frequent reports of oil sheens, plastic clusters, and low dissolved oxygen (DO) levels in the port basin, particularly in the summer season when tidal flushing is low.

Table 14: Current vs. Recommended Waste & Pollution Control Framework at Port Qasim.

Category	Current Practice	Recommended Practice	Impact
Ship Waste	Informal contractors, no standard facility	MARPOL-compliant Port Reception Facility (PRF)	Legal compliance, marine safety
Solid Waste Sorting	Manual disposal or open dumping	Segregated bins, smart tracking, composting	Waste diversion from landfill
Liquid Effluents	Untreated discharge from industries	Centralized Effluent Treatment Plants (ETPs) with reuse options	Water quality restoration
Oil Spill Response	Periodic drills with minimal resources	Oil skimmers, containment booms, response boats	Fast containment
Air Quality Monitoring	Not systematic, no dashboard	IoT-based sensors and live dashboards (PM, NOx, SOx, VOC)	Pollution control & transparency

Several solutions can be implemented at Port Qasim to drastically improve its waste and pollution profile:

a. Install a certified PRF to receive waste from ships with capacity to handle oil, sewage, food waste, plastics, and chemicals, supported by digital manifests and fee incentives for compliance.

b. Establish a Waste-to-Energy (WtE) pilot project for non-recyclable municipal waste generated by port workers and nearby industries, using pyrolysis or incineration technologies under strict emissions control.

c. Deploy real-time water and air quality monitoring stations, particularly near cargo berths, LNG terminals, and mangrove zones, with data shared publicly via an online dashboard.

d. Integrate stormwater runoff systems with bio-filtration cells and sediment traps to prevent chemical and solid waste from entering the natural creeks during the monsoon season.

e. Enforce the Polluter Pays Principle through port tariff adjustments, incentivizing sustainable behavior and penalizing non-compliance.

7.5 Energy Efficiency and Carbon Neutrality Strategies

Energy efficiency and carbon neutrality have emerged as core performance metrics for modern ports worldwide. With maritime emissions now representing nearly 3% of global GHG emissions, the pressure on ports to transition toward low-carbon operations is immense. For Port Qasim, which is heavily reliant on fossil fuels and aging infrastructure, the pursuit of energy-efficient practices and carbon offsetting strategies can yield significant environmental, operational, and economic benefits.

7.6 Energy Consumption Profile at Port Qasim

Port Qasim's energy consumption is dominated by:

1. Lighting for vast cargo yards, warehouses, and security perimeters.

2. Powering cargo handling equipment (CHE) and storage facilities.

3. Office and administrative utilities (air conditioning, computing, surveillance).

4. Auxiliary power for vessels docked at port (currently running on their own diesel engines).

Most of this demand is met through the national electricity grid, supplemented by diesel generators during outages, particularly in peak summer months. According to IEA (2023)[148] estimates and port-level data comparisons, such a system is not only inefficient but also vulnerable to power quality issues, voltage sags, and outages, which directly impact cargo handling performance.

[148]IEA. (2023). Port Decarbonization Pathways: Energy Efficiency in Shipping Infrastructure.

7.7 Strategies for Improving Energy Efficiency

7.7.1 LED-Based Smart Lighting Systems

Upgrading from conventional sodium vapor and halogen lamps to motion-activated LED lighting in container yards and warehouses can result in 41–61% energy savings, with improved luminance and safety. Ports like Colombo and Busan have adopted this successfully.

7.7.2 HVAC Optimization in Administrative Areas

Using smart thermostats, solar reflective paints, and energy recovery ventilators (ERVs) can reduce the energy footprint of port offices by 31% or more. When integrated with rooftop solar, such systems can be entirely off-grid[149].

7.7.3 Energy Management Systems (EMS)

Implementing an EMS allows for the real-time tracking of power usage, peak load optimization, and energy benchmarking of different terminals. These systems, linked with predictive analytics, can identify power leakages, inefficient devices, and maintenance needs.

7.7.4 Regenerative Braking in Cranes

New-generation electric RTGs and quay cranes are equipped with regenerative braking systems that capture and reuse kinetic energy, feeding it back into the grid or a battery system.

7.7.5 Port Electrification Roadmaps

A port-wide electrification plan can identify opportunities to transition from diesel to electricity across yard tractors, cooling systems, and vessel support services, aiming for 71–81% decarbonization of terminal operations[150].

7.8 Pathways to Carbon Neutrality:

While energy efficiency reduces consumption, carbon neutrality requires balancing remaining emissions through offset mechanisms. Globally, ports pursue carbon neutrality via[151].

a. *Carbon Credit Trading:* Participating in compliance or voluntary carbon markets (e.g., Verra, Gold Standard) by purchasing carbon credits equivalent to annual emissions.

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149 UNCTAD. (2022). Maritime Transport and Climate Resilience Report. United Nations Conference on Trade and Development.
150 REN21. (2023). Renewables Global Status Report: Ports and Infrastructure Chapter.
151 Verra. (2021). Verified Carbon Standard Methodology for Coastal Blue Carbon.

b. *Carbon Insetting:* Investing in local ecosystem restoration, such as mangrove reforestation and coastal blue carbon projects within the port's ecological buffer zone. Given Port Qasim's proximity to degraded mangrove forests, this presents a dual opportunity for ecological and carbon restoration.

c. *Green Procurement Policies:* Focusing on the vendors and subcontractors offering low-carbon goods and services, e.g., bio-based packaging, electric forklifts, and eco-certified lubricants.

d. *Internal Carbon Pricing:* When an internal equivalent is set of the price of each ton of CO2 released, it will encourage the department to prefer the use of low-carbon solutions before they are required by the upfront regulations.

Table 15: Tiered Roadmap to Port Carbon Neutrality.

Phase	Timeline	Key Actions	Expected CO_2 Reduction
Phase 1: Audit & Baseline	Year 1	GHG inventory, energy audits, EMS setup	Baseline data
Phase 2: Efficiency Upgrades	Years 2–3	LED lighting, HVAC retrofit, EMS integration	21–31%
Phase 3: Electrification	Years 3–5	Electric CHE, solar-powered buildings, vessel shore power	31–51%
Phase 4: Offsets & Neutrality	Years 5–7	Mangrove projects, carbon credits, insetting programs	Net Zero

7.9 Role of Digitization and Automation in Sustainable Port Operations

The global port environment is becoming digitalized and automated and, as a result, allows the paradigm shift of manual and resource-intensive systems to data-driven, automated, and sustainable logistics ecosystems. In the case of Port Qasim, the potential to utilize the mechanisms to achieve significant energy savings, emissions mitigation, safety and operational transparency, which are major pillars of a green port structure, can be unlocked through the utilization of these technologies.

Digitization is a concept of using digital tools, systems, and platforms to oversee the activities of ports, including cargo clearance and equipment scheduling, and environmental protection and safety regulations. In Port Qasim where paper records and manual clearance of customs remain the order of the day, computerization is a giant leap.

The main part of port digitization is the deployment of Port Community System (PCS), the common platform that unites all stakeholders (customs, terminals, shipping lines, logistics companies) and helps to exchange the data in real-time. According to the World Bank (2022)[152], The implementation of PCS in the South Asian ports of the same nature resulted in a 41 percent decrease in the time of clearance, a 71 percent decrease in the quantity of paper usage and an increase in environmental and custom regulation compliance.

[152] World Bank. (2022). Digitalizing South Asia's Ports: A Toolkit for Modernization.

Also, RFID tag cargo tracking, GPS, and blockchain supply chain ledger make cargo tracking transparent, alleviate cargo theft, and streamline inventory management. Emission reduction is also achieved through optimization of truck route and timing which is achieved through these digital systems.

Automation is the process that aims at the mechanization of repetitive or dangerous tasks that the port has to complete, lessening the amount of people necessary to complete them and increasing the accuracy of the operations. High-tech ports such as Singapore and Rotterdam have fully automated terminals, in which automated stacking cranes (ASCs), driverless yard vehicles, and automated gate systems process container flows 24/7 with very low emissions. Although complete automation is not likely to be possible at Port Qasim in the short term, it can greatly benefit by narrow-focused automation such as:

a. Automated truck gates to reduce congestion and queuing emissions.

b. Auto-stacking systems in container yards for space optimization.

c. AI-based crane alignment systems that reduce loading/unloading times.

d. Maintenance that would be digitally scheduled to avoid faults and reduce energy wastage.

In addition, predictive analytics, which is a machine learning-based technology, may predict the arrival of vessels, equipment maintenance, and cargo changes. Such insights can be used in forward planning, less fuel burning and improved manpower investment.

Table 16: Digitization and Automation Benefits Across Port Functions (Source: IMO, 2021[153] and Maersk TradeLens, 202[154]).

Function	Digital/Automated Intervention	Sustainability Benefit
Cargo Processing	PCS, RFID, blockchain logistics	Reduced paperwork, faster clearance
Equipment Maintenance	Predictive analytics, digital twins	Lower downtime, energy-efficient operations
Truck Management	Gate automation, AI traffic scheduling	Reduced idling emissions and traffic bottlenecks
Yard Management	Automated stacking, RFID inventory	Space optimization, energy savings
Safety Monitoring	IoT-based sensors, drones, thermal imaging	Lower accident risks, real-time hazard detection

[153] IMO. (2021). FAL Convention: Digitizing Port Clearance Processes.
[154] Maersk TradeLens. (2022). Blockchain Logistics Pilot Report.

7.10 Digital Sustainability Reporting and Compliance

Environmental compliance and reporting Digital platforms may also facilitate environmental compliance and reporting, by automating the collection of:

a. GHG emissions data

b. Waste disposal logs

c. Water and air quality monitoring

Environmental KPIs can be shown in real-time in cloud-based dashboards and regulatory reporting to Pakistan Environmental Protection Agency (Pak-EPA) and IMO frameworks (e.g., MARPOL) can be performed faster. This can in the long run assist Port Qasim to have green port certifications, including:

a. Eco Ports (European Sea Ports Organization)

b. Green Marine Certification

c. World Ports Sustainability Program (WPSP)

Despite these benefits, successful digitization and automation require:

a. Stable ICT infrastructure (fiber optic backbone, edge servers).

b. Cyber security systems to protect trade data and control systems.

c. Skilled workforce, trained in operating digital platforms and interpreting analytics.

d. Policy-level incentives for private terminal operators to co-invest in digital upgrades.

Collaboration between the Port Qasim Authority (PQA), Ministry of Maritime Affairs, and academic/tech institutions is essential for building a digital roadmap aligned with sustainability goals.

Chapter 8

Integration of Digital Technologies

With the introduction of digital technologies, port operations have been transformed and is now the source of efficient and effective ports are the backbone of the global supply chain through which more than 80 percent of the world trade is carried out.[155] [156]. The maritime industry is under increasing pressure to become more sustainable as issues of environmental concern get increasingly more pressing. In the 2020-2024 period, there are major trends that have been observed in sustainable port development based on the global focus on environmental responsibility and efficiency in operations[157].

The growing pressures of climate change, regulatory challenges and changing expectations of stakeholders have increased speed in the shift to more environmentally friendly port operations[158]. International organizations, governments and individual stakeholders are working to put in place mechanisms that will reduce the environmental impact of ports and still achieve economic development and competitiveness[159]. Most ports are making bold sustainability goals, including creating a carbon-neutral city, lessening air and water pollution, and improving the protection of biodiversity within the local marine environment[160]. International Maritime Organization (IMO) has announced more strict provisions on the volume of emissions, which forces ports all over the world to switch to a cleaner energy source and more efficient logistics framework[161] [162].

Moreover, the idea of smart ports has become one of the prominent ones, as it uses digital resources, including artificial intelligence (AI), big data analytics, and block chain to streamline port logistics, minimize congestion, and enhance resource management[163]. These technological innovations lead to more efficient vessel scheduling, real-time cargo tracking, automated port operations and, as a result, less energy usage and emissions. The leading ports in terms of the adoption of the

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[155] Su, Zhenqing, Yanfeng Liu, Yunfan Gao, Keun-Sik Park, and Miao Su. "Critical success factors for green port transformation using digital technology." *Journal of Marine Science and Engineering* 12, no. 12 (2024): 2128.
[156] Trade and Development Report 2024 | UN Trade and Development (UNCTAD)
[157] Mba, Joy Uchechukwu. "Advancing sustainability and efficiency in maritime operations: Integrating green technologies and autonomous systems in global shipping." *Int. J. Sci. Res. Arch* 13 (2024): 2059-2079.
[158] Mohite, Abhijit Arvind, and Emil Mathew. "Exploring the necessary upgrades in port infrastructure to accommodate and support the operation of the next-generation green ships." *Marine Systems & Ocean Technology* 20, no. 2 (2025): 26.
[159] Argyriou, Ioannis, and Theocharis Tsoutsos. "Sustainable solutions for small/medium ports a guide to efficient and effective planning." *Journal of Marine Science and Engineering* 11, no. 9 (2023): 1763.
[160] Jiménez, María Luisa Gómez. "SDGs and port systems: new challenges and opportunities for marine protection from the EU green deal perspective." *The EU Green Deal and its Implementation*: 289.
[161] IMO makes progress on net-zero framework for shipping
[162] 2023 | Logistics Performance Index (LPI)
[163] Koritarov, Todor, and Dimitar Dimitrakiev. "THE IMPACT OF DIGITALIZATION ON SMART PORTS: ENHANCING EFFICIENCY, SUSTAINABILITY, AND COMPETITIVENESS IN THE MARITIME INDUSTRY." *The scientific heritage* 152 (2024): 28-33.

technologies to increase the level of sustainability and the effectiveness of the work include Rotterdam, Singapore, and Hamburg[164 165 166].

Investment in renewable energy infrastructure has also become a priority, with ports increasingly utilizing wind, solar, and hydrogen power to reduce dependency on fossil fuels[167]. The implementation of shore power, which allows docked ships to plug into the local electrical grid instead of running diesel engines, is another critical development in reducing port-related emissions. Ports like Los Angeles and Antwerp have already deployed extensive shore power systems, significantly cutting down greenhouse gas emissions and improving air quality in port cities [168 169 170].

Along with the environmental approach, the sustainability of the port development also focuses on economic and social agility. Investments in infrastructure modernization, the growth of the workforce, and partnership with local communities will help to make ports competitive and contribute to the positive socio-economic effects[171]. The sustainability of the port system in the future depends on further innovation, harmonization of the regulation, and international collaboration in order to manage environmental issues without ignoring the significant role of ports in the global economy[172]. Smart ports use IoT, AI, and block chain to streamline the logistics, minimize congestion, and minimize environmental impact. As an example, the Port of Rotterdam has already introduced a virtual replica of the port called a digital twin to simulate and optimize operations which lead to the decrease of emissions and better use of resources[173]. On the same note, the Port of Hamburg also applies smart traffic management systems to optimize vessel traffic to reduce fuel rates and related emission[174].

8.1 Adoption of Renewable Energy Sources

The ports are also increasingly investing in renewable energy to operate in their ports so that they can decrease the use of fossil fuels and decrease their carbon footprints[175]. Seizing the opportunities presented by wind and solar power and

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[164]Port of Hamburg Download Center

[165] 2024 Annual Report Port of Rotterdam Authority: Navigating towards a sustainable future | Port of Rotterdam

[166] Trade and Development Report 2024 | UN Trade and Development (UNCTAD)

[167] Li, Linfeng, Ming Zhong, Xiaofeng Ma, Haowei Zhao, Muhammad Safdar, Dung David Chuwang, and Ziran Zhang. "Optimal planning of renewable energy infrastructure for ports under multiple design scenarios considering system constraints and growing transport demand." *Journal of Cleaner Production* 477 (2024): 143827.

[168]kentico.portoflosangeles.org/getmedia/a3851b33-5af1-4ef5-9726-9116ef7f25fe/annual-financial-report-fy2022-23

[169] Port of Antwerp-Bruges Sustainability Summary 2023 - Circular Flanders

[170] IAPH 2022 - 2023 Annual Report is available | IAPH

[171] Karagkouni, Konstantia, and Maria Boile. "Classification of green practices implemented in ports: The application of green technologies, tools, and strategies." *Journal of Marine Science and Engineering* 12, no. 4 (2024): 571.

[172] International Transport Forum. (2022). Decarbonizing maritime transport: Pathways to zero-carbon shipping by 2050. OECD Publishing. https://www.itf-oecd.org/decarbonising-maritime-transport

[173] Port of Rotterdam Authority presents 2023 annual report | Port of Rotterdam

[174] hafen-hamburg.de/site/assets/files/605478/rz_hhm_jahresbericht2022_en.pdf

[175] Schulz, Veronica, Michael GH Bell, John M. Rose, and D. Glenn Geers. "From fossil fuels to biofuels: Circular economy diversification for fossil fuel ports." *Transportation Research Part D: Transport and Environment* 144 (2025): 104796.

other clean energy solutions can make the work of the ports more sustainable and help preserve the environment. Indicatively, the Port of Los Angeles has incorporated solar panels into its set up and makes a large percentage of its energy requirements using renewable sources[176].

8.2 Electrification of Port Operations

Electrification is a trend in sustainable port development. The ports are developing infrastructure to accommodate electric vehicles (EVs) and equipment to mitigate greenhouse gas emissions and enhance air quality. To reach zero emission operation by 2030, the Port of Los Angeles has implemented electric cargo handling equipment and trucks, which intends to transform into zero-emission operations[177]. Likewise, the Port of Antwerp is increasing the shore power plants to enable trading vessels to power off their engines during docking to minimize emissions and noise pollution [178].

8.3 Implementation of Alternative Fuels

The use and development of other energy sources like hydrogen, LNG and ammonia have taken off in the maritime sector[179]. In September 2024, the world consortium successfully transferred a cargo of ammonia into Australia, which leads to ammonia bunkering in the area[180]. These programs are important measures in decarbonizing sea transport.

8.4 Circular Economy Practices

The focus of sustainable port development is to minimize waste production and resource use by recycling waste materials, recovering waste materials, and utilizing environmentally friendly materials. These practices of the circular economy help to achieve a smaller ecological footprint and environmental sustainability in port practices[181].

8.5 Strategic Infrastructure Investments

Considerable amounts of investment are to be made to develop the old port infrastructures sustainable hubs[182]. Examples include the redevelopment plan of the former Hunter ston coal terminal in Ayrshire to a renewable energy and offshore wind centre worth 150 million[183] . Ports can be viewed as key participants in the energy transition around the world with such projects.

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[176]kentico.portoflosangeles.org/Annual-Financial-Report-FY2023-24#page=23.24
[177]kentico.portoflosangeles.org/_Audit Report in accordance with the auditing, issued our report thereon dated December 2022.
[178] Port of Antwerp-Bruges Sustainability Summary 2023 - Circular Flanders
[179] Standards & Guidance | GHG Protocol
[180] Shipping industry still at sea as it tries to navigate to net zero | Reuters

[181] IDENTEC SOLUTIONS Wireless Technology. Because It Works
[182] Clemente, Daniel, Tomás Calheiros-Cabral, Paulo Rosa-Santos, and Francisco Taveira-Pinto. "Blue seaports: the smart, sustainable and electrified ports of the future." *Smart Cities* 6, no. 3 (2023).
[183] In charts: 7 global shifts defining 2025 so far | World Economic Forum

8.6 Strengthening Environmental Regulations and Policies

Strict environmental laws are being enforced by governments and international bodies to enhance sustainability in the operation of ports. An example of this is Norway, which has imposed rules that cruise liners should be emission free by 2032 in its world heritage fjords resulting in cruise lines being invested in green technologies[184] .

8.7 Community Engagement and Social Responsibility

The other sustainable port development is dealing with the local communities to handle environmental and social issues[185]. In Peru the building of a mega port has left some concerns to locals on environmental effects and sharing economic gains as to emphasize the need to include the planning aspect in port development[186].

8.8 Resilience to Climate Change

Climate change has led to a rise in extreme weather occurrences and ports have been making an effort to become more resilient. This is done by improving infrastructure to meet extreme conditions and coming up with backup plans to ensure that operations remain unaffected by inconvenience. As an example, the Port of New Orleans has invested in high-rise buildings and flood prevention measures to reduce the effects of hurricanes and upsurge of sea levels[187]. On the same note, Port of Rotterdam is taking adaptive actions to be able to deal with possible challenges posed by climate so that trade and economic operations can continue[188].

8.9 Global Collaboration and Knowledge Sharing

Sustainable port development has led to international cooperation and the sharing of knowledge among ports, industry players and the international bodies. Programmes like the World Ports Sustainability Program (WPSP) offer forums where ports can exchange best practices, joint projects as well as sustainability guidelines[189].

World Ports Sustainability Program (WPSP) was established in March 2018 by the International Association of Ports and Harbors (IAPH) is dedicated to 17 UN Sustainable Development Goals (SDGs). It provides ports with a platform to exchange experience, to address best practices and to collaborate with those in the supply chain, shipowners and regulators. WPSP assists ports in enhancing their sustainability activities and addressing such important issues

[184] Bright ideas in travel 2023 | CN Traveller
[185] Jansen, Maurice. "Ports and the Sustainable Development Goals: An Ecosystems Approach." In *International Business and Sustainable Development Goals*, vol. 17, pp. 263-283. Emerald Publishing Limited, 2023.
[186] Why is the shipping industry not decarbonizing faster? | World Economic Forum

[188] Port of Rotterdam Authority presents 2023 annual report | Port of Rotterdam
[189] ESI Portal

like reducing air pollution by ships. It has one of its key programs the Environmental Ship Index (ESI) to be used to drive cleaner and greener shipping activities. The ESI makes shipowners add low-emitting vessels by giving recognition and potential incentives of ports involved, hence contributing to local environmental improvement and global climate change[190].

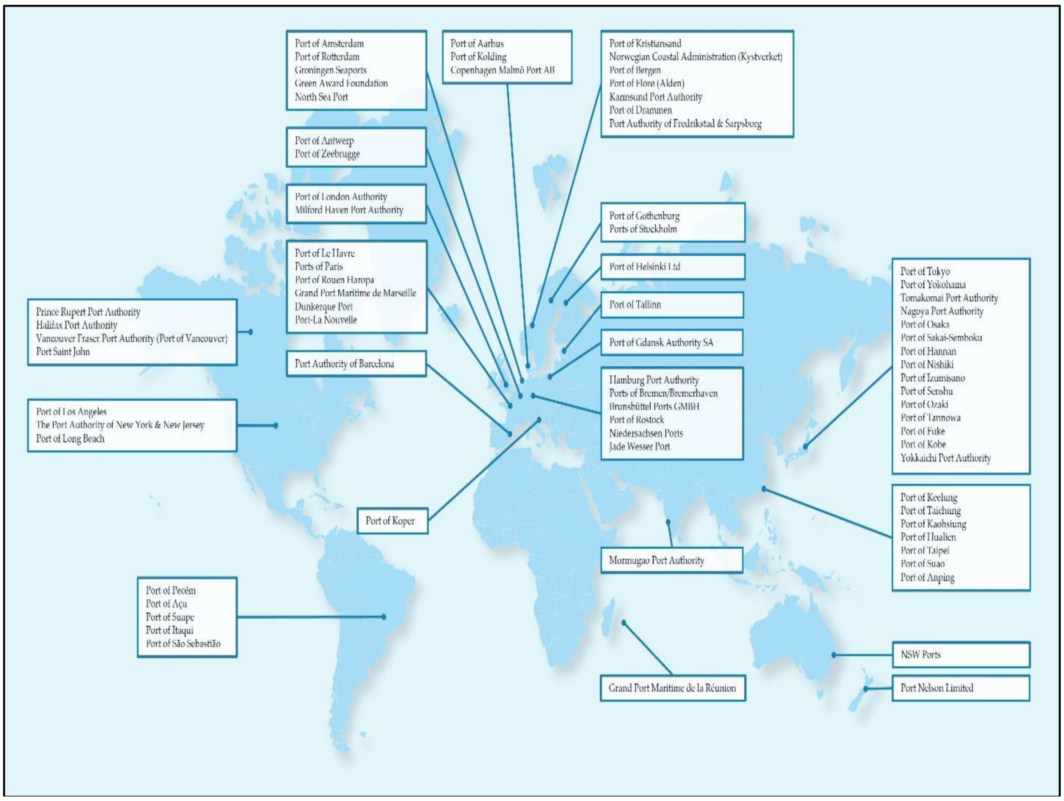

Figure 22: Participating ports and Incentive Providers of ESI

[190] International Association of Ports and Harbors (IAPH), *Environmental Ship Index (ESI)*, accessed August 20, 2025, https://environmentalshipindex.org/.

Chapter 9

Current Green Initiatives at Port Qasim

The increasing environmental issues, the tightening of international regulations, the urgent necessity to achieve the net-zero emissions level, and sustainable port operations have become the focus of attention in the global maritime policy[191]. The ports have been regarded as some of the most important sites where green innovation and operational efficiency can be embraced as opposed to being treated as sites where cargo can be handled. This change requires adoption of environmentally friendly practices, including shore power provision, incorporation of renewable energy, waste minimization, and use of digital technology in real-time monitoring of the environment[192] [193]. International Maritime Organization (IMO) and other regional initiatives such as the European Green Deal are attempting to ensure that sustainability is embedded in every aspect of port management; By making ports develop low-carbon infrastructures, enhancing multimodal transport connectivity, and establishing stakeholder collaboration frameworks[194].

Green technologies are the pillars supporting this change and offer scalable methods of reducing environmental impact without reducing operational capacity. The developments are transforming the interaction between the ports and the surrounding ecosystems, introducing automated pollution control systems, electrified cargo-handling machinery, etc[195]. Using IoT, AI, and blockchain, smart port systems will optimize the vessel scheduling process, facilitate predictive maintenance, and decrease fuel consumption, all of which will lead to the decrease in the greenhouse gas emissions[196]. Meanwhile, transitioning to the framework of a circular economy promotes sustainable water management practices, energy reuse, and reuse of material in port operations.[197]. By implementing green technologies into the scope of their activities, ports can gain a competitive advantage in a rapidly decarbonizing world trade, at the same time being able to meet the requirements of the environment[198].

The Qasim one of the major marine gateways of Pakistan has also started to welcome the international gradual trend of promoting environmentally friendly port activities though at a low pace. The existing green program of the port consists of air and water

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191 Andriamanantena, A. N., Mbena, J. Y., & Viala, C. (2025). Enabling circular economy transitions in ports: The role of innovation ecosystems in North Sea Port. *Journal of Environmental Management*.
192 Galvão, C. B., Robles, L. T., & Cutrim, S. S. (2025). Best practices in ESG: a benchmarking for Brazilian seaports sustainability journey. *Journal of Shipping and Trade*.
193 Bulak, Muhammet Enis. "A Frontier Approach to Eco-Efficiency Assessment in the World's Busiest Sea Ports." *Sustainability* 16, no. 3 (2024): 1142.
194 Ali, S. S. S., Abd Razak, M. H., & Shukri, M. S. B. I. N. (2024). Magnitudes of carbon footprint in Port Klang towards Net Zero Port 2050 in Malaysia. *Journal of Engineering Science and Technology*.
195 Hu, H., Wang, N., Zhang, C., & Yang, Y. (2025). Optimizing the portfolio of smart technologies to maximize port carbon emission efficiency: A configurational theory approach. *Maritime Policy & Management*
196 Delfin-Ortega, O. V. (2025). Technological gaps and sustainability in maritime transportation (2000–2023): An analysis using the SFA-based metafrontier approach. *Research Square*.
197 Czermański, Ernest, Izabela Kotowska, Aneta Oniszczuk-Jastrząbek, Michał Pluciński, and Elżbieta Szaruga. "Factors influencing the adoption of circular economy practices in polish seaports: an analysis of determinants and challenges." *Frontiers in Marine Science* 11 (2024): 1465204.
198 Andriamanantena, A. N., Mbena, J. Y., & Viala, C. (2025). Enabling circular economy transitions in ports: The role of innovation ecosystems in North Sea Port. *Journal of Environmental Management*.

quality pilot level monitoring, the installation of energy-saving systems of lighting and simple training of operational personnel on environmental awareness. They are mostly reactive, as a result of the pressure of external compliance and not an overall sustainability strategy. They however, are an indication of an increasing awareness of the environmental externalities of the port and industrial activities.

One of such efforts is the fact that private terminal operators have limited the use of solar photovoltaic (PV) systems in powering office infrastructure. Other operators have installed storm water drains, which contained sediment traps, which stop the discharge into the nearby Korangi Creek that has been exposed to massive dumping of industrial effluents. Moreover, the ISO 14001 Environmental Management System (EMS) certification activities are being done in a few oil and bulk terminals and this is a beginning of a normative environmental performance[199].

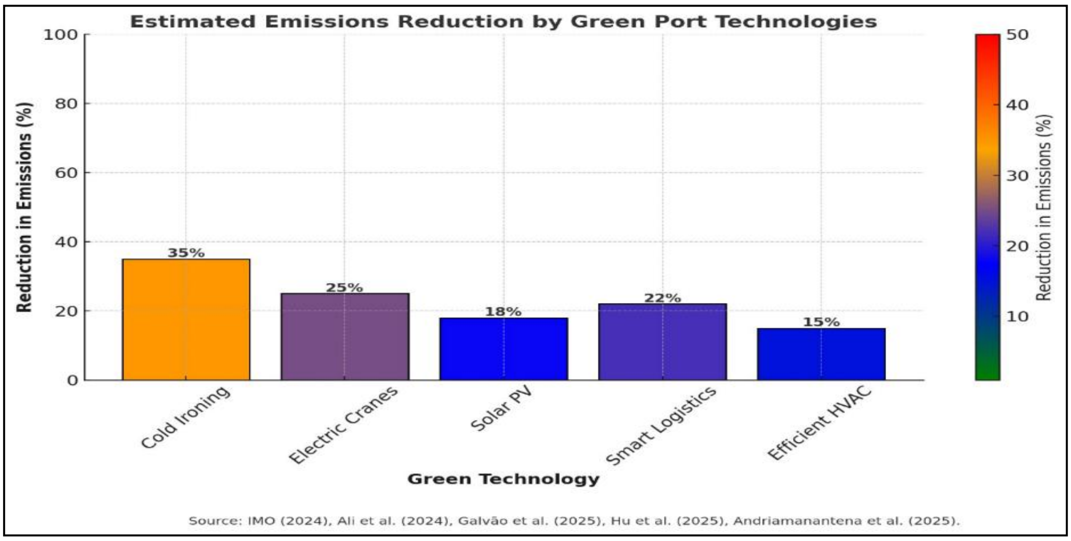


Figure 23: Reduction of GHG emission by adopting Green Technologies

Regardless of these trends, Port Qasim does not have an established Green Port Master Plan and has not embraced any of the established frameworks such as the World Ports Sustainability Program (WPSP) or the Eco-Ports initiative. Conversely, major Asian ports, including Singapore, Busan, and Shanghai, have adopted an overall low-carbon policy with smart infrastructure, emissions control, and waste-to-energy[200].

[199] WMU. (2023). Green Port Strategies for South Asia: A Comparative Study. World Maritime University Dissertations.
[200] Ren, Y., Xie, T., & Ning, Z. (2024). Degradation, Ecological Restoration and Adaptive Management of Estuarine Wetlands under Intensifying Global Changes. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2024.1429612

9.1 Air Quality analysis of PQA from Jan-Jul 2025

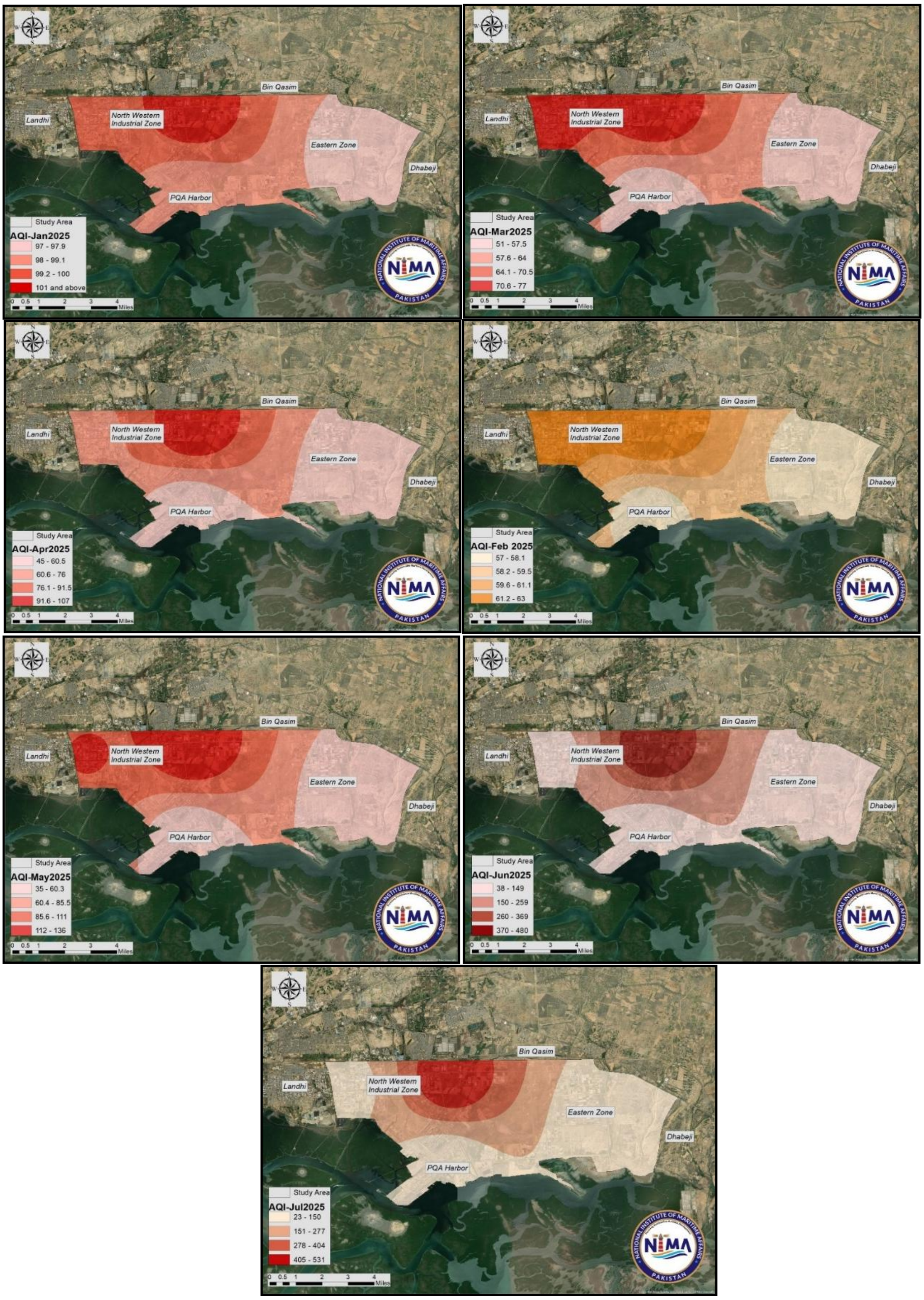


Table 17: AQI Status by Month and Zone (Jan–Jul 2025)

Month	Zones	AQI Rating	Remarks
January	NW Industrial Zone, PQA Harbor, Eastern Zone	Poor 97–101+	Winter inversion traps pollutants; industrial smoke buildup.
February	Industrial Belt, Harbor Zone	Moderate 57–63	Winds disperse pollutants, temporary relief.
March	NW Industrial Zone, Port Areas	Moderate → USG 51–77	Hotspots remain over industries; port cleaner.
May	Industrial & Harbor Zones	Unhealthy 35–136	Summer ozone + haze worsen AQI.
June	NW Industrial Zone, Communities	Very Unhealthy → Hazardous 38–480	Sharp rise; stagnant summer air + emissions.
July	Industrial Belt, Harbor, Eastern Zone	Hazardous 23–531	Widespread health emergency; severe pollution.

9.1.1 Air Quality Index (AQI)

Air Quality Index (AQI) of Port Qasim reflected a gradual degradation of the air quality between January and July 2025. In the first quarter the values were within the range of Moderate to Unhealthy for Sensitive Groups (USG) and they ranged between 57 and 101. This shot up to AQI of 136 in April and May, which is classified in the Unhealthy category. The most alarming observations were recorded in June and July, where values escalated to 480 and 531 respectively, classifying the air quality as *Very Unhealthy to Hazardous*. These extreme levels highlight the worsening air quality conditions during the summer months, primarily driven by particulate matter pollution, intensified port operations, and meteorological factors that restrict pollutant dispersion.

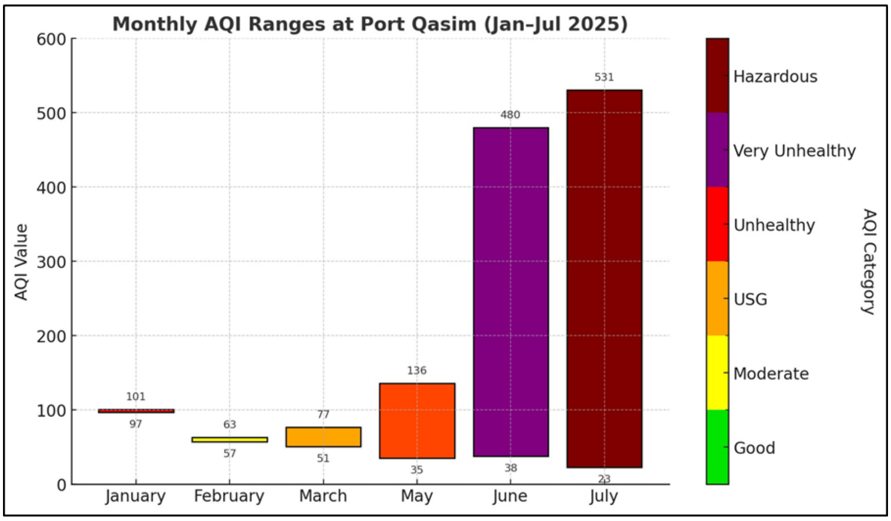
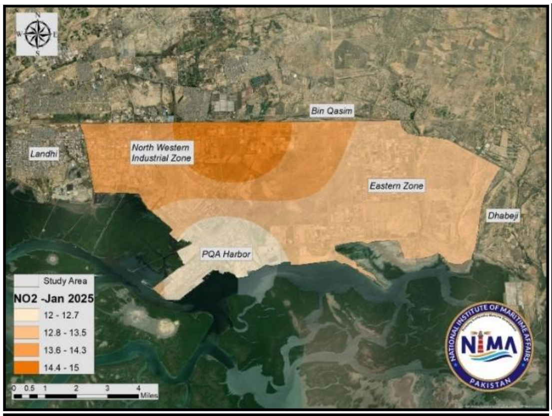
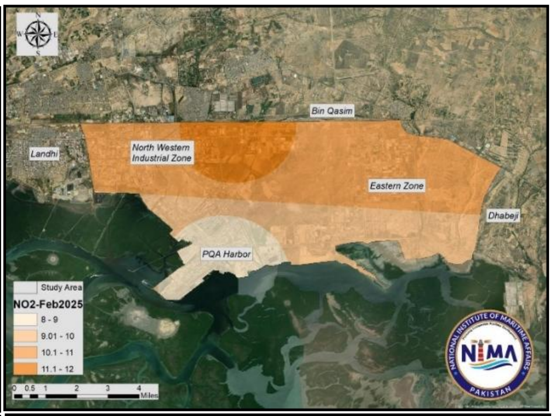
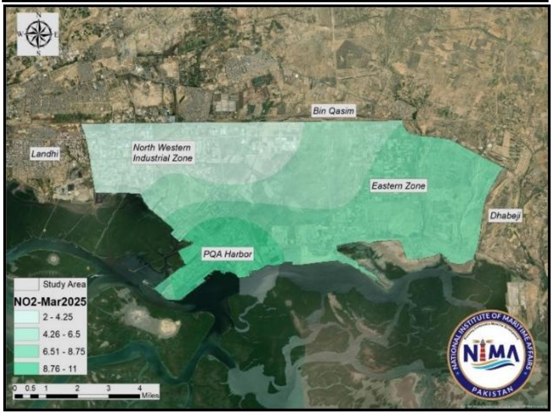


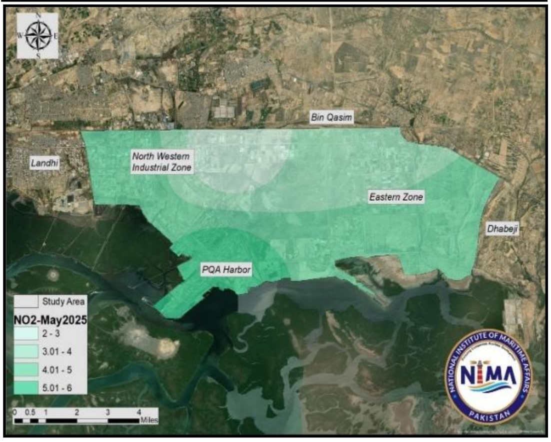
Figure 24: AQI data of PQA

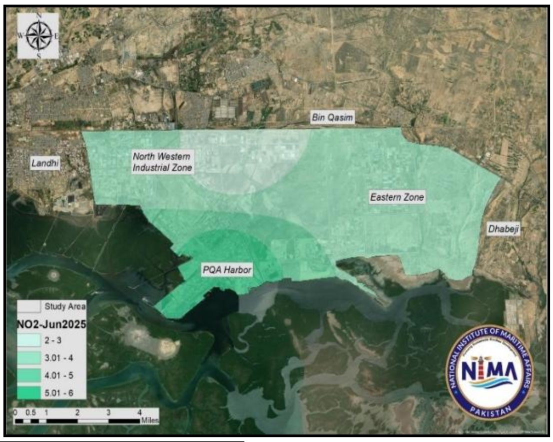
9.2 NO_2 Concentration











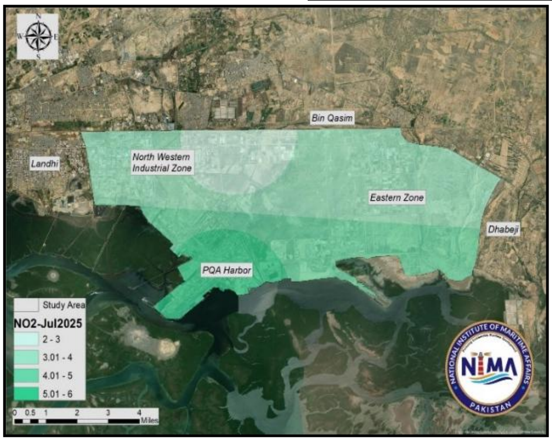


Table 18: NO2 Concentration of PQA

Month	Zones	NO_2 (µg/m³)	Remarks
January	NW Industrial Zone, PQA Harbor	12.0 – 15.0	Peak levels; winter inversion traps pollutants.
February	NW Industrial Zone, Harbor	8.0 – 12.0	High emissions from industries & traffic.
March	NW Industrial Zone, Harbor	2.0 – 11.5	Decline begins, hotspots near harbor.
April	NW Industrial Zone, Eastern Zone	2.0 – 6.5	Cleaner air, strong dispersion.
May	Industrial Belt, Harbor	2.0 – 6.0	Sustained low concentrations.
June	Harbor, Communities	2.0 – 6.0	Stable, low-level emissions.
July	All zones	2.0 – 6.0	Lowest levels, cleanest phase.

9.2.1 Nitrogen Dioxide (NO_2)

Nitrogen dioxide concentrations were relatively elevated in the winter months, with January recording the peak value of 15 µg/m³. Levels gradually declined over subsequent months, stabilizing at 6 µg/m³ between May and July. This trend reflects seasonal atmospheric dynamics where cooler conditions in winter allow greater accumulation of NO_2, while warmer months enhance its dispersion. Although the observed concentrations remained below the WHO annual guideline of 10 µg/m³ on average, localized short-term peaks in the early months suggest emissions linked to shipping traffic, cargo handling equipment, and nearby industrial sources.

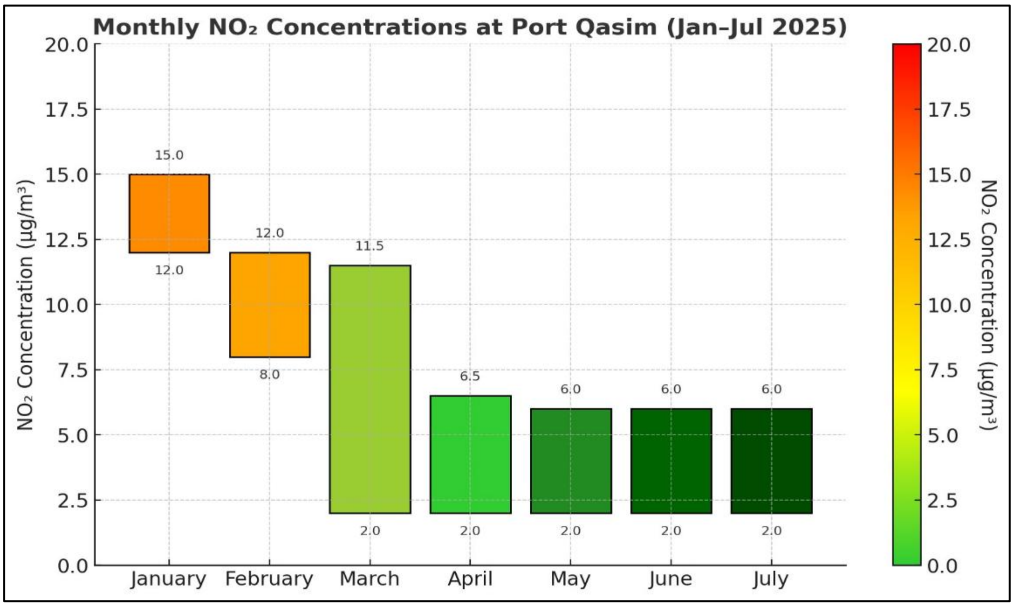
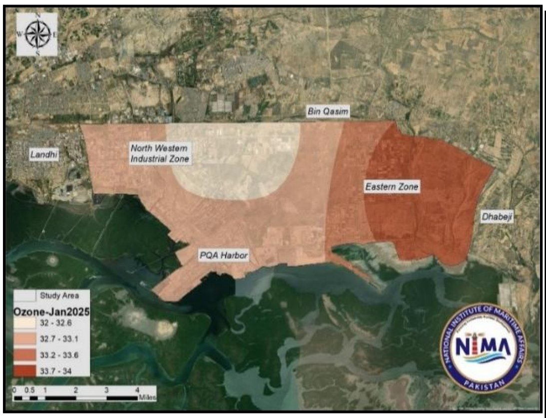
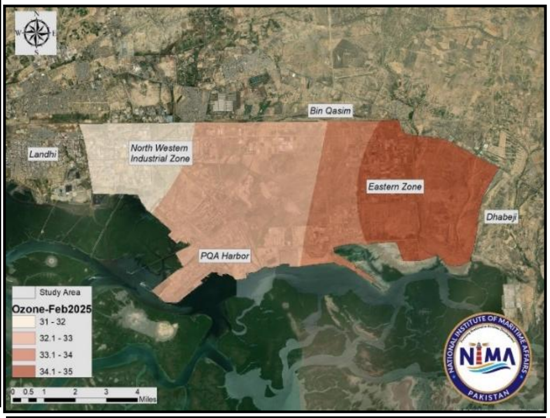
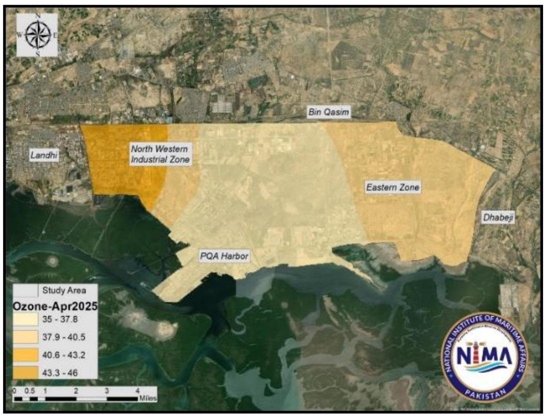


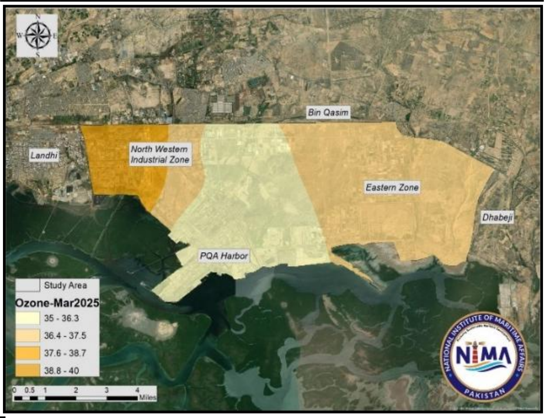
Figure 25

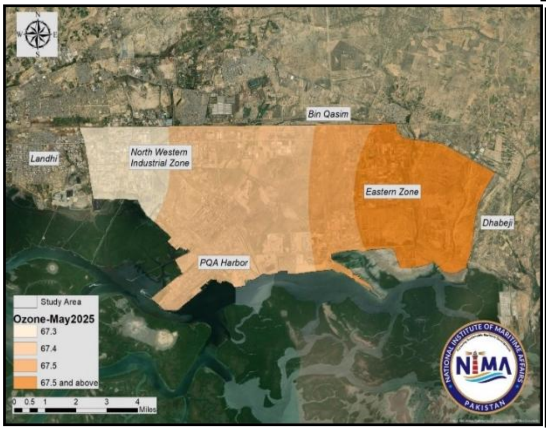
9.3 Ozone O_3 Concentration

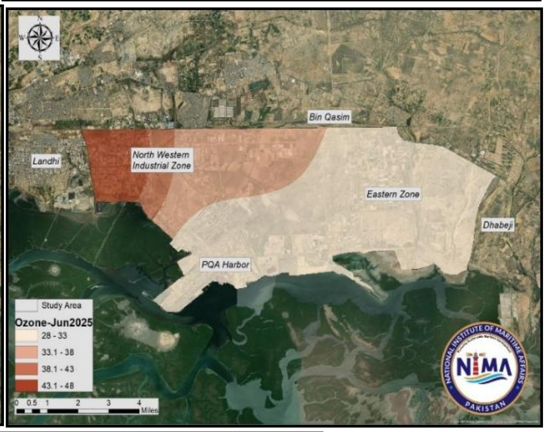












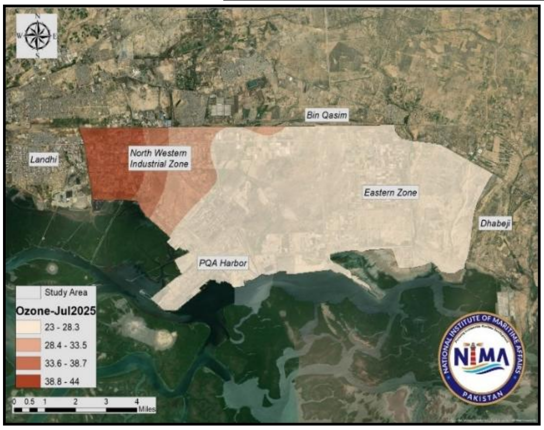


Table 19: Ozone (O_3) Concentrations at Port Qasim (Jan–Jul 2025)

Month	Zones	O_3 (µg/m³)	Hazard Category	Remarks
January	Eastern Zone	32 – 34	Moderate	Winter stagnation, mild buildup.
February	Eastern Zone	31 – 35	Moderate	Persistent elevated levels.
March	Industrial & Harbor Zones	36 – 40	Moderate	Transition to higher photochemical activity.
April	All Zones	35 – 43	Elevated	Widespread buildup, beginning of summer photochemistry.
May	Eastern Zone	67+	High	Peak ozone levels; health risks evident.
June	NW Industrial Zone	28 – 48	Moderate → Elevated	Variable; hotspots near industries.
July	NW Industrial Zone	23 – 44	Moderate → Elevated	Industrial belt shows strong ozone formation.

9.3.1 Ozone (O_3)

Ozone concentrations exhibited a rising trend from January to May, with values increasing from around 32–35 µg/m³ in the early months to a peak of 70 µg/m³ in May. While these levels remained below the WHO 8-hour guideline of 100 µg/m³, the upward pattern indicates enhanced photochemical activity during the summer due to stronger solar radiation and the interaction of nitrogen oxides with volatile organic compounds (VOCs). Concentrations slightly decreased in June and July but still remained elevated compared to the winter period. Although not exceeding global thresholds, persistent high ozone levels in the warmer months can contribute to respiratory stress for port workers and communities living near the port.

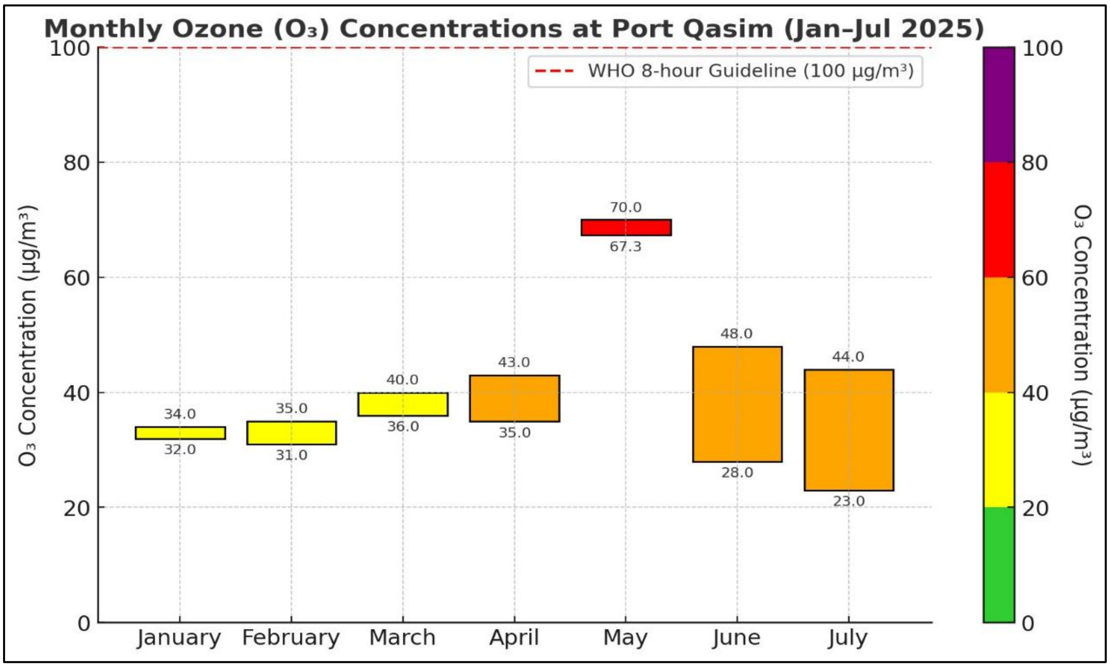
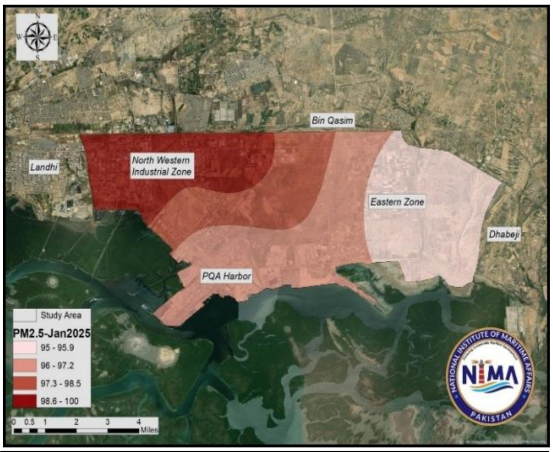
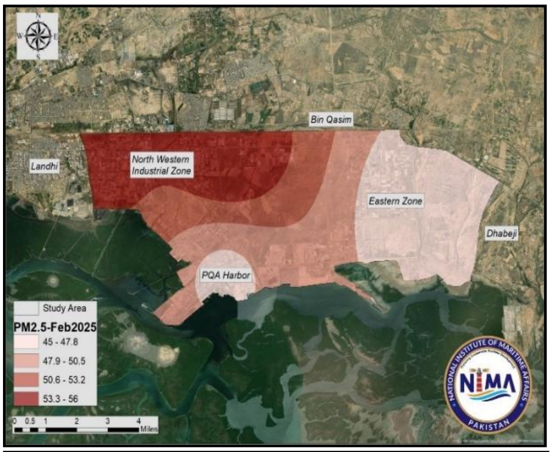
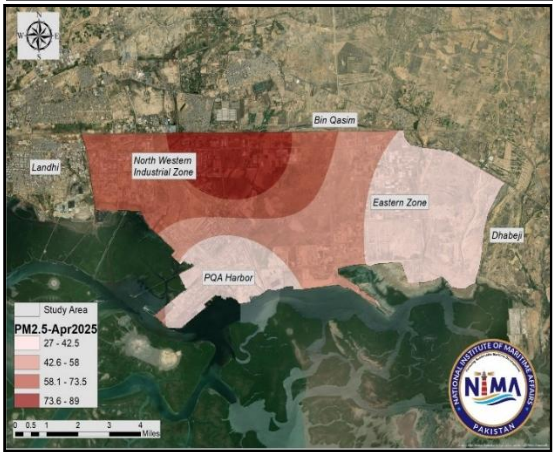


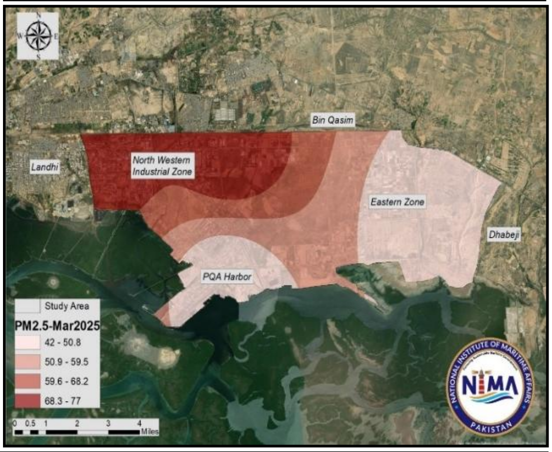
Figure 26: Concentration at PQA

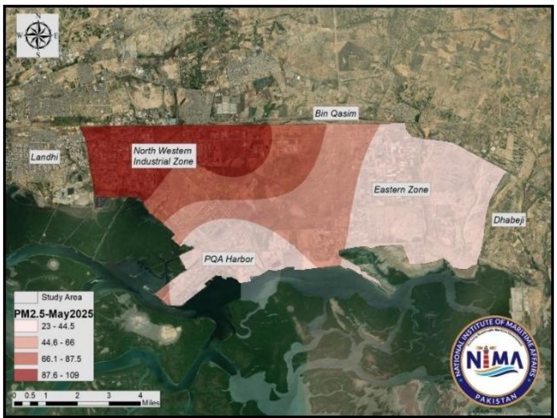
10.4 PM 2.5 Concentration

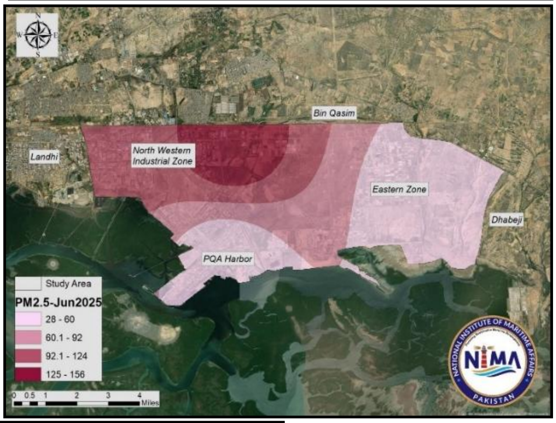












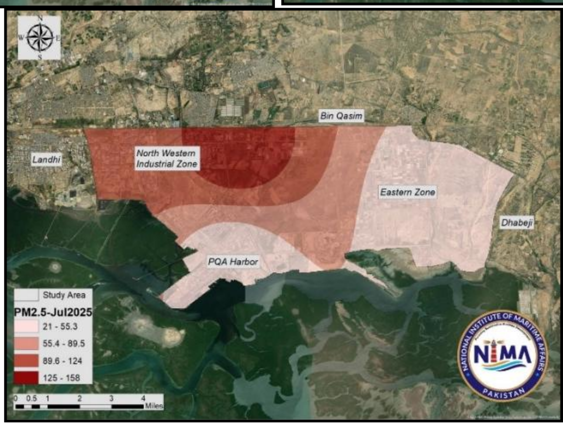


Table 20: $PM_{2.5}$ Concentrations at Port Qasim (Jan–Jul 2025)

Month	Zones	$PM_{2.5}$ (µg/m³)	Hazard Category	Remarks
January	NW Industrial Zone, Harbor, Eastern Zone	96 – 100	Very Unhealthy	Extremely high, poor dispersion.
February	Industrial Belt, Harbor	45 – 56	Unhealthy	Reduced but still elevated.
March	NW Industrial Zone, Harbor	42 – 77	Unhealthy → Very Unhealthy	Persistent hotspots.
April	All Zones	37 – 74	Unhealthy	Region-wide elevated $PM_{2.5}$.
May	Industrial & Harbor Zones	23 – 109	Moderate → Very Unhealthy	Fluctuating; episodic peaks.
June	NW Industrial Zone, Harbor	28 – 156	Unhealthy → Hazardous	Severe exceedances in industrial belt.
July	NW Industrial Zone, Harbor, Eastern Zone	21 – 158	Moderate → Hazardous	Highest levels recorded; peak risk month.

9.4.1 Particulate Matter ($PM_{2.5}$)

Fine particulate matter ($PM_{2.5}$) presented a critical challenge for air quality at Port Qasim. In January, concentrations were recorded at 100 µg/m³, significantly exceeding the WHO daily guideline of 15 µg/m³. Levels remained high throughout the first half of the year, fluctuating between 56 and 77 µg/m³ from February to April, before rising again to 109 µg/m³ in May. The most severe concentrations were observed in June and July, with values peaking at 156 and 158 µg/m³ respectively, falling within the *Very Unhealthy to Hazardous* categories. These results confirm $PM_{2.5}$ as a dominant pollutant at the port, originating from ship emissions, diesel-powered equipment, and nearby industrial processes, with serious implications for respiratory and cardiovascular health.

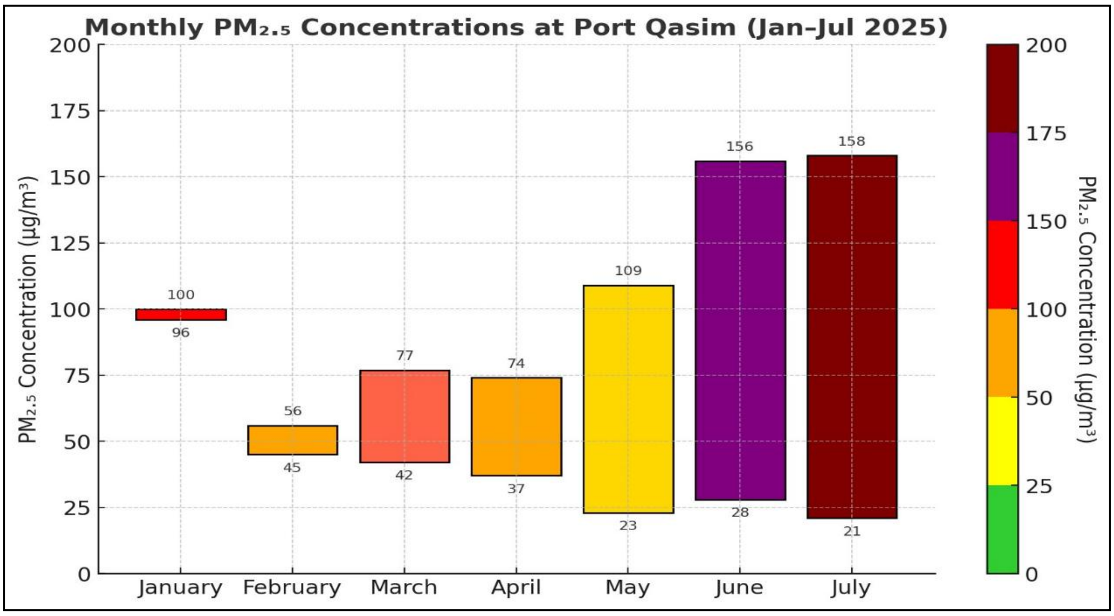
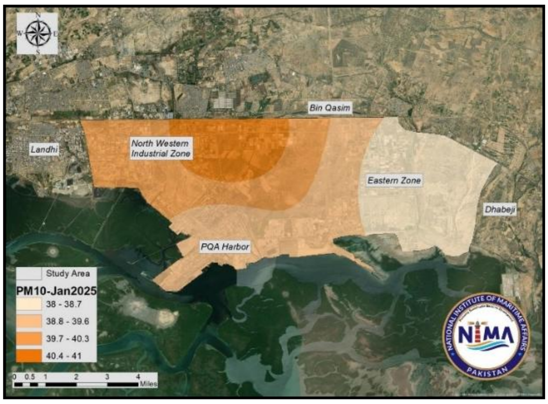
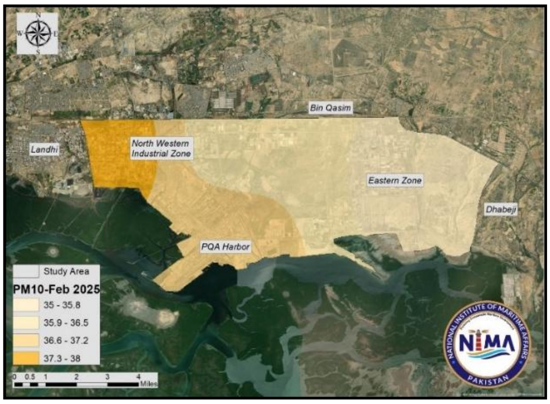
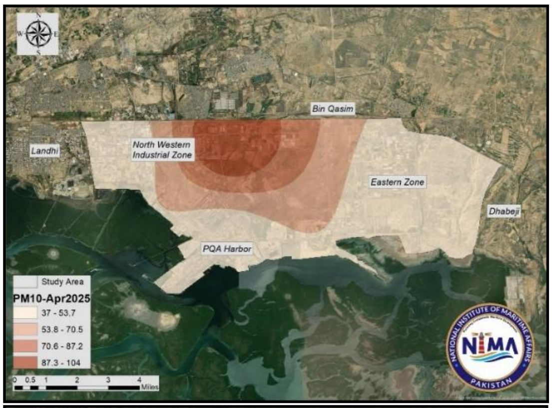


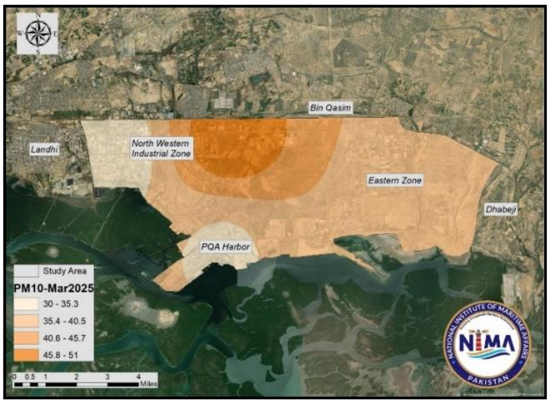
Figure 27: $PM_{2.5}$ Concentration at PQA

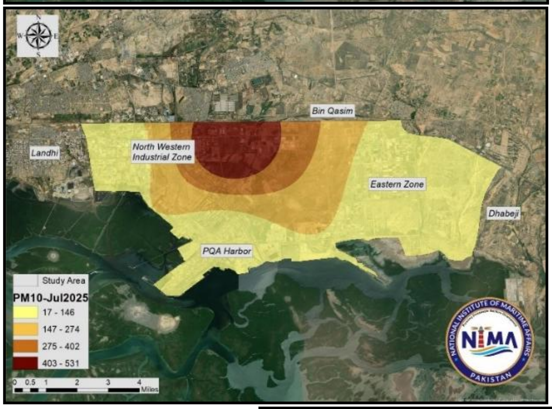
9.5 PM 10 Concentration

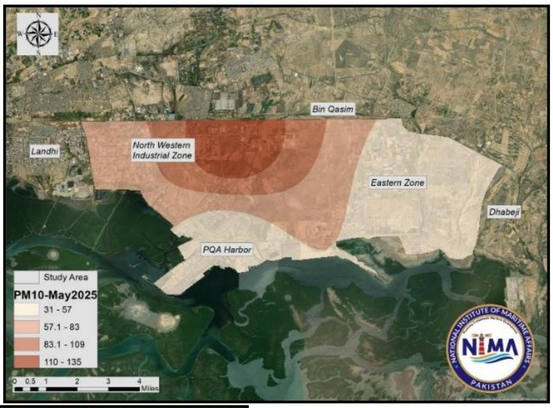












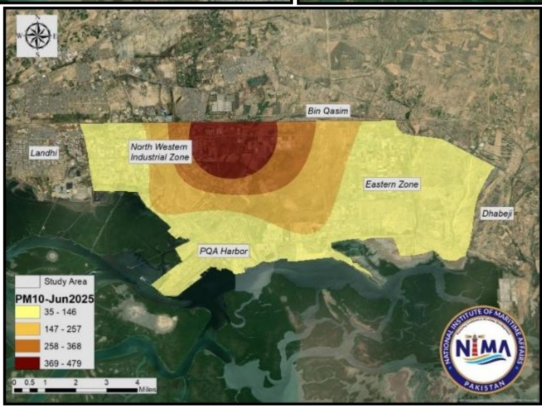


Table 21: PM_{10} Concentrations at Port Qasim (Jan–Jul 2025)

Month	Zones	PM_{10} (µg/m³)	Hazard Category	Remarks
January	NW Industrial Zone, Harbor, Eastern Zone	38 – 41	Moderate	Near WHO limits; industrial dust observed.
February	All Zones	35 – 38	Moderate	Stable, but persistent emissions.
March	NW Industrial Zone, Harbor	30 – 51	Moderate → Unhealthy	Hotspots forming.
April	All Zones	37 – 87	Unhealthy	Rising PM_{10}; start of high dust season.
May	NW Industrial Zone, Harbor	31 – 135	Unhealthy → Very Unhealthy	Exceedances across regions.
June	NW Industrial Zone, Harbor	35 – 479	Very Unhealthy → Hazardous	Severe industrial & dust emissions.
July	NW Industrial Zone, Harbor, Eastern Zone	17 – 531	Good → Hazardous	Peak month; extreme exceedances.

9.5.1 Particulate Matter (PM_{10})

PM_{10} concentrations showed a dramatic rise over the monitoring period. From relatively moderate levels in January to March (30–51 µg/m³), values surged to 87 µg/m³ in April and 135 µg/m³ in May. A critical escalation occurred in June and July, where concentrations spiked to 479 µg/m³ and 531 µg/m³ respectively, pushing the air quality into *Very Unhealthy to Hazardous* ranges. This sharp seasonal increase suggests that PM_{10} is heavily influenced by port-related activities such as bulk cargo handling, construction, and vehicular movement, compounded by summer dust events and stagnant meteorological conditions. The sustained high values not only endanger human health but also pose risks to operational efficiency and equipment longevity at the port.

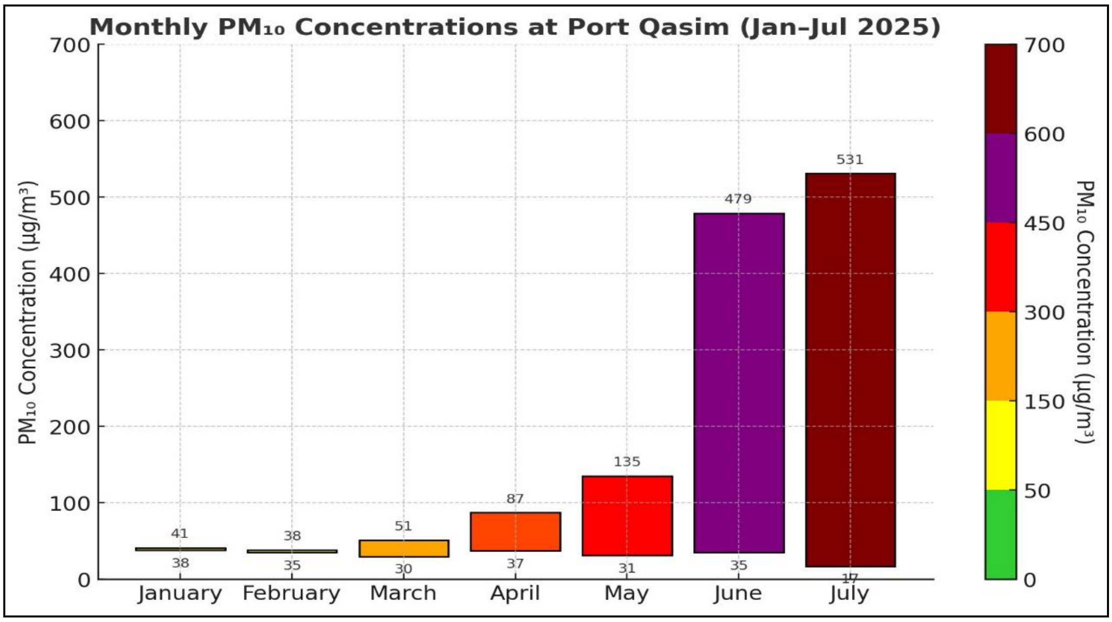


Figure 28: PM_{10} Concentrations at Port Qasim (Jan–Jul 2025)

9.6 Assessment of Sustainability Implementation at PQA

An evaluation based on several interviews was carried out to analyze the present implementation status of several sustainability-related procedures and technologies at the port facilities. The evaluation covers six major categories: energy and emissions, air quality and pollution control, water and waste management, digitalization and efficiency, ecosystem protection, and certification and standards. Each category was evaluated on a four-point scale ranging from 1 to 4, where:

1 = Not Implemented

2 = In Progress,

3 = Partially Implemented,

4 = Fully Implemented

Table 22: Assessment of Sustainability implementation indicators of Port Qasim

Category	Technology / Practice	Remarks
Energy and Emissions	Cold ironing (shore power at berth)	1
	Alternative fuels (LNG, hydrogen, methanol, ammonia)	1
	Electrification of cargo handling equipment (RTGs, cranes, trucks)	1
	Hybrid or electric port vehicle fleet	1
	Renewable energy installations (solar, wind, tidal)	2
Air Quality and Pollution Control	Emission monitoring systems (stack monitoring, CEMS)	1
	Dust suppression systems (sprinklers, filters)	2
	Low-sulfur fuel enforcement and compliance	3
	On-site air quality monitoring stations	1
Water and Waste Management	Sewage treatment plant (capacity, compliance)	2
	Bilge water reception and treatment facility	2
	Ballast water treatment and compliance systems	1
	Solid waste recycling facilities	3
	Hazardous waste disposal system	1
Digitalization and Efficiency	Port Community System (PCS) implementation	4
	Vessel Traffic Management System (VTMS)	3
	Smart logistics platforms (AI for congestion reduction)	1
	IoT-enabled cargo and equipment monitoring	1
Ecosystem Protection	Dredging sediment management practices	4
	Mangrove plantation and coastal green belts	4
	Marine biodiversity monitoring systems	2
	Noise and light pollution control	1
Certification and Standards	ISO 14111 Environmental Management certification	1
	EcoPorts PERS certification	1
	IMO compliance with MARPOL Annexes	3
	EU/International Green Deal alignment	1

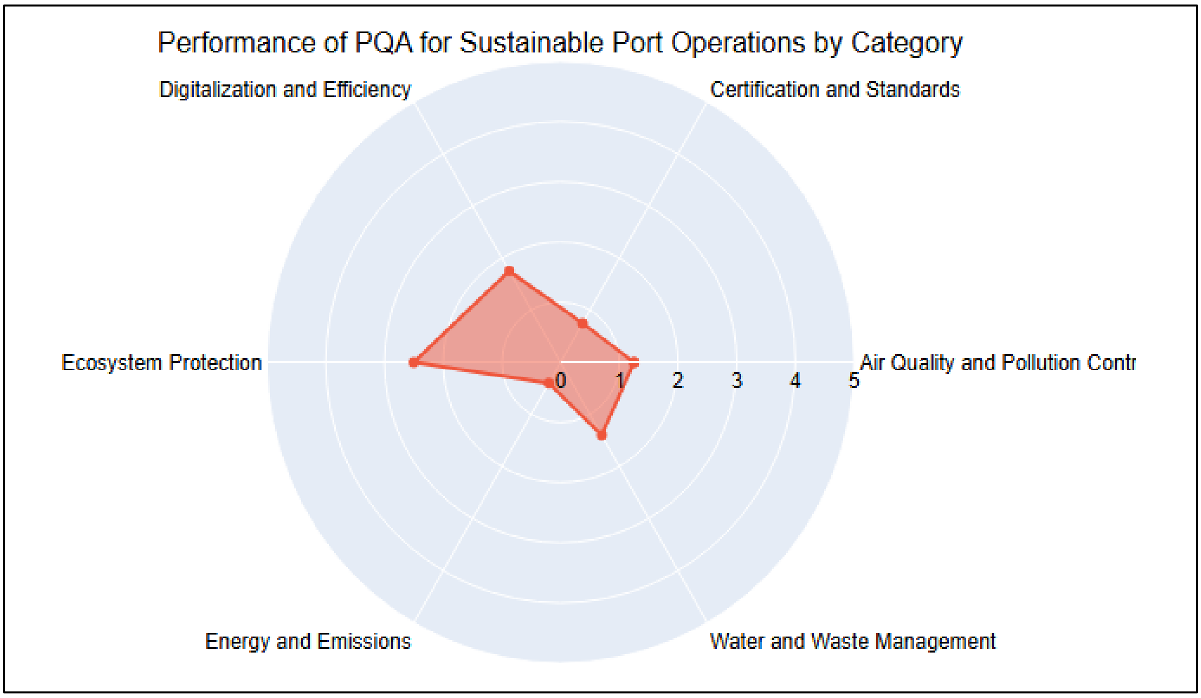


Figure 29: PQA sustainability performance indicator

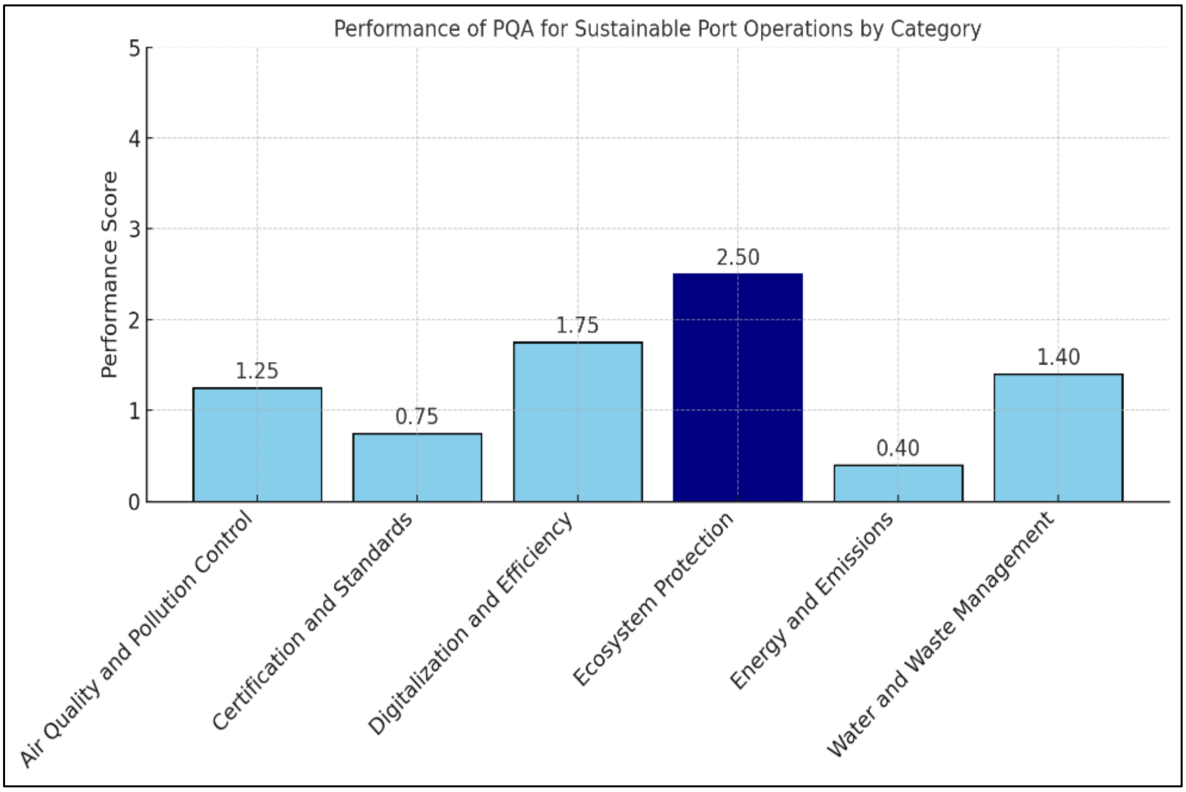


Figure 30: PQA sustainability performance indicator

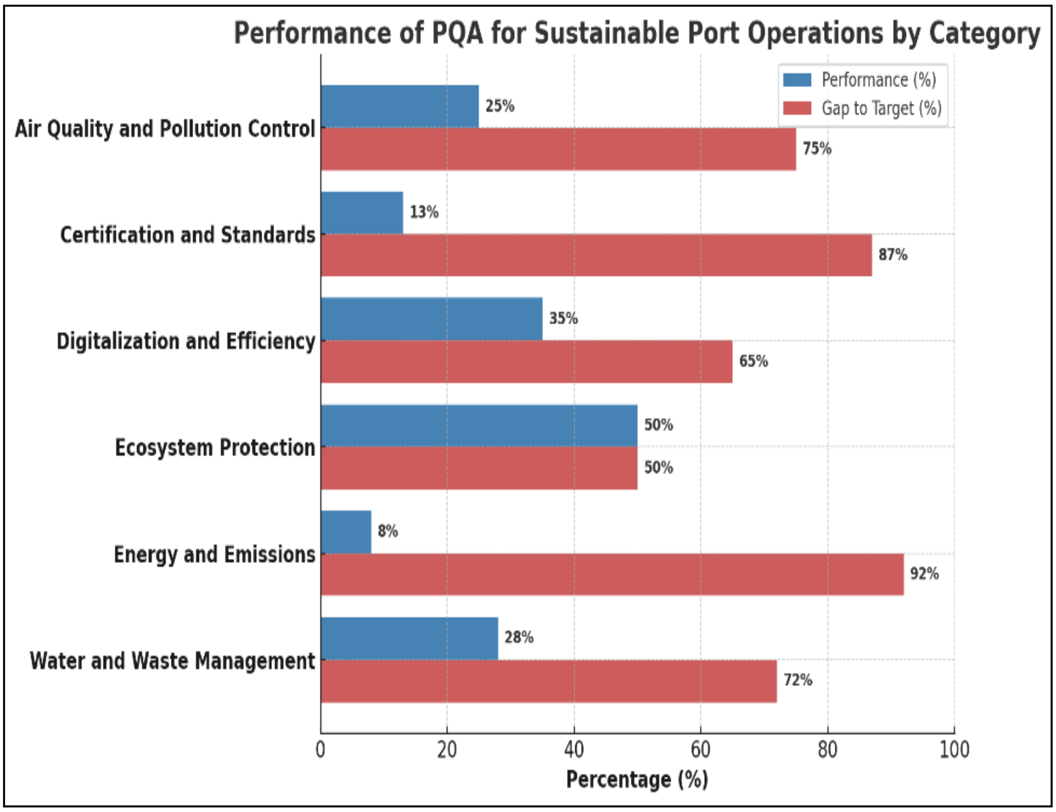


Figure 31: Assessment of Sustainability Implementation at PQA:

9.6.1 Energy and Emissions

This domain shows modest progress. Cold ironing, use of alternative fuels (e.g., LNG, hydrogen, methanol, ammonia), the electrification of cargo handling equipment, and the use of hybrid or electric port vehicles are all still to be introduced. Renewable energy installations (solar, wind, and tidal) are being developed, with an implementation level of 2, meaning that they are now underway.

9.6.2 Air Quality and Pollution Control

Performance in this category has been uneven. Low-sulfur fuel enforcement and compliance have reached the partial implementation stage (state 3), while dust suppression measures (e.g., sprinklers, filters) are being developed (status 2). However, important infrastructures such as emission tracking systems (e.g., stack monitoring, CEMS) and on-site air quality monitoring stations have not yet been installed (status 1), indicating a gap in real-time environmental monitoring.

9.6.3 Water and Waste Management

In this arena, there has been moderate improvement. Sewage treatment facilities and bilge water receipt and treatment systems are currently under development (state 2), while solid waste recycling facilities are partially operational (level 3). However, no implementation has happened for ballast water treatment systems or hazardous waste disposal systems, both scored at zero.

9.6.4 Digitalization and Efficiency

Digital technology has made some of the most important advances in all areas. The Port Community System (PCS) has been fully completed (state 4), whereas the Vessel Traffic Management System (VTMS) has been partially deployed (status 3). Despite this, there has been no development on AI-powered smart logistics platforms or IoT-enabled cargo and equipment observing, both of which have yet to be deployed (status 1), showing potential for digital innovation and congestion reduction.

9.6.5 Ecosystem Protection

This grade represents the most developed implementation state overall. Both dredging sediment management measures, as well as mangrove plantation and coastal greenbelt projects, are completely implemented (state 4). Marine biodiversity monitoring systems are presently in development (state 2). However, no action has been taken to limit noise and light pollution (status 1), indicating a need for more environmental attention.

9.6.6 Certification and Standards

This area is the least developed. No certifications have been obtained, including EcoPorts PERS, ISO 14111 ecological management[201], or alignment with the EU/International Green Deal (all status 1). Only IMO compliance with the MARPOL Annexes has been partially implemented (state 3), indicating a need for better harmonization with internationally accepted norms and frameworks.

Overall, the port has achieved significant progress in ecosystem preservation, as well as digitization and efficiency, with a number of programs now fully implemented. However, significant gaps persist in areas such as energy transition, real-time environmental monitoring, and conformity with international standards. A more comprehensive and balanced approach to sustainability, including neglected areas such as emissions reduction and certification, is required to connect port operations with global environmental goals.

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Recommendations

Table 23: Short Term Recommendations

Area of Action	Recommendation	Purpose/Outcome
Legal and Regulatory Compliance	Review and update national legislation and port regulations to ensure alignment with IMO instruments (SOLAS, MARPOL, STCW, etc.).	Ensure compliance with mandatory IMO instruments and eliminate legislative gaps.
Environmental Compliance (MARPOL)	Implement and document procedures for waste reception, oil spill response, emissions monitoring, and marine pollution control.	Ensure environmental protection measures are in line with IMO MARPOL regulations.
Training and Certification	Ensure all port and maritime personnel are trained and certified under STCW and related IMO frameworks.	Demonstrate competence of personnel in line with international standards.
Record Keeping and Documentation	Maintain updated logs, audit trails, inspection reports, and regulatory compliance documents in a centralized and accessible system.	Provide verifiable evidence of compliance and enable efficient audit responses.
Stakeholder Engagement	Conduct awareness sessions and audit readiness meetings with terminal operators, agents, and service providers.	Promote a culture of compliance and ensure all actors are aligned with audit expectations.
Self-Assessment and Internal Audits	Perform a mock audit or internal IMSAS-compliance review with third-party consultants prior to the official audit.	Identify and rectify weaknesses proactively before the IMSAS audit.
Air, Land, and Water Pollution Documentation	Initiate monthly monitoring of emissions, effluents, and waste with third-party validation and maintain digital records.	Establish baseline pollution data and demonstrate environmental due diligence.
Biodiversity Conservation	Map and document existing ecological assets (mangroves, avifauna, marine life) in port vicinity and initiate mitigation plans.	Demonstrate environmental stewardship in line with IMO and national biodiversity frameworks.

Table 24: Long-Term Recommendations

Area of Action	Recommendation	Purpose/Outcome
Port State Control (PSC) Procedures	Standardize PSC inspection procedures and train personnel in accordance with IMO guidelines.	Strengthen enforcement mechanisms and improve vessel inspection quality.
Maritime Safety and Security	Conduct safety drills, update ISPS Code implementation, and ensure all terminals maintain certified safety management systems.	Demonstrate operational readiness and compliance with international maritime safety standards.

Search and Rescue (SAR) Readiness	Coordinate with PMSA and other agencies to ensure SAR plans, protocols, and coordination mechanisms are updated and tested regularly.	Fulfill IMO obligations related to maritime SAR services and regional cooperation.
Vessel Traffic Services (VTS)	Upgrade VTS infrastructure and ensure trained operators monitor vessel movements and respond to emergencies.	Enhance navigational safety and port control efficiency in line with IMO recommendations.
Hinterland Connectivity	Enhance multimodal transport integration (rail, road, ICDs) and digitize logistics tracking to support sustainable trade flows.	Improve cargo throughput, reduce delays, and support SDG-aligned port development.
Renewable Energy Integration	Develop on-site renewable energy sources (solar rooftops, wind power units) and integrate energy-efficient systems across port operations.	Reduce carbon footprint and align with IMO GHG reduction targets and national energy transition goals.
Long-Term Biodiversity Offset Programs	Implement ecological offsetting through mangrove reforestation, marine protected zones, and artificial reef development.	Institutionalize conservation as part of port expansion and development.
Advanced Pollution Control Systems	Deploy real-time monitoring and AI-based early-warning systems for air and water pollution across the port and surrounding zones.	Establish proactive pollution control to exceed compliance requirements.

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