MARITIME SUSTAINABILITY AND GREEN PORT OPERATIONS IN INDIA INTEGRATING GREEN MARITIME SECTOR UNDER MARITIME AMRIT KAAL VISION 2047

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Abstract

The maritime sector is undergoing a significant transformation toward sustainability, decarbonisation and environmental responsibility in response to global climate commitments and greenhouse gas reduction targets. This study examines the strategic pathways for developing a safe, sustainable and green maritime sector under India's Maritime Amrit Kaal Vision (MAKV) 2047. Adopting a documentary research methodology, the study utilizes secondary data collected from policy documents, sustainability reports, International Maritime Organization (IMO) strategies, COP26 commitments and relevant academic literature. The analysis explores global best practices in green port development, maritime decarbonisation, shore power systems, renewable energy integration and digital transformation initiatives. The findings reveal that leading ports worldwide are advancing carbon-neutral strategies through renewable energy adoption, equipment electrification, alternative fuels and digital technologies that enhance operational resilience and environmental performance. The study further highlights India's roadmap for carbon-neutral port development, including hydrogen and ammonia hubs, LNG bunkering infrastructure, circular port initiatives and shore power implementation. A comprehensive sustainability framework comprising thirteen strategic areas and key performance indicators is proposed to support long-term green port development. The results indicate that successful implementation of MAKV 2047 will require coordinated efforts among port authorities, shipping companies, policymakers and technology providers, supported by investments in green infrastructure and digital innovation. The study concludes that the MAKV 2047 framework provides a strategic pathway for positioning India as a global leader in sustainable maritime development while balancing economic growth, environmental protection and social well-being.

Keywords: Sustainable Ports; Maritime Decarbonisation; Carbon Neutral Ports; Green Shipping

1. Introduction

The Government of India's vision is to cut emissions from the maritime sector in line with the IMO GHG reduction strategy and to facilitate the development of zero- or low-emission technologies (IMO, 2023; MoPSW, 2023a). Under COP26, the climate goals aim to keep global warming well below 2 °C and to ensure it does not exceed 1.5 °C above pre-industrial levels (UNFCCC, 2021; IPCC, 2023). Major ports have taken numerous initiatives, including more solar and wind energy, shore power for ships

and electric port equipment (MoPSW, 2023b; PIB, 2024). Beyond the ports, the shipping sector has seen increased use of ships powered by alternative fuels, and such ships are at various stages of development (MoPSW, 2023a). To lead in safe, sustainable and green shipping, initiatives for both ports and shipping have been considered under the Maritime Amrit Kaal Vision 2047 action plan (MoPSW, 2023a; PIB, 2023).

The theme has 22 initiatives in total (MoPSW, 2023a). Major port initiatives for 2047 include a strategy to make all major ports carbon-neutral and a phased shift to alternative fuels such as LNG, hydrogen/ammonia and biofuels for port vehicles (MoPSW, 2023a; MoPSW, 2023b). For shipping, initiatives include a De-Carbonisation Cell at the DG Shipping, over 20 pilot projects under India's green maritime shipping programme, and incentives for low-carbon vessels and retrofits of existing vessels (MoPSW, 2023a).

The primary objectives of this study are:

i) To examine global best practices in maritime sustainability, green port operations, decarbonisation initiatives in the maritime sector.
ii) To analyse the strategic initiatives, targets and implementation pathways proposed for developing a safe, sustainable and carbon-neutral maritime sector.
iii) To develop a Key Performance Indicator (KPIs) for promoting green port operations and achieving sustainable maritime development in India by 2047.

2. Literature Review

i. **Ren, X., et al., (2024)** conducted research on the impact of digital development on port security resilience in China, highlighting the growing importance of technology-driven solutions in modern port management. The study evaluated digital development through indicators such as digital infrastructure, digital applications and digital industry development, while port security resilience was measured using water traffic safety, rescue and recovery capabilities and operational efficiency. Using panel data from 16 Chinese coastal and Yangtze River Economic Belt provinces between 2010 and 2019, the authors found that digital development significantly improves port security resilience, demonstrating both long-term benefits and regional variations in impact.

   The findings are highly relevant to maritime sustainability and green port operations; as digital transformation serves as a critical enabler for sustainable maritime practices. Advanced digital infrastructure and smart port technologies facilitate real-time monitoring, efficient traffic management, resource optimization and enhanced operational performance, all of which contribute to reducing environmental impacts and improving port resilience. The study emphasizes that sustainable and green port operations are increasingly dependent on digital innovation, which not only improves security resilience but also supports the broader objectives of environmentally responsible and efficient maritime transportation systems.

ii. **He et al. (2023)** examined the influence of digital transformation on the operational resilience of port firms, particularly under conditions of supply chain disruption. The study developed measurement frameworks for Digital Transformation Grade (DTG), Technological Innovation Capacity (TIC) and Port Operational Resilience (POR) and analysed data from 334 Chinese port firms, comprising 3,586 observations collected between 2011 and 2021. Using ordinary least squares and fixed-effect regression models, the authors found that digital transformation significantly enhances the operational resilience of port firms by improving the coordination of human resources, information systems and technological capabilities. The study further identified technological innovation capacity as a mediating factor through which digital transformation strengthens resilience. Additionally, supply chain disruptions were found to

reinforce the positive relationship between digital transformation and operational resilience. The results also revealed an inverted U-shaped relationship between digital transformation and operational resilience, indicating that firms may experience initial adjustment challenges before realizing long-term resilience benefits, while leading firms obtain diminishing marginal gains from further digital investments.

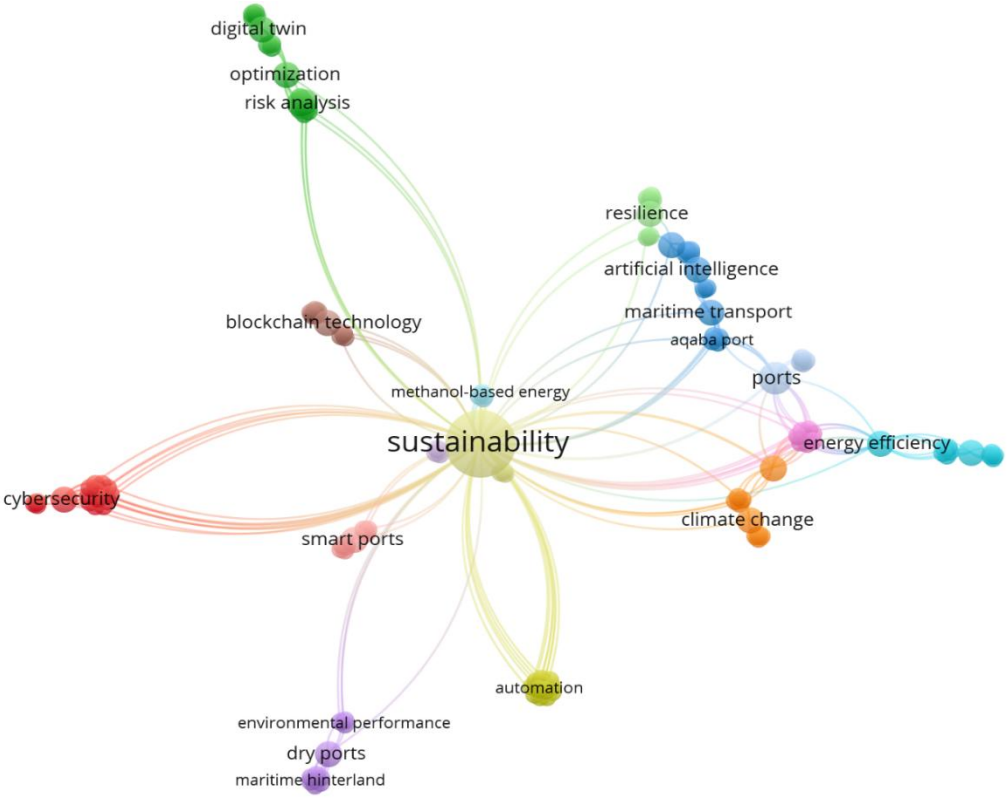
The findings provide important insights for maritime sustainability and green port operations. Digital transformation enables ports to optimize resource utilization, improve operational efficiency and enhance the adaptability of maritime logistics systems during disruptions. Technological innovation supports the implementation of smart and environmentally sustainable port practices, including automated operations, digital monitoring systems and data-driven decision-making processes. These advancements contribute to reduced energy consumption, improved service reliability and greater resilience of green maritime operations. The study highlights that continuous investment in digital technologies is essential for building sustainable and resilient port ecosystems capable of supporting long-term environmental and economic.

iii. **Wang et al. (2023)** investigated port resilience as a critical component of sustainable maritime transportation systems, recognizing the increasing vulnerability of ports to disruptions and disasters in the post-pandemic era. The study proposed a four-stage circular framework to assess and enhance port resilience by identifying major disturbances affecting ports and evaluating resilience capabilities through readiness and response capacities. A Bayesian Network-based assessment model was developed using expert judgments and statistical analysis, with the Shanghai Yangshan Deepwater Port serving as the case study. The adoption of automated terminal technologies, real-time monitoring systems and advanced data analytics contributes not only to resilience but also to operational efficiency and environmental sustainability. Enhanced visibility and rapid recovery mechanisms enable ports to optimize resource utilization, reduce delays and support greener logistics operations. The research highlights that integrating digital technologies, automation and resilience-building strategies is fundamental for developing sustainable and environmentally responsible port systems that align with the objectives of the green maritime sector.

iv. **Ayaz et al. (2022)** explored the resilience strategies adopted by container ports during the COVID-19 pandemic through the lens of chaos theory. Recognizing the unprecedented disruptions experienced by the maritime sector, the study aimed to identify and prioritize resilience strategies implemented by Turkish container ports to maintain operational continuity under highly uncertain conditions. Subsequently, the identified strategies were evaluated and prioritized using the Fuzzy Analytic Hierarchy Process (AHP), which incorporates fuzzy logic to reduce subjectivity and inconsistencies in decision-making. The findings revealed that control mechanisms, hygienic measures and information exchange were the most effective strategies for enhancing port resilience during the pandemic.

The findings contribute significantly to the understanding of maritime sustainability and green port operations by emphasizing the importance of resilience-oriented management practices in maintaining sustainable port performance during crises. Effective information exchange and control mechanisms support operational efficiency, reduce disruptions and facilitate coordinated responses to emergencies. Furthermore, resilient port management practices enhance the continuity of maritime supply chains while minimizing economic and environmental inefficiencies associated with operational interruptions. These strategies support the broader objectives of the green maritime sector by ensuring that port operations remain efficient, safe and environmentally responsible even under conditions of uncertainty

and disruption.



(Source: Author's analysis using VOSviewer (based on Google Scholar database)

v. **Zhou et al. (2021)** proposed a Digital Twin-based Decision Support System (DSS) to enhance port resilience assessment and decision-making under disruptive conditions. The study introduced digital twinning as an advanced analytical tool capable of creating a virtual representation of port infrastructure and operations, enabling the evaluation of resilience under various disruption scenarios. The proposed DSS assesses port resilience by considering port design, operational processes, potential disruptive events and predefined recovery actions. Unlike conventional resilience assessment methods, the digital twin approach incorporates both disruption-related risks and routine operational uncertainties, providing a more comprehensive evaluation of port performance.
The results demonstrated that the DSS effectively supports resilience estimation and strategic decision-making while emphasizing the importance of accounting for operational uncertainties in resilience planning. Digital twin technology enhances the ability of ports to monitor, simulate and optimize operational activities in real time, leading to improved resource utilization and reduced environmental impacts. By enabling proactive planning and efficient recovery from disruptions, digital twins contribute to the continuity and sustainability of maritime logistics operations. Furthermore, data-driven resilience assessment supports informed decision-making, minimizes operational inefficiencies and strengthens the adaptability of port systems to emerging challenges.

vi. **Farhadi et al. (2016)** examined the resilience of marine transportation systems by utilizing nationwide Automatic Identification System (AIS) data to assess port operational performance following disruptive events. The study focused on developing a quantitative approach to measure resilience using archival vessel movement data obtained from the United States Coast Guard. To demonstrate the applicability of the methodology, the researchers analyzed

disruptions caused by the 2014 collision in the Houston Ship Channel, Texas and the impacts of Superstorm Sandy on the Port of New York and New Jersey in 2012.

The research by Farhadi et al. (2016) contributes to the advancement of maritime sustainability and green port operations by highlighting the importance of real-time data and performance monitoring in resilience management. Furthermore, data-driven resilience measurement supports the development of sustainable maritime infrastructure by enabling port authorities to identify vulnerabilities, optimize operational strategies and strengthen the long-term resilience of green maritime systems.

3. Research Methodology

This study adopts a documentary research methodology based exclusively on secondary data sources to examine the pathways towards a safe, sustainable and green maritime sector under the Maritime Amrit Kaal Vision (MAKV) 2047. The data were collected from official policy documents and reports, including the Maritime Amrit Kaal Vision (MAKV) 2047, International Maritime Organization (IMO) greenhouse gas reduction strategies, COP26 climate commitments and sustainability roadmaps published by major international ports. In addition, peer-reviewed journal articles related to port resilience, digital transformation, maritime sustainability, decarbonisation, shore power systems and green port operations were reviewed to identify global best practices and emerging trends. The collected documents were systematically examined to identify key themes associated with maritime sustainability, carbon-neutral port development, renewable energy adoption, alternative fuels, shore power implementation, digital transformation and environmental performance indicators. A comparative analysis was subsequently undertaken to evaluate the alignment between global port sustainability initiatives and the targets proposed under MAKV 2047.

4. Overview of Safe, Sustainable & Green Maritime Sector

The maritime sector is increasingly transitioning towards safe, sustainable and green operations to address environmental challenges and enhance long-term resilience. Growing concerns over climate change and greenhouse gas emissions have encouraged ports and shipping companies to adopt cleaner technologies and sustainable practices (IPCC, 2023). International initiatives such as the IMO GHG Strategy and the COP26 commitments have accelerated the shift towards low-carbon maritime transportation (IMO, 2023; UNFCCC, 2021). Green maritime development focuses on renewable energy adoption, alternative fuels, shore power systems, equipment electrification and circular economy principles (MoPSW, 2023b; PIB, 2023). Safe maritime operations emphasize risk management, environmental protection and resilient port infrastructure. Digital technologies further support operational efficiency and sustainability through real-time monitoring and data-driven decision-making (MoPSW, 2023b). In India, the Maritime Amrit Kaal Vision (MAKV) 2047 provides a strategic roadmap for developing carbon-neutral ports, green shipping and sustainable maritime infrastructure (MoPSW, 2023a; PIB, 2024).

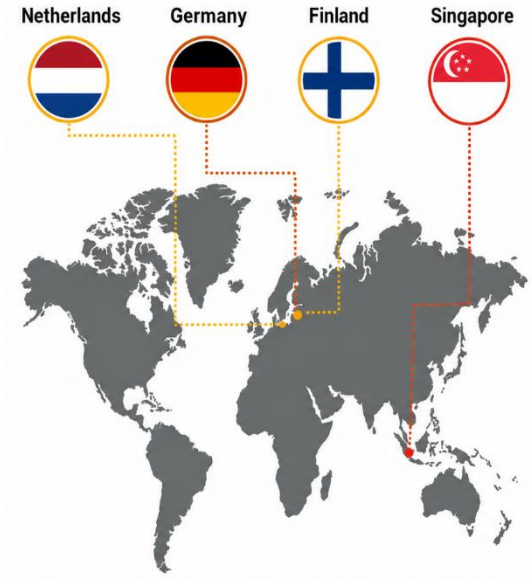
4.1 Maritime Decarbonisation Practices in Global Ports

Controlled increase in the average temperature of the earth through reducing carbon dioxide emissions is the shared global objective of mankind. Similarly, ports and maritime sector will also have to reduce their share of carbon emissions and go for carbon neutrality in coming years. There are several ports across the world who are trying to achieve this objective by formulating strategies and targets.

i. The Port of Rotterdam has set the target to become carbon neutral by 2050. In this connection, they are taking initial measures in the following areas - supply and reuse of surplus energy through steam exchange and heat networks, use of captured CO2 in greenhouses,

replacement of coal by gas and offshore wind energy for the production of electricity, international recycling hub, biomass hub and hydrogen hub.

Table 1: Global ports aiming to become carbon neutral by 2050

	Port of Rotterdam by 2050	• Storage/ use of captured CO_2 • Gas and offshore wind power for electricity generation • International recycling, biomass & hydrogen hubs
	Port of Hamburg by 2040	• Shore power facilities by 2030 • Green electricity for Quayside facility • Emissions reduction certificates to compensate CO2
	Port of Helsinki by 2035	• Shore power capabilities • Incentives for low-emission vehicles • Electrification of machine • Use of biofuels, LED & solar panels
	Singapore Decarbonisation Strategy 2025	• Low/ zero carbon energy sources • Carbon accounting & reporting • Decarbonisation R&D hub

(Source: MoPSW, 2021; UNCTAD, 2020)

ii. The Hamburg Port Authority (HPA) is based on the objective of the city of Hamburg to become carbon neutral by 2040. According to this objective, all the major terminals of the port will have onshore power facilities by 2030. The Hamburg quay side facility is at present fully powered with green electricity (electricity from renewable sources). Moreover, the port makes good the carbon emissions from ongoing port activities by obtaining emissions reduction certificates which will fund projects like wind farms in India, low friction anti-fouling paints for ships and reforestation of rain forests in Panama.

iii. Carbon neutrality will be achieved by Port of Helsinki in 2035. Initiatives undertaken by the port to reach the target include providing shore power facilities at nine berths, introducing incentives to use low emission vehicles, electrification of work machinery infrastructure, promoting biofuel, reduction of energy usage by using LED lights and increase in the number of solar panels.

iv. The Maritime Port Authority of Singapore has formulated a roadmap for decarbonisation to switch to low/zero carbon energy sources by 2050. Moreover, a separate R&D center for decarbonisation technology has been established.

4.2 Roadmap for Carbon-Neutral Port Development in India

The carbon dioxide emissions are because of the boats, work machinery, traffic and operation at the port itself. Considering the source of the emission, below mentioned strategies have been selected for implementation towards achieving carbon neutral ports.

Table 2: Strategic areas to achieve carbon neutrality

Strategic Areas	Already Implemented up to 2021	Short term				Medium Term	Long Term		
		2022	2023	2024	2025	2026-2030	2030-35	2035-40	2040-47
Clean Fuel - Land Based		Battery-operated vehicles MHC electrification		Pilot adoption of alternative fuels such as LNG, blended biofuel-based vehicles		All port equipment including cranes electrified	Adoption of alternative fuels such as LNG, hydrogen-based fuel, biofuel by all ports		
Clean Fuel - Water Based	Port crafts provided with shore electricity at many ports		License for supply of shore power to vessels; Truck-to-ship LNG bunkering		Shore electricity to coastal vessels	Shore electricity to EXIM vessels; Ship-to-ship/Shore-to-ship bunkering	Complete use of shore power for all vessels in ports		
Renewable / Clean Energy	20 MW wind energy generation			Converting port buildings into IGBC Platinum buildings	Hybrid energy generation	Transfer of hybrid energy to other ports/industries; Develop hydrogen hubs at ports	Complete hydrogen supply system for port including energy generation	Develop systems to capture carbon dioxide	Zero carbon footprint at ports
Recycling / Greening	Green belt at many ports	Mechanized truck for fogging and	Decarbonisation cell	Solid waste management and sewage treatment		Use of dredged material for constructi	Achieve target of 33% green cover on ports Implement Circular Port Strategy including		

		road sweeping Green belt at vacant areas			on activities	for the Coastal Economic Zone

(Source: MoPSW, 2021)

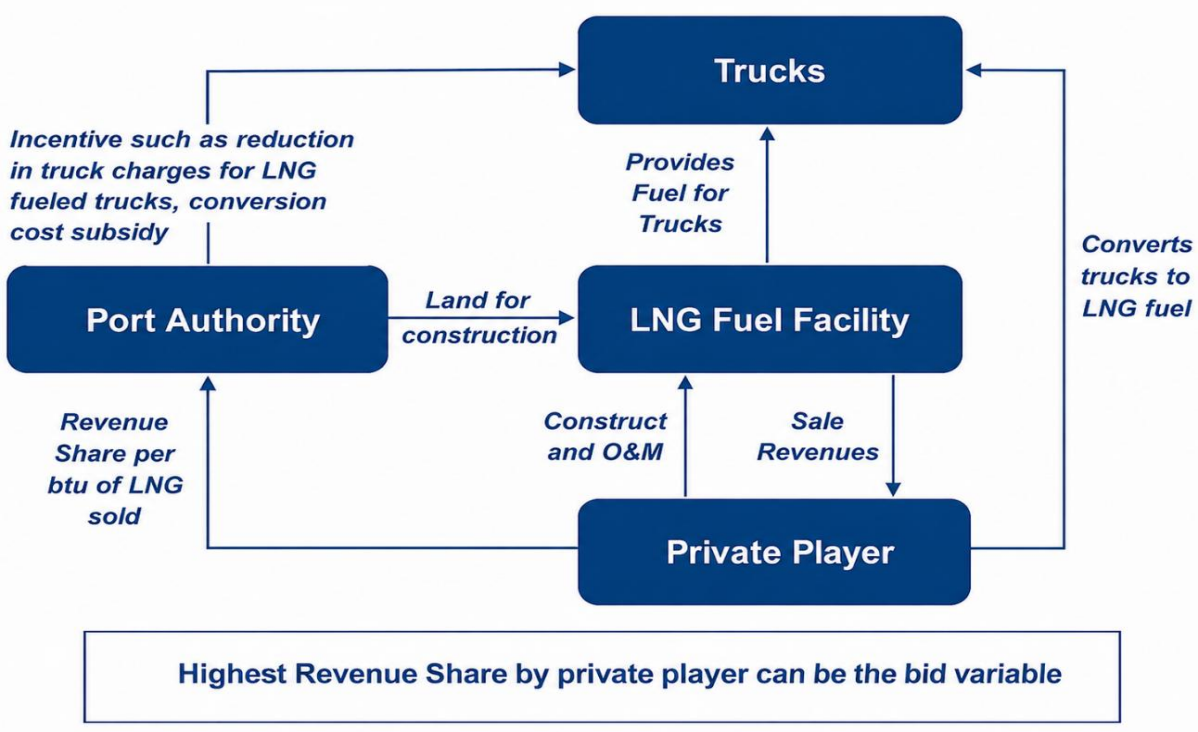
Air pollution is caused primarily by ports. Air pollution results from two different activities taking place in the ports - land-based activities and sea-based activities.

i. Land based activities: In the land side ports use a large number of diesel-operated machineries like straddle carriers, terminal tractors, reach lifters. Such diesel operated machineries contribute to pollution in form of emission of different pollutants. Further, they are also very noisy, which is another form of pollution. Moreover, the ports deal with bulk materials e.g., aggregates, food stuffs, fertilizer and wood products. Such materials in dry and windy conditions create pollution due to drifting of dust into the surrounding environment. Dust being a visible pollutant causes nuisance to people affected.
ii. Sea based activities: At the seaside ships are loaded or unloaded with cargo at the terminals. Ship operates using Heavy Fuel Oil. The price of HFO is much less than the petrol used in the land transportation, but it also contributes more pollution than petrol. The Sulphur dioxide (SO_2) content of HFO is 2700 times more than the road fuel. In developed countries SO_2 emissions have decreased such that SO_2 pollution rarely exists in urban areas. The major SO_2 source left is from ships coming into port.
iii. Clean fuels for lowering emission in land-based operations: In India, presently, only diesel contributes to around 72% of fuel requirement in terms of transport, then petrol accounts for 23% and rest is met through other fuels including CNG, LPG etc., whose requirements have been increasing consistently. The use of green fuels has been made in numerous ports worldwide to decrease the usage of fossil fuels and minimize the emission of air pollution.

PPPs will be investigated in Port Authorities for conversion of trucks and developing and O&M of LNG Fueling Station at ports. Investigation of pilot PPPs will be conducted at JNPT, Chennai and Paradip port and further the model will be expanded to other ports. Following PPP structure (refer below Figure 1) is proposed for faster adoption of LNG based trucks.

i. Private player will provide services for installation of LNG engines on diesel trucks, construction of LNG station on port premises and offering LNG to truck drivers
ii. Oil companies will offer LNG to LNG stations

Figure 1: Structure for developing LNG fuel facility for trucks

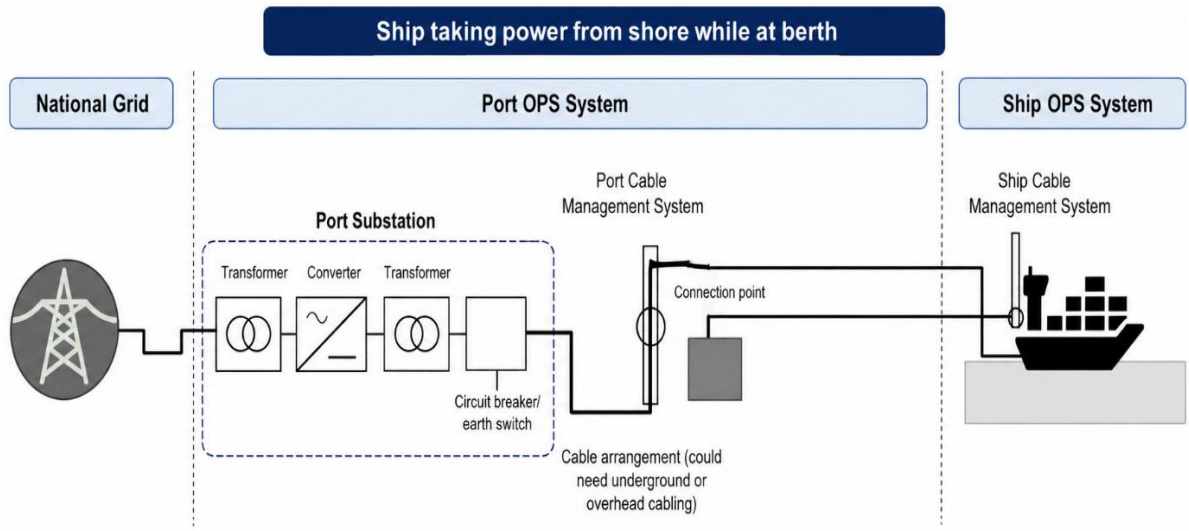


(Source: MoPSW, 2021)

iii. Port management will offer land for constructing LNG station. It will cost money for converting diesel trucks into LNG trucks; hence, port management will pay for subsidies in conversion cost. In exchange, port management will earn share revenue from private party on the basis of per btu of LNG sold. Furthermore, for prompt adoption of LNG trucks, port management will give a specified time period (2-3 years), after which it will not allow entry of diesel-based trucks

LNG FSU can be utilized in the environmental condition wherein LNG storage tank cannot be built on land. Moreover, it can also be applied to the project which is not economical in terms of profit when LNG storage tank is built on the land considering the cost of construction of the land terminal. It can be used in the scenario of using an existing vessel as a replacement for FSU because of tight construction time frame. It can be utilized in case there is a need for extra storage facility while operating a FSRU wherein large capacity regasification plant is installed.

Figure 2: Ship taking power from shore while at berth



(Source: MoPSW, 2021)

Shore Power System (Onshore Power Supply - OPS) is an environmentally sustainable technology that enables ships to receive electricity directly from the shore-side power grid while berthed at a port. As illustrated in Figure X, electricity is supplied from the national grid to the port's Onshore Power Supply (OPS) system, where it passes through a port substation comprising transformers, converters and protective devices such as circuit breakers and earth switches. These components adjust the voltage and frequency of the incoming power to match the electrical requirements of the vessel. The conditioned electricity is then transmitted through the port cable management system to a designated connection point at the berth. From there, power is transferred via the ship's cable management system to the vessel's on board electrical network, enabling the operation of lighting, ventilation, refrigeration, communication and other auxiliary systems.

By utilizing shore power, ships can shut down their auxiliary diesel generators during port stays, thereby significantly reducing greenhouse gas emissions, air pollutants, fuel consumption and noise levels. Consequently, OPS has emerged as a key strategy for promoting green port operations, enhancing environmental sustainability and supporting global maritime decarbonisation objectives, including the International Maritime Organization's (IMO) greenhouse gas reduction targets and national initiatives such as India's Maritime Amrit Kaal Vision (MAKV) 2047.

4.3 Classification of Vessel Categories for Shore Power Implementation

The implementation of shore power infrastructure can be prioritized based on vessel type, operational characteristics and the anticipated environmental and socio-economic benefits. In the short term, shore power adoption can focus on port crafts and ancillary vehicles, such as tugboats and other vessels engaged in internal port operations. These vessels generally consume relatively low amounts of electrical power due to their smaller size; however, they spend significant periods within port areas, resulting in higher localized emissions. Electrification of these vessels can provide direct socio-economic benefits to local vessel owners and operators by offering a cost-effective and environmentally sustainable alternative to conventional fuel-based operations.

Table 3: Phase wise implementation of shore power supply at Indian ports

Key Model Parameters	Short Term	Long Term
	Port crafts & ancillary vehicles	Indian coastal and EXIM

Power consumed by vessel *(Power supply readiness of State electricity board a constraint)*	Low: Lesser power consumed due to smaller vessel size	Medium for shorter/coastal navigation; High for long-haul transport
Residence at Port *(Degree of emissions at ports)*	High: Vessels used for internal port operations	Medium for vessels moving from one Indian port to another; Low for in-transit vessels at particular Indian ports
Socio-economic benefit *(Cheaper options first for local Indians owning smaller vessels)*	Benefits flowing to local Indians owning/operating the vessels	Benefits flowing to local and international trade
Vessel description	Port-based tug boats	Indian vessels carrying cargo on shorter-duration routes and foreign vessels for export/import operations

(Source: MoPSW, 2021)

In the long term, the scope of shore power implementation can be expanded to encompass Indian coastal vessels and export-import (EXIM) shipping operations. Power requirements in this category vary according to vessel size and voyage duration, ranging from medium demand for coastal shipping services to high demand for long-haul international vessels. While coastal vessels regularly call at domestic ports, international vessels may have comparatively shorter port stays at individual Indian ports. Nevertheless, extending shore power facilities to these vessels can significantly reduce emissions from maritime transport and support broader environmental objectives. Furthermore, the benefits of such investments extend beyond local stakeholders by enhancing the sustainability and competitiveness of both domestic and international trade. Consequently, a phased approach that prioritizes port-based vessels in the short term and expands to coastal and EXIM shipping in the long term provides a practical pathway for achieving maritime decarbonisation and sustainable port operations. Therefore, prioritizing port crafts and ancillary vessels in the initial phase, followed by the gradual inclusion of coastal and international shipping operations, represents a practical and economically viable pathway toward achieving sustainable maritime transport, green port operations and the objectives outlined under the IMO decarbonisation agenda and India's Maritime Amrit Kaal Vision 2047.

4.4 Maritime Sustainability Framework for Green Ports

Integrating sustainability into core business practices is considered essential to futureproof the port industry (PIANC, 2014). A sustainability toolkit may be developed to monitor the performance of ports across thirteen key areas of sustainable development (PIANC, 2014). Land use planning is the first step towards becoming a Green Port and applies to both new developments (Greenfield projects) and the upgrading of existing facilities. Port authorities should determine whether the selected location supports long-term operational viability by considering social, ecological and environmental factors such as workforce availability, hinterland connectivity, natural habitats, sedimentation, erosion, flooding and river discharges (PIANC, 2014). Modalities and connectivity are also critical, as growing global trade increases maritime transport demand and requires sustainable hinterland connectivity (PIANC, 2014). Air quality management requires port authorities to ensure that port development does not adversely affect local air quality (PIANC, 2014). In India, major ports are expected to monitor air quality, marine water quality and noise through real-time systems linked to the Ministry's dashboard (MoPSW, 2023). Soil and groundwater quality must be managed to address historical

pollution and control environmental, health and safety risks (PIANC, 2014). Dredging activities should be monitored to test the effectiveness of Best Management Practices (BMPs) and to identify opportunities for beneficial reuse of dredged material (PIANC, 2014). Sound and noise impacts should be controlled through monitoring and zoning (PIANC, 2014; MoPSW, 2023).

Table 4: 13 Areas for Sustainable Strategy

S. No.	Area	S. No.	Area
1.	Land Use Planning	8.	Habitat & Species Health
2.	Air Quality	9.	Surface Water & Sediment Quality
3.	Soil & Ground Water Quality	10.	Ship-Related Waste Management
4.	Modalities & Connectivity	11.	Sustainable Resource Management
5.	Dredging Impacts	12.	Landscape Management & Quality of Life
6.	Sound Impacts	13.	Energy & Climate Change Mitigation
7.	Climate Adaptation		

(Source: MoPSW, 2021)

Energy and climate change mitigation form another important component of the sustainability monitoring toolkit (PIANC, 2014). Since greenhouse gas emissions from maritime activities contribute significantly to global warming, port authorities should focus on reducing energy consumption, improving operational efficiency, modernizing industrial processes and achieving emission reduction. Climate adaptation measures are equally important, requiring ports to prepare for sea-level rise, increased storm surges and other climate-related impacts by developing resilient infrastructure and transport corridors. Habitat and species management should be integrated into port planning through eco-structures, habitat creation initiatives and biodiversity conservation measures, particularly in environmentally sensitive areas. Landscape management and quality of life considerations require ports to conduct visual impact assessments and implement mitigation strategies such as sensitive site planning, landscaping, appropriate design and visual screening. Ship-related waste management should focus on eliminating marine pollution through adequate port reception facilities and incentive schemes that encourage the proper disposal of ship-generated waste and cargo residues. Sustainable resource management aims to minimize waste generation and promote circular economy principles by encouraging cooperation among stakeholders to exchange reusable materials, share experiences and adopt best practices (PIANC, 2014). Collectively, these thirteen sustainability areas should be regularly monitored by a dedicated Program Management Unit (PMU) Cell, with assessments conducted every six to twelve months or following significant interventions to evaluate performance, measure impacts and support continuous improvement in sustainable port operations.

4.5 Key Performance Indicators

The sustainability roadmap for the maritime sector establishes a series of ambitious targets aimed at transforming ports into environmentally sustainable, resource-efficient and low-carbon hubs by 2030 and 2047. The framework envisions the development of one carbon-neutral port by 2030 and the expansion of this achievement to all 14 major ports by 2047, reflecting a long-term commitment to net-zero operations. Similarly, the development of hydrogen and ammonia hubs is targeted at three major ports by 2030 and all fourteen major ports by 2047, facilitating the adoption of alternative clean fuels in maritime transport. The concept of circular ports, which emphasizes resource efficiency, waste minimization and circular economy principles, is also expected to be implemented across all major ports by 2047. In support of cleaner marine fuels, LNG bunkering facilities are planned to increase from one major port in 2021 to four ports by 2030 and eight ports by 2047, providing greater access to lower-emission fuel options for vessels.

Table 5: Key Performance Indicators towards MIV 2030 & MAKV 2047

Metric	Status (as of 2021)	Target (2030)	Target (2047)
Carbon neutral ports	-	1	14
Developing Hydrogen/Ammonia Hubs at major ports	-	3	14
Develop circular ports	-	-	14
LNG Bunkering in major ports	1	4	8
Port equipment electrification (%)	-	50%	>90%
Area under green belt (%)	<10%	20%	33%
Share of renewable energy at ports (%)	<10%	>60%	>90%
GHG emission reduction in domestic/short sea shipping ferries, port vessels (tugs/crafts/dredgers) & OSVs/PSVs	-	30%	70%
GHG emission reduction in all coastal/EXIM vessels	-	10%	50%

(Source: MoPSW, 2021)

The roadmap also emphasizes the transition toward renewable energy and electrification of port operations. The electrification of port equipment is targeted to reach 50 percent by 2030 and exceed 90 percent by 2047, significantly reducing dependence on fossil fuels. The proportion of green belt coverage within port areas is expected to increase from less than 10 percent in 2021 to 20 percent by 2030 and 33 percent by 2047, enhancing environmental quality and ecological resilience. Likewise, the share of renewable energy in port operations is projected to rise from less than 10 percent in 2021 to more than 60 percent by 2030 and exceed 90 percent by 2047. These initiatives are expected to contribute substantially to greenhouse gas (GHG) emission reductions. For domestic and short-sea shipping ferries, port vessels, tugs, crafts, dredgers and offshore support vessels, GHG emissions are targeted to decline by 30 percent by 2030 and 70 percent by 2047. Similarly, all coastal and export-import (EXIM) vessels are expected to achieve a 10 percent reduction in GHG emissions by 2030 and a 50 percent reduction by 2047. Collectively, these targets provide a strategic pathway for achieving sustainable maritime transport, green port operations and the broader objectives of India's Maritime Amrit Kaal Vision 2047.

5. Results and Discussion

The findings indicate that the global maritime industry is undergoing a significant transition towards sustainability, decarbonisation and resilience-driven development. Ports across the world have established ambitious carbon-neutrality targets supported by renewable energy adoption, shore power systems, alternative fuels and digital technologies. The experiences of Rotterdam, Hamburg, Helsinki and Singapore demonstrate that integrated environmental strategies can substantially reduce greenhouse gas emissions while improving operational efficiency.

The analysis of MAKV 2047 reveals that India has adopted a comprehensive roadmap for transforming its maritime sector into a sustainable and low-carbon ecosystem. The roadmap emphasizes electrification of port equipment, renewable energy integration, development of hydrogen and ammonia hubs, LNG bunkering infrastructure, circular port strategies and increased green cover within port premises. These initiatives align closely with international sustainability goals and the IMO decarbonisation agenda.

The study also highlights the growing importance of digital technologies in strengthening maritime sustainability. The literature review confirms that digital transformation, digital twin technology, AIS-based monitoring systems, automation and data-driven decision-making significantly enhance port resilience and operational efficiency. Such technologies facilitate resource optimization, reduce environmental impacts, improve emergency response capabilities and support long-term sustainability objectives.

Further, the phased implementation of shore power infrastructure emerges as a practical strategy for reducing emissions from vessels at berth. Prioritizing port crafts and ancillary vessels in the short term, followed by coastal and EXIM vessels in the long term, offers a technically feasible and economically viable pathway toward maritime decarbonisation.

The proposed sustainability framework consisting of thirteen strategic areas provides a holistic approach to green port development. These areas encompass environmental protection, climate adaptation, energy management, biodiversity conservation, waste management, sustainable resource utilization and community well-being. Continuous monitoring of these dimensions through dedicated sustainability management units can significantly improve the environmental performance of ports.

Overall, the results suggest that the successful implementation of MAKV 2047 will require coordinated efforts among port authorities, shipping companies, technology providers, regulatory agencies and other maritime stakeholders. Investments in green technologies, renewable energy infrastructure and digital innovation will play a decisive role in achieving the envisioned sustainability targets.

6. Conclusion

The maritime sector plays a critical role in global trade and economic development; however, it also faces increasing pressure to reduce environmental impacts and contribute to climate change mitigation. This study examined global best practices, recent academic literature and the strategic initiatives proposed under Maritime Amrit Kaal Vision 2047 to assess pathways toward a safe, sustainable and green maritime sector. The findings indicate that achieving carbon-neutral and environmentally sustainable ports requires a combination of renewable energy adoption, electrification of port equipment, alternative fuel infrastructure, shore power systems, circular economy practices and digital transformation. The MAKV 2047 framework provides a comprehensive roadmap that aligns India's maritime development objectives with international sustainability commitments and IMO greenhouse gas reduction targets.

Managerial Implications

- Port authorities should prioritize investments in renewable energy generation, shore power facilities and equipment electrification.
- Maritime organizations should integrate digital technologies such as digital twins, AIS analytics, automation and smart monitoring systems into operational decision-making.
- Shipping companies should progressively adopt low-carbon and alternative-fuel vessels to meet future environmental regulations.
- Sustainability performance should be monitored using measurable Key Performance Indicators (KPIs) linked to emissions reduction, renewable energy utilization and resource efficiency.
- Public-private partnerships can accelerate the development of LNG, hydrogen and ammonia infrastructure across major ports.

Social Implications

- Reduction in air pollution and greenhouse gas emissions will improve public health and environmental quality in port cities and coastal regions.
- Green maritime initiatives will contribute to national climate goals and support sustainable economic development.
- Development of renewable energy, alternative fuels and green technologies will generate new employment opportunities and promote skill development within the maritime sector.
- Enhanced environmental stewardship will strengthen community well-being, biodiversity conservation and long-term resilience of coastal ecosystems.

In conclusion, the successful realization of MAKV 2047 has the potential to position India as a global leader in sustainable maritime development by creating a resilient, low-carbon and environmentally responsible maritime ecosystem that supports economic growth while safeguarding future generations.

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