

Foundations of Maritime

Decarbonization Alternative Fuels,
Technologies and Regulatory Frameworks

Vahit Çalışır



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☎ +90.850 260 09 97

📞 +90.532 289 82 15

🌐 www.ozgurayinlari.com

✉ info@ozgurayinlari.com

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Vahit Çalışır

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Introduction to Maritime Shipping and Climate Change

1.1 The Role of Maritime Shipping in Global Trade

Maritime shipping constitutes the backbone of international commerce, facilitating the transport of approximately 80% of global goods by volume (Sadiq et al., 2025). Indeed, approximately 90% of international trade travels by sea, underscoring the sector's indispensable role in sustaining global supply chains (Profumo et al., 2025). This sector enables the movement of raw materials, manufactured products, and energy resources across continents, supporting economic development and global supply chains.

1.2 Environmental Impact of the Shipping Industry

Despite its economic significance, the maritime sector represents a substantial contributor to global greenhouse gas emissions. The industry produces over one billion metric tons of carbon dioxide (CO₂) annually, accounting for approximately 3% of total anthropogenic GHG emissions worldwide (Sadiq et al., 2025). According to the International Energy Agency, international shipping accounts for approximately 2% of global energy-related CO₂ emissions, with total annual emissions reaching approximately 1 GtCO₂eq (Di Micco et al., 2022). These emissions predominantly result from the combustion of heavy fuel oils (HFOs) in marine propulsion systems.

The environmental footprint of maritime operations extends beyond vessels at sea. A comprehensive breakdown of emissions within port and maritime ecosystems reveals that maritime transport—including vessel operations, at-berth emissions, and auxiliary engines—accounts for 60–70% of total

emissions, while hinterland transport via trucks, rail, and logistics contributes 20–30%, and port operations including cargo handling, equipment, and energy use represent 10–20% (Sadiq et al., 2025).

When compared to other transport modes, maritime shipping demonstrates superior carbon efficiency. The global transport sector accounts for approximately 21% of total CO₂ emissions, distributed as follows: road passenger transport (9.7%), road freight (6.5%), aviation (2%), and rail (0.2%). Maritime transport, despite handling the vast majority of global trade volumes, remains the most carbon-efficient mode of freight transportation (Profumo et al., 2025).

Data from 2023 indicate that maritime transport emissions have shown modest improvement, contributing 2.1% to global CO₂ production with 822 million tonnes—a slight decrease from 2022 levels (2.3%, 845 million tonnes), attributable primarily to the adoption of slow steaming practices (Profumo et al., 2025). Over the decade spanning 2009 to 2019, CO₂ emissions from maritime transport decreased by approximately 14%, contrasting with increases observed in road transport (20%) and aviation sectors (Profumo et al., 2025).

1.2.1 Maritime Shipping Within the Global Transport Challenge

Understanding maritime decarbonisation requires situating shipping emissions within the broader transport sector context. In 2018, global transportation emitted approximately 8 billion tons of CO₂—24% of CO₂ emissions from fuel combustion—making transport the second-largest source of CO₂ emissions worldwide and the largest source in the United States. Emissions have grown steadily over recent decades, driven by economic growth, increased delivery services, and consumer preferences for larger vehicles such as SUVs and pickup trucks (Naimoli & Tsafos, 2020).

Table 1 Global Transport CO₂ Emissions by Mode (2018)

Mode	Share of Transport Emissions	Absolute (Billion t CO ₂)
Passenger vehicles	45%	3.6
Road freight vehicles	29%	2.3
Aviation	12%	1.0
International shipping	11%	0.9
Rail	<1%	<0.1
Other	2%	0.2
Total	100%	~8.0

Source: Naimoli & Tsafos (2020), based on IEA data

While maritime shipping accounts for 11% of transport emissions, it handles the vast majority of global trade by volume, reinforcing its position as the most carbon-efficient mode of freight transportation. However, absent significant action, aviation and shipping are projected to represent an increasing share of transport emissions as passenger vehicle electrification advances while these harder-to-abate sectors face more persistent technological barriers (Naimoli & Tsafos, 2020).

The scale of the global transport decarbonisation challenge is substantial. Over 1.3 billion cars currently operate on roads worldwide, and even a complete ban on new fossil-fuelled vehicle sales would require 10 to 15 years to eliminate in-use emissions given prevailing fleet turnover patterns (Naimoli & Tsafos, 2020). This fleet turnover dynamic applies similarly to shipping, where vessel operational lifespans of 15–40 years create path dependencies that render near-term investment decisions critical for achieving mid-century targets.

For maritime shipping specifically, the decarbonisation challenge is compounded by the lack of commercially viable zero-emission solutions at scale, distinguishing it from passenger vehicles where electric vehicle technology has matured. Achieving net-zero maritime emissions will require technological breakthroughs in drop-in liquid fuels, hydrogen propulsion, or other innovative energy carriers—solutions that may take decades to develop and deploy at scale (Naimoli & Tsafos, 2020).

1.3 Regulatory Framework and Decarbonization Targets

The International Maritime Organization (IMO) has established ambitious decarbonization objectives to address the sector's environmental impact. The IMO strategy encompasses multiple milestones: a 50% reduction in total GHG emissions from international shipping by 2050 compared to 2008 levels, alongside carbon intensity reductions of at least 40% by 2030 and 70% by 2050 relative to the 2008 baseline (Di Micco et al., 2022; Sadiq et al., 2025). Achievement of these objectives necessitates a fundamental transformation from conventional fossil fuels to low-carbon and zero-carbon alternatives, supported by technological innovations and the adoption of alternative fuels.

The maritime sector transports over 80% of global merchandise trade by volume, rendering this transition particularly complex and consequential for the world economy (Lin et al., 2025). Global seaborne trade volumes are projected to increase from 12.6 billion tons (2023) to 14.7 billion tons by 2029, intensifying pressure on the sector to decouple economic activity from emissions growth (Lin et al., 2025).

1.4 Scope and Structure of This Book

This book provides a comprehensive examination of the technological, regulatory, economic, and infrastructural dimensions of maritime decarbonization. Drawing upon an extensive review of contemporary academic literature, policy documents, and industry reports, it synthesizes current knowledge and emerging developments to present a holistic understanding of the low-carbon shipping transition.

The scope encompasses the full spectrum of decarbonization pathways—from alternative fuels and energy efficiency technologies to digital innovations and market-based mechanisms—while maintaining focus on practical implementation challenges and solutions. The analysis integrates technical feasibility assessments with economic viability considerations, regulatory compliance requirements, and environmental impact evaluations across the complete fuel lifecycle.

Chapter 2: Alternative Marine Fuels examines the portfolio of fuel options available for maritime decarbonization, including hydrogen, ammonia, methanol, liquefied natural gas (LNG), and biofuels. The chapter provides detailed technical assessments of storage requirements, energy density characteristics, safety considerations, and technology readiness levels for each alternative. Comparative analyses enable stakeholders to evaluate trade-offs between different fuel pathways based on vessel type, operational profile, and route characteristics.

Chapter 3: Energy Efficiency Technologies for Ships addresses the technical measures available to reduce fuel consumption and emissions through improved vessel design and operation. Topics include hull form optimization, propulsion system enhancements, waste heat recovery, wind-assisted propulsion, air lubrication systems, and voyage optimization strategies. The chapter evaluates both mature technologies and emerging innovations, with particular attention to retrofitting options for existing fleets.

Chapter 4: IMO Regulations and International Policy Framework provides comprehensive coverage of the regulatory landscape governing maritime emissions. The chapter analyzes the IMO's GHG strategy, including the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), and Ship Energy Efficiency Management Plan (SEEMP) requirements. Discussion extends to MARPOL Annex VI provisions, Emission Control Areas (ECAs), and the evolving framework of technical and operational measures.

Chapter 5: Carbon Pricing and Market-Based Mechanisms explores economic instruments designed to incentivize emission reductions through price signals. The chapter examines the European Union Emissions Trading System (EU ETS) and its application to maritime shipping, the FuelEU Maritime regulation, carbon tax proposals, and emerging market-based measures under consideration at the IMO. Analysis addresses carbon leakage concerns, competitiveness impacts, and the design of equitable transition mechanisms.

Chapter 6: Infrastructure and Bunkering Systems investigates the shore-side infrastructure requirements for alternative fuel adoption. Coverage includes port facilities for LNG, ammonia, hydrogen, and methanol bunkering; shore power (cold ironing) systems; green shipping corridors; and smart port technologies. The chapter addresses the chicken-and-egg challenge of coordinating infrastructure investment with fleet transitions.

Chapter 7: Life-Cycle Assessment of Maritime Fuels presents methodological frameworks and empirical findings for evaluating the full environmental impact of alternative fuels. The chapter covers well-to-tank, tank-to-wake, and well-to-wake assessment boundaries; greenhouse gas and air pollutant emissions across fuel pathways; and the critical importance of production methods in determining lifecycle performance. Particular attention is given to uncertainties and variability in LCA results.

Chapter 8: Digital Technologies and Smart Shipping examines the role of artificial intelligence, machine learning, Internet of Things (IoT), digital twins, and data analytics in maritime decarbonization. Applications include predictive maintenance, voyage optimization, autonomous navigation, emission monitoring, and fleet management systems. The chapter evaluates the potential of digital solutions to enhance both energy efficiency and regulatory compliance.

Chapter 9: Regional Perspectives and Case Studies provides geographical context through analysis of decarbonization initiatives across major maritime regions. Coverage includes European Union policies, Asian shipping developments (China, Japan, Korea, Singapore), North American initiatives, and emerging market perspectives. Case studies illustrate successful implementation strategies and lessons learned from pioneering projects.

Chapter 10: Future Pathways and Conclusions synthesizes findings from preceding chapters to chart potential decarbonization trajectories for the maritime sector. The chapter addresses technology development roadmaps, policy evolution scenarios, investment requirements, and research priorities.

Discussion encompasses barriers to transition, enabling factors, and the conditions necessary to achieve the IMO's net-zero ambitions by mid-century.

Throughout the book, quantitative data is presented in standardized table formats to facilitate comparison and reference. Cross-referencing between chapters enables readers to trace connections between technological options, policy requirements, economic considerations, and practical implementation challenges. The integrated approach reflects the reality that successful maritime decarbonization requires coordinated action across multiple domains simultaneously.

Alternative Marine Fuels

2.1 Overview of Fuel Options

Among the emerging alternatives for maritime decarbonization, hydrogen and ammonia have emerged as leading candidates due to their clean combustion profiles and potential for global availability (Sadiq et al., 2025). Additional alternatives including methanol and biofuels also demonstrate significant potential for the transition toward sustainable maritime energy.

2.2 Hydrogen as a Marine Fuel

2.2.1 Properties and Advantages

Hydrogen combustion produces water vapor as its primary byproduct, though nitrogen oxides (NO_x) may be generated at high combustion temperatures. The high gravimetric energy density of hydrogen renders it suitable for short- to medium-range maritime applications when produced from renewable sources (Sadiq et al., 2025).

2.2.2 Technical Challenges

Hydrogen as a marine fuel faces three principal technical challenges. First, its low volumetric density requires either cryogenic storage at -253°C or high-pressure systems. Second, both storage methods are costly and energy-intensive, adding complexity to vessel design and operations. Third, hydrogen's high flammability necessitates updated regulatory frameworks and enhanced safety protocols (Sadiq et al., 2025).

2.2.3 Hydrogen Storage Technologies

Three primary on-board hydrogen storage technologies have been evaluated for maritime applications: compressed gaseous hydrogen (GH₂), liquid hydrogen (LH₂), and metal hydrides (MH). Each technology presents distinct characteristics in terms of gravimetric and volumetric energy densities (Di Micco et al., 2022):

Table 2 Hydrogen Storage Technology Energy Density Characteristics

Storage Technology	Gravimetric Energy Density (kWh/kg)	Volumetric Energy Density (kWh/m ³)
GH ₂ at 350 bar	1.7	545.5
GH ₂ at 700 bar	1.8	740.7
LH ₂ (18 bar, -253°C)	4.8	2,183.2
Metal Hydrides (AB2)	0.4	1,257.5

Liquid hydrogen demonstrates the highest gravimetric and volumetric energy densities among these options, rendering it the most space-efficient solution for long-distance maritime applications. Compared to gaseous hydrogen, liquid hydrogen density reaches 70.85 kg/m³—approximately 848 times denser than gaseous form—with volumetric energy density of 2.36 kWh/L and gravimetric energy density of 33.3 kWh/kg. However, the cryogenic storage requirements at -253°C at atmospheric pressure introduce additional complexity and energy consumption for maintaining storage conditions (Di Micco et al., 2022; Fu et al., 2023).

Comprehensive techno-economic analysis reveals significant cost-efficiency trade-offs among storage technologies, with implications for maritime operational requirements (Jayabal, 2025):

Table 3 Hydrogen Storage Method Cost and Efficiency Comparison

Storage Method	Cost (\$/kg H ₂)	Round-Trip Efficiency	Maritime Suitability
Compressed (350-700 bar)	\$1.5–3.0	60–65%	Short-sea routes; rapid refuelling
Cryogenic (LH ₂)	\$2.0–5.0	80–85%	Long-distance; highest density
Solid-state (metal hydrides)	\$2.5–6.0	50–60%	Emerging; safety advantages
Ammonia-based carrier	\$1.0–2.5	30–40%	Existing infrastructure; conversion losses

Solid-state storage technologies—including metal hydrides, advanced carbon structures, and chemical hydrides—offer inherent safety advantages by eliminating high-pressure containment requirements and reducing ignition risks compared to compressed gaseous systems. Emerging materials under development include metal-organic frameworks (MOFs), graphene-based structures, and high-entropy alloys, with research demonstrating potential for improved gravimetric density and cycling stability (Jayabal, 2025).

2.2.4 Comparative Energy Density of Alternative Marine Fuels

Comparative analysis of energy properties across leading alternative marine fuels reveals distinct trade-offs between gravimetric and volumetric energy density (Semchukova et al., 2025):

Table 4 Alternative Marine Fuel Energy Density Comparison

Fuel	Physical State (Ambient)	Energy by Mass (MJ/kg)	Energy by Volume (MJ/L)	TRL (Two-Stroke)
Hydrogen	Gas	120	8	4
Ammonia	Gas	18.6	12.77	5–6
Methanol	Liquid	19.9	15.6	9

Hydrogen exhibits the highest gravimetric energy density (120 MJ/kg) but the lowest volumetric density (8 MJ/L), necessitating larger storage volumes. When stored as liquid hydrogen at -252.8°C , volumetric density improves to 70.8 kg/m^3 , while compressed hydrogen at 700 bar achieves only 42 kg/m^3 —both substantially lower than diesel’s $720\text{--}860\text{ kg/m}^3$. These storage characteristics have significant implications for marine vessel design and range capabilities (Semchukova et al., 2025).

2.2.5 Technology Readiness Levels for Marine Hydrogen Applications

Fuel cell technology for maritime applications has achieved varying levels of maturity across different vessel types. Proton exchange membrane fuel cells (PEMFC) achieve electrical efficiency of 60%, while solid oxide fuel cells (SOFC) with heat capture can reach 85% system efficiency, compared to 42% for modern diesel brake thermal efficiency (Semchukova et al., 2025).

Marine hydrogen applications have achieved varying technology readiness levels: fuel cell tugboats have reached TRL 7 with the ELEKTRA hybrid project demonstration; shore power fuel cells are at TRL 5 with demonstrations

completed at Honolulu and San Diego; and hydrogen combustion in two-stroke engines remains at TRL 4, with Mitsui completing the first test in 2024 (Semchukova et al., 2025).

Methanol, with a TRL of 9 for two-stroke marine engines, has achieved commercial readiness with 138 vessels on order as of 2023. Ammonia engine development (TRL 5–6) continues, with MAN Energy Solutions projecting first engine delivery in 2025. Direct hydrogen application in marine propulsion remains at TRL 4 for two-stroke engines, with current deployments limited primarily to fuel cells for auxiliary power and short-sea shipping (Semchukova et al., 2025).

Hydrogen fuel cell propulsion offers substantial environmental benefits compared to conventional diesel systems. Quantified emission reductions from hydrogen-powered maritime operations include up to 90% reduction in nitrogen oxide (NO_x) emissions, 99% reduction in particulate matter (PM), and 90% reduction in total greenhouse gas (GHG) emissions when utilising green hydrogen produced from renewable electrolysis. Hybrid fuel cell configurations—combining PEM fuel cells with battery systems—demonstrate efficiency improvements of approximately 35% compared to conventional diesel propulsion, while maintaining operational flexibility for variable power demands typical of port manoeuvring and berthing operations (Jayabal, 2025).

Compressed hydrogen storage utilises carbon fiber reinforced plastic (CFRP) tanks capable of withstanding high pressures. Type IV hydrogen storage cylinders can achieve mass hydrogen storage density of up to 5.7 wt% at 70 MPa operating pressure, representing a significant improvement over earlier Type I (1.7 wt%) and Type II (2.1 wt%) vessels (Fu et al., 2023).

2.2.6 Liquid Hydrogen vs LNG: Physical Properties for Maritime Trade

International hydrogen trade via maritime carriers necessitates careful consideration of liquid hydrogen's distinct physical properties compared to established LNG infrastructure. While LNG carrier technology is commercially mature, liquid hydrogen presents unique handling challenges that influence port infrastructure requirements (Chen et al., 2023):

Table 5 Physical Property Comparison of Liquid Hydrogen and LNG for Maritime Trade

Property	Liquid Hydrogen (LH ₂)	LNG	Implications
Density at boiling point	70.8 kg/m ³	422.5 kg/m ³	LH ₂ requires ~6× larger tanks for equivalent mass
Boiling point	-252.8°C	-161.5°C	LH ₂ requires more stringent cryogenic systems
Flammable range in air	4–75%	5.3–17%	LH ₂ presents broader ignition risk; ventilation critical
Minimum ignition energy	0.017 mJ	0.28 mJ	LH ₂ ignites more readily; stringent controls required
Lower heating value	120.0 MJ/kg	50.0 MJ/kg	LH ₂ superior gravimetric energy density

Hydrogen's substantially lower density at boiling point compared to LNG (70.8 kg/m³ versus 422.5 kg/m³) presents the most significant challenge for maritime transport economics. A liquid hydrogen carrier requires approximately six times the tank volume of an equivalent-capacity LNG carrier, with corresponding implications for vessel design and construction costs. The wider flammable range (4–75% versus 5.3–17%) and lower minimum ignition energy (0.017 mJ versus 0.28 mJ) necessitate enhanced safety systems and operational protocols at port facilities (Chen et al., 2023).

Hydrogen also exhibits indirect global warming potential (GWP) of 5.8 on a 100-year time horizon. While hydrogen itself is not a greenhouse gas, atmospheric hydrogen can extend the lifetime of methane and tropospheric ozone, contributing indirectly to radiative forcing. This indirect effect reinforces the importance of minimising fugitive emissions throughout the hydrogen supply chain, including at port handling facilities (Chen et al., 2023).

2.2.7 Alternative Hydrogen Carriers

Ammonia and methanol offer advantages as hydrogen carriers compared to direct hydrogen storage. Ammonia has a boiling point of -33.4°C at atmospheric pressure, making it considerably easier to store as a liquid than hydrogen. Critically, ammonia's hydrogen storage capacity reaches 123 kg-H₂/m³, substantially exceeding liquid hydrogen's 70.8 kg-H₂/m³ volumetric capacity (Fu et al., 2023).

Methanol can be stored at room temperature with minimal modification to existing fuel storage systems. As a hydrogen carrier, methanol achieves

12.5 wt% gravimetric and 99 kg/m³ volumetric hydrogen storage density. Green methanol production via CO₂ hydrogenation ($\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$) can occur at 230°C and 5 MPa, providing a pathway to renewable hydrogen storage (Fu et al., 2023).

2.2.8 Hydrogen Production Pathways and Economics

The viability of hydrogen as a maritime fuel depends fundamentally on the decarbonisation and cost reduction of hydrogen production. In the European Union, current hydrogen supply capacity is approximately 339 TWh per year—roughly 3% of final energy demand—with over 95% produced from fossil fuels and less than 5% via electrolysis (McWilliams & Zachmann, 2021).

The dominant production route, steam methane reforming (SMR), separates hydrogen from methane but generates significant CO₂ emissions. The carbon intensity comparison between production methods reveals a critical transition threshold: SMR without carbon capture produces approximately 270 g CO₂/kWh, while electrolysis using EU grid electricity generates 430 g CO₂/kWh at current grid carbon intensity. Electrolysis achieves lower emissions than SMR only when average electricity grid emissions fall below 200 g CO₂/kWh—a threshold the EU is projected to reach by approximately 2025 as renewable generation increases (McWilliams & Zachmann, 2021).

Current hydrogen production costs vary significantly by method: steam methane reforming (SMR) ranges from €40–65/MWh and serves as the baseline at €20/MWh gas prices; electrolysis costs €60–100/MWh and becomes competitive when electricity prices fall below €20/MWh; at high carbon prices of €200/t CO₂, electrolysis at €80–120/MWh achieves competitiveness with fossil-based production (McWilliams & Zachmann, 2021).

Multiple low-carbon hydrogen production pathways are under development, each with distinct cost profiles and technology readiness levels. Alternative methods present varying cost characteristics relevant to future maritime fuel supply:

Table 6 Alternative Low-Carbon Hydrogen Production Methods

Production Method	Energy Source	Cost (€/MWh)	Technology Stage
Autothermal reforming with CCS	Natural gas	50	Commercial
Methane pyrolysis	Internal steam	54-57	Prototype
Biomass pyrolysis	Internal steam	42-74	Demonstration
Biomass gasification	Internal steam	60-69	Demonstration
Nuclear thermolysis	Nuclear	73-89	Research
Solar thermal electrolysis	Solar	172-354	Research

Source: McWilliams & Zachmann (2021), based on Kayfeci et al. (2019)

For maritime applications specifically, the analysis indicates that hydrogen fuel cells may be suitable for short-distance light shipping where power requirements are not excessive. However, liquefied hydrogen, synthetic fuels derived from hydrogen, and ammonia present greater potential for decarbonising longer-distance shipping. The projected 2050 hydrogen demand for the maritime sector in the EU ranges from 20 TWh (lower scenario) to 120 TWh (upper scenario), representing 6.6% of EU transport greenhouse gas emissions. This estimate excludes additional indirect demand from ammonia produced as a maritime fuel, which would substantially increase total hydrogen requirements (McWilliams & Zachmann, 2021).

The global coordination challenge for maritime hydrogen adoption arises because ships refuel in multiple locations across different countries. Bunkering facilities currently storing heavy fuel oil would require transformation to accommodate hydrogen or hydrogen-derived fuels. This coordination problem favours the emergence of one or two dominant fuels, as the shipping industry is unlikely to support multiple parallel fuel infrastructures. Port hydrogen infrastructure may benefit from economies of scope through multiple end-use cases—hydrogen forklift trucks, with 25,000 already deployed globally, exemplify how port-based hydrogen storage and distribution can serve multiple applications, improving economic efficiency (McWilliams & Zachmann, 2021).

2.3 Ammonia as a Marine Fuel

2.3.1 Properties and Advantages

Ammonia presents a practical option for large-scale maritime adoption due to its ability to leverage existing global infrastructure from the chemical industry. It can be stored as a liquid under moderate pressure or refrigeration (Sadiq et al., 2025). According to the International Energy Agency, green ammonia represents one of the most promising low-emission fuels for maritime applications, with projections indicating consumption of 130 million tonnes by 2070 through shipping alone (Profumo et al., 2025).

Green ammonia—produced using CO₂-free energy sources in the Haber-Bosch process—offers specific advantages over competing alternative fuels. Ammonia can be maintained in liquid form at 0.8 MPa at 20°C, or at atmospheric pressure at -33°C, making it significantly less complicated to transport and store than hydrogen. Critically, ammonia contains 40% greater hydrogen content than methanol and exhibits slightly higher volumetric energy density than both methanol and hydrogen, rendering it suitable for both deep-sea and short-sea shipping applications. Ammonia is available for both combustion engines and fuel cells, providing flexibility in propulsion system selection (Balci et al., 2024).

2.3.2 Technical Challenges

- Toxicity concerns requiring stringent handling protocols
- Combustion efficiency requiring optimization
- NO_x emission production necessitating advanced treatment systems
- Lower energy density compared to oil (ships consume up to five times more fuel by volume)

2.3.3 Production Requirements

Meeting projected ammonia demand for maritime decarbonisation will require substantial expansion of production capacity. Ammonia production is expected to increase by 440 million tonnes—more than three times current global production—necessitating approximately 750 GW of renewable energy generation capacity (Profumo et al., 2025).

2.4 Methanol

Methanol has emerged as a leading alternative fuel choice for maritime applications, demonstrating rapid growth in adoption rates. The year 2022

witnessed sustained growth in orders for alternative fuel vessels, with methanol attracting increasing interest from major shipping companies. Dual-fuelled methanol vessels have increased at a faster rate relative to the overall orderbook, with orders exceeding LNG for the first time in terms of ordered capacity during the second half of 2022 (Profumo et al., 2025).

Major container shipping companies have committed substantial investments to methanol propulsion, with CMA CGM ordering 342,000 TEU of methanol-capable capacity, Maersk ordering 300,000 TEU, and OOCL ordering 168,000 TEU across seven 24,000 TEU vessels (Profumo et al., 2025).

Maersk has signed pre-agreements with nine green methanol producers, including Carbon Sink, European Energy, Ørsted, and Proman, to secure fuel supplies. The agreement between Shanghai Port and Maersk to develop green methanol bunkering cooperation, effective from 2024, exemplifies the industry's commitment to establishing the necessary supply infrastructure (Profumo et al., 2025).

2.5 Biofuels

Biofuels are currently available and utilised as drop-in fuels blended with conventional marine fuels. However, their high cost and limited available quantities present objective obstacles to expansion at present. In the medium and long term, biofuels are anticipated to be supplemented and progressively replaced by liquid synthetic fuels and second- and third-generation biofuels (Profumo et al., 2025). Biofuels currently contribute 4.2% of global transportation sector energy consumption, representing a practical and environmentally friendly alternative with high energy density, reduced lifecycle emissions, and compatibility with existing infrastructure (Wang et al., 2024).

Systematic review of decarbonisation pathways indicates that biofuels offer GHG reduction potential ranging from 25% to 100% depending on feedstock and production processes. Their drop-in compatibility with existing engines and infrastructure makes them particularly suitable for short-term decarbonisation of domestic ferry fleets, avoiding significant capital expenditure on engine retrofits. Biofuels enable a pathway to future e-fuels and require minimal modifications to existing bunkering infrastructure (Vakili et al., 2025).

Biofuels are categorised into three generations: first-generation (from food crops), second-generation (from non-food biomass and agricultural residues), and third-generation (from algae and microorganisms). While first-generation biofuels face sustainability concerns related to food competition and land

use, advanced biofuels offer lower environmental footprints. For domestic shipping in Small Island Developing States (SIDS) and Least Developed Countries (LDCs), biofuels represent a particularly practical option given their compatibility with existing vessel engines and the potential for local production (Vakili et al., 2025).

2.5a Lifecycle Carbon Reduction Comparison

Comparative analysis of lifecycle carbon reduction potential reveals significant variation across alternative fuel options. The following table summarises key fuel characteristics relevant to maritime decarbonisation decisions (Wang et al., 2024):

Table 7 Lifecycle Carbon Reduction and Energy Characteristics of Alternative Marine Fuels

Fuel	Density (kg/m ³)	Calorific Value (MJ/kg)	Vol. Energy Density (MJ/L)	Lifecycle Carbon Reduction
LNG	448	48.6	21.8	Up to 28%
LPG	495	46.5	23.1	Up to 17%
Methanol	796	20	15.9	Up to 86%
Biodiesel	870–880	37.5	33.3	Up to 88%
Diesel (reference)	830–860	42–44	36–39	Baseline

LNG, comprising over 95% methane, offers a lifecycle carbon reduction of up to 28% through low carbon and sulphur content combinations. However, methane’s warming effect—85 times that of CO₂ per gram over a 20-year timeframe—necessitates careful attention to methane slip management. LPG achieves more modest lifecycle reductions of up to 17% whilst offering simpler storage requirements at 10–20 bar liquefaction pressure (Wang et al., 2024).

Methanol’s lower volumetric energy density (15.9 MJ/L versus diesel’s 36–39 MJ/L) implies that vessels require approximately double the fuel storage volume to achieve comparable range. However, methanol’s liquid state at ambient temperature enables utilisation of existing fuel infrastructure with minimal modification. When produced from renewable feedstocks (biomass, captured CO₂, renewable electricity), methanol achieves lifecycle carbon reduction rates up to 86% (Wang et al., 2024). Renewable methanol production costs remain 1.5–4 times higher than conventional fossil methanol, though this differential is expected to narrow with scaling of production capacity.

Methanol combustion offers substantial reductions in local air pollutants compared to conventional marine gas oil (MGO): 99% less SO_x, 95% less particulate matter, and up to 80% less NO_x (Meyer-Larsen & Schories, 2025). Unlike competing alternative fuels such as hydrogen or ammonia, methanol requires neither cooled nor compressed storage and presents significantly lower toxicity than ammonia. Methanol is also readily biodegradable, an important characteristic for minimising environmental impact in the event of maritime accidents. These favourable storage and handling characteristics enable existing tank farms and fuel transporters to be converted with minimal modification, reducing infrastructure transition costs (Meyer-Larsen & Schories, 2025).

Biofuels demonstrate the highest lifecycle carbon reduction potential at up to 88%, whilst offering drop-in compatibility with existing engines. Used cooking oil biodiesel has demonstrated lifecycle emission reductions up to 40% in operational trials (Wang et al., 2024).

2.6 Fuel Comparisons for Domestic and Short-Sea Shipping

Domestic and short-sea shipping, which contributes approximately 26.2% of global maritime GHG emissions on a voyage-based allocation (or 9.2% when considering only vessels exclusively engaged in domestic trade), faces unique constraints in fuel selection due to shorter voyages, smaller vessels, and limited onboard storage capacity. The lower volumetric energy density of alternative fuels compared to conventional marine fuels poses particular challenges for this segment, where space limitations can restrict cargo capacity and impact economic viability (Vakili et al., 2025).

Comparative assessment of fuel suitability for domestic shipping reveals the following considerations:

Table 8 Alternative Fuel Suitability Assessment for Domestic Shipping

Fuel	Domestic Suitability	Key Advantage	Key Limitation
Biofuels	High	Drop-in compatibility	Scalability and cost
Methanol	High	Lower capital/space constraints	Tank sizing (2.3× larger)
Hydrogen	Moderate	Zero carbon; suited to short routes	Storage complexity (4-5× more space than HFO)
LNG	Low-Moderate	Mature technology	Methane slip; 2.5-3× tank volume
Ammonia	Low	Zero tank-to-wake carbon	Toxicity; unsuitable near populated areas

Ammonia, despite its zero tank-to-wake carbon profile, presents significant safety concerns for domestic shipping. Toxicity risks and the potential for environmental harm from leaks render it impractical for vessels operating near urban areas and densely populated coastal regions where domestic fleets frequently operate (Vakili et al., 2025).

2.6 Liquefied Natural Gas (LNG)

Liquefied natural gas represents the most mature alternative fuel solution currently deployable at scale in the maritime sector. LNG has been the most popular choice among alternative fuels, with 39% of the total orderbook tonnage destined for LNG use as of mid-2023 (Profumo et al., 2025).

Major shipping companies including MSC, CMA CGM, and Hapag Lloyd have invested in LNG-powered vessels as part of their fleet renewal strategies. MSC has signed bunkering agreements with Gasum, while Hapag Lloyd has established supply arrangements with Shell (Profumo et al., 2025). In the short term, LNG appears to be the only alternative fuel solution that can be effectively applied at scale. Medium-term projections anticipate gradual substitution of LNG by bio-methane as production capacity expands.

2.7 Fuel Transition Timeline

The development pathway for alternative marine fuels can be categorised into three temporal phases (Profumo et al., 2025):

Short-term: LNG emerges as the primary scalable solution, with biofuels serving as drop-in supplements to conventional fuels.

Medium-term: Bio-methane is anticipated to gradually replace LNG, while bio-methanol and electro-methanol solutions mature for commercial deployment.

Long-term: Hydrogen is projected to become the terminal solution for light gas applications, with ammonia serving as the endpoint for heavy gas pathways. Liquid synthetic fuels will progressively replace first-generation biofuels.

2.8 Comparative GHG Emission Reduction by Vessel Size

GHG emission reduction potential varies significantly across alternative fuels and vessel size categories, reflecting differences in engine technology, storage capacity, and operational profiles. A systematic review of decarbonisation measures reveals vessel-size-dependent performance patterns (RobaloCabrera2025):

Table 9 GHG Emission Reduction Potential by Vessel Size Category

Alternative Fuel	Large (>20k GT)	Medium (5–20k GT)	Small (<5k GT)
LNG	15–23%	10–18%	5–15%
Biodiesel	50–85%	50–85%	50–85%
Bio-methanol	50–90%	50–90%	50–90%
Green ammonia	90–100%	90–100%	Near zero
Green hydrogen	90–100%	90–100%	90–100%
Post-combustion CCS	70–90%	40–70%	<30%

Note: Large vessels utilise two-stroke dual-fuel engines; medium vessels use four-stroke engines; percentages represent well-to-wake reductions.

LNG demonstrates higher emission reductions in larger vessels due to more efficient dual-fuel two-stroke engine technology, though methane slip remains a constraint requiring slip rates below 0.8–1.6% to ensure net environmental benefit. Biodiesel and bio-methanol exhibit consistent performance across vessel sizes due to their drop-in compatibility with existing engine architectures.

Green ammonia presents an inverse vessel-size relationship—achieving near-total decarbonisation in large and medium vessels but offering minimal benefit for small vessels where four-stroke engine emissions dominate and cold-start problems persist. Conversely, green hydrogen delivers consistent 90–100% reductions across all vessel categories, particularly suited to small vessels and short-sea shipping where fuel cell integration is most practical.

Carbon capture systems demonstrate pronounced scale economies: large vessels can achieve 70–90% capture rates with post-combustion technology, while small vessels struggle to exceed 30% due to space constraints for absorption equipment and storage tanks. This suggests carbon capture serves primarily as a bridging solution for large vessels rather than a universal decarbonisation pathway.

As of mid-2023, approximately 6.5% of the operating fleet (by gross tonnage) utilises alternative fuels, while 51% of vessels on order incorporate dual-fuel or alternative-fuel capability—indicating a substantial pipeline of cleaner tonnage entering service over the coming decade (RobaloCabrera2025).

Energy Efficiency Technologies for Ships

3.1 Propulsion System Innovations

3.1.1 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

Polymer electrolyte membrane fuel cell technology represents one of the most promising propulsion alternatives for maritime decarbonization. PEMFC systems demonstrate significant advantages over conventional diesel engines in terms of weight and volume requirements. Technical assessments have revealed that PEMFC-based powertrains achieve approximately 60% reduction in volume and 56% reduction in mass compared to equivalent diesel engine configurations (Di Micco et al., 2022).

The operational characteristics of marine PEMFC systems include system power densities of 256 kW/ton and volumetric power densities of 99 kW/m³, with operating temperatures maintained at approximately 60°C. The average hydrogen-to-electric (DC) conversion efficiency reaches 45% across typical marine load profiles (Di Micco et al., 2022).

3.1.2 Fuel Cell Types for Maritime Applications

Fuel cells convert chemical energy directly into electricity without combustion, achieving efficiencies of 40-60% in actual operation—significantly higher than internal combustion engines, which are thermodynamically constrained by the Carnot Cycle. Additionally, fuel cells operate quietly due to the absence of moving parts, and produce zero emissions of nitrogen oxides, sulphur oxides, and particulate matter when using hydrogen (Fu et al., 2023).

Three fuel cell types demonstrate particular suitability for maritime applications:

Table 10 Fuel Cell Types for Maritime Applications

Fuel Cell Type	Operating Temperature	Maritime Advantages	Demonstrated Applications
PEMFC	60-80°C	Fast start-up, high energy density	Small vessels, manoeuvrability-critical
HT-PEMFC	120-200°C	CO-tolerant, simplified water management	Reformed fuel applications
MCFC	~700°C	Fuel flexibility (CH ₄ , LNG), heat recovery	Large ships, long operating periods
SOFC	Up to 1000°C	Solid electrolyte stability, cogeneration	Large ships, GT hybrid systems

PEMFC technology is susceptible to carbon monoxide poisoning and requires complex water management systems. High-temperature proton exchange membrane fuel cells (HT-PEMFC) address these limitations through enhanced CO tolerance and simplified thermal management. High-temperature fuel cells such as MCFC and SOFC, while exhibiting slower start-up characteristics, offer fuel flexibility and substantial recoverable heat for cogeneration applications (Fu et al., 2023).

3.1.3 Fuel Cell Demonstration Projects

Numerous demonstration projects have validated fuel cell technology across various maritime applications:

Table 11 Fuel Cell Maritime Demonstration Projects

Project/Vessel	FC Type	Power	Fuel	Status
Cobalt 233 Zet (2007)	PEMFC hybrid	50 kW (24 kW FC)	Hydrogen	Completed
MS Mariella (Pa-X-ell)	HT-PEMFC	90 kW	Methanol	Auxiliary power demonstration
Viking Lady	MCFC	320 kW	LNG	44.1% efficiency at 100% load
SchiBZ2 (2017-2019)	SOFC + Li-ion	—	Diesel	General cargo feasibility
Energy Observer	PEMFC	—	H ₂ (electrolysis)	Global circumnavigation

The Viking Lady represents a particularly significant milestone, demonstrating 44.1% system efficiency for its 320 kW LNG-fuelled MCFC system with internal reformer. The Energy Observer vessel produces hydrogen through onboard seawater electrolysis using a PEM electrolyser capable of generating 4 Nm³ of hydrogen per hour while consuming 3.66 L of deionised water (Fu et al., 2023).

3.1.4 Hybrid Fuel Cell Propulsion Architectures

Fuel cell hybrid systems combine fuel cells with complementary power sources to optimise performance across varying operational demands. Three primary configurations have emerged for maritime applications:

FC-Energy Storage Hybrid: Combining fuel cells with batteries or supercapacitors addresses load variations and provides peak power capability. The battery's rapid response compensates for slower fuel cell dynamics, while energy management strategies based on fuzzy logic control, nonlinear model predictive control (NMPC), or Pontryagin minimum principle optimise power distribution between sources (Fu et al., 2023).

FC-Gas Turbine Hybrid: High-temperature fuel cells (MCFC, SOFC) generate substantial waste heat recoverable through gas turbine integration based on the Brayton Cycle. Direct systems route fuel cell exhaust to drive the turbine, while indirect systems use heat exchangers for thermal coupling. SOFC-gas turbine hybrid systems can potentially achieve electrical efficiency exceeding 70%, with some optimisation studies demonstrating 75% efficiency at 50 bar operating pressure (Fu et al., 2023).

FC-Internal Combustion Engine Hybrid: Combining fuel cells with internal combustion engines improves overall system efficiency and enables rapid start-up. Anode off-gas from high-temperature fuel cells can preheat fuel and support reforming, with excess thermal energy driving combustion. Such hybrid configurations may achieve exergy efficiency up to 70% whilst maintaining the operational flexibility of conventional propulsion (Fu et al., 2023).

Advanced MCFC-ICE-ORC integrated systems demonstrate significant potential for combining propulsion efficiency with onboard carbon capture. Techno-economic analysis of methanol-fuelled MCFC systems integrated with internal combustion engines and organic Rankine cycle (ORC) waste heat recovery indicates electrical efficiency of 49% and exergy efficiency of 56%. The MCFC's inherent carbon concentrating capability—achieved through electrochemical reactions rather than energy-intensive solvent absorption—enables 93.2% CO₂ capture rate with an efficiency penalty of only 8.4%.

This approach reduces equivalent mass intensity (EMI) from 358.7 kg/MWh (ICE baseline) to 32.1 kg/MWh, representing a 91.5% reduction in effective emissions (Berry et al., 2025).

3.1.5 Fuel Consumption Comparison

Comparative analyses of fuel consumption between hydrogen fuel cell and conventional diesel propulsion systems demonstrate substantial mass reductions. For a chemical tanker operating on medium-distance voyages (242 hours, 2,855.6 nautical miles), hydrogen consumption amounts to 51.8 tons compared to 250 tons of diesel fuel, representing a 79% reduction in fuel mass. Furthermore, this transition enables the avoidance of approximately 786 tons of CO₂ emissions per voyage (Di Micco et al., 2022).

3.2 Wind-Assisted Propulsion Technologies

Wind-assisted propulsion represents a promising retrofitting option for accelerating decarbonisation without requiring newbuild investments. Modern wind power technologies, including advanced sail rigs and Flettner Rotors (vertical rotating columns that generate propulsion force through the Magnus effect), can be fitted on the upper deck of existing vessels. Studies demonstrate that these technologies can achieve fuel savings of up to 20%, even when ships maintain their operational speed and established routes (Mahmoudi et al., 2024).

Agent-based modelling of technology transitions in the shipping industry indicates that wind-assisted technology represents the most cost-effective retrofitting option available to shipowners. Unlike alternative fuel retrofits that require significant modifications to propulsion systems and operational procedures, wind assistance can be implemented with minimal operational changes. Simulation results suggest that wind-assisted technology could capture up to 28% market share by 2050 under regulation-driven transition scenarios (Mahmoudi et al., 2024).

Deployment of wind-assisted propulsion technology (WPT) remains in early stages, though the fleet is expanding. As of 2024, approximately 40 vessels operate with Flettner rotors, 43 with suction wings, 18 with rigid sails, and 4 with wind kites. Suction wing technologies—such as VentiFoil, which generates lift through mechanical aeration analogous to aircraft wing principles—represent an emerging solution with demonstrated performance in commercial operations. Installation costs for rigid sail systems are substantial (approximately €321,000 per unit), with monthly maintenance costs of approximately €35. Baseline fuel savings of 2.875% have been recorded

under averaged conditions, though savings are highly dependent on wind conditions and vessel routing (Romero et al., 2025).

Extended fuel savings potential increases significantly when WPT is combined with operational measures. Empirical studies demonstrate a correlation between wind speed and fuel savings—a 5% increase in wind speed corresponds to approximately 12% increase in fuel savings. Slow steaming combined with WPT can achieve nearly 16% fuel reduction. Voyage optimisation on favourable wind corridors can yield fuel savings of up to 30%, contributing to carbon emission reductions of up to 60%. The most aggressive savings scenario—employing weather route planning with four Flettner rotors on an 80,000 DWT Panamax bulk carrier—has demonstrated potential fuel savings of up to 44% (Romero et al., 2025).

The Carbon Intensity Indicator (CII) is expected to drive increased WPT adoption, as shipowners seek cost-effective pathways to regulatory compliance. WPT offers particular advantages for developing economies, where the technology's compatibility with existing LNG and HFO hybrid systems provides a transitional pathway without requiring substantial investment in alternative fuel bunkering infrastructure (Romero et al., 2025).

3.3 Hull Design Optimization

Hull resistance reduction represents a fundamental approach to improving vessel energy efficiency. Ships are designed to operate at boundary speeds—the range within which resistance coefficients remain virtually constant before increasing rapidly. Modifications to the main ratios between beam, draught, and length can reduce block coefficients while maintaining cargo-carrying capacity. Studies indicate that novel slender hull designs are less full-bodied, which reduces drag and results in significantly lower power requirements and fuel consumption (Palaniappan & Vedachalam, 2022).

Additional measures contributing to improved hull performance include: - Lightweighting of structural components - Improved hull coatings to reduce surface friction - Better lubrication systems - Hull smoothness maintenance

The relationship between hull design and propulsion efficiency is interdependent. The shape of a ship's hull and the resulting wake directly affect propeller performance and underwater radiated noise generation. Consequently, integrated hull and propeller design optimisation yields greater efficiency gains than addressing either component in isolation (Palaniappan & Vedachalam, 2022).

3.3a Parametric Design Methods and CFD Optimization

Traditional hull design relying on empirical data and parent ships limits innovative design possibilities. Parametric design methods integrated with computational fluid dynamics (CFD) simulations demonstrate superior drag reduction performance and speed characteristics, reducing dependence on design experience whilst enhancing flexibility and stability of optimal solutions. Hull optimisation theory has evolved from single-objective resistance minimisation toward comprehensive energy efficiency design incorporating uncertainty considerations and multi-objective frameworks (Xu & Chen, 2025).

Table 12 Hull Optimization Approaches and Results

Approach	Optimization Method	Key Result
EEOI minimization	Uncertainty optimization considering speed perturbations	Energy efficiency achieved under variable speeds
Trimaran optimization	CFD-based multi-objective (resistance + seakeeping)	3.14% reduction in total resistance
JBC hull-propeller interaction	NSGA-II with CFD	Significant improvements in resistance and wake field deformation

The integration of hull-propeller interaction into optimisation frameworks yields additional benefits. Applying CFD and multi-objective genetic algorithms (NSGA-II) to optimise hull resistance and wake field deformation simultaneously enables streamlined aft-body lines that effectively suppress flow separation and reduce pressure drag (Xu & Chen, 2025).

3.4 Air Lubrication Systems

Air lubrication technology represents a promising energy-efficient solution for reducing GHG emissions in the maritime sector. The system operates by injecting a layer of air bubbles beneath the ship's hull, reducing hydrodynamic friction between the hull and seawater. This process minimises resistance, decreases turbulence within the boundary layer, and enhances hydrodynamic performance (Vakili et al., 2025).

Approximately 0.3% of the global fleet currently employs air lubrication technology, with growing adoption particularly on larger and faster vessels such as passenger ships, cruise liners, and Ro/Ro vessels. As of 2023, approximately 250 vessels have integrated air lubrication systems. Scaled model tests demonstrate that these systems can deliver 4–15% energy efficiency

improvements depending on vessel type and operating conditions. Additionally, the technology reduces underwater radiated noise by more than 10 dB, offering environmental co-benefits beyond fuel savings (Vakili et al., 2025).

Three primary methods exist for generating the bubble layer: the air cavity method, air film method, and small bubble method. The small bubble method—which utilises micro-bubbles and requires minimal hull modifications—has emerged as the most widely adopted due to its simplicity and effectiveness. The technology is applicable to both newbuilds and existing vessels as a retrofit solution (Vakili et al., 2025).

Air Lubrication Systems are recognised by IMO as Category B-1 (Innovative Energy Efficiency Technology). However, the benefits of ALS are speed-dependent, with effectiveness diminishing at lower vessel speeds. Empirical studies report reduced savings of 3.2% at 13 knots and 1.7% at 12 knots, suggesting that benefits below 14 knots may not justify implementation costs. Furthermore, ALS is not recommended for research vessels, as bubble sweep-down phenomena can degrade the acoustic performance of hull-mounted scientific survey equipment (Palaniappan & Vedachalam, 2022).

3.5 Energy-Saving Devices and Propulsion Improvement Devices

Energy-saving devices (ESDs) and propulsion improvement devices (PIDs) enhance energy efficiency by addressing hull shape, propulsion mechanisms, and vibration reduction. A significant milestone has been reached with 6,398 vessels—representing approximately 28.1% of total fleet tonnage—successfully integrating these technologies (Vakili et al., 2025).

Advanced ESD innovations include propeller ducts, twisted rudders, gate rudders, bulbous bows, propeller cap turbines, pre-swirl stators, Mewis ducts, and propeller boss cap fins. These technologies have demonstrated energy savings ranging from 1.5% to 25% and can reduce underwater radiated noise from commercial vessels by up to 5 dB. When assessing cost-effectiveness, the relatively short payback periods make ESDs an economically viable option for ship operators seeking to enhance operational efficiency (Vakili et al., 2025).

3.6 Waste Heat Recovery Systems

Waste heat recovery (WHR) systems capture and repurpose heat that would otherwise be lost during propulsion. In marine engines, 48–51% of fuel energy is lost to the environment through exhaust gases and cooling water. WHR systems have been shown to reduce fuel consumption by up to 12% depending on ship type, with the amount of energy recovered dependent

on engine size, operational conditions, and ambient temperature (Vakili et al., 2025).

Among various WHR technologies, the Organic Rankine Cycle (ORC) stands out for its ability to utilise low-temperature heat sources for power generation. Unlike the conventional Rankine Cycle, which requires high-temperature heat sources and uses water as the working fluid, the ORC operates efficiently with lower-temperature waste heat. When combined with strategies such as derating, slow steaming, and wind-assisted propulsion, WHR can yield an additional 1–3% fuel savings (Vakili et al., 2025).

3.7 Operational Energy Efficiency Measures

Operational measures offer immediate emission reduction potential without requiring capital-intensive technology investments. Systematic review identifies the following quantified benefits from operational interventions (Vakili et al., 2025):

Table 13 Operational Energy Efficiency Measures and Benefits

Operational Measure	Efficiency/Emission Benefit	Notes
Speed reduction (10%)	15-27% fuel savings	Higher impact for faster vessels
Weather routing	Up to 5% improvement	Depends on vessel type, route
JIT operations	14-23% GHG reduction	Requires port collaboration
Hull/propeller cleaning	7-10% energy efficiency	Critical for CII compliance
Machinery maintenance	2-8% emission reduction	Planned maintenance programs
Optimised trim/draft	5-10% power reduction	Within stability limits
Economies of scale	Up to 30% emission reduction	Requires port capacity

Complementary analysis across operational and technological measures provides additional quantification of emission reduction potentials under varying temporal horizons. PESTEL framework evaluation categorises measures as short-term (immediate to 2030), mid-term (2030–2040), or long-term (post-2040) solutions based on technology readiness and infrastructure requirements (Zincir, 2025):

Short-term Emission Reduction Measures:

Table 14 Short-Term Emission Reduction Measures and Potential

Measure	Reduction Potential
Autopilot improvement	0.5–4% fuel saving
Trim-draft optimization	1–2% fuel saving
Smart propulsion control	15% fuel saving
Hull-propeller cleaning	25–30% less GHGs
Shaft generator	3–5% efficiency increase
Air lubrication system	10% fuel saving
WHRS	10% fuel saving
Renewable energy systems	10–30% fuel saving
Hybrid power unit	15–25% fuel saving
LNG	20% less GHGs
Methanol	7% CO ₂ , 99% SO _x , 60% NO _x reduction

Mid-term Emission Reduction Measures:

Table 15 Mid-Term Emission Reduction Measures and Potential

Measure	Reduction Potential
Slow steaming	30–50% GHG reduction
Biofuels	40–80% less WtW carbon
CCS	70% CO ₂ reduction
E-diesel	79% lower WtW GWP
E-methanol	82% lower WtW GWP
E-LNG	93% lower WtW GWP

Long-term measures offer more substantial emission reduction potential: green hydrogen achieves 94% lower well-to-wake GWP; e-ammonia achieves 99.8% lower well-to-wake GWP; and electric propulsion with renewable shore power and nuclear energy can deliver zero emissions (Vakili et al., 2025).

Speed reduction represents a particularly effective strategy, as the power required for propulsion increases proportionally to the cube of vessel velocity. Complementary strategies including Just-in-Time operations, improved port efficiency, and reduced waiting times can enhance adoption. For domestic shipping characterised by shorter distances, the impact of JIT may be less

pronounced than on international routes, though benefits from minimised port stays and streamlined logistics remain significant (Vakili et al., 2025).

3.8 Propulsion Methods Comparison

Ship propulsion methods are categorised into mechanical, electric, and hybrid systems, each presenting distinct advantages and limitations relevant to low-carbon transition planning. Mechanical propulsion offers less mechanical loss, low cost, and straightforward structure, but suffers from poor manoeuvrability, excessive noise, and limited flexibility. Electric propulsion provides low emissions, high efficiency, good availability, and low noise, but involves more power loss, high cost, and demanding control requirements. Hybrid systems combine low emissions, low noise, and good power performance, though they face challenges of low technology maturity, high cost, and elevated crew requirements (Wang et al., 2024).

Mechanical propulsion, wherein internal combustion engines connect directly to the propeller through a gearbox, remains dominant due to established technology, high efficiency at design conditions, and cost-effectiveness. However, maneuverability constraints and emissions variability under off-design conditions limit its suitability for vessels requiring operational flexibility.

Electric propulsion enables power generation equipment to operate continuously at optimal efficiency regardless of vessel sailing status. The elimination of mechanical drive shafts permits flexible machinery arrangement and reduced noise propagation. Electric propulsion is particularly suited to passenger vessels, cruise ships, and ferries where noise reduction enhances passenger comfort (Wang et al., 2024).

3.9 Energy Storage: Supercapacitors

Supercapacitors serve as complementary energy storage devices in maritime hybrid systems, addressing the distinct requirements of high-power, short-duration energy exchange. Their characteristics differ fundamentally from batteries (Wang et al., 2024):

Table 16 Supercapacitor and Lithium-Ion Battery Comparison

Characteristic	Supercapacitor	Lithium-ion Battery
Power density	300–5,000 W/kg	250–340 W/kg
Energy density	5 Wh/kg	100–265 Wh/kg
Charging time	<10 seconds	1–4 hours
Lifecycle	Up to 500,000 cycles	500–2,000 cycles
Temperature range	–40°C to +70°C	0°C to 45°C

Supercapacitors excel at smoothing high-frequency grid fluctuations over brief periods but are unsuitable for long-term energy storage due to low energy density. Their extended lifecycle (up to 500,000 charge-discharge cycles) and wide operational temperature range make them particularly valuable for dynamic load applications such as dynamic positioning operations and crane cycles (Wang et al., 2024).

3.10 Hybrid Propulsion Systems

Emerging research explores hydrogen-diesel dual-fuel systems and ammonia-hydrogen hybrid engines as promising configurations for achieving higher efficiency and lower emissions. Advances in catalytic decomposition technologies could enable onboard hydrogen production from ammonia (Sadiq et al., 2025).

Hybrid fuel cell-battery powertrains represent a particularly disruptive technology pathway for both greenhouse gas and criteria air pollutant emissions reduction. Several European Union-funded projects have advanced this technology domain, including the ZEM/SHIPS project developing hydrogen-powered passenger vessels with 300-600 kW electric motors, the MARANDA project featuring 165 kW PEMFC hybrid propulsion systems, and the METHAPU project evaluating solid oxide fuel cells with methanol fuel (Di Micco et al., 2022).

Battery-hybrid propulsion has achieved significant deployment, particularly in offshore and coastal applications. Over the preceding decade, 365 all-electric or hybrid vessels have entered operation globally. Offshore support vessels (OSVs), which typically spend 37% of running hours in dynamic positioning mode and 23% at port, demonstrate particularly favourable economics for hybrid power systems using lithium-ion batteries. Environmental assessments indicate that hybrid configurations achieve 40–45% reduction in annual global warming potential in Arctic operating areas and approximately 20% reduction in the North Sea (Palaniappan & Vedachalam, 2022).

Battery and hybrid technology represents an eco-friendly solution for short-sea fleets, as these vessels travel shorter distances between potential recharging or refuelling stations. The International Association of Classification Societies (IACS) has advocated for all-electric and hybrid designs for newly-built coastal and support vessels, recognising both the emissions reduction potential and the operational fuel cost savings achievable through intelligent power management systems (Palaniappan & Vedachalam, 2022).

IMO Regulations and International Policy Framework

4.1 Evolution of Maritime Environmental Regulations

The international regulatory landscape for maritime emissions has evolved significantly over the past decade, driven by mounting environmental concerns and the imperative for climate action. In 2018, the United Nations International Maritime Organisation established ambitious targets for the industry, setting the foundation for sector-wide decarbonisation efforts. Key emissions regulations include the IMO 2030 short-term targets, which introduced the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), alongside the longer-term IMO 2050 targets (Profumo et al., 2025).

A significant regulatory advancement occurred in 2025 with the adoption of the IMO Net-Zero Framework at MEPC 83 in April 2025. This framework establishes phased reduction targets: a 17% reduction by 2028, 43% reduction by 2035, 76% reduction by 2042, and net-zero GHG emissions by 2050 (Lin et al., 2025). The framework represents a substantial strengthening of the IMO's original 2018 targets and reflects growing international consensus on the urgency of maritime decarbonisation.

4.1.1 Historical Foundation: IMO Air Pollution Prevention Framework

The IMO's engagement with atmospheric pollution from shipping predates the contemporary focus on greenhouse gases. Resolution A.719(17), adopted on 6 November 1991, entitled "Prevention of Air Pollution from Ships," established the urgent necessity for a coordinated policy to address ship-source

air pollution, including ozone-depleting substances, exhaust gases from harmful fuel components, and volatile organic compounds. This resolution advocated for introducing air pollution standards within the MARPOL Convention framework (Spera, 2023).

The international community responded with the adoption of MARPOL Annex VI, “Regulation for the Prevention of Air Pollution from Ships,” in London on 26 September 1997. The annex entered into force on 19 May 2005, establishing the foundational international framework for controlling ship emissions. MARPOL Annex VI comprises 25 regulations organised across five chapters covering scope and application, inspection and certification, emission control requirements, energy efficiency, and verification of compliance (Spera, 2023).

Table 17 MARPOL Annex VI Structure

Chapter	Content	Key Requirements
I	Scope and Application	Definitions, exceptions, exemptions
II	Inspection and Certification	IOPP Certificate, IECC Certificate
III	Emission Control	SO _x , NO _x standards, fuel requirements
IV	Energy Efficiency	EEDI, SEEMP, EEXI, CII
V	Verification	Regulations 24-25 compliance

Source: Spera (2023)

The Marine Environment Protection Committee (MEPC), one of five IMO committees with authority over environmental matters, has subsequently amended MARPOL Annex VI through numerous resolutions and implemented its provisions through detailed guidelines. Key amendments have addressed sulphur content limits, nitrogen oxide technical codes, energy efficiency requirements, and data collection systems for fuel consumption monitoring (Spera, 2023).

Energy Efficiency Operational Indicator Improvements:

The Fourth IMO GHG Study 2020 documented substantial progress in operational efficiency across the global fleet during the decade 2008-2018. Analysis of Energy Efficiency Operational Indicator (EEOI) trends revealed consistent improvements across major vessel categories, with oil tankers, container ships, and general cargo ships all achieving reductions of 25-26% in their EEOI values compared to 2008 baseline levels (Spera, 2023).

The Fourth IMO GHG Study 2020 documented consistent improvements across major vessel categories, with oil tankers, container ships, and general cargo ships all achieving EEOI reductions of 25–26% compared to 2008 baseline levels (Spera, 2023).

Earlier IMO studies documented even more substantial emission reductions for certain vessel categories. The Third IMO GHG Study 2014 reported that implemented measures had achieved emission reductions ranging from 50% to 70% for some categories of vessels, demonstrating the effectiveness of regulatory intervention when consistently applied (Spera, 2023).

4.2 MARPOL Annex VI and Air Pollution Standards

The development of MARPOL Annex VI illustrates the IMO's historical approach to emissions regulation. The current instrument mix addressing emissions to air from ships is primarily based on codes and certificates that ships must comply with, focusing on established technologies and operational practices. Analysis of the policy mix reveals a predominance of regulatory instruments including bans on non-compliant fuel oil, emission standards through global and regional sulphur caps, and technical standards for engine installations (Bach & Hansen, 2023).

Notably, the existing policy mix lacks economic instruments and contains very few instruments targeting GHG emissions directly, with the vast majority of instruments regulating air-polluting substances such as sulphur oxides and nitrogen oxides rather than carbon dioxide (Bach & Hansen, 2023). The effectiveness of IMO regulation when properly implemented was demonstrated by the 2020 global sulphur cap, which achieved a 77% reduction in SO_x emissions from ships (Bach & Hansen, 2023).

4.3 Energy Efficiency Design Index (EEDI)

Since 2011, the Energy Efficiency Design Index has been mandatory for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships, established as part of MARPOL Annex VI. The EEDI represents a technical measure aimed at promoting the use of more energy-efficient and less polluting equipment and engines in new vessel construction. The index requires a minimum energy efficiency level per capacity mile (gCO₂/ton-mile) for different ship type and size segments (Palaniappan & Vedachalam, 2022).

The EEDI formula quantifies the relationship between environmental impact and societal benefit:

$$\text{EEDI} = (\text{P} \times \text{SFC} \times \text{Cf}) / (\text{DWT} \times \text{Vref}) \text{ [gCO}_2\text{/ton-mile]}$$

Where: - P = 75% of rated installed shaft power - SFC = specific fuel consumption of engines - C_f = CO₂ emission rate based on fuel type - DWT = deadweight tonnage - V_{ref} = vessel speed at design load

The EEDI can therefore be improved by increasing the DWT, optimising vessel speed, and incorporating efficiency-enhancing technologies. Calculation is based on technical design parameters verified during both preliminary (design stage) and final (sea trial) assessment phases (Palaniappan & Vedachalam, 2022).

The CO₂ reduction targets are phased to keep pace with technological developments:

Table 18 EEDI CO₂ Reduction Phase Schedule

Phase	Period	Reduction Rate	Notes
Phase 0	2013-2014	0%	Baseline establishment
Phase 1	2015-2019	10%	(15% for cargo >15000 DWT)
Phase 2	2020-2024	20%	(15% for cargo; 5% for passenger >4000 GT)
Phase 3	2025 onwards	30%	All applicable categories

The reference line represents the average efficiency for ships built between 2000 and 2010. Applicable ship categories include bulk carriers (>20,000 DWT), gas carriers (>10,000 DWT), tankers (>20,000 DWT), and container ships (>15,000 DWT). In 2014, the IMO Marine Environment Protection Committee extended EEDI scope to include LNG carriers, ro-ro cargo ships, ro-ro passenger ships, and cruise passenger ships with non-conventional propulsion. These extensions mean that ship types responsible for approximately 85% of CO₂ emissions from international shipping are incorporated under the EEDI regulatory regime (Palaniappan & Vedachalam, 2022).

The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to the industry. Ship designers and builders are free to use the most cost-efficient solutions to comply with regulations, provided the required energy efficiency level is attained. This approach promotes diversified technical solutions and fosters innovation. Compliance is demonstrated through issuance of an International Energy Efficiency Certificate by a verifier (maritime administration or classification society), with verification conducted in two stages: preliminary assessment during design and final verification through sea qualification tests at design speed and load under calm-water conditions (Palaniappan & Vedachalam, 2022).

4.4 Carbon Intensity Indicator (CII) and EEXI

The IMO's regulatory framework includes carbon intensity indicators designed to measure and incentivize emission reductions across the global fleet (Sadiq et al., 2025). The introduction of EEXI and CII under IMO 2030 short-term targets represents a significant regulatory milestone, establishing measurable benchmarks against which vessel efficiency improvements can be assessed (Profumo et al., 2025). Ships are classified into five CII rating bands (A to E, with A representing superior performance), and vessels rated D or E for three consecutive years must implement corrective action plans demonstrating how they will achieve the required C rating or better (Garbatov et al., 2023).

Risk-based analysis employing EU-MRV data indicates that achieving satisfactory CII ratings by 2030 will require operational adjustments for a substantial proportion of the existing fleet (Garbatov et al., 2023):

Table 19 Fleet Proportion Requiring Operational Adjustments for CII Compliance

Vessel Type	Fleet Requiring Operational Adjustments
Containerships	92%
Bulk carriers	86%
Gas carriers	80%
Tankers	74%
LNG carriers	59%

CII reduction factors tighten progressively: 5% (2023), 7% (2024), 9% (2025), and 11% (2026) relative to the Required CII baseline. Analysis of Black Sea containership operations suggests non-compliance rates will increase from 52% (2023) to 63% (2026) under these tightening standards (Garbatov et al., 2023).

However, significant regulatory gaps persist in these instruments. Technical standards remain centred on conventional fossil fuels, and emission factors for alternative propulsion technologies are currently lacking in the Energy Efficiency Design Index (EEDI), EEXI, and CII calculations. Consequently, shipowners who have invested in alternative solutions such as battery-hybrid propulsion, biodiesel, liquefied biogas, or methanol may not receive appropriate credit under these regulations if emission standards are not developed. Furthermore, many vessels can achieve compliance through implementing engine power limitation or shaft power limitation on existing engines rather than adopting

cleaner technologies, which limits the instruments' effectiveness in driving genuine emission reductions (Bach & Hansen, 2023).

Critical analysis has identified potential paradoxes in CII implementation. The Baltic and International Maritime Council (BIMCO) has cautioned that CII's calculation methodology—which prioritises distance and maximum capacity rather than actual cargo carried—may paradoxically reward higher-polluting ships under certain operational conditions. Ships operating on longer routes with substantial ballast legs receive more favourable CII ratings despite generating higher absolute emissions, while vessels with frequent port stays and shorter routes receive poorer ratings due to continued emissions at berth without corresponding distance denominators (Garbatov et al., 2023). Speed reduction remains an effective compliance strategy: vessels of 2,500 TEU can achieve EEXI compliance by reducing service speed to 19 knots, while larger ships require speeds of 21.5 knots or lower; maintaining CII ratings in the A to C range requires service speeds at or below 19.5 knots (Garbatov et al., 2023).

4.4.1 EEDI versus EEXI: Regulatory Design Comparison

While both EEDI and EEXI address energy efficiency, they represent fundamentally different regulatory approaches with distinct scopes, targets, and compliance pathways (RobaloCabrera2025):

Table 20 Comparison of EEDI and EEXI Regulatory Frameworks

Consideration	EEDI	EEXI
Applicable Vessels	New ships above 400 GT	New and existing ships
GHG Target	10% reduction per decade (phased)	30% reduction by 2022, net-zero by 2050
Technical Aspects	Hull design and propulsion optimisation	Hybrid systems, carbon capture, energy saving devices
Operational Aspects	Design-focused (reference conditions)	Speed reduction and engine power limits
Compliance Mechanism	Design verification during construction	Operational verification throughout vessel life

EEDI primarily influences newbuild decisions through design-stage requirements, while EEXI addresses the existing fleet through operational measures. This distinction creates a critical gap: even vessels meeting EEDI requirements at construction may require substantial operational modifications to satisfy EEXI requirements as targets tighten. Furthermore, EEDI's focus on

design conditions does not guarantee real-world efficiency, as actual operational profiles frequently diverge from reference parameters.

Stakeholder engagement in regulatory compliance extends across the maritime value chain. EEDI requires coordination among shipbuilders, shipowners, operators, technology providers, and classification societies during the design and construction phases. EEXI implementation additionally involves ship crews in day-to-day compliance through speed management and energy saving device operation. The Ship Energy Efficiency Management Plan (SEEMP) further requires active involvement of ship crew and stakeholders in continuous efficiency monitoring and improvement (RobaloCabrera2025).

4.5 Policy Mix Consistency Analysis

Evaluation of maritime decarbonisation policies using the Policy Mix Consistency (PMC) Index reveals notable variations in policy coherence across jurisdictions. The PMC Index, which measures the alignment and coherence of policy instruments within a given regulatory framework, indicates the following scores (Lin et al., 2025):

Table 21 Policy Mix Consistency Index Scores Across Jurisdictions

Policy Framework	PMC Index Score	Classification
IMO MEPC 83 Framework	8.017	High consistency
EU ETS Maritime Extension	7.925	High consistency
FuelEU Maritime	7.692	High consistency
China Maritime Policies	6.0-8.0	Moderate-high consistency

These findings suggest that international and regional maritime decarbonisation policies have achieved relatively high levels of internal coherence, though variations in implementation mechanisms and enforcement capacity remain significant challenges.

Despite shipping being one of few sectors with a main global regulatory body—which theoretically should enable comprehensive and consistent policy development—analysis indicates that the IMO’s policy mix lacks both consistency and comprehensiveness. The instrument mix is characterised by homogeneity, with most instruments being similar regulatory measures (emission standards, bans, technical specifications), while economic instruments and measures targeting innovation remain absent (Bach & Hansen, 2023). Three principal challenges impede the development of more effective GHG regulation: limited IMO capacity to regulate multiple and emerging technologies after having

regulated the same fuel type for over 50 years; uncertainty regarding the IMO’s regulatory mandate for market-based measures and research funding; and persistent lack of political consensus among member states during negotiations (Bach & Hansen, 2023).

4.6 IMO GHG Strategy Evolution (2018 to 2023)

The IMO’s greenhouse gas reduction strategy has undergone significant strengthening between its initial 2018 adoption and subsequent 2023 revision. The 2023 strategy responds to record global GHG emissions of 574 GtCO_{2e} in 2021–2022, recognising that a 28% reduction by 2030 is necessary to align with the Paris Agreement 2°C pathway (Wang et al., 2024):

Table 22 Comparison of 2018 and 2023 IMO GHG Reduction Strategies

Aspect	2018 Strategy	2023 Strategy (Revised)
2030 Target	40% carbon intensity reduction	20–30% absolute GHG reduction
2040 Target	Not specified	70–80% absolute GHG reduction
2050 Target	50% absolute GHG reduction	Net-zero GHG emissions
Character	Initial mandatory measures	More aggressive, ambitious targets
Context	First sector-wide strategy	Response to record emissions

The 2023 Revised IMO Strategy established explicit interim reduction milestones with aspiration levels: at least 20% GHG reduction by 2030 (striving for 30%), at least 70% reduction by 2040 (striving for 80%), and net-zero emissions by or around 2050, all relative to the 2008 baseline. These targets substantially exceed the original 2018 ambitions and reflect mounting evidence regarding the urgency of maritime decarbonisation (Zincir, 2025).

The 2018 strategy established the following targets relative to the 2008 baseline (Profumo et al., 2025):

The 2018 strategy established CO₂ intensity reduction targets of 40% by 2030 and 70% by 2050 relative to the 2008 baseline, alongside a 50% reduction in total GHG emissions by 2050 (Profumo et al., 2025).

The 2025 Net-Zero Framework adopted at MEPC 83 substantially strengthens these commitments, establishing more aggressive interim targets and explicitly committing to net-zero emissions by 2050 rather than the previous 50% reduction target (Lin et al., 2025).

4.7 European Union Maritime Regulations

The European Union has adopted more aggressive decarbonisation targets through its 'Fit for 55' package, outlining intentions to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. To ensure the shipping sector contributes to these climate ambitions, the European Commission applies a carbon tax through the Emissions Trading Scheme (ETS) covering CO₂ emissions from large ships exceeding 5,000 gross tonnage, regardless of flag state (Profumo et al., 2025).

The ETS extension encompasses: - 100% of emissions from intra-EU voyages - 50% of emissions from extra-EU voyages (beginning or ending outside EU) - All emissions occurring while ships are berthed in EU ports

Under the reformed ETS, emissions in covered sectors must be reduced by 62% by 2030 compared to 2005 levels. This regulatory framework creates an economic signal incentivising improved energy efficiency and low-carbon solutions while reducing the price differential between alternative and conventional marine fuels (Profumo et al., 2025).

The EU ETS maritime sector phase-in schedule establishes progressive coverage requirements (Du et al., 2025):

Table 23 EU ETS Maritime Sector Phase-In Schedule

Year	GHG Emissions Covered
2024	40%
2025	70%
2026+	100% (including CH ₄ and N ₂ O)

Coverage applies to 50% of emissions for voyages to and from EEA ports, and 100% of emissions while navigating and berthing within the EEA.

4.8 FuelEU Maritime Regulation

The FuelEU Maritime (FEUM) regulation, adopted in July 2023, represents the world's most ambitious legislation to stimulate decarbonisation of maritime shipping beyond EU borders. The regulation establishes mandatory greenhouse gas intensity reduction targets for ships above 5,000 gross tonnage on a well-to-wake basis, encompassing 100% of intra-EU voyages and 50% of voyages between EU and third-country ports. This threshold captures approximately 55% of ships calling at EU ports while covering approximately 90% of maritime GHG emissions (von Malmborg, 2025).

The FEUM regulation establishes progressively stringent GHG intensity targets against a 2020 baseline of 91.16 gCO₂e/MJ (Du et al., 2025). The 2025 target corresponds to an absolute limit of 89.34 gCO₂e/MJ (Zincir, 2025):

Table 24 FuelEU Maritime GHG Intensity Reduction Targets

Year	GHG Intensity Reduction (from 2020 baseline)
2025	-2% (89.34 gCO ₂ e/MJ)
2030	-6%
2035	-14.5%
2040	-31%
2045	-62%
2050	-80%

These final targets reflect strengthening during the legislative process. The European Commission's original proposal specified more moderate reductions (-13% by 2035, -26% by 2040, -59% by 2045, -75% by 2050), but concerted advocacy by the European Parliament and progressive member states resulted in increased ambition in the adopted regulation (von Malmborg, 2025).

4.8.1 FuelEU Maritime Policy-Making Process and Advocacy Coalitions

The negotiation of the FuelEU Maritime regulation illustrates the role of advocacy coalitions in shaping ambitious climate policy. Analysis using the Advocacy Coalition Framework (ACF) reveals two principal coalitions competing to influence regulatory outcomes (von Malmborg, 2023):

Table 25 FuelEU Maritime Policy-Making Advocacy Coalitions

Coalition	Key Actors	Core Positions
Progressive	European Parliament, Transport & Environment, environmental NGOs, advanced biofuel and e-fuel producers	Higher GHG intensity targets, stronger RFNBO sub-quotas, earlier implementation dates
Moderate	European Commission, Council majority, ECSA (European Community Shipowners' Associations)	Technology neutrality, flexibility mechanisms, phased implementation

Member state positions within the Council reflected divergent economic interests. A progressive coalition comprising Austria, Belgium, Denmark, Germany, Ireland, Luxembourg, the Netherlands, and Sweden advocated for enhanced ambition and mandatory RFNBO subquotas. Conversely, shipping-dependent Mediterranean states—Cyprus, Greece, and Malta—initially resisted ship operator obligations, preferring requirements targeting fuel suppliers rather than vessel operators. The European Parliament adopted its position with 451 votes in favour, 137 against, and 54 abstentions, supporting strengthened targets beyond the Commission proposal (von Malmborg, 2023).

The RFNBO sub-quota emerged as among the most contentious negotiating issues, reflecting tensions between technology-neutral approaches favoured by incumbent interests and targeted support for nascent fuel pathways advocated by green hydrogen and e-fuel producers. The final compromise—a contingent 2% RFNBO mandate by 2034, triggered only if market mechanisms prove insufficient to achieve 1% RFNBO share by 2031—exemplifies how coalition bargaining shapes regulatory design (von Malmborg, 2023).

Penal provisions demonstrate similar coalition influences. Non-compliance penalties of €2,400 per tonne of VLSFO equivalent shortfall, with multipliers for repeated violations, reflect progressive coalition preferences for strong enforcement. Revenue allocation to member state maritime decarbonisation funds addresses concerns regarding regulatory burden distribution (von Malmborg, 2023).

The case demonstrates that economically weaker policy entrepreneurs advocating transformative change can overcome resistance from dominant incumbents when they successfully couple attractive problem framings with viable policy solutions during responsive political windows—in this instance, the European Green Deal momentum and COVID-19 recovery emphasis on green transition (von Malmborg, 2023).

Key provisions of the FEUM regulation include:

- **RFNBO subquota:** A mandatory 2% subquota for renewable fuels of non-biological origin (RFNBOs) will be adopted by 2034 if analysis demonstrates that a multiplier mechanism is insufficient to achieve 1% RFNBO share in the fuel mix by 2031.
- **On-shore power requirement:** Ships moored at EU ports must connect to on-shore power supply (OPS) for all electrical power demand at berth, unless demonstrating use of alternative zero-emission technology.

- **Well-to-wake accounting:** Emissions are calculated across the complete fuel lifecycle, from extraction and refining through to combustion.

The FEUM regulation, together with the extension of EU ETS to maritime transport, represents a significant assertion of EU regulatory influence beyond its territorial waters. Impact assessments project that compliance costs will increase shipping costs by approximately 7% for EU shipowners and 17.8% for third-country operators by 2050 (von Malmborg, 2025).

4.9 EU-IMO Policy Interaction

The development of EU maritime climate legislation reflects a pattern of unilateral regional action in response to perceived insufficient progress at the international level. The EU played a leading role in the development of the IMO's initial climate strategy in 2018, but slow progress in adopting binding measures motivated EU policymakers to develop independent regulatory instruments (von Malmborg, 2025).

The European Commission's 2013 strategy for integrating maritime transport emissions into EU climate policy established a three-staged approach: (1) monitoring, reporting, and verification requirements; (2) establishment of GHG targets; and (3) introduction of policy instruments. This sequential approach culminated in the 2021 'Fit for 55' package, which simultaneously proposed EU ETS extension and the FuelEU Maritime regulation (von Malmborg, 2025).

The relationship between EU and IMO governance creates both opportunities and tensions. EU action serves as 'exemplary leadership' that may influence other jurisdictions and accelerate IMO negotiations. However, concerns have been raised regarding the EU's approach being perceived as 'soft imperialism' by states in the Global South, potentially undermining multilateral climate cooperation. The absence of 'just transition' provisions in EU maritime legislation—contrasting with discussions in global climate governance—may affect the EU's credibility in advocating for equitable international agreements (von Malmborg, 2025).

4.10 International Code of Safety for Ships Using Gases or Low-Flashpoint Fuels (IGF Code)

The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), adopted by the IMO and effective from January 2017, provides an international standard for vessels utilising low-flashpoint and gaseous fuels. The code addresses arrangement, installation, control, and

monitoring requirements to minimise risks to ships, crew, and the environment (Fu et al., 2023).

The IGF Code has evolved to accommodate emerging fuel technologies:

The IGF Code has evolved to accommodate emerging fuel technologies: entering force in 2017 with initial focus on LNG; in 2016 (CCC3), including fuel cell provisions as a separate section; in 2020, adding interim guidelines for methyl/ethyl alcohol fuels; and in 2021 (CCC7), agreeing interim guidelines for ships with fuel cell power units (Fu et al., 2023).

The fuel cell provisions address hydrogen purity monitoring, definition of ‘fuel cell space’, fire protection systems, and gas/vapour detection requirements. The International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) establishes complementary requirements for gas carrier construction and operation, though hydrogen-specific provisions remain under development (Fu et al., 2023).

4.11 International Standards for Fuel Cell Maritime Applications

The International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) have developed comprehensive standards for fuel cell system safety and testing applicable to maritime contexts:

IEC 62282 Series (Fuel Cell Technologies):

Table 26 IEC 62282 Series Standards for Fuel Cell Technologies

Standard	Scope
IEC 62282-1:2012	Fuel cell terminology
IEC 62282-2:2012	Fuel cell module safety and performance requirements
IEC 62282-3-100:2012	Stationary fuel cell power system safety
IEC 62282-3-200:2015	Performance test methods (>10 kW electrical output)
IEC 62282-3-300:2012	Installation requirements for indoor/outdoor systems

ISO Standards for Hydrogen Systems:

Table 27 ISO Standards for Hydrogen Systems

Standard	Scope
ISO 16110-1:2007	Hydrogen generators using fuel processing technologies—Safety
ISO/TR 15916	Basic considerations for hydrogen system safety
ISO 26142:2010	Hydrogen detection apparatus for stationary applications
ISO 15649:2001	Piping for petroleum and natural gas industries (including H ₂)
ISO/TS 19880-1:2016	Gaseous hydrogen fuelling stations—General requirements
ISO/TS 18683	LNG supply systems and installations for ships

National Classification Society Guidelines:

The American Bureau of Shipping (ABS) published ‘Fuel Cell Power Systems for Marine and Offshore Applications’ (2019), providing comprehensive guidance on design, evaluation, and construction in accordance with the IGF Code. DNV GL has issued similar rules addressing material selection principles for fuel cell systems. Japan’s Maritime Bureau developed hydrogen fuel cell guidelines specifically for small ships in 2018, covering mechanical strength, fuel cell arrangement, leak prevention, and safety monitoring (Fu et al., 2023).

4.12 Emission Control Areas (ECAs)

Emission Control Areas (ECAs) represent designated maritime zones where stricter emission standards apply than in open ocean areas. These zones have progressively expanded in geographic scope and pollutant coverage, creating regional compliance requirements that influence fuel choices and technology adoption patterns (Zincir, 2025):

Table 28 Emission Control Areas and Pollutants Regulated

ECA Region	Pollutants Regulated	Effective Date
Baltic Sea	SO _x , NO _x	1997 (SO _x), 2021 (NO _x)
North Sea	SO _x , NO _x	2006 (SO _x), 2021 (NO _x)
North American Sea	SO _x , NO _x , PM	2012
US Caribbean Sea	SO _x , NO _x	2014
Mediterranean Sea	SO _x , PM	2025
Canadian Arctic Sea	NO _x , SO _x , PM	1 January 2025
Norwegian Sea	SO _x , NO _x , PM	1 March 2026

Within ECAs, ships must use fuel with sulfur content not exceeding 0.10% (compared to the global 0.50% cap outside ECAs), or employ equivalent compliance measures such as exhaust gas cleaning systems. NO_x Tier III standards apply to ships constructed on or after specified dates when operating within designated NO_x ECAs, requiring either engine modifications, aftertreatment systems (SCR), or use of alternative fuels with inherently lower NO_x formation (Zincir, 2025).

4.13 Aftertreatment Technologies for Emission Reduction

While alternative fuels reduce emissions at source, aftertreatment technologies provide complementary means to address pollutants from combustion systems. Four principal technologies address NO_x and SO_x emissions (Wang et al., 2024):

Principal aftertreatment technologies address NO_x and SO_x emissions with varying effectiveness: Selective Catalytic Reduction (SCR) achieves up to 95% NO_x elimination and remains the only IMO-approved NO_x technology for marine diesel engines; Exhaust Gas Recirculation (EGR) reduces NO_x formation by lowering combustion temperature but may increase particulate matter; Non-Thermal Plasma (NTP) represents an emerging technology with potential for 60% NO_x and 80% SO_x removal, though high costs limit current application; and Seawater Flue Gas Desulphurisation (SWFGD) achieves up to 99% SO_x elimination through open, closed, or hybrid loop configurations (Wang et al., 2024).

Selective Catalytic Reduction (SCR): Injects urea-water solution into exhaust gas, where thermally decomposed NH₃ reacts with NO_x and O₂ to form harmless N₂ and H₂O. SCR has achieved NO_x elimination rates up to 95% in conventional diesel applications and remains the only IMO-approved

technology for reducing NO_x emissions from marine diesel engines. Metal oxide catalysts (V₂O₅, WO₃) accelerate reaction rates, though heavy metals, SO₂, hydrocarbons, and particulate matter can reduce catalyst efficiency (Wang et al., 2024).

Exhaust Gas Recirculation (EGR): Redirects exhaust gases into the combustion chamber after cooling and purification. The increased exhaust gas concentration and reduced oxygen content lower combustion temperature, thereby reducing NO_x formation. However, EGR may increase particulate matter emissions, necessitating optimisation of fuel injection strategies and complementary measures (Wang et al., 2024).

Non-Thermal Plasma (NTP) Catalysis: An emerging technology utilising non-thermal plasma to enhance catalytic reactions for NO_x and SO_x reduction. NTP shows potential for 60% NO_x and 80% SO_x removal rates, with NTP-SCR combinations enabling rapid low-temperature response. Despite promising efficiency, high technology costs and predominantly laboratory-scale applications necessitate further development (Wang et al., 2024).

Seawater Flue Gas Desulphurisation (SWFGD): Neutralises SO_x by passing exhaust gases through alkaline cleaning solution, achieving up to 99% SO_x elimination. Systems are categorised as open-loop (seawater, lower cost, simple structure), closed-loop (recirculated alkaline solution, higher efficiency), or hybrid (switchable between modes). Hybrid systems enable closed-loop operation in coastal areas and open-loop cleaning in oceanic regions (Wang et al., 2024).

4.14 Maritime CO₂ Transport Regulations for Carbon Capture and Storage

The maritime transport of captured CO₂ for geological storage presents a distinct regulatory challenge, requiring coordination across international environmental, trade, and liability frameworks. As CCS emerges as a critical mitigation technology—with 122 projects globally (26 fully operational) capturing approximately 35 Mt CO₂/year against global emissions of 33.5 Gt/year—the regulatory architecture for transboundary CO₂ shipping demands particular attention (Gola & Noussia, 2022).

London Protocol Framework: The London Protocol was not originally designed with CCS in mind. The 2006 amendment to Annex I permitted CO₂ storage in sub-seabed geological formations, while the 2009 Article 6 amendment (Resolution LP.3(4)) addressed transboundary export by allowing CO₂ transfer between contracting parties for offshore storage. However, as of December 2020, only six of the required 35 ratifications (two-thirds of 53

Parties) had been achieved—Norway, UK, Netherlands, Iran, Finland, and Estonia. To address this implementation gap, Resolution LP.5(14) established provisional application mechanisms in October 2019, enabling participating states to conduct transboundary CO₂ transport pending formal ratification (Weber, 2021).

Liability Frameworks: The HNS Convention provides the primary liability mechanism for CO₂ shipping casualties, though it has not yet entered into force. For vessels of approximately 12,600 GT—the estimated size for dedicated CO₂ carriers—shipowner liability under HNS would be limited to approximately US\$25.9 million, with the HNS Fund providing additional compensation up to US\$360 million. The liability formula applies a tiered calculation: 10 million SDR for the first 2,000 GT, plus 1,500 SDR per GT for tonnage between 2,001 and 50,000 GT, plus 360 SDR per GT exceeding 50,000 GT. The absence of an operative HNS Convention represents a significant regulatory gap that must be addressed before large-scale CO₂ shipping deployment (Weber, 2021; Gola & Noussia, 2022).

Regional Frameworks: The OSPAR Convention was amended in 2007 to permit CO₂ placement via pipeline from land-based sources into sub-seabed formations. However, ship-based injection remains more ambiguous under OSPAR provisions. The Convention on Biological Diversity introduced a geoengineering moratorium in 2010 (extended in 2016) that may affect certain CCS deployment scenarios, though conventional geological storage is generally distinguished from broader geoengineering definitions (Gola & Noussia, 2022).

EU ETS Integration: A critical regulatory gap exists regarding CO₂ ship transport within the EU ETS framework. The Monitoring Regulation explicitly defines “CO₂ transport” as “transport of CO₂ by pipelines,” with no mention of maritime transport. The drafters of the legislative framework focused on pipelines and did not plan for ship transport of CO₂. Following a query from the Norwegian Environment Agency, the European Commission confirmed that emissions from shipped CO₂ can be subtracted from installation totals for ETS purposes, though this interpretation lacks formal regulatory codification (Weber, 2021).

Trade Facilitation: Under the WTO/GATS framework, 44 of 164 members have committed to liberalising “cleaning of exhaust gases” services (CPC 9404), potentially encompassing CCS technology deployment. CO₂ is currently traded internationally with import duties ranging from 0 to 26%, and no fundamental impediments exist to CO₂ trade for industrial purposes. Trade modes relevant to CCS deployment include Mode 3 (commercial

presence) and Mode 4 (movement of natural persons), enabling technology transfer and operational expertise exchange. An impasse in WTO negotiations on Environmental Goods and Services does not preclude bilateral or regional liberalisation of CCS technologies through reduced tariffs on CCS components (Gola & Noussia, 2022).

Insurance Solutions: The insurance industry has developed specialised products addressing CCS operational risks. The Zurich CCS Liability Policy provides coverage for pollution events, business interruption, well control, transmission liability, and geo-mechanical liability over periods of 30–50 years. Short-term coverage options include “all risk” cargo insurance and “named peril” policies. However, existing liability policies do not extend coverage to long-term liability risks—the centuries-long timescales inherent to geological storage—representing a persistent gap in risk management frameworks (Gola & Noussia, 2022).

Carbon Pricing and Market-Based Mechanisms

5.1 Emissions Trading Systems in Maritime Context

The European Union Emissions Trading System (EU ETS) represents a primary market-based mechanism for pricing carbon emissions. Carbon prices within the EU ETS have demonstrated steady increases, reaching 78.25 €/ton in 2021. Projections indicate further escalation to approximately 129 €/tCO₂ by 2030 and 212 €/tCO₂ by 2040 (Di Micco et al., 2022). These price trajectories have significant implications for the economic viability of alternative fuel adoption in the maritime sector.

The EU incorporated the shipping industry into the carbon emission trading system in 2024, marking a significant milestone in maritime decarbonisation policy (Huang et al., 2025). With over 105,000 merchant ships participating in international trade and shipping CO₂ emissions accounting for 2–3% of the global total, market-based mechanisms are increasingly viewed as essential instruments for achieving sectoral emission reductions (Huang et al., 2025).

Policy analysis using the PMC Index indicates that the EU ETS maritime extension achieves a consistency score of 7.925, reflecting strong alignment between policy objectives and implementation instruments. The FuelEU Maritime regulation, which establishes greenhouse gas intensity limits for marine fuels, demonstrates comparable coherence with a PMC score of 7.692 (Lin et al., 2025). These findings suggest that European market-based mechanisms have been designed with attention to internal policy consistency, though cross-jurisdictional interactions with IMO frameworks warrant continued monitoring.

5.1a Combined GHG Emission Costs for Conventional Marine Fuels

The combined effect of EU ETS carbon pricing and FuelEU Maritime compliance requirements creates substantial additional costs for very low sulphur fuel oil (VLSFO). Projections of total GHG emission costs demonstrate an exponential trajectory through 2050 (Du et al., 2025):

Table 29 Projected GHG Emission Costs for VLSFO

Year	GHG Cost (€/t VLSFO)	Year-on-Year Increase
2025	313.94	—
2030	598.02	90%
2035	858.62	44%
2040	1,260.12	47%
2045	2,100.64	67%
2050	2,538.26	21%

These projections incorporate both direct carbon pricing under the EU ETS and penalty costs for non-compliance with FuelEU Maritime GHG intensity targets. The accelerating cost trajectory—representing an eight-fold increase from 2025 to 2050—creates powerful economic incentives for alternative fuel adoption. At 2024 VLSFO prices of 540–1,002 €/t, the projected GHG emission costs by 2050 would exceed the base fuel cost, fundamentally altering the economic calculus for marine fuel selection.

5.2 Carbon Price Sensitivity and Stakeholder Behaviour

Evolutionary game analysis of stakeholder interactions within carbon emission trading systems reveals significant behavioural dependencies on carbon price levels. Simulation studies demonstrate that when carbon trading prices remain in the range of USD 10–40 per tonne, carriers exhibit minimal propensity to invest in low-carbon transportation technologies. As carbon prices increase within reasonable ranges, carrier investment motivation rises substantially, as the cost of purchasing additional emission allowances exceeds the investment required for emission reduction measures (Huang et al., 2025).

This price sensitivity creates a threshold effect wherein carriers transition from maintaining conventional operations to actively pursuing emission reductions once carbon prices reach critical levels. At higher carbon prices, carriers can generate additional revenue by reducing emissions below allocated quotas and selling surplus allowances on the carbon market. The IMO has

considered Market-Based Measures (MBMs) as a means to address uncertainties regarding the availability and affordability of alternative marine fuels (Huang et al., 2025).

5.2a Evolutionary Game Dynamics of Shipping Company Zero-Carbon Transition

The integration of shipping into the EU ETS from 2024 (reaching 100% coverage by 2026) creates complex strategic interactions between governments and shipping enterprises. Unlike other industries, the shipping market experiences cyclical changes and high uncertainty, with many factors and complex systems involved in the zero-carbon transition process (He et al., 2024).

Global shipping CO₂ emissions have demonstrated sustained growth, rising from 794 million tonnes in 2008 to 8.334 billion tonnes in 2023—representing approximately 3% of total global emissions with an average annual growth rate of 3.1%. Without effective carbon reduction policies, the shipping industry’s share of global GHG emissions may increase to 17% by 2050 (He et al., 2024).

Evolutionary game analysis of government-enterprise interactions under carbon quota trading reveals critical thresholds that determine transition behaviour:

Table 30 Critical Thresholds for Zero-Carbon Transition Behaviour

Critical Point	Formula	Interpretation
Carbon trading price	$p = 2u(Qd - e)$	Price at which enterprise shifts from buying to selling carbon allowances
Government regulatory behaviour	$\Delta e = (p + \varepsilon)/2u$	Emission reduction level minimizing regulatory probability
Emission reduction intensity	$k = (R_1 - R_2)/M$	Threshold for government regulatory strategy change

Where u = zero-carbon transition effect parameter; e = carbon allowance; Qd = emissions without transition; ε = market benefit coefficient; M = government subsidy

Simulation analysis of policy parameter effects demonstrates asymmetric impacts on transition probability:

Policy parameter simulation demonstrates asymmetric impacts on transition probability: decreasing government regulatory costs and increasing penalty caps both enhance zero-carbon transition probability, with penalty cap increases

demonstrating particularly significant effects; government subsidies positively affect transition strategies but with comparatively minor impact; and higher zero-carbon transition effectiveness reduces government regulation probability (He et al., 2024).

A critical finding concerns the differential effectiveness of policy instruments: penalty mechanisms demonstrate significantly greater influence on shipping company transition decisions than subsidy mechanisms. Increasing penalty caps benefits zero-carbon transition substantially, whilst subsidies positively affect transition strategies but with comparatively minor impact. This suggests that regulatory frameworks combining dynamic penalty mechanisms with targeted subsidies may achieve superior outcomes compared to subsidy-dominated approaches (He et al., 2024).

Under static penalty mechanisms, evolutionary trajectories of government and enterprise behaviour cycle around equilibrium points without stabilising. However, dynamic penalty mechanisms—where penalty intensity varies with enterprise transition behaviour according to $W(x) = (1 - x)W_m$ —produce spiral convergence toward a unique evolutionarily stable strategy regardless of initial conditions. Government regulatory changes lag behind changes in enterprise zero-carbon transition behaviours, indicating that regulatory authorities should enhance information exchange with enterprises to improve regulatory efficiency and effectiveness (He et al., 2024).

5.3 Carbon Taxation Approaches

Economic analyses indicate that carbon taxation represents a critical mechanism for improving the economic feasibility of alternative fuels. Studies suggest the following carbon tax thresholds to achieve cost parity (Sadiq et al., 2025):

Carbon tax thresholds required to achieve cost parity with conventional fuels vary significantly by alternative fuel type: hydrogen requires approximately 965 €/t, while ammonia—due to its higher production costs and lower energy density—requires approximately 2,647 €/t to achieve equivalent economic competitiveness (Sadiq et al., 2025).

5.3a External Costs of Maritime Air Pollutants

Beyond carbon dioxide pricing, comprehensive economic assessment of maritime fuels requires monetisation of broader environmental externalities including air pollutants that generate health impacts and environmental degradation. Impact Pathway Analysis (IPA), developed through the ExternE project and applied via the Clean Air for Europe (CAFE) Programme and

HEATCO frameworks, provides methodology for translating emissions into monetary damages (Helgason et al., 2020).

External cost estimates for maritime air pollutants at sea demonstrate substantial economic valuations for conventional fuel emissions:

Table 31 External Cost Estimates for Maritime Air Pollutants

Pollutant	Low (€/tonne)	Medium (€/tonne)	High (€/tonne)
NO _x	2,272	4,795	7,318
SO ₂	3,196	5,798	8,400
Particulate Matter	1,458	1,458	1,458
NMVOC	76	809	1,543

For heavy fuel oil combustion, NO_x and SO₂ combined contribute 97–99% of total external costs, with particulate matter and non-methane volatile organic compounds representing marginal contributions. This external cost structure fundamentally shifts when comparing methanol to conventional fuels: methanol combustion eliminates SO₂ and NMVOC emissions entirely whilst reducing NO_x emissions by approximately 82% and particulate matter by 95% (Helgason et al., 2020).

European maritime external costs have been estimated at €8.4 billion annually (2000), projected to increase to €4.1 billion by 2020—representing 7% to 12% of total health effects attributable to air pollutants in Europe. Shadow carbon prices following European Investment Bank methodology indicate trajectories from €15–55/tonne in 2018 to €50–200/tonne by 2050, depending on assumed annual escalation rates. When these external costs are internalised through policy mechanisms, natural gas-derived methanol becomes cost-competitive with heavy fuel oil across most scenarios (Helgason et al., 2020).

5.3b Carbon Tax versus Carbon Trading: Comparative Analysis

Multi-objective speed optimization analysis for China–Europe liner routes provides empirical comparison of carbon tax and carbon trading mechanisms operating alongside the EU ETS. Using the AEX-1 route (11 segments connecting Shanghai, Ningbo, Xiamen, Yantian, Singapore, Felixstowe, Zeebrugge, Gdansk, and Wilhelmshaven), two policy scenarios were evaluated: carbon tax combined with EU ETS (Situation A) versus carbon trading combined with EU ETS (Situation B) (Sun et al., 2025).

Single Voyage Comparison:

Comparison of single voyage performance reveals carbon tax combined with EU ETS achieves total voyage costs of USD 13,039,928 (versus USD 13,263,806 under carbon trading), carbon emissions of 16,865 tonnes (versus 17,989 tonnes), voyage time of 1,672 hours (versus 1,654 hours), and carbon emission costs of USD 1,504,063 (versus USD 1,553,947). The carbon tax scenario demonstrates superior performance on both cost and emissions metrics for single voyages, saving USD 223,878 while reducing emissions by 1,124 tons CO₂. However, the shorter voyage time under carbon trading enables 5.30 annual voyages compared to 5.24 under carbon taxation (Sun et al., 2025).

Annual Operations Comparison:

On an annual basis, carbon trading enables marginally more voyages per year (5.30 versus 5.24), but carbon taxation demonstrates superior performance on both cost and emissions metrics—producing annual voyage costs of USD 68.3M versus USD 70.3M under trading (a USD 2.0M advantage), whilst reducing annual carbon emissions to 88,373 tonnes compared to 95,342 tonnes under trading (a reduction of 6,969 tonnes) (Sun et al., 2025).

Applying social cost of carbon at approximately USD 171/ton, the annual emissions difference translates to USD 1.19 million in avoided external costs under the carbon tax scenario, reinforcing its overall economic and environmental superiority (Sun et al., 2025).

Sensitivity to Fuel Price Fluctuations:

Analysis across fuel price ranges of USD 350–650/ton reveals differential policy stability. Carbon trading mechanisms maintain stable emissions (~16,000 tonnes) regardless of fuel price levels, while carbon tax emissions fluctuate: at USD 350/ton fuel prices, carbon tax emissions reach approximately 17,500 tonnes; at USD 460/ton, they fall to 16,865 tonnes; and at USD 650/ton, emissions decline to approximately 15,500 tonnes. This stability advantage suggests carbon trading may provide more predictable environmental outcomes in volatile market conditions, though at higher overall cost (Sun et al., 2025).

EU Carbon Quota Sensitivity:

As the EU ETS quota ratio increases from 40% (2024 level) toward 100% (full coverage by 2026), policy differences converge. At 100% EU coverage, both mechanisms demonstrate similar performance, with carbon trading showing slight advantages in both cost and emissions. This convergence indicates that as EU ETS expands to full coverage, the choice between

supplementary domestic carbon mechanisms becomes less critical to overall voyage economics (Sun et al., 2025).

The analysis demonstrates that speed optimization—balancing cubic fuel consumption relationships with time window constraints—enables shipping companies to mitigate carbon pricing impacts. Optimized speeds ranged from 6.1 to 24.1 knots across route segments, with Suez Canal transit limited to 7.2 knots and average voyage speeds stabilising around 14–15 knots regardless of policy scenario.

5.3c Game-Theoretic Analysis of Decarbonisation Technology Investment

The strategic interdependencies governing shipping company decisions on green technology adoption reveal systematic barriers to industry-wide decarbonisation. Cournot duopoly analysis integrating operational efficiency and carbon reduction effects into competitive frameworks demonstrates a tripartite prisoner's dilemma in technology adoption—a phenomenon with significant implications for policy design (Wu et al., 2025).

Strategic Scenario Analysis:

Four competitive configurations emerge depending on whether each firm adopts traditional (T) or digital/green (D) technologies:

Four competitive configurations emerge depending on technology adoption strategies: when both firms maintain traditional technology (TT), baseline competition produces industry-wide inefficiency; asymmetric adoption (TD/DT) creates “winner-takes-all” dynamics wherein the technology leader captures market share at the laggard's expense; and simultaneous digital adoption (DD) intensifies competition such that collective profits fall below the unilateral adoption scenario (Wu et al., 2025).

Cost Threshold Conditions:

Optimal technology strategy depends critically on cost parameters:

Optimal technology strategy depends critically on cost parameters: when unit operating costs and installation costs are both low, unilateral adoption (TD/DT) enables technology leaders to gain competitive advantage; when either cost parameter is high, mutual reliance on traditional technology (TT) represents the Pareto optimal outcome by avoiding destructive competition; and moderate cost conditions produce Nash equilibrium through simultaneous digital adoption (DD), though this outcome is collectively suboptimal (Wu et al., 2025).

When digital technology costs are low relative to efficiency gains ($c < a - dT - rE$, where c = unit operating cost, a = market size, d = transportation time sensitivity, T = digital transit time, r = carbon emission sensitivity, E = digital emissions), freight rates decrease and market demand increases. Conversely, high technology costs reverse these effects, forcing price increases that dampen demand (Wu et al., 2025).

Tripartite Prisoner's Dilemma:

The analysis identifies three distinct dilemma configurations:

- 1. Unilateral Application Dilemma (TD/DT):** The technology adopter gains market share and profitability while the laggard suffers corresponding losses. This creates first-mover advantages but also competitive instability.
- 2. Simultaneous Application Dilemma (DD):** When both firms adopt digital technology, total industry profit falls below the unilateral scenario due to intensified competition and duplicated investment costs.
- 3. Non-Application Dilemma (TT):** Mutual reliance on traditional technology produces industry-wide inefficiency and the lowest aggregate environmental performance.

The model quantifies technology effects using calibrated parameters: digital technology reduces transit time by 40% (from 10 to 6 units) and carbon emissions by 50% (from 8 to 4 units). Transportation time sensitivity ($d = 0.3$) and carbon emission sensitivity ($r = 0.2$) reflect empirical evidence on customer valuation of efficiency and environmental performance under current regulatory frameworks (Wu et al., 2025).

Policy Implications:

These findings suggest that market forces alone may produce suboptimal decarbonisation outcomes. Coordinated policy interventions addressing specific barriers include:

Policy responses to address these decarbonisation barriers include: targeted financial incentives (digitalisation subsidies, tax credits, green technology funds) to overcome high installation cost barriers; mandatory industry-wide data-sharing platforms and green shipping corridors to mitigate winner-takes-all competitive risks; and coordinated infrastructure investment programmes to address collective action failures. The analysis highlights that “individual rationality can lead to collective inefficiency,” underscoring the necessity for alliance-based governance mechanisms to overcome adoption barriers and align corporate strategies with sectoral decarbonisation objectives (Wu et al., 2025).

5.3d EU ETS Impacts on Short-Sea Shipping and Modal Shift

The extension of the EU ETS to maritime transport creates significant competitive implications for short-sea shipping (SSS), potentially undermining European policies designed to promote modal shift from road to maritime transport. Analysis of the Spain–Northern Italy Ro-Ro corridor—handling 37% of Mediterranean Ro-Ro tonnage—reveals that full EU ETS implementation could divert up to 25% of maritime traffic back to road transport (Martínez-Moya et al., 2025).

EU ETS Phase-In Cost Impacts:

The progressive coverage schedule creates escalating cost burdens for Ro-Ro operations:

The progressive EU ETS coverage schedule creates escalating cost burdens for Ro-Ro operations: at 40% coverage in 2024, additional costs of approximately €80 per 14-metre semi-trailer create moderate impacts; 70% coverage in 2025 raises additional costs to approximately €130 with substantial impacts; and full 100% coverage from 2026 imposes approximately €190 in additional costs, representing the full burden of carbon pricing (Martínez-Moya et al., 2025).

Operator Type Response Patterns:

Transport operator responses to EU ETS cost increases vary systematically by business model. INTERMODAL operators—those with logistics systems specifically designed to exploit Ro-Ro cost advantages—demonstrate greatest sensitivity, while predominantly road-based operators show minimal response:

Table 32 Modal Share Reduction by Operator Type Under EU ETS

Operator Type	Market Share	2024 Impact (pp)	2025 Impact (pp)	2026 Impact (pp)
INTERMODAL	42% of shipments	-10.6 (-13%)	-16.4 (-20%)	-25.9 (-31%)
MIXED	21% of shipments	-6.2 (-23%)	-8.7 (-33%)	-12.0 (-45%)
ROAD	37% of shipments	Minimal	Minimal	Minimal

pp = percentage points of Ro-Ro modal share decline

INTERMODAL operators exhibit highest cost sensitivity precisely because their intermodal business structure is specifically designed to benefit from cost savings associated with Ro-Ro transport. As these savings diminish under EU ETS, their competitive model becomes compromised (Martínez-Moya et al., 2025).

Policy Instrument Interactions:

European policy instruments designed to support short-sea shipping—such as Spain’s ECO-incentivo subsidy programme (€25–100 per shipment depending on route)—operate in direct conflict with EU ETS cost impositions. Analysis of combined policy effects reveals that ETS impacts may cancel or exceed subsidy benefits:

Analysis of combined policy effects on Valencia routes reveals that ECO-incentivo subsidies (providing +8.0 percentage points support across all years) are insufficient to offset escalating EU ETS impacts: net combined effects shift from –1.0 percentage points in 2024 (–9.6 pp from ETS) to –8.4 percentage points in 2025 (–16.4 pp from ETS) and –17.9 percentage points by 2026 when full ETS coverage imposes –25.9 percentage point impacts (Martínez-Moya et al., 2025).

This creates a net budgetary paradox wherein firms are simultaneously taxed (through EU ETS allowance purchases) and subsidised (through ECO-incentivo) for the same Ro-Ro transport activity. A deadweight effect compounds this inefficiency: subsidy recipients are largely established operators with intermodal systems already in place, meaning public funds support activities that would have occurred regardless (Martínez-Moya et al., 2025).

Policy Conflict with Motorways of the Sea:

The findings reveal fundamental tension between EU climate and transport policies. While the Motorways of the Sea programme and associated subsidy schemes aim to lower SSS costs to enhance competitiveness against road transport, the EU ETS imposes additional costs that weaken this advantage. The expected benefits from incentive programmes can be significantly reduced, or entirely cancelled out, by EU ETS effects along strategic routes. Recommendations include maintaining reduced ETS coverage (40%) for SSS until 2027 when road transport enters ETS2, thereby allowing convergence of competitive conditions across modes (Martínez-Moya et al., 2025).

5.3e Carrier-Port Coordination Under Carbon Tax Policy

The implementation of carbon taxation in maritime supply chains creates complex strategic interactions between ocean carriers, ports, and governments. Game-theoretic analysis using multi-stage Stackelberg models reveals that carriers and ports have fundamentally conflicting preferences regarding supply chain power structures, with implications for carbon tax policy effectiveness (Wang & Zhu, 2023).

Maritime Emissions Context:

Global maritime CO₂ emissions increased from 962 million tonnes in 2012 to 1,056 million tonnes in 2018—a 9.3% rise over six years. The maritime sector's contribution to global emissions correspondingly increased from 2.76% to 2.89%, with projections indicating potential growth to 18% by 2050 absent effective policy intervention. The consolidation of carrier market power through alliance formation complicates carbon tax implementation: the three major alliances (2M, Ocean Alliance, and THE Alliance) have controlled over 80% of global shipping since April 2017 (Wang & Zhu, 2023).

Strategic Preferences Under Carbon Tax:

Game-theoretic analysis reveals systematic differences between stakeholder preferences across supply chain power structures. Carriers rank profit outcomes from highest to lowest as: alliance-led, equal power, port-led (alliance), and port-led (competition)—preference favouring alliance formation and leadership. Ports rank preferences inversely: port-led (competition), port-led (alliance), equal power, and alliance-led—preference favouring decentralised carriers under port leadership. The supply chain as a whole achieves maximum welfare under integrated structures, followed by equal power, port-led (competition), and port-led (alliance) (Wang & Zhu, 2023).

This fundamental conflict creates continuous competitive cycles—carriers preferring alliance formation and bargaining power while ports prefer scattered carriers under port leadership—creates continuous competitive cycles of resource integration and capacity expansion as each party seeks dominant market position (Wang & Zhu, 2023).

Coordination Contract Effectiveness:

Analysis of coordination mechanisms to resolve carrier-port conflicts under carbon taxation reveals differential effectiveness: conventional revenue-sharing combined with cost-sharing fails because cost-sharing is insufficient to compensate carriers for revenue shared with ports; however, subsidy combined with revenue-sharing succeeds because port subsidies stimulate shipping demand, improving total profits available for redistribution (Wang & Zhu, 2023).

The failure of conventional supply chain coordination contracts (revenue-sharing with cost-sharing) in maritime contexts under carbon taxation contrasts with their success in general supply chain literature. The critical difference lies in the absence of demand elasticity with respect to emission reduction or service quality investments—shippers do not demonstrably prefer low-carbon

shipping services, limiting the profit-enhancing potential of emission reduction investments (Wang & Zhu, 2023).

Carbon Tax Policy Sensitivity:

The effectiveness of carbon taxation varies with the proportion of emissions attributable to carriers versus ports: when ports bear higher emissions ($r = 0.4$), ports increase service prices to pass carbon costs to carriers; conversely, when carriers bear higher emissions ($r = 0.6$), ports decrease service prices to maintain cargo volumes, exhibiting altruistic behaviour that buffers carriers from carbon tax impacts whilst maintaining port throughput (Wang & Zhu, 2023).

Policy Failure Conditions:

Carbon tax policy may fail to achieve emission reduction objectives when governments do not consider market conditions. Failure modes include: demand misjudgment when government assumes high demand ($a=3000$) whilst actual demand is low ($a=600$), setting carbon tax rates too high relative to market capacity; scenario mismatch when tax rates designed for integrated supply chains are applied to competitive markets, imposing inappropriate tax burdens; high competition intensity ($b \leq 0.64$) that causes carriers and ports to refuse to operate entirely; and moderate competition ($b > 0.64$) that reverses alliance incentives and destabilises market structure. The 2012 failure of EU maritime carbon taxation proposals exemplifies these dynamics (Wang & Zhu, 2023).

Vertical Integration Benefits:

Game-theoretic comparison of coordinated versus vertically integrated supply chains reveals that integration produces superior outcomes on both economic and environmental dimensions:

- Social welfare higher under integration than coordination contracts
- Environmental damage ratio: $ED^{\wedge} \text{ integrated} / ED^{\wedge} \text{ coordinated} < 0.4$
- Carbon tax revenue provides excess compensation for environmental damage under integration

These findings support government policies encouraging deeper carrier-port cooperation through strategic partnerships, joint ventures, and cross-ownership arrangements as pathways toward supply chain integration that benefits both economic performance and emission reduction effectiveness (Wang & Zhu, 2023).

5.3f Trilateral Game Model for Maritime Emission Reduction

Beyond bilateral carrier-port interactions, a comprehensive understanding of maritime decarbonisation requires analysis of trilateral strategic dynamics among governments, port authorities, and shipping companies. Evolutionary game theory provides a framework for examining how these stakeholders' strategies evolve under bounded rationality—where decision-making is constrained by limited information and imperfect judgment (Ruslan et al., 2025).

Trilateral Stakeholder Strategies:

Each stakeholder faces a choice between active and passive approaches to emission reduction:

- **Government:** Active regulation (enforce regulations, provide incentives, implement carbon pricing) versus passive regulation (maintain status quo, rely on voluntary measures)
- **Port Authorities:** Active emission reduction (invest in green infrastructure, adopt sustainable operations) versus passive approach (operate without sustainability investment)
- **Shipping Companies:** Active emission reduction (transition to alternative fuels, retrofit vessels) versus passive approach (continue traditional practices)

Evolutionary Stable Strategy Conditions:

The probability of stakeholders adopting active strategies depends on cost-benefit relationships. For port authorities, the net incremental benefit condition determines strategy choice: when $Pp2 - Pp1 - Cp1 > 0$ (where $Pp2$ represents benefits when shipping companies adopt green strategies, $Pp1$ represents benefits when shipping companies maintain traditional practices, and $Cp1$ represents modernisation costs), adopting active emission reduction becomes economically advantageous. Illustrative analysis suggests that without shipping company alignment, port modernisation investments may generate net losses of approximately \$200,000, whilst alignment with green shipping strategies can produce net benefits exceeding \$300,000 (Ruslan et al., 2025).

For shipping companies, additional costs of fleet retrofitting (estimated at approximately \$1.5 million per company for comprehensive upgrades) represent significant financial burdens. The viability of active emission reduction strategies depends on whether potential operational efficiencies and market advantages outweigh these transition costs. Government incentives

prove critical in offsetting initial high costs and shifting stakeholder behaviour toward active strategies (Ruslan et al., 2025).

Economies of Scale in Green Technology:

Cost functions that incorporate economies of scale reveal that per-unit costs decline as adoption expands, following the relationship $C(n) = C_0 \times n^{-\alpha}$, where α represents the scale factor ($0 < \alpha < 1$). When policy-driven subsidies are incorporated, the function becomes $C(n) = C_0 \times n^{-\alpha} - S(n)$, where $S(n)$ represents government subsidies or incentives. This approach reflects empirical trends where increased production volume and infrastructure development lead to cost reductions, as observed in LNG bunkering, shore power facilities, and alternative fuel vessel retrofitting (Ruslan et al., 2025).

Policy Design Implications:

Analysis of subsidy adjustment mechanisms reveals significant differences between gradual phase-out and abrupt termination scenarios. Gradual subsidy phase-out produces smoother convergence toward active stakeholder strategies, as replicator dynamics remain relatively stable and adaptation occurs incrementally—minimising disruption and sustaining momentum in green investment. In contrast, abrupt subsidy termination introduces sudden cost burdens that cause temporary destabilisation of strategic equilibria, with delayed or reduced convergence toward active emission reduction strategies, particularly among shipping companies. This distinction is critical for designing transition pathways that align economic feasibility with environmental policy goals (Ruslan et al., 2025).

Coordination Benefits:

The interdependence of government actions, port operations, and shipping company decisions underscores the need for a collaborative approach. As each party's strategies directly influence the others, coordinated investment timing and aligned incentive structures prove essential. Public-private partnerships can facilitate shared investments in infrastructure projects, technology upgrades, and regulatory compliance measures, distributing costs effectively whilst maximising collective benefits across the maritime industry (Ruslan et al., 2025).

5.4 Fuel Cell System Costs

The capital cost of fuel cell propulsion systems represents a significant barrier to widespread maritime adoption. Current cost estimates indicate substantial variation by fuel cell type and scale of deployment:

Table 33 Fuel Cell and Propulsion System Component Costs

Component	Cost	Notes
PEMFC	~\$1,000/kW	Most mature technology
SOFC	~\$5,500/kW	Higher efficiency, fuel flexibility
SOFC (alternative estimate)	€2,000/kW	Cruise ship applications
Lithium-ion battery	~\$500/kW or €800/kWh	Hybrid system energy storage
DC/DC converter	\$200/kW	Power conditioning
Propulsion motor	\$135/kW	Electric drive system

For a 4,100-passenger cruise ship configuration, total SOFC power requirements reach 14.1 MW complemented by 25.71 MW battery discharge capacity (3.601 MWh rated capacity). The environmental cost of SOFC technology, expressed as willingness to pay for emission avoidance, is estimated at €20/tCO₂eq—indicating the premium that operators might accept to achieve emission reductions (Fu et al., 2023).

5.5 Marine Fuel Production Cost Comparison

Comparative analysis of alternative marine fuel production costs reveals significant variation across fuel categories. Using 2019 data with electricity costs of 33 €/MWh and electrolyser efficiency of 69%, biofuels represent the lowest-cost category at 69–95 €/MWh (including bio-methanol and biodiesel), followed by bio-electrofuels at approximately 116 €/MWh (such as e-bio-diesel), with electrofuels representing the highest-cost category at approximately 158 €/MWh for products like e-diesel (Fu et al., 2023).

For liquid hydrogen specifically, cost components distribute as follows: electricity (~40% of total), electrolyser (~23%), infrastructure (~23%), and liquefaction treatment (~14%). A 50% increase in electricity prices would result in approximately 25% increase in liquid hydrogen fuel cost, whereas bio-electrofuels demonstrate lower sensitivity to electricity price fluctuations (Fu et al., 2023).

5.5a Green Methanol Levelised Production Costs

Techno-economic analysis of offshore wind-powered green methanol production reveals significant cost variation based on system configuration and geographic location. Four principal system scenarios have been evaluated (Du et al., 2025):

Table 34 Green Methanol Levelised Production Cost Scenarios

Scenario	Electricity Source	Carbon Source	Average LCOM (2025)
Pure Scenario I	OWF-E (DC/PPA)	DAC	1,123.70 €/t
Pure Scenario II	OWF-E (DC/PPA)	ICC	1,008.35 €/t
Mix Scenario III	OWF-E + Grid-E	DAC	1,077.43 €/t
Mix Scenario IV	OWF-E + Grid-E	ICC	952.91 €/t

OWF-E = Offshore Wind Farm Electricity; DAC = Direct Air Capture; ICC = Industrial Carbon Capture; DC = Direct Connection; PPA = Power Purchase Agreement

Geographic analysis of seven major EU ports demonstrates significant LCOM variation driven primarily by offshore wind resource quality:

Table 35 Green Methanol Production Costs at Major EU Ports

Port	LCOM (€/t)	Avg Wind Speed (m/s)
Gdansk	907.63	9.41
Marseille	912.71	9.31
Antwerp-Bruges	934.89	9.32
Rotterdam	966.94	9.40
Hamburg	1,019.72	9.96

Mediterranean ports with lower average wind speeds demonstrate substantially higher production costs: Valencia (1,976 €/t), Piraeus (2,039 €/t), and Barcelona (2,122 €/t). LCOM composition analysis indicates electricity consumption represents more than 60% of total costs, with alkaline water electrolysis accounting for approximately 50% of electricity consumption. Facility construction contributes 20–25% and operations and maintenance approximately 15–20% (Du et al., 2025).

GHG emission savings across all scenarios exceed the 70% minimum threshold required for Renewable Fuels of Non-Biological Origin (RFNBO) certification under EU regulations, with pure scenarios achieving 95.96% savings and mix scenarios ranging from 87.77% to 95.01%.

5.5b International Green Methanol Supply Chain Economics

Analysis of Power-to-X pathways across developing and emerging countries reveals substantial geographic variation in green methanol supply costs delivered to European markets. Evaluation of 34 regions across 10 countries, incorporating production costs and maritime transport to Germany, demonstrates a pronounced cost range from 190 to 274 €/MWh (Meyer-Larsen & Schories, 2025):

Table 36 International Green Methanol Supply Chain Costs to European Markets

Country	Levelized Supply Cost (€/MWh)	Delivered Cost (€/t)*
Colombia	190–274	1,052–1,517
Australia	192–200	1,063–1,108
Algeria	202–222	1,119–1,230
Tunisia	214–224	1,185–1,240
Spain	216–230	1,196–1,274
Namibia	222–240	1,230–1,329
Morocco	225–247	1,246–1,368
South Africa	226–236	1,252–1,307
India	232–264	1,285–1,462
Mexico	237–244	1,312–1,351

**Based on methanol energy content of approximately 5.54 kWh/kg.*

The lowest-cost region identified is La Guajira, Colombia, with a levelized supply cost of 190 €/MWh (approximately 1,052 €/t delivered to Germany), with carbon dioxide sourced from direct air capture. Australia demonstrates consistently low production costs across all analyzed regions despite substantially longer transport distances to European markets, with analysis indicating that transport distance is of minor relevance compared to renewable energy resource quality and local production conditions. Spain's Pedrola and Gibraltar regions offer promising European production potential, though additional investigation of Iceland, Norway, Scotland, and the United Kingdom is warranted to achieve comprehensive assessment of European green methanol production capabilities (Meyer-Larsen & Schories, 2025).

Renewable methanol production via carbon capture and utilisation (CCU) pathways demonstrates specific electricity requirements of 8.2–10.9 MWh per tonne methanol, corresponding to process efficiencies of 51–68%. Electricity costs represent 23–65% of total production costs depending on

plant configuration and local energy prices. In geothermal-rich regions such as Iceland, CCU-pathway methanol production costs have been estimated at 921 €/tonne (2018), with projected learning-curve reductions of 20–30% by 2050. However, this production cost remains substantially higher than conventional natural gas-derived methanol at 380 €/tonne, representing a 112% cost premium. Cost-competitiveness analysis indicates renewable methanol achieves parity with heavy fuel oil only when environmental externalities are fully internalised, with crossover projected between 2042 and 2047 under high external cost scenarios (Helgason et al., 2020).

5.5c Onboard Carbon Capture System Economics

The economic viability of onboard carbon capture represents a critical consideration for achieving deep decarbonisation of existing vessel fleets. Techno-economic analysis of MCFC-based carbon capture systems integrated with methanol-fuelled propulsion provides detailed cost breakdowns for large container vessel applications (Berry et al., 2025).

For a 10,000 TEU container vessel retrofit, total capital expenditure is estimated at \$46.4 million, with MCFC stack costs representing 49% of CAPEX—a significant reduction from 74% reported in 2021 estimates, reflecting ongoing technology cost reductions. The levelised cost of electricity (LCOE) for the integrated MCFC-ICE-ORC system is 0.16 \$/kWh, compared to 0.12 \$/kWh for conventional MDO-fuelled propulsion—a 25% premium for near-complete decarbonisation:

Table 37 LCOE Component Breakdown for MCFC-Based Carbon Capture System

LCOE Component	Share (%)	Cost Impact
Fuel (green methanol)	73.5%	Primary cost driver
Capital expenditure	21.5%	MCFC + ORC + CCS equipment
Operations & maintenance	5.0%	Including stack replacement

Carbon capture costs for the MCFC-based system are estimated at 105.9 \$/tonne CO₂, competitive with land-based post-combustion capture systems whilst avoiding the significant efficiency penalties associated with conventional solvent-based absorption. Annual revenues from CO₂ sales and carbon credits are projected at \$12.35 million, effectively subsidising the system's operational costs. Sensitivity analysis indicates green methanol price exerts the strongest influence on system economics, followed by electricity price and CO₂ market value (Berry et al., 2025).

5.5d Onboard Carbon Capture Technology Comparison

Bibliometric analysis of maritime decarbonisation research identifies carbon capture as an emerging but underexplored technology area, with only 12 papers (5.71% of the literature) published between 2011 and 2024. Research attention has increased since 2021, driven by recognition that onboard CCS may serve as a bridging solution for existing vessel fleets. Four principal capture technologies have been evaluated for maritime applications, each with distinct performance characteristics and operational requirements (Tran et al., 2025):

Table 38 Onboard Carbon Capture Technology Comparison

Method	Capture Rate	Energy Requirement	Key Characteristics
MEA absorption	90%	3.7 GJ/tCO ₂	Mature technology; requires amine regeneration
MDEA/PZ mixed solvent	~90%	3.3 GJ/tCO ₂	10% energy reduction vs MEA
Temperature Swing Adsorption (TSA)	~90%	Minimal (waste heat utilisation)	High efficiency using existing thermal energy
Alkaline absorption (NaOH)	~20% reduction	Lower complexity	Simpler system for low-concentration applications

The energy penalty associated with conventional MEA-based post-combustion capture (3.7 GJ/tCO₂) represents a significant operational cost. Mixed MDEA/PZ solvents achieve comparable capture rates with approximately 10% energy reduction (3.3 GJ/tCO₂), improving economic viability. Temperature Swing Adsorption (TSA) systems offer the most favourable energy economics by utilising waste heat from ship engines, achieving approximately 90% capture rates with minimal additional energy input. Alkaline absorption using sodium hydroxide (NaOH) provides a simpler technical solution suitable for low-concentration applications, though with more modest emission reduction potential (~20%).

The relatively limited research attention to maritime CCS—compared to dominant focus on alternative fuels (40.95% of literature)—suggests opportunities for expanded investigation as regulatory pressure intensifies and zero-carbon fuel availability remains constrained (Tran et al., 2025).

5.6 Subsidies and Incentives for Green Fuels

Targeted incentives for green energy projects and renewable energy production are essential for creating competitive market conditions for alternative maritime

fuels (Sadiq et al., 2025). Techno-economic analyses indicate that hydrogen-based propulsion systems can achieve cost competitiveness with conventional diesel when hydrogen retail prices reach 4 \$/kg, provided that carbon incentives of approximately 112 \$/ton CO₂ are implemented (Di Micco et al., 2022).

The anticipated evolution of fuel prices further influences the economic calculus. Hydrogen prices are projected to decline from current levels of approximately 16.5 \$/kg to 4 \$/kg by 2050, while diesel prices are expected to increase from 0.5 \$/kg to 1.3 \$/kg over the same period. These converging trends, combined with carbon pricing mechanisms, are anticipated to render fuel cell systems economically competitive within the target scenario timeframe (Di Micco et al., 2022).

Evolutionary game analysis indicates that government subsidies covering approximately 10–30% of carriers' low-carbon investment costs yield optimal effectiveness in motivating emission reduction behaviour. However, the marginal utility of subsidies diminishes as total subsidy levels increase; consequently, as subsidy intensity rises, its incremental incentive effect on carrier behaviour decreases (Huang et al., 2025). This finding suggests that subsidy policies should be dynamically calibrated to avoid diminishing returns on public expenditure.

5.6a Subsidy Targeting Strategies for Green Technology Adoption

Agent-based simulation research demonstrates that strategic targeting of subsidies to specific vessel subsets can substantially improve adoption rates compared to uniform subsidy distribution. Rather than allocating small subsidies across all potential adopters, concentrating equivalent budgets on strategically selected seed vessels achieves markedly higher technology diffusion. When the same total budget is distributed uniformly across all vessels, adoption rates approach zero due to insufficient individual incentive levels; conversely, targeted allocation to approximately 10% of the fleet at economically meaningful subsidy levels (approximately €300,000 per vessel for wind-assisted propulsion installations) generates measurable adoption cascades (Romero et al., 2025).

The selection criteria for targeted subsidy recipients significantly influence policy effectiveness. Degree-based targeting—selecting vessels whose owners demonstrate high social connectivity through networking activities, conference attendance, and industry engagement—achieves the highest adoption rates when budgets are substantial, as these owners influence the adoption decisions of their network contacts. However, at mid-level budget constraints (€250,000–€275,000 per vessel), combining degree-based criteria with energy

consumption metrics yields superior outcomes, ensuring that targeted vessels are both economically motivated to adopt and socially positioned to influence others (Romero et al., 2025).

Saturation points exist in subsidy effectiveness, above which additional funding yields diminishing returns. For wind-assisted propulsion technology, adoption rate growth becomes statistically non-significant above approximately €290,000–€300,000 per vessel. These thresholds enable optimal resource allocation—ensuring subsidies are neither insufficient to motivate adoption nor excessive relative to marginal benefit. The identification of such saturation points is essential for policy efficiency, particularly given constrained public budgets for maritime decarbonisation incentives (Romero et al., 2025).

5.6b Government Incentive Programs for Maritime Decarbonisation

Government incentive programs across major maritime nations have established diverse mechanisms to accelerate fleet decarbonisation. These programs vary in structure—encompassing direct grants, port dues reductions, tax incentives, and infrastructure investment co-funding—but share the common objective of reducing financial barriers to alternative fuel and efficiency technology adoption (Zincir, 2025):

Table 39 Government Incentive Programs for Maritime Decarbonisation

Country/Region	Program	Key Provisions
United States	Clean Ports Program	\$3 billion for zero-emission port equipment
United States	Port Infrastructure Development	\$662 million/year for modernisation and electrification
United Kingdom	Clean Maritime Demonstration Competition	£128 million for green maritime technologies
Singapore	Green Port Program	30% port dues discount for zero-carbon fuels; 25% for low-carbon
Norway	Green Shipping Program	Grants for zero-emission vessels and retrofits
Canada	Halifax Port Authority	Rebates for Environmental Ship Index compliance
Colombia	Differentiated Port Tariffs	Reduced fees for environmentally compliant ships
European Union	Horizon Europe	Funding for H ₂ /NH ₃ propulsion and port electrification

These incentive structures influence technology adoption trajectories by altering the economic calculus for shipowners and operators. Port dues reductions—particularly in high-traffic hubs such as Singapore—provide recurring operational cost benefits that improve payback periods for alternative fuel investments. Direct grants and infrastructure co-funding address capital expenditure barriers that disproportionately affect smaller operators lacking access to favourable financing terms (Zincir, 2025).

5.7 Economic Barriers to Adoption

The high capital expenditures required for retrofitting vessels and elevated operational costs of hydrogen and ammonia compared to conventional marine fuels create significant financial obstacles to widespread adoption (Sadiq et al., 2025).

5.8 Market Cyclicity and Policy Effectiveness

The effectiveness of carbon emission trading policies in the shipping sector is significantly influenced by shipping market cyclicity. During periods of market prosperity, when transportation demand exceeds available capacity, carriers possess greater pricing power and can transfer a higher proportion of emission reduction costs to shippers through surcharges. This enhanced cost-transfer capability increases carrier willingness to invest in low-carbon technologies. Conversely, during market downturns characterised by excess capacity and insufficient demand, carriers' ability to pass through additional costs is constrained, reducing the effectiveness of emission reduction incentives (Huang et al., 2025).

According to evolutionary game analysis, governments should consider implementing shipping emission reduction policies—such as the two-tier compliance system proposed at MEPC 83—during periods of shipping market prosperity rather than depression. The cyclical nature of shipping markets (depression, recovery, prosperity, recession) should inform the timing of policy implementation to maximise effectiveness. When shippers face transportation cost increases from emission reduction measures, their sensitivity to the differential between maritime and alternative transport costs determines modal choice behaviour; specifically, when alternative transport costs fall below approximately 2.5 times shipping costs, shippers demonstrate increased propensity to switch transport modes (Huang et al., 2025).

5.9 Trilateral Game Analysis of Government-Port-Shipping Interactions

The strategic interactions governing maritime decarbonisation extend beyond bilateral relationships to encompass trilateral dynamics among governments, port authorities, and shipping companies. Evolutionary game theory analysis of these three-way interactions reveals complex patterns of strategic interdependence that determine the pace and effectiveness of emission reduction efforts (Ruslan et al., 2025).

Trilateral Strategic Framework:

Each stakeholder faces a binary strategic choice between active and passive approaches to emission reduction. Government active strategies include strict regulation, financial incentives, and enforcement, while passive strategies involve weak enforcement and reliance on voluntary compliance. Port authorities may pursue active strategies through infrastructure investment and green technology adoption, or passive strategies maintaining status quo operations with minimal investment. Shipping companies face similar choices between fleet modernisation, alternative fuels, and efficiency measures versus traditional operations with conventional fuels (Ruslan et al., 2025).

The evolutionary stable strategy (ESS) outcomes depend critically on cost-benefit thresholds. For governments, the probability of active regulation decreases when regulatory costs are high and port authority incentives are limited, but increases when higher penalties are imposed for non-compliance. Critically, as port authorities and shipping companies become more proactive in reducing emissions independently, the likelihood of government intervention decreases—suggesting that industry self-regulation can substitute for government action when stakeholders perceive sufficient market or reputational benefits (Ruslan et al., 2025).

Port Authority Decision Dynamics:

Port authorities demonstrate counterintuitive behaviour: they become more likely to actively reduce emissions when emission reduction costs increase, as higher costs signal greater competitive differentiation opportunities. However, port authority action probability decreases when government regulation is already strong or when shipping companies are already acting—indicating potential free-riding behaviour when other stakeholders bear the decarbonisation burden (Ruslan et al., 2025).

Synchronisation Requirements:

Analysis reveals that misaligned investment timing between port authorities and shipping companies produces suboptimal outcomes. When port authorities modernise infrastructure but shipping companies do not adopt greener vessels, port investments may fail to generate expected returns. Numerical scenario analysis demonstrates that full alignment (both active) generates +\$1.0 million in port net benefit, misalignment (port active, shipping passive) results in −\$200,000 losses, whilst both passive strategies produce break-even outcomes. This synchronisation requirement underscores the importance of coordinated policy interventions that simultaneously incentivise both port infrastructure development and shipping company fleet modernisation (Ruslan et al., 2025).

Subsidy Transition Pathways:

The manner in which government subsidies are phased out significantly affects long-term stakeholder behaviour stability. Gradual phase-out produces smooth convergence toward active strategies with high stability and sustained momentum, whereas abrupt termination creates cost function shocks and delays active strategy adoption, producing low stability particularly for shipping companies facing sudden cost increases. These findings suggest that subsidy programmes should incorporate explicit transition pathways with predictable phase-out schedules (Ruslan et al., 2025).

Policy Design Implications:

The trilateral game framework yields several policy recommendations for effective maritime decarbonisation governance:

- 1. Penalty mechanisms demonstrate greater effectiveness than subsidies** in driving shipping company transition decisions, suggesting regulatory frameworks should emphasise compliance enforcement alongside financial incentives
- 2. Dynamic penalty mechanisms**—where penalty intensity varies with enterprise transition behaviour—produce stable convergence toward decarbonisation goals, unlike static penalties that generate cyclical behaviour
- 3. Public-private partnerships** can distribute infrastructure investment costs while maximising collective benefits
- 4. Information sharing mechanisms** between government and industry improve regulatory efficiency by reducing the lag between enterprise behaviour changes and regulatory responses

These findings complement earlier bilateral analyses of carrier-port dynamics by incorporating the government regulatory dimension, providing a more complete framework for understanding the strategic landscape of maritime decarbonisation (Ruslan et al., 2025).

5.10 Port Implementation Schemes for GHG Emission Reduction

Beyond market-based mechanisms targeting vessels, port and public authorities deploy a range of implementation schemes to drive GHG emission reduction across the maritime supply chain. Systematic analysis of 112 studies identifies five main groupings and nine categories of policy instruments and tools available to port policymakers (Alamouh et al., 2022).

Implementation Framework:

Port GHG emission reduction implementation involves four interconnected dimensions: implementers (port policymakers comprising port authorities and public authorities), target groups (port polluters including port operators, oceangoing vessels, and land transport), outcomes (uptake of technical and operational measures), and outputs (implementation schemes driving measures adoption). Analysis of global best practices indicates that approximately 60% of implementation schemes are administered by port authorities, with 40% managed by public authorities such as municipal, central, or federal governments (Alamouh et al., 2022).

Table 40 Port Implementation Schemes Framework

Grouping	Category	Mechanism
Regulation and Standards	Regulations	Enforcement of international, national, and local GHG regulations
Economic Incentives/Disincentives	Incentives and grants	Rebates, discounts, subsidies for GHG reduction measures
	Tariff change	Differentiated charges based on environmental performance
	Market-based measures	Emission trading, carbon taxation
Voluntary/Compulsory Agreements	Voluntary agreements	Non-binding commitments beyond regulatory requirements
	Concessions and licences	Environmental requirements in terminal contracts
Capacity Building	Training programmes	Education and awareness raising
	Knowledge sharing	Best practice dissemination
Planning	Port plans	Sustainability targets in master plans

Target Group Distribution:

Analysis of implementation scheme targeting reveals differentiated focus across polluter categories: port operators receive 45% of implementation attention (primarily through concession contracts and regulations), land transport operators 31% (predominantly through regulations and tariff changes), and oceangoing vessels 24% (mainly through incentive programmes). This distribution reflects jurisdictional constraints wherein international shipping remains subject primarily to port state control within territorial waters, while port and land transport operators fall under more comprehensive national/local regulatory frameworks (Alamouh et al., 2022).

Ship Environmental Indices:

Economic incentive schemes for vessels predominantly utilise environmental indices and certifications including the Environmental Ship Index (ESI) based on EEOI reporting, Clean Shipping Index (CSI) comparing emissions to reference ships, Green Award (GA) recognising current emission levels, and GHG Emission Rating (GHG ER) under RightShip certification based on EEDI/EVDI performance. However, analysis reveals that GHG or CO₂ is not the primary determinant in most incentive schemes—only GHG ER places GHG reduction as the central criterion—meaning port incentives contribute only partially to overall GHG emission reduction (Alamouh et al., 2022).

Incentive Effectiveness Constraints:

Critical analysis of port-based ship incentives reveals structural limitations. Economic incentives account for 48% of shipping emission reduction measures, with 56% of EU ports offering ship incentives and 34% explicitly encouraging GHG reduction. However, whole port dues constitute only approximately 1% of voyage costs, suggesting incentives may influence newbuild investment decisions but have limited impact on operational changes in existing vessels. At the Port of Rotterdam, only 7% of calling ships qualify for environmental incentives due to stringent eligibility thresholds (Alamouh et al., 2022).

Vessel Speed Reduction Incentives:

Despite structural limitations, targeted VSR incentive programmes demonstrate measurable results. The POLB and POLA Green Flag Incentive Program achieved 29% CO₂ reduction between 2002 and 2007 through economic incentives for voluntary speed reduction approaching port waters (Alamouh et al., 2022).

Tariff Change Effectiveness:

The PierPass programme at POLB/POLA demonstrates tariff change effectiveness: an additional USD 50 charge for peak-hour container handling shifted 35% of containers to night hours within six months of implementation, reducing congestion and associated idling emissions whilst generating revenue neutrality through offsetting off-peak operational costs (Alamouh et al., 2022).

GHG Reduction Potential:

Ship-port interface measures collectively offer approximately 4% shipping GHG reduction potential (OPS contributing 3% plus other operational measures contributing 1%). Combined with OGV technical and operational measures offering 40–70% reduction potential, and assuming comprehensive regulation enforcement, total shipping GHG reduction of up to 75% by 2050 appears achievable (Alamouh et al., 2022).

Best Combination Approach:

Analysis indicates implementation schemes are most effective when deployed in combinations rather than isolation. The San Pedro Bay Ports Clean Air Action Plan successfully employs an integrated mix of lease requirements, tariff changes, incentives and grants, and voluntary agreements, supported by regulatory requirements as an ultimate backstop. This combination approach maintains flexibility should single mechanisms prove insufficient whilst creating multiple reinforcing pressure points for polluter compliance (Alamouh et al., 2022).

5.11 Bayesian Networks for EU ETS Decision-Making

The complexity of the EU ETS maritime extension necessitates advanced analytical tools to understand how monitoring, reporting, and verification (MRV) indicators influence compliance costs. Bayesian network modelling provides a probabilistic framework for analysing interdependencies between key variables, facilitating identification of the most influential factors in ETS cost determination and enabling data-driven strategic decision-making by shipping companies, port operators, and policymakers (Vaca-Cabrero et al., 2025).

MRV System Framework:

The EU MRV system, introduced in 2018, requires vessels exceeding 5,000 GT operating within the European Economic Area to monitor and report fuel consumption and CO₂ emissions. The mechanism operates through three

fundamental pillars: monitoring (collecting data on fuel consumption, cargo carried, distances travelled, and ports visited), reporting (annual submission to competent authorities via the THETIS-MRV platform), and verification (evaluation by independent entities to ensure accuracy and regulatory compliance). This data infrastructure provides the foundation for ETS cost calculations (Vaca-Cabrero et al., 2025).

Bayesian Network Methodology:

Bayesian networks were applied to analyse 18 MRV indicators including total fuel consumption, CO₂ emissions, technical efficiency, sailing times, and other operational factors. Using structural learning algorithms (HillClimbSearch with BIC optimisation) and Bayesian parameter estimation with Dirichlet priors, the model identified dependency relationships between variables and quantified their relative influence on ETS cost determination. Network pruning using expert criteria and adjacency matrix analysis eliminated weak relationships whilst consolidating clearer dependencies between emission indicators and compliance costs (Vaca-Cabrero et al., 2025).

Table 41 Most Influential MRV Indicators on EU ETS Costs

Indicator	Description	Influence Level
I_15	Annual average CO ₂ emissions per distance	Highest
I_9	CO ₂ emissions from voyages between ports in MS jurisdiction	High
I_12	CO ₂ emissions at berth within MS jurisdiction	High (exceeded expectations)
I_8	Total CO ₂ emissions	Moderate
I_7	Total fuel consumption	Moderate

Key Findings:

Analysis reveals that fuel efficiency—measured as annual CO₂ emissions per nautical mile (I_15)—represents the most influential variable in determining ETS costs. This finding suggests that cost reduction strategies should prioritise operational efficiency improvements and average emissions reduction rather than focusing solely on total emission volumes. The prominence of per-distance efficiency metrics indicates that route optimisation and speed management may offer greater cost mitigation potential than previously recognised (Vaca-Cabrero et al., 2025).

Port Emissions Significance:

A particularly significant finding concerns the unexpectedly high influence of port emissions (I_12) on ETS cost determination. CO₂ emissions generated during vessel stays at berth appear in prominent positions within the network hierarchy, highlighting the importance of port-based emission mitigation strategies. Cold ironing—enabling vessels to connect to shore-side electrical power rather than operating auxiliary engines—emerges as a key intervention for reducing ETS compliance costs. This finding reinforces the case for accelerated shore power infrastructure investment at European ports (Vaca-Cabrero et al., 2025).

Navigation Patterns and Carbon Leakage Risk:

The analysis identifies strong interdependence between intra-EU voyage emissions (I_9) and ETS cost structures. Navigation patterns and the regionalisation of maritime traffic significantly shape regulatory exposure, suggesting that shipping companies may reconfigure routes to minimise ETS coverage by favouring calls at third-country ports with less stringent environmental regulations. This carbon leakage potential poses competitive challenges for European ports and requires monitoring by policymakers to ensure that ETS implementation does not inadvertently divert traffic to jurisdictions with lower environmental standards (Vaca-Cabrero et al., 2025).

Decision-Making Applications:

The probabilistic model provides stakeholder-specific guidance:

For shipping companies: Optimise routes and improve vessel technical efficiency; focus on reducing average emissions per nautical mile rather than absolute emission volumes; evaluate route reconfiguration implications for ETS exposure.

For port operators: Prioritise port emission reduction investments; implement cold ironing infrastructure; develop emission mitigation capabilities as a competitive differentiator.

For policymakers: Design regulations accounting for the significant weight of port emissions in ETS costs; monitor carbon leakage risks arising from route reconfiguration; consider impacts on EU port competitiveness when evaluating ETS implementation effectiveness (Vaca-Cabrero et al., 2025).

Advantages Over Traditional Approaches:

Unlike deterministic models or traditional multi-criteria decision-making frameworks, Bayesian networks explicitly model uncertainty and conditional

dependencies, enabling dynamic updating of predictions as new data become available. This adaptability is particularly valuable in evolving regulatory environments where unforeseen variables influence compliance costs. The hierarchical network structure facilitates interpretation by distinguishing between primary influencers and secondary dependencies, enabling stakeholders to prioritise key indicators for targeted intervention (Vaca-Cabrero et al., 2025).

5.11a MRV Implementation Challenges and Industry Preparedness

The parallel development of EU MRV and IMO DCS frameworks represents a significant regulatory evolution requiring systematic data collection from the global fleet. The EU's monitoring, reporting, and verification (MRV) regulation commenced data collection on 1 January 2018, whilst IMO's data collection system (DCS) followed one year later on 1 January 2019. Both regimes apply to ships exceeding 5,000 GT, though critical implementation differences exist in data handling, verification processes, and disclosure requirements (Rony et al., 2019).

Framework Comparison:

The two regimes differ fundamentally in their approach to data transparency. EU MRV requires annual disclosure of aggregated emission data on a ship-by-ship basis through the publicly accessible THETIS MRV database. In contrast, IMO DCS maintains data confidentiality, with ship-specific information held within the IMO database but not publicly released. This distinction reflects differing regulatory philosophies regarding market incentives versus commercial sensitivity (Rony et al., 2019).

Table 42 EU MRV vs IMO DCS Implementation Comparison

Aspect	EU MRV	IMO DCS
Monitoring Plan	Separate document; verified by accredited verifier	SEEMP Part II; flag state/RO confirmation
Reporting Destination	European Commission (THETIS MRV)	Flag State → IMO database
Verification Entity	Independent accredited verifier	Flag State/Recognised Organisation
Emissions Coverage	EU voyages + at berth	All global voyages
Data Disclosure	Publicly available	Confidential

Emission source coverage also varies between frameworks. Both EU MRV and IMO DCS cover main engines, auxiliary engines, boilers, gas turbines, and inert gas generators. However, incinerators are covered only under EU MRV. The SEEMP/EEOI framework, by contrast, covers main engines, auxiliary engines, and boilers but excludes gas turbines and inert gas generators (Rony et al., 2019).

Industry Preparedness Assessment:

Survey research among 74 maritime professionals in Singapore and Bangladesh revealed substantial optimism regarding MRV's potential impact on existing energy efficiency frameworks. Notably, 73% of respondents anticipated that MRV implementation would positively affect Ship Energy Efficiency Management Plans (SEEMP) to a large extent, whilst an additional 24% expected minor positive impacts. No respondents identified negative effects, indicating broad industry confidence in the framework's complementarity with existing efficiency measures (Rony et al., 2019).

However, preparedness varies considerably across the industry. Analysis of ISO standards adoption revealed that whilst 73% of surveyed organisations complied with ISO 9001:2015 (Quality), only 49% met ISO 14001:2015 (Environmental Management) requirements, and merely 34% complied with ISO 50001:2011 (Energy Management). This gradient suggests that energy-specific management systems remain underdeveloped relative to general quality frameworks. More concerning, 22% of organisations reported that energy efficiency was not included in any form within their management structures (Rony et al., 2019).

Table 43 Industry Survey Results: MRV Impact and Preparedness (n=74)

Survey Question	Finding	Percentage
MRV positive impact on SEEMP (large extent)	54 respondents	73%
MRV positive impact on SEEMP (minor)	18 respondents	24%
ISO 9001:2015 compliance	54 respondents	73%
ISO 14001:2015 compliance	36 respondents	49%
ISO 50001:2011 compliance	25 respondents	34%
Energy efficiency not included in organisation	16 respondents	22%

Data Quality Challenges:

The effectiveness of MRV implementation depends critically on data quality. Survey findings identified the human element as the dominant factor

in data inaccuracy: 50% of respondents attributed inaccuracies primarily to human error in collection and interpretation, whilst 27% cited lack of correct procedures. Combined, human element factors accounted for 77% of identified data quality issues. Equipment-related errors accounted for only 9% of concerns (Rony et al., 2019).

More troubling findings emerged regarding misreporting. Whilst 69% of respondents attributed reporting errors to human error or knowledge gaps, 29% indicated awareness of intentional misreporting—including 18% citing fraudulent data entry and 11% citing intentional maintenance of undeclared fuel stocks. These findings highlight data integrity as a substantive concern requiring verification mechanisms and compliance enforcement (Rony et al., 2019).

Technology Infrastructure:

Computerised Maintenance Management Systems (CMMS) provide platforms for systematic data collection and transmission. Survey results indicated that 54% of organisations utilised CMMS for maintenance and data functions, whilst 10% operated without any such system. Notably, 28% of respondents were uncertain whether their organisations employed CMMS, revealing potential communication gaps between operational and shore-side functions. CMMS adoption facilitates MRV compliance by enabling automated data collection, reducing manual entry errors, and providing standardised formats for information exchange (Rony et al., 2019).

Assessment of data collection problems showed that 70% of surveyed organisations had identified issues and implemented corrective measures, demonstrating proactive engagement with data quality improvement. However, 16% of organisations had conducted no assessment, indicating gaps in compliance readiness that require attention prior to enforcement deadlines (Rony et al., 2019).

Staged Regulatory Approach:

EU MRV represents the first stage of a broader strategy for incorporating maritime emissions into the European GHG reduction framework. The staged approach envisions: (1) monitoring, reporting, and verification of emissions; (2) establishment of sector-specific GHG reduction targets; and (3) introduction of market-based measures including emissions trading. Expected benefits from MRV implementation include 2% emission reduction compared to business-as-usual scenarios and cost savings of €2 billion by 2030 through improved operational efficiency incentivised by transparent performance data (Rony et al., 2019).

Data Quality Management Requirements:

Effective MRV implementation requires robust Data Quality Management (DQM) encompassing data integrity, reliability, and noise reduction. DQM addresses data holes arising from sensor interval gaps, manual recording interference, and equipment failures. Verification procedures include plausibility checks for fuel consumption data and cross-referencing vessel activity against Automatic Identification System (AIS) records. Per ISO 19030-1:2016, data uncertainty assessments require expert evaluation of available resources and case-specific applicability determination (Rony et al., 2019).

Monitoring plans must incorporate procedures for measuring fuel uplift and tank quantities, ensuring measurement uncertainty compliance with regulatory standards, recording distance travelled and cargo carried, and detecting surrogate data whilst eliminating gaps. Regular review—at minimum annually—ensures continued alignment with operational changes and regulatory updates (Rony et al., 2019).

Glossary of Abbreviations

A

Abbreviation	Full Term
ACO	Ant Colony Optimization
AFIR	Alternative Fuels Infrastructure Regulation
AGI	Artificial General Intelligence
AI	Artificial Intelligence
AIS	Automatic Identification System
ALDE	Adaptive Lagrangian Differential Evolution
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network

B

Abbreviation	Full Term
BAU	Business As Usual
BDN	Bunker Delivery Note
bio-LNG	Bio-Liquefied Natural Gas

C

Abbreviation	Full Term
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CII	Carbon Intensity Indicator
CMA CGM	Compagnie Maritime d'Affrètement - Compagnie Générale Maritime
CNCI	Category Normalized Citation Impact

Abbreviation	Full Term
CNN	Convolutional Neural Network
CO ₂	Carbon Dioxide
CO ₂ eq	Carbon Dioxide Equivalent
COE	Cost of Energy
COSCO	China Ocean Shipping Company

D

Abbreviation	Full Term
DC	Direct Current
DCS	Data Collection System
DNV	Det Norske Veritas
DOI	Digital Object Identifier
DWT	Deadweight Tonnage

E

Abbreviation	Full Term
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EGCS	Exhaust Gas Cleaning System
ETS	Emissions Trading System
EU	European Union
EU ETS	European Union Emissions Trading System

F

Abbreviation	Full Term
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FFNN	Feedforward Neural Network
FL	Fuzzy Logic
FuelEU	FuelEU Maritime Regulation

G

Abbreviation	Full Term
GA	Genetic Algorithm

Abbreviation	Full Term
GANs	Generative Adversarial Networks
GDP	Gross Domestic Product
GH ₂	Gaseous Hydrogen
GHG	Greenhouse Gas
GP	Genetic Programming
GSC	Green Shipping Corridor
GT	Gross Tonnage
GW	Gigawatt
GWP	Global Warming Potential

H

Abbreviation	Full Term
H ₂	Hydrogen
HFO	Heavy Fuel Oil
HMM	Hidden Markov Model
HVO	Hydrotreated Vegetable Oil

I

Abbreviation	Full Term
IACS	International Association of Classification Societies
ICE	Internal Combustion Engine
ICS	International Chamber of Shipping
IEA	International Energy Agency
IFC	International Finance Corporation
IMO	International Maritime Organization
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

J-K

Abbreviation	Full Term
JCI	Journal Citation Indicator
kW	Kilowatt
kWh	Kilowatt-hour

L

Abbreviation	Full Term
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCH ₄	Liquefied Methane
LH ₂	Liquid Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
LSFO	Low Sulphur Fuel Oil
LSTM	Long Short-Term Memory

M

Abbreviation	Full Term
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-Based Measure
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MJ	Megajoule
ML	Machine Learning
MRV	Monitoring, Reporting and Verification
MSFD	Marine Strategy Framework Directive
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt-hour

N

Abbreviation	Full Term
NDC	Nationally Determined Contribution
NECA	Nitrogen Emission Control Area
NH ₃	Ammonia
NPC	Net Present Cost
NO _x	Nitrogen Oxides
N-R HES	Nuclear-Renewable Hybrid Energy System

O

Abbreviation	Full Term
OA	Optimization Algorithm
OPEX	Operational Expenditure
OPS	On-shore Power Supply
ORC	Organic Rankine Cycle

P

Abbreviation	Full Term
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
PMC	Policy Mix Consistency
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSO	Particle Swarm Optimization

R

Abbreviation	Full Term
R&D	Research and Development
RBF	Radial Basis Function
RF	Random Forest
RL	Reinforcement Learning
RNN	Recurrent Neural Network
Ro-Ro	Roll-on/Roll-off
RoRo	Roll-on/Roll-off

S

Abbreviation	Full Term
SCIE	Science Citation Index Expanded
SDG	Sustainable Development Goal
SEEMP	Ship Energy Efficiency Management Plan
SL	Supervised Learning
SMR	Steam Methane Reforming
SO ₂	Sulphur Dioxide
SOFC	Solid Oxide Fuel Cell
SO _x	Sulphur Oxides
SSCI	Social Science Citation Index

Abbreviation	Full Term
SVM	Support Vector Machine

T

Abbreviation	Full Term
TEU	Twenty-foot Equivalent Unit
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
TTW	Tank-to-Wake

U

Abbreviation	Full Term
UK	United Kingdom
UL	Unsupervised Learning
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United States Dollar

V-W

Abbreviation	Full Term
VLCC	Very Large Crude Carrier
VLSFO	Very Low Sulphur Fuel Oil
WoS	Web of Science
WtT	Well-to-Tank
WtW	Well-to-Wake

X-Z

Abbreviation	Full Term
XAI	Explainable Artificial Intelligence
5GP	Fifth Generation Port
6GP	Sixth Generation Port

Glossary of Terms

A

Alternative Fuels Non-conventional energy sources used to power ships as substitutes for traditional fossil fuels (heavy fuel oil, marine diesel oil). Key alternatives include liquefied natural gas (LNG), methanol, ammonia, hydrogen, biofuels, and electricity. Selection criteria involve energy density, storage requirements, infrastructure availability, safety considerations, and lifecycle emissions.

Ammonia (NH₃) A compound of nitrogen and hydrogen that can serve as a zero-carbon fuel when produced from renewable sources (green ammonia). Advantages include high energy density compared to hydrogen and existing global production/distribution infrastructure. Challenges include toxicity, corrosivity, and low combustion speed requiring pilot fuel or engine modifications.

Autonomous Shipping Vessels capable of operating with minimal or no human intervention, utilising artificial intelligence, sensors, and communication systems for navigation, collision avoidance, and operational decision-making. Degrees of autonomy range from remote-controlled operation to fully autonomous voyages.

B

Bibliometric Analysis Quantitative research method that analyses publication patterns, citation networks, author collaborations, and keyword frequencies to map research landscapes, identify trends, and evaluate scientific output in specific fields.

Biofuels Fuels derived from biological sources including waste oils, agricultural residues, and purpose-grown crops. First-generation biofuels use food crops; second-generation use non-food biomass; third-generation

use algae. Maritime applications face scalability and cost-competitiveness challenges.

Blue Hydrogen Hydrogen produced from natural gas through steam methane reforming with carbon capture and storage to reduce associated emissions. Considered a transitional solution between grey hydrogen (without carbon capture) and green hydrogen (from renewable electricity).

Bunkering The process of supplying fuel to ships. Traditional bunkering involves heavy fuel oil or marine diesel; alternative fuel bunkering requires specialised infrastructure for LNG, ammonia, hydrogen, or methanol delivery at ports.

C

Carbon Capture and Storage (CCS) Technology suite for capturing carbon dioxide emissions from combustion processes, transporting the captured CO₂, and storing it permanently in geological formations or utilising it in industrial processes. Shipboard carbon capture systems enable compliance with emission regulations while using conventional fuels.

Carbon Intensity Indicator (CII) IMO regulatory measure rating vessels from A (best) to E (worst) based on operational carbon efficiency—the ratio of CO₂ emissions to transport work (deadweight tonnage × distance travelled). Ships rated D for three consecutive years or E for one year must submit corrective action plans.

Carbon Leakage The phenomenon where emissions reduction policies in one jurisdiction lead to increased emissions elsewhere, typically when economic activities relocate to regions with less stringent environmental regulations. A concern for regional maritime policies like the EU ETS.

Carbon Neutrality Achieving net-zero carbon dioxide emissions through elimination of emissions, offsetting remaining emissions through carbon removal, or a combination thereof. The IMO targets carbon neutrality for international shipping by or around 2050.

Carbon Pricing Economic mechanisms that assign a cost to carbon emissions to incentivise emission reductions. Includes carbon taxes (fixed price per tonne CO₂) and emissions trading systems (cap-and-trade markets where emission allowances are traded).

Carbon Tax A government-imposed fee on carbon emissions, typically charged per tonne of CO₂ or CO₂-equivalent. Creates direct financial incentive for emission reduction by increasing costs of carbon-intensive activities.

Classification Society Independent organisations that establish and maintain technical standards for ship construction and operation, verify compliance through surveys and inspections, and issue certificates. Major societies include DNV, Lloyd's Register, Bureau Veritas, and American Bureau of Shipping.

Cold Ironing Shore power technology enabling ships at berth to connect to port electrical grid rather than running auxiliary engines. Eliminates emissions, noise, and vibration during port stays. Also known as Alternative Maritime Power (AMP) or On-shore Power Supply (OPS).

D

Decarbonisation The process of reducing carbon content of energy sources and eliminating carbon dioxide emissions from economic activities. Maritime decarbonisation involves transitioning from fossil fuels to zero-carbon alternatives and implementing energy efficiency measures.

Digital Twin Virtual representation of a physical asset, process, or system that enables real-time monitoring, simulation, and optimisation. Maritime applications include vessel performance modeling, predictive maintenance, and scenario testing for efficiency improvements.

Drop-in Fuel Alternative fuel that can be used in existing engines and infrastructure with minimal or no modifications. Biofuels and some synthetic fuels qualify as drop-in solutions, simplifying the transition from conventional fuels.

E

Emission Control Area (ECA) Designated sea regions where stricter emission standards apply. SO_x ECAs (Baltic Sea, North Sea, North American, Caribbean) limit sulphur content to 0.10%; NO_x ECAs require Tier III engine standards. Ships must use compliant fuels or exhaust treatment systems within ECAs.

Emissions Trading System (ETS) Market-based mechanism where emission allowances are capped and tradeable. Entities must surrender allowances equal to their emissions; those reducing emissions below their allocation can sell surplus allowances. The EU ETS includes maritime shipping from 2024.

Energy Efficiency Design Index (EEDI) IMO measure quantifying the energy efficiency of new ships in grams of CO₂ per cargo-tonne-nautical mile. Increasingly stringent reference lines require new vessels to be progressively more efficient than baseline.

Energy Efficiency Existing Ship Index (EEXI) One-time certification requirement for existing ships to meet minimum energy efficiency standards comparable to EEDI Phase 2/3 requirements. Ships failing to meet requirements must implement technical modifications.

Explainable Artificial Intelligence (XAI) AI systems designed to provide interpretable outputs and transparent reasoning, enabling human understanding of automated decisions. Critical for safety-related maritime applications where accountability and regulatory compliance require audit trails.

F

Fit for 55 European Union legislative package targeting 55% greenhouse gas emission reduction by 2030 compared to 1990 levels. Includes maritime-specific measures through EU ETS expansion and FuelEU Maritime regulation.

Fleet Turnover The gradual replacement of older vessels with new builds in a shipping fleet. With typical vessel lifespans of 15-40 years, fleet turnover dynamics create path dependencies where today's ordering decisions determine emission trajectories for decades.

Fuel Cell Electrochemical device converting chemical energy directly to electrical energy through controlled reactions. Maritime applications focus on Proton Exchange Membrane Fuel Cells (PEMFC) using hydrogen and Solid Oxide Fuel Cells (SOFC) compatible with multiple fuels.

FuelEU Maritime EU regulation requiring progressive reduction in greenhouse gas intensity of energy used onboard ships calling at EU ports. Targets 2% reduction by 2025, 6% by 2030, and 80% by 2050 compared to 2020 baseline.

G

Green Ammonia Ammonia produced using renewable energy for electrolysis-based hydrogen production and subsequent Haber-Bosch synthesis. Offers zero-carbon fuel pathway when combustion emissions (NO_x) are adequately controlled.

Green Hydrogen Hydrogen produced through water electrolysis powered by renewable electricity, resulting in zero-carbon production pathway. Distinguished from grey hydrogen (fossil fuel-based) and blue hydrogen (with carbon capture).

Green Methanol Methanol produced from renewable sources—either through hydrogenation of captured CO₂ using green hydrogen (e-methanol)

or from biomass gasification (bio-methanol). Offers substantial lifecycle emission reductions compared to conventional fuels.

Green Port Port facility integrating environmental sustainability into operations through renewable energy, shore power, alternative fuel bunkering, emission monitoring, and sustainable supply chain practices. Part of broader Green Shipping Corridor initiatives.

Green Shipping Corridor Designated maritime route where zero-emission shipping solutions are demonstrated and scaled through coordinated action among ports, shipping companies, fuel suppliers, and governments. Examples include LA-Shanghai and Singapore-Rotterdam corridors.

H

Heavy Fuel Oil (HFO) Traditional marine fuel derived from crude oil refining residues. High energy density and low cost but contains sulphur and produces significant air pollutant emissions. Being phased out in favour of compliant fuels under IMO 2020 regulations.

Hybrid Propulsion Vessel power system combining multiple energy sources—typically diesel engines with battery storage and/or fuel cells. Enables optimisation across different operating modes, improving efficiency and reducing emissions particularly in variable-demand applications.

Hydrogen (H₂) Lightest element; potential zero-emission fuel when produced from renewable sources. Maritime applications face challenges including low volumetric energy density requiring cryogenic storage or high-pressure systems, and limited bunkering infrastructure.

I

IMO 2020 Regulation limiting global sulphur content in marine fuels to 0.50% (from 3.50%), implemented January 2020. Ships can comply through low-sulphur fuels, exhaust gas cleaning systems (scrubbers), or alternative fuels.

Internal Combustion Engine (ICE) Heat engine converting chemical energy of fuel into mechanical work through combustion. Two-stroke and four-stroke diesel engines dominate maritime applications; modifications enable operation on alternative fuels including LNG, methanol, and ammonia.

L

Life Cycle Assessment (LCA) Methodology evaluating environmental impacts throughout a product's lifecycle—from raw material extraction through production, use, and disposal. Maritime LCA encompasses well-to-tank (fuel production) and tank-to-wake (onboard combustion) phases.

Liquefied Natural Gas (LNG) Natural gas cooled to -162°C for storage and transport at 1/600th of gaseous volume. Offers 20-25% CO_2 reduction versus HFO but faces methane slip concerns. Viewed as transitional fuel with established bunkering infrastructure.

Low-Sulphur Fuel Oil (LSFO) Marine fuel with sulphur content meeting IMO 2020 requirements ($\leq 0.50\%$ globally, $\leq 0.10\%$ in ECAs). Produced through refining processes or blending to achieve compliance specifications.

M

MARPOL International Convention for the Prevention of Pollution from Ships, adopted 1973/1978. Annex VI addresses air pollution including SO_x , NO_x , and greenhouse gas emissions through technical and operational requirements.

Market-Based Measure (MBM) Economic instrument using price signals to incentivise emission reductions. Maritime examples include carbon taxes, emissions trading systems, and fuel levies. Under consideration at IMO to complement technical and operational measures.

Methane Slip Unburned methane escaping during LNG combustion or fuel handling. Significant concern because methane's global warming potential is approximately 80 times greater than CO_2 over 20 years, potentially negating lifecycle benefits of LNG.

Methanol (CH_3OH) Liquid alcohol fuel offering lower carbon intensity than conventional fuels, particularly when produced from renewable sources. Advantages include liquid-state handling similar to traditional fuels and existing production/distribution infrastructure.

Monitoring, Reporting and Verification (MRV) Regulatory framework requiring systematic measurement and documentation of emissions. The EU MRV regulation mandates annual reporting of CO_2 emissions from ships over 5,000 GT calling at EU ports.

N

Net-Zero Emissions State where anthropogenic greenhouse gas emissions are balanced by anthropogenic removals. The IMO's revised 2023 strategy targets net-zero GHG emissions from international shipping by or around 2050.

Nitrogen Oxides (NO_x) Combustion by-products contributing to air pollution and acid rain. IMO Tier III standards in NO_x ECAs require 80%

reduction compared to Tier I through selective catalytic reduction, exhaust gas recirculation, or LNG propulsion.

O

Operational Measures Non-structural modifications to improve vessel efficiency and reduce emissions: slow steaming, weather routing, trim optimisation, hull cleaning, and voyage planning. Typically lower-cost than technical measures but dependent on continuous management attention.

P

Pathway Comprehensive approach to achieving policy objectives through coordinated technical, regulatory, and market developments. Decarbonisation pathways for shipping encompass fuel transitions, efficiency improvements, and supporting infrastructure.

Proton Exchange Membrane Fuel Cell (PEMFC) Fuel cell technology using hydrogen and oxygen to generate electricity with water as the only emission. Operating at relatively low temperatures (80°C), PEMFCs offer quick startup and high power density suitable for marine applications.

R

Reinforcement Learning (RL) Machine learning paradigm where algorithms learn optimal actions through interaction with dynamic environments. Maritime applications include autonomous navigation, route optimisation, and real-time vessel control.

Retrofitting Modification of existing vessels to improve efficiency or enable alternative fuel use. Options include engine conversion, propulsion optimisation devices, wind-assisted systems, and shore power connections. Economics depend on remaining vessel lifespan.

S

Scrubber Exhaust Gas Cleaning System (EGCS) removing sulphur oxides from engine exhaust, enabling continued use of high-sulphur fuels while meeting emission regulations. Open-loop systems discharge washwater to sea; closed-loop systems retain residues for shore disposal.

SEEMP (Ship Energy Efficiency Management Plan) IMO-mandated operational plan for improving vessel energy efficiency. Part II requirements include CII calculations and corrective actions for ships rated D or E.

Shore Power See Cold Ironing.

Short-Sea Shipping Maritime transport over relatively short distances, typically within a region or between neighbouring countries. Often serves as alternative to road freight; faces unique decarbonisation challenges due to smaller vessels and diverse port calls.

Slow Steaming Operational practice of reducing vessel speed below design specifications to decrease fuel consumption and emissions. Power requirements vary approximately with the cube of speed, yielding significant savings from modest speed reductions.

Smart Port Port integrating digital technologies—IoT sensors, AI analytics, blockchain, 5G connectivity—to optimise operations, enhance efficiency, and support sustainability objectives. Evolution towards autonomous and zero-emission facilities.

Solid Oxide Fuel Cell (SOFC) High-temperature fuel cell technology operating at 600-1000°C, compatible with hydrocarbon fuels including natural gas and ammonia. Offers high efficiency and potential for integration with waste heat recovery.

Sulphur Oxides (SO_x) Combustion products from sulphur-containing fuels, contributing to acid rain and respiratory health impacts. IMO regulations progressively tighten permissible sulphur content—0.50% globally (2020), 0.10% in ECAs.

T

Technical Measures Physical modifications to vessel design or equipment to improve efficiency or reduce emissions: hull form optimisation, propeller upgrades, waste heat recovery, wind-assisted propulsion, air lubrication systems.

Technology Readiness Level (TRL) Scale from 1-9 measuring maturity of technologies from basic research (TRL 1) through commercial deployment (TRL 9). Used to assess alternative fuel and propulsion system development status.

Transformer (Neural Network) Deep learning architecture using self-attention mechanisms to model relationships in sequential data. Increasingly applied to maritime time-series forecasting, outperforming traditional recurrent networks in accuracy and computational efficiency.

V

Voyage Optimisation Real-time adjustment of route and speed based on weather forecasts, ocean conditions, and commercial requirements to

minimise fuel consumption while meeting schedule constraints. Enabled by digital technologies and predictive analytics.

W

Waste Heat Recovery Technology capturing heat from engine exhaust or cooling systems for electricity generation or onboard heating. Improves overall energy efficiency without additional fuel consumption; options include steam turbines and Organic Rankine Cycle systems.

Weather Routing Navigation planning considering meteorological and oceanographic forecasts to select routes minimising fuel consumption, voyage duration, or adverse weather exposure. Digital services integrate real-time data for continuous optimisation.

Well-to-Wake (WtW) Lifecycle assessment boundary encompassing both fuel production (well-to-tank) and onboard use (tank-to-wake). Provides comprehensive emissions accounting including upstream impacts essential for comparing alternative fuels.

Wind-Assisted Propulsion Technologies harnessing wind energy to reduce propulsion power requirements: rotor sails (Flettner rotors), rigid wing sails, soft sails, and kites. Fuel savings of 5-30% achievable depending on route and wind conditions.

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Foundations of Maritime Decarbonization Alternative Fuels, Technologies and Regulatory Frameworks

Vahit Çalışır