Implementing Low-Carbon Shipping

Infrastructure, Assessment and Regional Pathways

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CHAPTER 1

Infrastructure and Bunkering Systems

1.1 Current Bunkering Infrastructure

The development of alternative fuel bunkering infrastructure represents a critical enabler for maritime decarbonisation. As of mid-2023, there are 169 active LNG bunkering ports worldwide, with an additional 95 facilities in planned or development stages. Furthermore, over 2,000 ships are equipped or scheduled to be equipped with shore-side electricity connections (Profumo et al., 2025).

LNG offers significant environmental advantages over conventional marine fuels, reducing CO_2 emissions by approximately 25% due to its increased calorific value (approximately 20% higher than heavy fuel oil) and relatively low density (approximately 50% lower than heavy fuel oil). European LNG bunkering infrastructure is particularly developed, with approximately 50 operational bunkering stations and an additional 13 facilities under construction. Major LNG-promoting nations including the USA, China, Singapore, and South Korea continue to invest in port-based bunkering facilities (Raihan et al., 2025).

The provision of alternative fuels constitutes a competitive asset for ports, enhancing their appeal to vessels transitioning toward sustainability. Approximately 120 ports around the world are currently involved in the transport of ammonia by sea, with cargo typically stored in surface tanks. Fuel can be transported from central hubs to vessels via trucks, pipelines, or dedicated bunkering vessels (Profumo et al., 2025).

1.2 Hydrogen Bunkering Requirements

The implementation of hydrogen as a marine fuel necessitates consideration of cargo capacity implications associated with different storage technologies. Feasibility assessments for chemical tanker vessels indicate varying degrees of cargo capacity reduction: compressed H_2 at 350 bar requires 1.3% cargo capacity reduction, compressed H_2 at 700 bar requires 1.1% reduction, liquid H_2 requires only 0.1% reduction, while metal hydrides impose a substantial 9.0% reduction due to the weight of the storage medium (Di Micco et al., 2022). Liquid hydrogen emerges as the most favorable option from a space utilization perspective, requiring minimal cargo capacity sacrifice. The compressed hydrogen alternatives present moderate reductions, whereas metal hydride storage, despite favorable volumetric energy density, imposes substantial mass penalties due to the weight of the storage medium itself (Di Micco et al., 2022).

1.3 Ammonia Supply Chain Development

Ammonia bunkering infrastructure development is progressing through industry initiatives. Yara, the largest ammonia plant construction company globally trading approximately one-third of global ammonia, announced plans to construct 15 bunkering plants throughout Scandinavia by 2024. In port facilities, ammonia cargo is typically stored in surface tanks and can be distributed to vessels via trucks, pipelines, or bunkering vessels (Profumo et al., 2025).

1.4 Hydrogen Maritime Transportation Infrastructure

Large-scale maritime hydrogen transportation employs two primary methods: pipeline transport and carrier ships. Pipeline transportation is generally most economical for large-scale, long-distance hydrogen delivery, though the existing hydrogen pipeline network (4,500 km globally) remains substantially less developed than natural gas infrastructure (3 million km). Utilising existing natural gas pipelines for hydrogen transport represents a transitional strategy, with optimal hydrogen blending ratios of 15-20% by volume balancing transport efficiency with material compatibility considerations. Offshore hydrogen pipeline costs are approximately 57% higher than onshore equivalents due to the challenging operating environment (Fu et al., 2023).

Techno-economic analysis indicates that hydrogen pipeline transport becomes more cost-effective than high-voltage direct current (HVDC) electricity transmission at distances exceeding 60-100 km from offshore wind installations. This crossover distance varies by study, with some analyses indicating advantages emerging at 300 km or beyond. For distances exceeding 300 km, offshore hydrogen production and pipeline transport may represent a more economically viable solution than transmitting electricity for onshore hydrogen production. The levelized cost of hydrogen from integrated offshore wind platforms ($2.09/kg) compares favourably to conventional configurations with onshore electrolysis ($3.86/kg), demonstrating the economic potential of direct offshore production (Meharban et al., 2025).

Global electrolyzer capacity must increase from current negligible levels to an estimated 5,722 GW by 2050 under IRENA's 1.5°C scenario to achieve projected hydrogen demand. Green hydrogen and its derivatives are projected to contribute 12% of emission reductions and represent 14% of final energy consumption by mid-century. Less than 10% of planned low-emission hydrogen production by 2030 (approximately 3 Mt) is expected to derive from offshore wind sources, though announced seawater electrolysis hydrogen projects total 32 GW globally (Meharban et al., 2025).

Liquid Hydrogen Carrier Ships:

Kawasaki Heavy Industries developed the world's first liquid hydrogen carrier, SUISOFRONTIER, launched in 2019. The vessel measures 116 metres in length and 19 metres in width, with a gross weight of approximately 8,000 tonnes. A concept design based on the 345-metre LNG tanker Mozah proposes four hydrogen storage tanks (141.36 metres each) with total capacity of 5,000 tonnes liquid hydrogen at 0.5 MPa operating pressure (Fu et al., 2023).

Liquid hydrogen carrier operations must address boil-off phenomena—vaporisation caused by heat ingress that increases tank pressure and results in hydrogen loss. Mitigation strategies include minimising surface-area-to-volume ratios, enhanced insulation, double-layer tank construction, and cryogenic cooler integration. Additionally, liquid hydrogen sloshing during vessel motion can cause pressure and temperature fluctuations; empirical measurements indicate that at maximum hull roll angles of 5°, vaporised hydrogen pressure and temperature increase at rates of 0.67 MPaG/h and 1.0 K/min respectively (Fu et al., 2023).

1.4a Global Port Readiness for Hydrogen Trade

The emergence of international hydrogen trade has prompted early-stage port infrastructure development across multiple continents. A systematic review of global initiatives identifies 20 ports actively developing hydrogen handling capabilities, distributed between export-oriented facilities in resourcerich regions and import terminals in energy-demanding economies (Chen et al., 2023):

Hydrogen Export Ports (12 identified): - **Australia (8 ports):** Pilbara, Gladstone, Darwin, Bell Bay, Port Kembla, Newcastle, Townsville, Port Hedland - **Other regions:** Mejillones (Chile), Punta Arenas (Chile), Nouadhibou (Mauritania), Neom (Saudi Arabia), Hammerfest (Norway)

Hydrogen Import Ports (8 identified): - **Germany:** Wilhelmshaven, Hamburg - **Netherlands:** Rotterdam - **United Kingdom:** Teesside - **Japan:** Kobe, Kawasaki - **South Korea:** Ulsan - **Singapore:** Jurong Island

The first intercontinental liquid hydrogen shipment was completed in 2022 when the *Suiso Frontier*—the world's first purpose-built liquid hydrogen carrier—transported hydrogen from Australia to Japan. This demonstration voyage validated the technical feasibility of seaborne hydrogen transport, though significant infrastructure gaps remain before commercial-scale operations can commence (Chen et al., 2023).

Port of Rotterdam has announced ambitious hydrogen import targets of 4.6 million tonnes per year by 2030, increasing to 20 million tonnes per year by 2050. Achieving these volumes will require substantial investment in large-scale liquid hydrogen storage tanks, cryogenic handling systems, and distribution infrastructure. Current port facilities designed for LNG cannot be directly repurposed for liquid hydrogen due to the significantly lower storage temperature (−252.8°C versus −161.5°C) and different material compatibility requirements (Chen et al., 2023).

Critical infrastructure gaps identified for international hydrogen trade include: (1) absence of large-scale liquid hydrogen storage tanks at commercial ports; (2) lack of harmonised international regulations for hydrogen bunkering and cargo transfer operations; (3) limited availability of trained personnel with liquid hydrogen handling certifications; and (4) insufficient data on long-term material degradation under repeated cryogenic cycling. Addressing these gaps represents a prerequisite for scaling hydrogen maritime trade beyond demonstration projects (Chen et al., 2023).

Global hydrogen demand projections indicate requirements exceeding 200 million tonnes by 2030, rising to 530 million tonnes by 2050. The International Energy Agency projects that maritime transport of hydrogen will constitute a substantial share of this demand, particularly for intercontinental trade between production centres with low-cost renewable energy and consumption centres with limited domestic renewable resources. Australian hydrogen production costs are projected to reach A$2.00–4.00 per kilogram by 2030, potentially enabling competitive export to Asian markets (Chen et al., 2023).

1.4b Hydrogen Vessel Demonstrations and Bunkering Infrastructure

Despite growing interest in hydrogen as a maritime fuel, fewer than ten ports globally currently possess operational hydrogen refuelling capabilities, representing a critical infrastructure bottleneck for commercial deployment. This limitation has confined hydrogen-powered vessel operations primarily to demonstration projects and short-sea routes where shore-based refuelling can be coordinated (Jayabal, 2025).

MF Hydra (Norway): The MF Hydra, operated by Norled, represents the world's first hydrogen-powered car ferry, commencing commercial service in March 2023 on the Hjelmeland–Skipavik–Nesvik route. The vessel features a 400 kW proton exchange membrane (PEM) fuel cell system with 260 kg of compressed hydrogen storage. Operational data indicate approximately 90% reduction in GHG emissions compared to conventional diesel ferry operations. The vessel incorporates a hybrid battery system enabling zero-emission operation throughout its service profile, demonstrating the technical viability of hydrogen propulsion for short-sea passenger and vehicle transport (Jayabal, 2025).

Port of Kobe Hydrogen Hub: The Port of Kobe (Japan) has established a comprehensive hydrogen hub infrastructure with total investment exceeding $500 million, representing one of the most advanced hydrogen maritime facilities globally. The development incorporates ammonia cracking systems achieving greater than 85% efficiency for hydrogen extraction, enabling utilisation of ammonia as a hydrogen carrier for maritime applications. Economic analysis projects a 15-year break-even horizon for the facility, contingent upon projected increases in hydrogen demand and carbon pricing mechanisms. The Kobe facility serves as the primary receiving terminal for liquid hydrogen shipments from Australia via the Suiso Frontier carrier (Jayabal, 2025).

Rotterdam Hydrogen Delta Initiative: The Rotterdam Hydrogen Delta project targets 1 GW of green hydrogen production capacity by 2030, positioning the port as the principal European hydrogen import and distribution hub. This initiative expands upon Rotterdam's existing hydrogen import targets through integration of domestic electrolysis capacity with import terminal facilities. Port-based hydrogen applications—including shore power generation, cargo handling equipment, and maritime bunkering—are projected to achieve up to 70% reduction in port-related GHG emissions upon full implementation. The infrastructure timeline anticipates gaseous hydrogen (GH_2) bunkering availability in the 2020s, liquid hydrogen (LH_2) hybrid systems in the 2030s, and full LH_2 bunkering integration by 2040 (Jayabal, 2025).

1.4c Offshore Hydrogen Production Facilities

Offshore hydrogen production represents an emerging paradigm for maritime fuel supply chains, leveraging offshore wind resources for direct electrolyser integration. Global offshore wind capacity reached 72.6 GW in 2023 (approximately 40 GW in Asia, 32 GW in Europe), with projections indicating potential to supply 16,000 TWh/year by 2050—sufficient to deliver 420 Mt/year of green hydrogen (Meharban et al., 2025).

Several demonstration and pilot-scale offshore hydrogen projects are advancing toward commercial operation:

Table 1 Offshore Hydrogen Production Projects

Project	Location	Capacity	Status
Sealhyfe	France	400 kg/day	Operational 2023
PosHYdon	Netherlands (North Sea)	1.25 MW	Pilot phase
Dolphyn	United Kingdom	4 GW (target)	Development
AquaVentus	Germany	10 GW by 2035	Planning
AquaSector	Germany (Dogger Bank)	300 MW	Planning
Dongfu No.1	China	1,200 Nm^3/h	Development

The existing global hydrogen infrastructure includes approximately 5,000 km of hydrogen pipelines, predominantly located in Europe, North America, and Gulf regions, along with operational large-scale hydrogen storage facilities with combined capacity exceeding 500 GWh, including the Teesside (UK) and Gulf Coast (USA) salt cavern projects. Equipment efficiency specifications indicate that proton exchange membrane water electrolysis (PEMWE) systems operate at approximately 70% efficiency, while alkaline electrolysis (AEL) achieves 60–80% efficiency. Emerging anion exchange membrane water electrolysis (AEMWE) technology demonstrates energy consumption of approximately 59 kWh/kg hydrogen (Meharban et al., 2025).

1.5 Port Infrastructure Investments

The lack of robust bunkering infrastructure remains a significant obstacle compounding the challenges of large-scale deployment of alternative fuels (Sadiq et al., 2025).

1.5a Methanol Bunkering and Demonstration Projects

Methanol bunkering infrastructure for deep-sea shipping is expanding rapidly, with more than 115 major ports worldwide now offering methanol bunkering capabilities. This growing network substantially reduces operational constraints for methanol-fuelled vessels compared to alternative fuels such as hydrogen or ammonia, which require specialised handling infrastructure (Berry et al., 2025). However, current supply at many ports remains limited to truck delivery or small bunker vessels. Safety assessments indicate that methanol bunker fuel can be designed into a tolerable safety risk region comparable to conventional fossil marine fuels through specific safety measures (Meyer-Larsen & Schories, 2025).

The German MariSynFuel project, initiated in January 2023, demonstrates practical implementation of green methanol production and maritime application. Based in Bremerhaven—Germany's second largest seaport—the project develops a demonstration-scale green methanol synthesis facility with target production capacity of at least 500 kg per day. The project is coordinated by Technology Transfer Center (ttz) Bremerhaven in partnership with the Alfred Wegener Institute, Institute of Shipping Economics and Logistics, and industry partners including shipping company F. Laeisz (Meyer-Larsen & Schories, 2025).

The project's principal end-user, the research vessel 'Uthörn' (christened November 2022), represents the first German seagoing vessel equipped with methanol-based propulsion. The vessel utilises two diesel engines retrofitted for methanol combustion, which generate electrical energy for electric propulsion. Production facility development follows a three-stage scale-up approach: Stage 1 (pilot) at 1–2 kg/day for process parameter and catalyst optimisation; Stage 2 at 5–10 kg/day with finalised reactor design; and Stage 3 achieving full production capacity of ≥500 kg/day, matching the Uthörn's expected daily consumption (Meyer-Larsen & Schories, 2025).

1.6 Green Shipping Corridors

Ports are evolving into strategic hubs facilitating the energy transition, giving rise to the concept of 'Green Ports'—zero-emission ecosystems incorporating sustainability into their operational strategies. These ports offer services related to energy production and storage, including cold ironing (shore-side electricity supply) and alternative fuel bunkering (Profumo et al., 2025).

Green Shipping Corridors (GSCs) are defined as specific routes between two or more ports where zero/low-emission shipping solutions are implemented and supported by collaborative efforts among governments, shipping companies, and port authorities. GSC development has accelerated substantially since the 2021 Clydebank Declaration, where 22 countries pledged to establish at least six green corridors by 2025. By the end of 2024, 62 global GSC initiatives had been announced, engaging 244 stakeholders across diverse maritime segments (Dolatabadi et al., 2025).

Table 2 Global Green Shipping Corridor Development (End of 2024)

Metric	Value
Total GSC initiatives globally	62
Public-private partnership led	18
Industry/3rd sector led	17
Port led	14
Government led	13
Total engaged stakeholders	244

GSC initiatives demonstrate clear sectoral preferences, with Ro-Ro and ferry services (21 initiatives) and container shipping (15 initiatives) leading adoption, whilst 20 initiatives remain in the determination phase regarding target segments. Alternative fuel selection varies considerably across corridors: methanol (18 initiatives), ammonia (15), electric (15), and multiple fuels (14), with 31 initiatives yet to specify fuel strategy. Most corridors remain in early stages—24 in advanced exploration, 18 in initiation, 14 in early exploration, and only 6 in preparation phase (Dolatabadi et al., 2025).

The cruise sector presents particular decarbonisation challenges for GSC development. Despite comprising only approximately 1% of the global fleet, cruise vessels account for 2.2% of global shipping GHG emissions, with a single cruise ship emitting approximately 40,000 tonnes of CO_2 annually—significantly exceeding LNG carriers (33,000 tonnes), container ships (23,000 tonnes), and bulk carriers (5,000 tonnes). Cruise vessels require substantially higher power at sea (35,000–90,000 kW versus 20,000–80,000 kW for container ships) and consume 1.2–4.2 tonnes of fuel per hour while moored due to extensive hoteling services. Additionally, cruise ships emit approximately 3–6 times more black carbon than container vessels and tankers—particularly concerning in Arctic and near-Arctic regions where black carbon contributes significantly to warming and ice melting (Dolatabadi et al., 2025).

The environmental imperative for port transformation is substantial. Seagoing vessels moored at quaysides consume electricity equivalent to 250,000-300,000 households annually while releasing harmful emissions including 600,000 tonnes of CO_2 and 8,000 tonnes of nitrogen compounds. Cold ironing strategies at major ports such as Rotterdam are projected to achieve carbon emission savings of approximately 200,000 tonnes per year by 2030 (Profumo et al., 2025).

1.7 Port Decarbonisation and Shore Power Infrastructure

Approximately 5% of total shipping CO_2 emissions occur within ports, with domestic vessels—due to their longer port stays—responsible for a higher share of these emissions compared to international shipping (Vakili et al., 2025). The IMO has highlighted the pivotal role of ports in achieving net-zero emissions by 2050 through shore-based electricity supply, alternative fuel bunkering infrastructure, sustainability incentive programs, and optimised Just-in-Time operations.

The scale of European port emissions underscores the imperative for decarbonisation. European Union maritime activities produced 124 million tonnes of CO_2 in 2021, representing 3–4% of total EU carbon emissions. Without effective decarbonisation strategies, the maritime sector could contribute 15% or more of global emissions by 2050 (Montuori et al., 2025).

Shore power (cold ironing) technology has potential to cover up to 7% of the total energy consumption of ships while at ports. This solution is particularly effective in mitigating air emissions in port areas when the electricity supplied from the grid is sourced from cleaner alternatives compared to onboard generation. Shore power also significantly decreases underwater noise pollution, enhancing overall environmental performance (Vakili et al., 2025).

The emission reduction potential of shore-side electricity is substantial: implementation across the European Economic Area could achieve approximately 5 million tonnes of CO_2 reduction annually, representing roughly 4% of global shipping emissions (Montuori et al., 2025). This quantification positions cold ironing as one of the most immediately impactful decarbonisation measures available to ports.

European shore power deployment demonstrates significant emission reduction potential:

Table 3 European Shore Power Implementation Benefits

Implementation	Quantified Benefit
Europe-wide adoption	~800 kilotonnes CO_2 annually
EEA cold ironing potential	~5 Mton CO_2/year (~4% global shipping)
Stena Line (13 ships, 7 terminals, 2018)	3,800 tonnes oil saved; 12,340 tonnes CO_2; 8 tonnes SOx
Port of Felixstowe (battery tractors + ReARTG cranes)	6,662 tonnes CO_2; 59.38 tonnes NOx annually
Port of Felixstowe carbon reduction	30% since 2015

Global cold ironing deployment has accelerated significantly. China has implemented approximately 7,500 berths with cold ironing capability by 2021, representing one of the most extensive shore power networks globally. European nations including Finland, Norway, and Belgium incorporated cold ironing into port renovation plans beginning in 2010, while the United States had operational high- and low-voltage cold-ironing systems in more than ten ports by 2017 (Raihan et al., 2025).

Port Emission Context:

Understanding the scale of port-area emissions is essential for prioritising decarbonisation investments. Ships' emission intensity in ports increases to approximately five times higher than underway emissions, with port-area shipping emissions potentially accounting for 5% to 15% of total shipping GHG emissions. Notably, ship emissions at berth are approximately ten times higher than emissions from port operations themselves, whilst land transport (trucks) typically generates double the CO_2 emissions of port operations—as demonstrated at the Port of Felixstowe (Alamoush et al., 2022).

Table 4 Global Port GHG Emission Inventories

Port	Annual Emissions	Year	Notes
Shenzhen	580,128 tonnes	2013	40% from port activities
Five UK ports	548,075 CO_2 tonnes	2008	Combined inventory
Barcelona	331,390 GHG tonnes	2008	Half attributed to shipping
Chennai, India	280,558 CO_2e tonnes	—	Port inventory
Valencia	15,814 CO_2e tonnes	2011	Port operations
Limassol, Cyprus	6,172 CO_2 tonnes	—	Port inventory

Emission inventories vary considerably across ports due to differences in scope, calculation methodologies, and cargo throughput. However, the aggregate port GHG emission burden is substantial given thousands of ports worldwide. Combined with projected shipping emission increases of 50–250% by 2050 without effective mitigation, port-area emissions represent a significant and growing contributor to global transport sector climate impact (Alamoush et al., 2022).

Port Operational Optimization for Emission Reduction

Berth allocation problem (BAP) optimization incorporating carbon emission objectives represents a growing research focus for sustainable port operations. Joint scheduling optimization models that integrate carbon emission costs into objective functions achieve simultaneous green and efficient port operations. Bi-objective mixed-integer linear programming approaches that minimise carbon emissions whilst maximising vessel completion time reduction demonstrate the feasibility of balanced operational and environmental performance (Xu & Chen, 2025).

Table 5 Port Operational Optimization Results

Optimization Approach	Methodology	Result
Berth-quay crane joint optimization	PSO-GA	24.1% operational cost reduction; 15.3% carbon emission decrease
Shore power collaborative scheduling	NSGA-III + TOPSIS	7.31% pollutant reduction; 11.46% efficiency improvement
Intermediate pumping strategy	Hybrid genetic algorithm	9.42% port stay time reduction
Integrated traffic-deballasting	Multi-objective model	20.84% reduction in total weighted delays

Shore-based equipment electrification contributes significantly to port decarbonisation. Diesel–electric hybrid rubber-tired gantry cranes (RTGs) equipped with energy recovery systems achieve up to 82.17% emission reduction compared to diesel-only RTGs. Hydrogen fuel cell port vehicles demonstrate zero local emissions during continuous high-load operation, providing experimental support for large-scale hydrogen deployment in port settings (Xu & Chen, 2025).

1.7a Methodology for Assessing Port Sustainability Progress

Systematic comparison of port decarbonisation strategies requires standardised assessment methodologies. A novel framework employing the Ports Potential Sustainability (PPS) factor enables ranking of ports by their combined traffic activity and emission profile, identifying those with greatest potential impact from sustainability interventions (Montuori et al., 2025).

The PPS factor is calculated as:

$$PPS_i = \frac{CT_i}{\sum CT_i} \cdot \frac{MSCE_i}{\sum MSCE_i} \cdot 100$$

Where CT represents container traffic (TEU/year) and MSCE represents maritime supply chain emissions (tCO_2/year), normalised against the total across analysed ports. This composite metric identifies ports where decarbonisation investments can achieve maximum systemic impact.

Application of this methodology to major European ports reveals substantial variation in sustainability potential:

Table 6 Major European Port Sustainability Potential Ranking

Port	Traffic (kTEU/yr)	Emissions ($MtCO_2$/yr)	PPS Factor
Rotterdam	14,455	13.67	159.48
Antwerp-Bruges	13,484	7.36	80.10
Hamburg	8,270	4.73	31.57
Valencia	5,076	2.67	10.94
Barcelona	3,522	2.80	7.96
Genoa	2,799	1.82	4.10

The eleven European ports with PPS ≥ 3 collectively account for 70% of total EU container traffic and 36% of maritime CO_2 emissions, demonstrating that targeted interventions at major hubs can achieve disproportionate sectoral impact (Montuori et al., 2025).

Classification of sustainability actions using the Avoid-Shift-Improve (A-S-I) framework reveals sectoral priorities. The AVOID category encompasses actions improving transport system efficiency (emission taxes, customs prioritisation); SHIFT addresses individual trip efficiency (traffic reassignment, modal shift); IMPROVE focuses on fuel and infrastructure efficiency (RES integration, low-carbon fuels, equipment upgrades). Analysis of 26 identified sustainability actions across major European ports indicates that 56% fall within the IMPROVE-ENVIRONMENTAL category, reflecting regulatory pressure and the maturity of shore-side electrification technologies. The second-largest category, SHIFT-ECONOMIC (19%), comprises actions related to monitoring systems and digitalisation for efficiency management (Montuori et al., 2025).

European Port Decarbonisation Targets:

Table 7 European Port Emission Reduction Targets

Port	2030 Target	2050 Target
Rotterdam	55% reduction	Carbon neutrality
Antwerp-Bruges	50% reduction	Carbon neutrality
Hamburg	50% (by 2025)	Carbon neutrality (by 2040)
Valencia	55% reduction	Carbon neutrality
Barcelona	55% reduction	Carbon neutrality
HAROPA	50% reduction	Carbon neutrality
Genoa	55% reduction	Carbon neutrality

OPS Implementation Status at Major European Ports:

Table 8 Onshore Power Supply Implementation Status at Major European Ports

Port	Investment/Capacity	Status
Hamburg	€13 million	Completion by 2026
Valencia	60 MW substation (expandable to 90 MW)	In progress
Barcelona	€110 million budget	Target 2030
Genoa	7 GWh/year capacity	Operational since 2010
HAROPA	78 OPS points	Operational
Piraeus	3 OPS stations (2×3 MW, 1×0.5 MW)	Target 2028

Notably, all eleven major European ports analysed have adopted cold ironing as their primary decarbonisation priority, demonstrating universal recognition of OPS as immediately deployable technology with quantifiable emission reduction benefits. Over 50% have simultaneously committed to photovoltaic installations and electrolysis facilities for green hydrogen production, indicating convergent strategic approaches despite varying national contexts (Montuori et al., 2025).

Principal barriers to accelerated OPS deployment include high capital expenditure for shore-side installations and ship retrofitting, frequency conversion requirements between 50 Hz and 60 Hz systems, absence of favourable electricity pricing mechanisms, and high operating expenses arising from peak demand charges. Addressing these barriers through targeted subsidies, market mechanism reform, and coordinated infrastructure investment represents a policy priority for European maritime decarbonisation (Montuori et al., 2025).

Systematic analysis of port decarbonisation strategies demonstrates that energy management solutions can reduce CO_2 emissions by 25-70%, while optimisation methodologies achieve reductions of 30-50%. Peak electricity demand accounts for 25-30% of monthly electricity costs at ports, creating substantial economic incentives for load management and renewable energy integration (Raihan et al., 2025).

Renewable energy integration in ports has accelerated, with a 2019 European Sea Ports Organisation survey revealing 38% of member ports invested in wind energy, 31% in solar, 26% in biomass, and 2% in wave energy. Smart lighting systems with LED fixtures and sensor controls have demonstrated energy savings of 50–60%, with the ECT Delta terminal in the Netherlands reporting potential annual electricity savings of €300,000 after implementing lighting control systems (Vakili et al., 2025).

Beyond infrastructure investments, port authorities can employ tariff-based incentive mechanisms to encourage vessel operators to adopt greener technologies. The Port of Amsterdam, for example, offers harbour dues discounts to vessels holding Green Award certificates, providing economic benefits that enhance the business case for environmental compliance investments. Such stakeholder-driven initiatives complement regulatory requirements and can accelerate the decarbonisation transition by creating market-based rewards for early adopters. Green corridors—specific trade routes between major port hubs where zero-emission solutions such as green ammonia and green hydrogen are supported—represent another mechanism through which coordinated port and shipping line initiatives can accelerate practical deployment of alternative fuels ahead of universal regulatory mandates (Spera, 2023).

Global Shore Power Leadership:

Leading ports worldwide have established varied approaches to shore power deployment and alternative fuel integration:

Table 9 Global Port Shore Power and Sustainability Initiatives

Port	Shore Power Status	Alternative Fuels	Key Initiatives
Rotterdam	Full electrification program	Hydrogen, ammonia, biofuels	Carbon neutrality 2050; CCS projects; AI logistics
Singapore	Advanced deployment	LNG, methanol, biofuels	Carbon tax; digital twin technology
Los Angeles	Full cargo coverage by 2035	Methanol, hydrogen	LA-Shanghai GSC
Vancouver	80% cruise utilization (2024)	Limited LNG/biofuel	75% harbour dues discount for OPS
Seattle	Mandatory by 2027	Under development	First US mandatory cruise OPS
Juneau	Pioneer (2001)	Limited	First global cruise shore power

North American port leadership in cruise ship shore power is notable: Juneau pioneered shore power for cruise vessels globally in 2001, whilst Seattle became the first US port to mandate 100% shore power utilization for homeported cruise ships. Vancouver achieved 80% shore power utilization for cruise vessels in 2024, with cumulative GHG reductions of up to 45,000 tonnes since 2009 (Dolatabadi et al., 2025).

1.8 Ports as Energy Hubs

To effectively support maritime decarbonisation goals, ports must evolve from traditional logistics hubs into energy hubs capable of producing, storing, and distributing alternative fuels. At the core of this transformation is the smart grid, which manages electricity flow between the national grid, microgrids, and renewable energy sources (Vakili et al., 2025).

Port microgrids have emerged as critical infrastructure enabling integrated management of distributed electrical resources, loads, and interconnecting equipment. Notable implementations include the Port of Los Angeles (completed 2016) with cold ironing, EV charging stations, 2.6 MWh Li-ion batteries, and 1 MW PV; the Port of Long Beach (activated 2021) with 300 kW PV, 670 kWh battery backup, and charging stations; the Port of Antwerp with operational cold ironing, PV, and wind power; and the Port of Rotterdam planning onshore and offshore PV integration (Vakili et al., 2025).

Port-specific emission reduction case studies demonstrate substantial decarbonisation potential. Alexandria Port achieved 80,441 tonnes annual

CO_2 reduction through integration of offshore wind power with fuel cell technology. The Port of Cartagena achieved approximately 10,000 tonnes annual CO_2 reduction using offshore wind power combined with floating solar installations. Energy storage systems at Port of Ancona demonstrated 87.4% CO_2 reduction through PV integration with battery storage (Raihan et al., 2025).

Ports can produce blue hydrogen through gasification processes and integrate Carbon Capture Utilisation and Storage (CCUS) technologies to generate e-methanol. Green hydrogen can be produced via electrolysis powered by renewable energy, and by combining hydrogen with nitrogen, ports can synthesise ammonia. This integrated approach positions ports as vital energy hubs enhancing the maritime energy supply chain in alignment with the IMO's revised GHG strategy (Vakili et al., 2025).

Economic analysis of hydrogen integration in port energy systems demonstrates measurable cost advantages. Hydrogen storage systems integrated with cold ironing infrastructure achieve levelized energy cost reductions of 8.41% compared to conventional configurations. Even without cold ironing integration, hydrogen storage systems deliver 2.20% levelized energy cost reduction, while large-scale hybrid clean energy systems with hydrogen storage achieve 3.33% cost reductions. Green hydrogen replacing natural gas syngas achieves 88% CO_2 reduction, and hydrogen used as secondary fuel with diesel in marine vessels reduces carbon emissions by more than 40% (Raihan et al., 2025).

Notable examples of port equipment decarbonisation include: - Port of Felixstowe: 48 battery-powered terminal tractors and 17 zero-emission ReARTG cranes - Port of Antwerp–Bruges: Hydrotug—the world's first hydrogen-powered tugboat with 415 kg hydrogen storage, offsetting emissions equivalent to 350 cars annually (Vakili et al., 2025)

1.9 Maritime CO_2 Transport Infrastructure

Maritime transport of captured CO_2 represents an emerging infrastructure component enabling deployment of offshore carbon storage at scale. The Northern Lights project, a sub-project of Norway's Longship CCS initiative, demonstrates the viability of ship-based CO_2 transport for geological sequestration.

Northern Lights Project Specifications:

Table 10 Northern Lights CCS Project Specifications

Parameter	Value
Phase 1 transport capacity	~0.8 Mt CO_2/year
Storage depth	~2,100 m below seabed
Storage formations	Johansen and Cook (Aurora site)
Receiving terminal	Kollsnes (west coast Norway)
Partners	Equinor, Shell, Total
Source facilities	Brevik cement plant, Oslo waste incineration

Unlike shallowly buried waste, injected CO_2 stored in deep geological formations has an extremely small probability of returning to the sea, making sub-seabed formations an effective long-term sequestration solution. The project involves collection of captured CO_2 from industrial sources in southeastern Norway, ship transport to the west coast receiving terminal, and pipeline injection into offshore geological formations (Weber, 2021).

Dedicated CO_2 carrier vessels of approximately 12,600 GT have been specified for the Northern Lights operations, representing a new vessel class purpose-built for pressurised CO_2 transport. These vessels integrate liquefied CO_2 cargo systems with specialised loading and offloading infrastructure at intermediate storage terminals. The project demonstrates scalable infrastructure design, with potential expansion beyond Phase 1 capacity as additional capture facilities come online (Weber, 2021).

The successful implementation of Northern Lights establishes a commercial precedent for transboundary CO_2 transport, enabling industrial facilities in countries without suitable domestic storage geology to access secure sequestration services. This infrastructure model positions maritime transport as a critical enabler of CCS deployment for hard-to-abate industrial sectors including cement, steel, and waste incineration (Gola & Noussia, 2022).

1.10 Smart Port Sustainability

The transformation of ports into smart infrastructure represents a critical development in maritime decarbonisation. A systematic literature review of 68 peer-reviewed articles (2017-2023) identifies four interconnected themes shaping smart port sustainability: digital transformation, green port initiatives, stakeholder governance, and implementation challenges (Dağistan et al., 2025).

The concept of smart ports emerged within the Industry 4.0 revolution framework, representing the fourth and fifth generation of port development. Historically, ports evolved from isolated loading/unloading nodes (pre-1960s) through transport and commercial hubs (1960s-1980s) to city-integrated facilities (1980s-2000s), before entering the current era of digital transformation characterised by real-time monitoring, automated operations, and data-driven decision-making. The World Ports Sustainability Program (WPSP), established in 2018, provides a global framework aligning port sustainability initiatives with the United Nations 17 Sustainable Development Goals (Dağistan et al., 2025).

Table 11 Smart Port Sustainability Research Trends (2017-2023)

Metric	Value
Total peer-reviewed articles	68
Average publications per year	9.7
Average citations per article	16.9
Peak citation year	2022 (400 citations)
Empirical studies	47 (69.1%)
Review articles	11 (16.2%)
Conceptual studies	10 (14.7%)

Research output demonstrates geographic concentration, with Spain (14 publications), China (13), and Italy (7) emerging as leading contributors. Universidad Politécnica de Madrid (7 publications) and Shanghai Maritime University (5 publications) represent the most productive institutions (Dağistan et al., 2025).

The research identifies four thematic pillars of smart port sustainability: Digital Transformation focusing on operational efficiency and real-time analytics through AI, IoT, Big Data, blockchain, 5G, and digital twins; Green Port Initiatives addressing decarbonisation and energy management through renewable energy, alternative fuels, and simulation models; Governance & Collaboration encompassing strategic policies and stakeholder engagement through public-private partnerships, maturity models, and transparency mechanisms; and Challenges & Opportunities addressing implementation barriers including cybersecurity, workforce adaptation, and financial incentives (Dağıstan et al., 2025).

The Triple Bottom Line (TBL) framework—encompassing economic prosperity, environmental quality, and social justice—provides the theoretical foundation for holistic smart port sustainability assessment. However, empirical research has predominantly focused on environmental metrics (carbon emissions, pollution, energy consumption), with economic dimensions (cost efficiencies, labour adjustments) and social dimensions (community engagement, inclusive governance) remaining under-researched. This imbalance reflects both regulatory pressure and the relative ease of measuring environmental performance, though comprehensive sustainability requires balanced attention across all three dimensions (Dağistan et al., 2025).

Digital transformation technologies identified as essential for smart port operations include Big Data analytics, artificial intelligence (AI), Internet of Things (IoT), automation systems, digitalisation platforms, digital twins, blockchain, 5G connectivity, and sensor networks. These technologies enable real-time data collection, predictive maintenance, enhanced transparency, and optimised resource allocation—contributing simultaneously to operational efficiency and environmental sustainability (Dağistan et al., 2025).

Identified research gaps across smart port domains include: Digital Transformation facing scaling challenges across diverse ports, requiring investigation of ethical/social dimensions of technology adoption; Green Initiatives with limited circular economy applications, necessitating research on economic impacts of renewable energy integration; Governance where balanced TBL approaches remain uncommon, calling for participatory frameworks that build stakeholder trust; and Implementation where cybersecurity concerns remain under-addressed, requiring financial models for sustainable technology investment (Dağıstan et al., 2025).

Green port initiatives emphasise decarbonisation through energy efficiency improvements, renewable energy integration (solar, wind), and alternative fuel adoption. Advanced energy management systems, AI-driven automation, and simulation-based optimisation are identified as mechanisms for reducing greenhouse gas emissions whilst maintaining operational productivity. Vehicle-to-grid systems, battery integration, and smart lighting infrastructure demonstrate measurable energy savings of 50-60% in implemented cases (Dağistan et al., 2025).

Effective smart port governance requires clear regulatory frameworks, public-private partnerships, data sharing protocols, and international cooperation mechanisms. Maturity models have emerged as tools for assessing and guiding smart port development trajectories, enabling benchmarking across diverse port communities. Blockchain-based solutions enhance transparency and trust among stakeholders, reinforcing collaborative decision-making processes essential for sustainable development (Dağistan et al., 2025).

Implementation challenges include technological limitations, financial constraints, cybersecurity risks, workforce adaptation requirements, and legacy infrastructure barriers. Data integration and interoperability difficulties persist even as digital twin technologies promise enhanced real-time decision-making and predictive maintenance capabilities. Converting these challenges into opportunities requires collaborative approaches, targeted technology acquisition, and regulatory refinement—enabling ports to build resilient, efficient, and sustainable ecosystems capable of thriving in the competitive global maritime landscape (Dağistan et al., 2025).

1.11 Collaborative Planning for Offshore Wind-Hydrogen-Seaport Integration

The integration of offshore wind farms (OWF) with seaport hydrogen infrastructure creates opportunities for coordinated decarbonisation but also introduces stakeholder conflicts requiring structured resolution mechanisms. A bilevel collaborative planning framework addresses these conflicts through Stackelberg game formulation, where the OWF owner acts as leader and the seaport owner as follower (Xie et al., 2025).

1.11.1 Stakeholder Conflict Structure

The fundamental tension in offshore wind-seaport hydrogen systems arises from opposing economic objectives:

- **OWF Owner (Leader):** Seeks to maximise revenue by selling power and hydrogen to the seaport
- **Seaport Owner (Follower):** Aims to minimise operational costs by reducing purchases from OWF while ensuring grid stability and meeting hydrogen demand

This conflict necessitates coordinated planning frameworks that balance stakeholder interests while achieving system-wide decarbonisation objectives (Xie et al., 2025).

1.11.2 Hydrogen Technology Investment Optimisation

Bilevel optimisation determines optimal infrastructure sizing across both OWF and seaport systems:

Table 12: OWF Hydrogen Technology Investment (Xie et al., 2025)

Component	Capacity	Investment Cost
Electrolyser	11.69 MW	~$769,000
Fuel Cell	3.69 MW	(combined)
Hydrogen Storage	833-855 kg	

Table 13: Seaport Hydrogen Refuelling Station Investment (Xie et al., 2025)

Station	PV Capacity	WT Capacity	Electrolyser	Storage	Location
HRS-1	4.09 MW	1.65 MW	4 MW	269 kg	Node 9
HRS-2	3.99 MW	1.97 MW	4 MW	244 kg	Node 23
HRS-3	4.0 MW	1.93 MW	4 MW	320 kg	Node 29
Total	**12.08 MW**	**5.55 MW**	**12 MW**	**833 kg**	**$4M investment**

The bilevel structure ensures that seaport-side hydrogen storage investment is directly influenced by OWF planning decisions, resulting in aligned capacity across both systems (Xie et al., 2025).

1.11.3 Emission Reduction Outcomes

Collaborative planning achieves substantial emission reductions compared to uncoordinated baseline operations:

Table 14: Emission Reduction Results from Collaborative Planning (Xie et al., 2025)

Metric	Base Case	After Collaboration	Reduction
Wind curtailment	525,538 kW	0 kW	100%
Unserved seaport demand	187,671 kW	23,890 kW	87.3%
Carbon emission cost (electricity)	$1,100,510	$137,012	87.6%
Grey hydrogen emission cost	N/A (100% unserved)	$292,347	N/A
Hydrogen demand satisfied	0%	100%	100% coverage

The elimination of wind curtailment represents a critical achievement, as excess offshore wind power is absorbed through electrolysis rather than being wasted. Fuel cells provide backup power during low wind periods, maintaining supply reliability (Xie et al., 2025).

1.11.4 Economic Outcomes

The collaborative framework transforms both OWF and seaport from cost centres to revenue-generating operations over the 40-year planning horizon:

Table 15: Economic Transformation from Collaborative Planning (Xie et al., 2025)

Stakeholder	Base Case (40-yr NPV)	After Collaboration	Change
OWF Owner	\$1,902,630 (cost)	-\$44,592,600 (revenue)	+\$46.5M
Seaport Owner	\$22,763,100 (cost)	-\$214,975 (revenue)	+\$23.0M

Note: Negative values indicate net revenue/profit

Revenue sources for OWF include: - Power sales to seaport and transmission system - Hydrogen sales to shore-side market (5,234.3 kg total across scenarios) - Elimination of wind curtailment penalties

Revenue sources for seaport include: - Reduced electricity purchases from upstream grid - Reduced grey hydrogen purchases - Hydrogen clearance sales (\$631,595 from 962.3 kg) - Lower carbon emission penalties

1.11.5 Hydrogen Transport via LH2 Ship

Green hydrogen produced offshore is transported to shore via liquid hydrogen (LH2) container ships rather than pipelines. The model constrains hydrogen sales to at most one batch per day, recognising the logistics of ship-based transport. When hydrogen storage level reaches the threshold (γE), a batch of hydrogen (between γE and E) is sold to shore (Xie et al., 2025).

Sale frequency varies by wind scenario: - High/Moderate/Typical wind: 3 sales over 72-hour scenario period - Low wind: 1 sale (more hydrogen consumed by fuel cells for power generation)

1.11.6 Carbon Emission Pricing Effects

Sensitivity analysis reveals threshold effects in carbon emission pricing on infrastructure investment decisions:

- Grey hydrogen purchase quantity remains stable until emission penalty reaches λ_em,h = 3.368 $/kg
- Beyond this threshold, emission penalty exceeds unmet hydrogen demand penalty

- Grey hydrogen purchasing becomes economically unfavorable at high emission costs

This threshold effect indicates that carbon pricing mechanisms can effectively shift hydrogen sourcing from grey to green hydrogen when set above critical levels (Xie et al., 2025).

1.11.7 Third-Party Coordination

The bilevel collaborative planning model operates through "a trusted non-biased third-party agent (neutral facilitator or mediator) that does not have a stake in the outcomes and can help navigate potential conflicts" (Xie et al., 2025). This coordinated optimisation approach differs from decentralised market mechanisms:

Coordination characteristics: - Centralised optimisation with shared data access - Perfect information within the planning framework - Scenario-based stochastic formulation for uncertainty management - Hierarchical decision-making preserving stakeholder autonomy

1.11.8 Implications for Maritime Infrastructure Development

The collaborative planning framework offers several lessons for maritime infrastructure development:

For Port Authorities: - Hydrogen refuelling station siting within port distribution networks requires coordinated renewable energy capacity - Multiple HRS deployment (e.g., 3 stations) achieves 100% hydrogen demand coverage vs 57% with single station - Investment sequencing should align with offshore wind development timelines

For Offshore Wind Developers: - Seaport partnerships provide additional revenue streams beyond electricity sales - Hydrogen storage enables wind power absorption during low-demand periods - Fuel cell backup ensures power supply reliability commitments

For Policy Makers: - Carbon emission pricing thresholds influence grey vs green hydrogen economics - Collaborative planning frameworks require neutral third-party facilitation - 40-year planning horizons appropriate for infrastructure investment analysis

For Financial Institutions: - Both OWF and seaport transition from cost centres to revenue generators - Coordinated investments reduce individual stakeholder risk - Net present value calculations should incorporate multi-revenue streams

The computational complexity of bilevel optimisation increases substantially with problem size (solving time: 0.26 seconds to 7.3 hours), suggesting that practical implementation requires appropriate computational resources and potentially decomposition methods for larger systems (Xie et al., 2025).

CHAPTER 2

Life-Cycle Assessment of Maritime Fuels

2.1 LCA Methodology for Marine Applications

The lifecycle sustainability of alternative fuels represents a critical area for evaluation. Current production methods for hydrogen and ammonia rely heavily on fossil fuels, which undermines their net-zero potential (Sadiq et al., 2025).

2.1a Power System Evaluation Methodology

Systematic evaluation of low-carbon power system configurations requires assessment across five principal dimensions (Wang et al., 2024):

Table 16 Low-Carbon Power System Evaluation Elements

Evaluation Element	Description	Key Considerations
Economy	Investment, operation, maintenance, replacement, fuel costs	System commercialisation viability
Environment	COx, NOx, SOx emissions	IMO compliance, local air quality
Power Performance	Operational capacity and manoeuvrability	Vessel operating requirements
Technology Maturity	Development status of system components	ICE mature; FC/battery less mature
Safety	Fuel handling and system operational risks	Crew and vessel protection

Evaluation Methods Applied in Maritime Research:

Table 17 Evaluation Methods for Maritime Power System Analysis

Method	Application	Suitability
Genetic Algorithm (GA)	Techno-economic optimisation	Multi-objective problems
Life Cycle Assessment (LCA)	Environmental impact comparison	Well-to-wake fuel analysis
Fuzzy Comprehensive Evaluation	Multi-criteria comparison	Subjective factor integration
Multi-Criteria Decision Analysis (MCDA)	Cost-environment-risk assessment	Trade-off analysis
Differential Evolution Algorithm	Techno-economic-environmental analysis	Complex system optimisation

The 'Demand-Configuration-Integration-Evaluation' methodology provides a structured approach to power system selection: (1) analyse requirements based on water conditions, routes, and vessel types; (2) select appropriate fuel, power, propulsion, aftertreatment, and propulsor configurations; (3) integrate components into coherent system design; (4) evaluate against economy, environment, power, technology, and safety criteria. This iterative process enables refinement until optimal configuration is identified (Wang et al., 2024).

2.2 Well-to-Wake Analysis

The Well-to-Wake (WtW) framework represents the comprehensive approach adopted by the IMO for evaluating lifecycle greenhouse gas emissions from marine fuels. This framework encompasses all emission sources from fuel production through vessel operation, ensuring that apparent "zero-emission" technologies are not assessed solely on their operational performance while ignoring significant upstream impacts (Wang et al., 2024).

2.2.1 Life Cycle Assessment Phases

Maritime LCA evaluates environmental impacts across four distinct phases:

Table 18 Well-to-Wake Life Cycle Assessment Framework

Phase	Scope	Key Considerations
Equipment Manufacturing (EM)	Material extraction, component production	Energy storage systems, fuel cells, converters
Well-to-Tank (WTT)	Fuel production, transportation, distribution	Hydrogen production pathway, electricity grid mix
Tank-to-Wake (TTW)	Onboard fuel consumption, operational emissions	Direct combustion emissions, energy conversion efficiency
End of Life (EoL)	Decommissioning, recycling, disposal	Material recovery potential, recycling infrastructure

2.2.2 Integrated Experimental-LCA Methodology

Conventional LCA methods face significant limitations in maritime applications due to missing or incomplete data in LCA databases, inconsistencies in assumptions and scopes across studies, and difficulty reflecting the varied nature of ship design and operational modes. The integration of experimental assessment with LCA methodology addresses these shortcomings by generating ship-specific data through tow tank testing based on actual vessel weight and propulsion system design (Wang et al., 2024).

This integrated approach comprises three interconnected phases:

1. **Ship Design and Performance Assessment:** Experimental determination of hull resistance and propulsion requirements based on specific vessel characteristics
2. **Dynamic System Simulation:** Time-series modelling of power and fuel consumption under realistic operational profiles
3. **Life Cycle Impact Assessment:** Application of characterisation factors to calculate environmental impact indicators

The methodology produces more reliable and case-specific outcomes than approaches relying solely on generic database values, enabling accurate evaluation of how ship design and operational mode variations influence lifecycle environmental performance.

2.2.3 Critical Upstream Emission Sources

For hydrogen and electricity-based propulsion systems, lifecycle emissions are predominant in the fuel production phase rather than during vessel operation. This represents a fundamental departure from conventional fossil fuels, where Tank-to-Wake emissions comprise the majority of lifecycle impacts (Wang et al., 2024).

Table 19 Lifecycle Emission Distribution by Power System

System Type	WTT Phase	TTW Phase	Key Finding
MGO Diesel	~20%	~75%	Combustion-dominated
Hybrid Electric	Variable	Variable	Electricity grid-dependent
Hydrogen (SMR)	~95%	~0%	Production-dominated
Hydrogen (AEL)	~95%	~0%	Production source critical

This analysis demonstrates that using electricity or hydrogen produced from carbon-intensive sources risks higher total GHG emissions than conventional MGO, underscoring the essential nature of Well-to-Wake evaluation per IMO LCA guidelines adopted at MEPC 80.

2.3 Green Hydrogen and Ammonia Production

Green hydrogen and ammonia, produced via renewable energy-driven electrolysis and innovative catalytic processes, represent more sustainable pathways. Research on integrating offshore wind energy and solar-powered electrolysis for green hydrogen production could significantly reduce lifecycle emissions (Sadiq et al., 2025).

2.4 Comparative Environmental Performance

Quantitative LCA studies provide essential evidence for comparing the environmental performance of alternative marine propulsion systems. A comprehensive assessment of an inland passenger barge demonstrates the critical importance of both technology selection and fuel production pathway in determining lifecycle environmental outcomes (Wang et al., 2024).

2.4.1 Lifecycle Impact Assessment Results

Table 20 Comparative Lifecycle Emissions for Alternative Marine Power Systems (per km)

Impact Category	MGO Diesel	Hybrid PV/ Battery	H_2 Fuel Cell (SMR)	H_2 Fuel Cell (Wind AEL)
GWP (kg CO_2-Eq)	4.22	1.85	4.48	0.61
Acidification (g SO_2-Eq)	9.34	8.21	0.97	0.56
Eutrophication (g PO_4-Eq)	3.93	4.63	0.19	0.07
Photochemical oxidation (g C_2H_4-Eq)	0.56	5.95	0.26	0.10

Key Findings: - Hydrogen fuel cell systems using wind-powered alkaline electrolysis (AEL) achieve **85.7% GWP reduction** compared to MGO baseline - Hybrid PV/diesel/battery systems deliver **56.2% GWP reduction** - Hydrogen from steam methane reforming (SMR) results in **6.3% GWP INCREASE** over MGO

This critical finding demonstrates that hydrogen systems reliant on fossil feedstocks risk increasing rather than reducing emissions, emphasising that a fuel cell system consuming SMR hydrogen cannot be considered "zero-carbon" despite having no operational emissions (Wang et al., 2024).

2.4.2 Hydrogen Production Pathway Comparison

The environmental performance of hydrogen fuel depends entirely on its production pathway:

Table 21 Hydrogen Production Pathway Environmental Comparison

Pathway	Description	Market Share	GWP (kg CO_2-Eq/km)	vs MGO
SMR (Grey)	Steam methane reforming	~80% US, >70% global	4.48	+6.3%
SMR + CCS (Blue)	SMR with carbon capture	Emerging	~4.0 (estimated)	Reduced but not eliminated
Wind AEL (Green)	Wind-powered electrolysis	<5%	0.61	-85.7%

Green hydrogen produced via wind-powered alkaline electrolysis represents the only pathway achieving substantial emission reductions. The current predominance of grey hydrogen production (~70-80% globally) presents a significant barrier to realising the decarbonisation potential of hydrogen-based maritime propulsion.

2.4.3 Electricity Grid Mix Sensitivity

For hybrid electric and battery systems, lifecycle emissions are highly sensitive to the carbon intensity of electricity production:

Table 22 Grid Decarbonisation Impact on Maritime Hybrid System Emissions

Scenario	Grid Description	Renewable Share	Lifecycle Emission Factor (g CO_2-Eq/ kWh)	Potential GHG Savings
SA1	Global 2018 average	Lower	556.98	Reduced
Baseline	UK 2019 grid	37.1%	292	56.2%
SA2	UK 2035 projection	79.5%	107.61	82.2%
SA3	UK 2050 projection	Higher	86.08	Further enhanced

With a transition to 79.5% renewables projected for 2035, savings of **82.2% lifecycle GHG emissions** become achievable for grid-connected hybrid systems. This underscores that significant advantages in environmental impacts are only realised if the maritime industry integrates higher shares of renewable energy sources in electricity production (Wang et al., 2024).

2.4.4 System Construction Environmental Impacts

Equipment manufacturing represents a significant component of lifecycle emissions for zero-emission technologies:

Hydrogen Fuel Cell System: - Hydrogen storage tanks: 55.8% of system construction GWP - Carbon fibre production: 51.6% of construction GWP (26 kg CO_2-Eq per kg) - Each Type IV tank: 76 kg carbon fibre + 26 kg epoxy resin

Hybrid Battery System: - Battery production and replacement: 20.1% of total lifecycle GWP - Lead-acid battery replacement: ~10% of lifecycle GWP - Battery lifetime: 1,000-1,500 full charge-discharge cycles (~10 years) - Lead-acid recycling: 14.9% GWP reduction vs disposal (99% recycling rate in US)

Maximising the operational lifetime of batteries and fuel cells contributes significantly to mitigating lifecycle environmental impacts, as extending component service life reduces the frequency of manufacturing emissions from replacement systems.

2.5 Green Ammonia as a Zero-Carbon Marine Fuel

Green ammonia represents one of the most promising zero-carbon fuel options for deep-sea shipping, offering complete elimination of carbon emissions during combustion while leveraging existing industrial infrastructure and handling expertise (Ahmed et al., 2023).

2.5.1 Ammonia Properties and Energy Characteristics

Table 23 Ammonia Compared with Conventional Marine Fuels

Property	Ammonia	Diesel	LPG	Bunker Fuel
Pressure (bar)	10	1	14	1
Density (kg/m³)	603	846	388	980
Lower Heating Value (kWh/kg)	5.18	12.1	12.6	10.8
Lower Heating Value (MWh/m³)	3.12	10.2	4.89	10.6
Cost (USD/kWh)	0.058	0.083	0.079	0.055

Ammonia's lower energy density compared to conventional fuels (approximately 43% of diesel on a mass basis) necessitates larger storage volumes, but its competitive cost per unit energy and zero-carbon combustion profile make it attractive for decarbonisation. When combusted, ammonia produces only nitrogen gas and water, eliminating carbon dioxide emissions entirely at the point of use.

2.5.2 Comprehensive Life Cycle Assessment of Ammonia-Powered Tankers

A cradle-to-grave LCA of a green ammonia-powered very large tanker (VLCC) on the Rotterdam-New York route demonstrates the environmental advantages of this fuel pathway. The assessment employed three complementary methodologies—IPCC AR5/AR6, Environmental Footprint EF 3.0, and ReCiPe Midpoint Hierarchist—with 30,000 Monte Carlo simulations to quantify uncertainty (Ahmed et al., 2023).

Table 24 Comparative Fuel Environmental Performance (per tonne-kilometer)

Fuel Type	GWP 100 Performance	GTP 100 Performance	Change vs HFO
HFO (Heavy Fuel Oil)	Baseline (Highest)	Baseline (Highest)	—
LNG	Lower	Lower	Negative
Blue Ammonia	Lower than LNG	Lower than LNG	Negative
Green Ammonia	**Lowest**	**Lowest**	**>−90%**

Critical Finding: Green ammonia exhibited the most substantial negative percentage difference values (greater than −90%) per tonne-kilometer compared to HFO baseline in both GWP 100 and GTP 100 categories. This represents the greatest environmental benefit of any alternative fuel assessed.

2.5.3 Impact Category Analysis

The comprehensive LCA revealed significant environmental implications across multiple impact categories:

Table 25 Climate Change Impact Assessment Results (Mean Values)

Impact Category	Mean Value	Unit
IPCC GWP 100	4.52E+11	kg CO_2 eq
IPCC GTP 100	4.29E+11	kg CO_2 eq
IPCC CGTP 100	3.13E+12	yr*kg CO_2 eq
Climate change: Fossil	4.69E+11	kg CO_2 eq

Process Contribution Analysis: - Dual-fuel diesel engine (entire lifecycle): 19-20% of GWP impact - Green ammonia production: ~19.37% of GTP 50 impact - Hydrogen and nitrogen production: ~19.37% each - Heavy fuel oil processes: ~20% of climate impacts

The analysis indicates that while green ammonia significantly reduces operational emissions, the production processes for ammonia, hydrogen, and nitrogen still contribute substantial shares to total lifecycle impacts, highlighting the importance of decarbonising the entire supply chain.

2.5.4 Green Ammonia Production Pathways

Three generations of green ammonia production technology offer progressively lower environmental impacts:

Table 26 Green Ammonia Production Technology Generations

Generation	Method	Characteristics
Gen 1	Haber-Bosch + Carbon Sequestration	Net-zero through offsets
Gen 2	Haber-Bosch + Renewable Hydrogen	Shifts to green H_2 feedstock
Gen 3	Direct Electrochemical $N_2 \rightarrow NH_3$	Eliminates Haber-Bosch process; scalable kW to GW

Electrolysis becomes cost-competitive with steam methane reforming (SMR) with carbon capture at electricity prices of 1.5-5.0 USD cents/kWh. The UK offshore wind strike price of approximately 4.0 GBP pence/kWh (5.2 USD cents/kWh) indicates near-competitiveness for green ammonia production in regions with favourable renewable resources.

2.5.5 Nitrogen Cycle Considerations

Large-scale adoption of ammonia as a marine fuel raises important concerns regarding the global nitrogen cycle. Current ammonia production stands at approximately 176 tera-grams annually, while powering the global maritime sector would require approximately 711 tera-grams—a fourfold increase (Ahmed et al., 2023).

Environmental Implications: - Marine nitrogen cycles have long durations (half-life approximately 100 years) - Effects of doubled fixed nitrogen on marine ecosystems not fully understood - Risk of nutrient loading, eutrophication, and ecosystem disruption - NOx and NH_3 emissions require rigorous control measures

As the authors caution: "Humanity must not counter one catastrophe caused by CO_2 emissions by causing another crisis due to NH_3 and NOx emissions." This underscores the need for comprehensive environmental management alongside ammonia adoption.

2.6 Uncertainty Analysis in Life Cycle Assessment

While LCA provides a standardised framework for evaluating the environmental impacts of alternative marine fuels, the reliability of LCA results depends critically on understanding and quantifying the uncertainties inherent in both production (well-to-tank) and operational (tank-to-wake) phases. Recent research demonstrates that "the actual environmental benefits of these fuels depend heavily on upstream production conditions and downstream onboard operations, both of which are subject to significant uncertainty" (Wang et al., 2025).

2.6.1 The Importance of Uncertainty Quantification

Traditional LCA studies often rely on static input values and fixed assumptions, which fail to capture the inherent variability of real-world fuel deployment. This limitation constrains the credibility of emissions estimates and their utility for carbon pricing, fuel policy design, and investment decisions. An uncertainty-integrated LCA framework addresses this gap by systematically quantifying variability across the entire fuel lifecycle.

Sources of Uncertainty: - Well-to-tank (WTT): Electricity sourcing factors, production efficiency, regional variations - Tank-to-wake (TTW): Vessel powertrain configurations, operational parameters, speed variations

2.6.2 Green Shipping Corridor Case Study: Singapore-Rotterdam

Research on the Singapore-Rotterdam corridor—one of the world's most prominent long-haul routes and a COP 26 designated pilot corridor—provides comprehensive uncertainty analysis for three renewable fuels: liquefied hydrogen (e-LH2), ammonia (e-NH3), and methanol (e-MeOH) (Wang et al., 2025).

Table 27 Renewable Fuel Properties and Production Pathways

Fuel	Physical State	LHV (MJ/kg)	Production Pathway
E-LH2	Cryogenic (-253°C)	120	Electrolysis + liquefaction
E-NH3	Liquid (18 bar)	18.6	Electrolysis + ASU + Haber-Bosch
E-MeOH	Liquid (ambient)	19.9	Electrolysis + DAC + hydrogenation

2.6.3 Well-to-Tank Uncertainties: Production Phase

Monte Carlo simulation (1,000 iterations) quantifies the uncertainty in electricity consumption across fuel production processes, revealing significant variability that affects lifecycle emissions estimates.

Table 28 Electricity Requirements in Renewable Fuel Production

Process	Energy Requirement	Unit Output
Electrolysis (H2)	50 kWh	1 kg H2
H2 Liquefaction	6.5 kWh	1 kg H2
Air Separation Unit (N2)	0.314 kWh	1 kg N2
Direct Air Capture (CO2)	0.7 kWh	1 kg CO2
Haber-Bosch (NH3)	0.472 kWh	1 kg NH3
MeOH Synthesis	0.858 kWh	1 kg MeOH

Table 29 Monte Carlo Uncertainty Results for WTT Emissions

Fuel	Process	CV (%)	95% CI Range (kg CO2-eq/voyage)
E-LH2	Electrolyzer	10.2	$1.87 – 2.72 \times 10^6$
E-LH2	Liquefaction	11.7	$1.81 – 2.99 \times 10^6$
E-NH3	Electrolyzer	11.5	$2.04 – 3.26 \times 10^6$
E-NH3	HB Synthesis	11.2	$2.18 – 3.48 \times 10^6$
E-MeOH	Electrolyzer	11.1	$2.00 – 3.07 \times 10^6$
E-MeOH	DAC	11.3	$1.94 – 3.08 \times 10^6$
E-MeOH	Synthesis	8.7	$1.95 – 2.95 \times 10^6$

The highest uncertainty is observed in hydrogen liquefaction (CV = 11.7%), while methanol synthesis shows the lowest variability (CV = 8.7%), suggesting greater technological maturity.

2.6.4 Impact of Electricity Source

The geographic origin and type of clean electricity introduces a fundamental source of uncertainty in upstream emissions. Comparative analysis reveals substantial differences between wind- and solar-sourced electricity.

Table 30 Decarbonisation Potential by Electricity Source (vs HFO Baseline)

Fuel	Wind-Based Reduction	Solar-Based Reduction
E-LH2	80.6%	57.3%
E-NH3	78.3%	56.2%
E-MeOH	74.7%	60.4%

Critical Finding: "Solar-based fuels achieve only 71%–81% of the emission reductions achieved by wind-based fuels" due to higher lifecycle emissions from solar PV manufacturing and lower capacity factors (Wang et al., 2025).

Regional Variation:

Table 31 Electricity Emission Factors by Region (Wind, 1-3MW Onshore)

Region	Emission Factor (kg CO2-eq/kWh)
Australia	0.013
Netherlands	0.017
South Africa	0.031
Solar (Netherlands)	0.0492

This regional variation means that "wind-based fuels from the Netherlands have 1.4 times higher lifecycle emissions than those from Australia," highlighting that "WTT emissions are far more sensitive to the carbon intensity of electricity than to fuel consumption itself" (Wang et al., 2025).

2.6.5 Tank-to-Wake Uncertainties: Operational Phase

Sensitivity analysis of operational parameters identifies four key factors affecting TTW emissions: vessel speed, pilot fuel ratio, powertrain configuration, and onboard carbon capture system (OCCS) efficiency.

Vessel Speed Impact: A ±10% variation in vessel speed results in approximately ±20% change in emissions. "Reducing vessel speed by 10% leads to a substantial decrease in total emissions to approximately 82% of the baseline level" (Wang et al., 2025).

Pilot Fuel Ratio (Dual-Fuel Engines):

Table 32 Impact of Pilot Fuel Ratio on Emission Reductions

Pilot Fuel Ratio	E-LH2 Reduction	E-NH3 Reduction	E-MeOH Reduction
0% (reference)	88.9%	86.6%	84.6%
5%	82.5%	80.3%	79.2%
7% (baseline)	80.6%	78.3%	77.2%
10%	77.0%	74.7%	74.1%

"Dual-fuel engines can lose up to 12.5% of their emission benefits due to pilot fuel ratios of 5%–10%" (Wang et al., 2025). Although pilot fuel contributes only 5–10% of total energy input, its high carbon intensity (3.16 kg CO2-eq/kg for HFO) significantly impacts lifecycle emissions.

Powertrain Configuration:

Table 33 Efficiency Comparison: Dual-Fuel Engines vs Fuel Cells

Technology	E-LH2	E-NH3	E-MeOH
Dual-fuel engine	36%	36%	40.5%
Fuel cell (PEMFC/SOFC)	50%	48%	48%

"Fuel cells consistently outperform dual-fuel engines in terms of lifecycle emission reductions… improvement ranges from approximately 10.3% to 12.8%" (Wang et al., 2025). The highest improvements are observed for e-NH3 (12.8%), driven by efficiency gains from 36% to 48%.

Onboard Carbon Capture (E-MeOH):

Table 34 OCCS Efficiency Impact on Net Emissions (ULCV)

OCCS Efficiency	Net Voyage Emissions (kg CO2-eq)
70%	-7.16×10^6
80%	-9.13×10^6
90%	-1.10×10^7

"An efficient onboard carbon capture system can achieve net-negative emissions during voyages" for e-MeOH, transforming it from a carbon-neutral to a carbon-negative solution (Wang et al., 2025).

2.6.6 Integrated Uncertainty Framework

The research demonstrates that "electricity consumption is the dominant uncertainty driver" in the WTT phase, while "vessel operational factor—vessel speed—has a notably greater influence on lifecycle emissions than other factors" in the TTW phase (Wang et al., 2025).

Key Insight: "The environmental superiority of a fuel is not fixed—it depends on where and how it is produced, and how it is operationally deployed" (Wang et al., 2025).

Policy Implications: - Align fuel production with low-carbon energy regions - Support flexible ship retrofitting pathways - Incorporate uncertainty into emissions regulation and carbon pricing frameworks - Develop green shipping corridors as integrated systems

“Green shipping corridors should not be treated as simple fuel-supply chains, but as integrated systems where energy infrastructure, vessel operations, and regulatory tools should be jointly developed” (Wang et al., 2025).

2.7 Real-Time Life Cycle Assessment with Digital Twin Integration

2.7.1 Limitations of Static LCA Methodologies

Conventional LCA methodologies, while valuable for establishing baseline environmental profiles, exhibit fundamental limitations when applied to vessels with variable operational profiles. “Static LCA calculations struggle to address the evolving environmental performance of technologies like hybrid systems or electric vessels, where energy use, operational strategies, and technological advancements change over time” (Kim, 2025). Ships operate under fluctuating conditions—variable weather patterns, changing cargo loads, shifting routes, and evolving regulatory requirements—that static assessments cannot adequately capture.

The transition to battery-hybrid electric propulsion systems and alternative fuels introduces additional complexity. Electric vessels drawing shore power from grids with varying renewable energy penetration, or operating on multiple fuel pathways with different production methods, require assessment frameworks capable of reflecting these dynamic characteristics. Conventional LCA’s fixed assumptions about fuel consumption patterns, operational profiles, and energy sources produce results that may diverge significantly from actual environmental performance (Kim, 2025).

2.7.2 Digital Twin Technology for Environmental Assessment

Digital twin technology enables real-time synchronisation between physical vessel operations and virtual models, creating opportunities for dynamic environmental assessment. “A particularly novel aspect of this research lies in the successful integration of real-time digital twin technology with the LCA model… enabling continuous environmental impact assessment by synchronizing real-time operational data with a virtual ship model” (Kim, 2025).

The real-time LCA framework operates with 10-second interval data updates, capturing instantaneous variations in: - Power demand and generation efficiency - Fuel consumption rates across different operating modes - Battery charging and discharging patterns - Grid electricity composition for shore power

This enables "the integration of real-time operational data, allowing for a more accurate and instantaneous assessment by reflecting the load characteristics and efficiency of propulsion and power generation systems" (Kim, 2025).

Table 35 Real-Time LCA versus Static LCA Comparison

Aspect	Static LCA	Real-Time LCA with Digital Twin
Data Input	Fixed assumptions	Continuous 10-second updates
Operational Variation	Not captured	Fully integrated
Decision Support	Retrospective	Proactive and predictive
Regulatory Compliance	Post-hoc assessment	Real-time verification
Fuel Switching	Pre-planned only	Dynamic optimisation

2.7.3 Battery-Hybrid Electric Propulsion Systems

The battery-hybrid approach combines conventional generators with battery storage, enabling optimised load management. Key design parameters include generator capacity at 110-115% of maximum output for redundancy, battery state-of-charge (SOC) operating range of 20-90% to preserve battery life, and power management systems maintaining engines at 85% load for optimal efficiency (Kim, 2025).

Table 36 Battery-Hybrid System Design Parameters (Korean Vessels)

Vessel Type	Tonnage	Generator Output (kW)	Battery Capacity (kWh)	SOC Range (kWh)
Port Cleaning	273 t	852 × 2	1,460	292-1,314
Fishery Patrol	1,339 t	1,136 × 2	1,020	204-918
Fishing Vessel C	5 t	264	240	48-216
Fishing Vessel D	10 t	514	720	144-648

Three propulsion scenarios demonstrate the framework: mechanical propulsion (conventional engine), electric propulsion with 20% initial SOC (self-charging during operation), and electric propulsion with 90% initial SOC (shore power pre-charging). Each scenario produces distinct lifecycle emission profiles depending on fuel selection and electricity source (Kim, 2025).

2.7.4 Fuel Pathway Analysis for Electric Vessels

The environmental performance of alternative fuels depends critically on production pathways. Well-to-Tank emission factors vary dramatically based on energy sources and production methods:

Table 37 Well-to-Tank Emission Factors by Production Pathway

Fuel Type	Production Method	WtT Factor (kg CO2-eq/kg)
MDO	Conventional refining	0.615
Ammonia (EU-28)	Natural gas, no CO2 recovery	2.72
e-Ammonia	Solar-powered electrolysis	0.558
Hydrogen (EU pipeline)	Mixed sources	3.83
Hydrogen (NL)	Steam reforming from NG	10.5
Hydrogen (DE)	Steam reforming from HFO	14.2
Hydrogen (RER)	Electrolysis, renewable mix	0.977
e-Hydrogen	Solar-powered electrolysis	3.598

"Renewable energy-powered hydrogen and ammonia show significantly lower lifecycle emissions compared to conventional fuels" (Kim, 2025). However, the same alternative fuel can exhibit vastly different emission profiles: hydrogen from steam reforming of heavy fuel oil (14.2 kg CO2-eq/kg) produces fourteen times the emissions of hydrogen from renewable electrolysis (0.977 kg CO2-eq/kg).

2.7.5 Regional Electricity Grid Impacts

For electric vessels charging from shore power, the electricity grid composition determines a substantial portion of lifecycle emissions. "Identical electric vessels can yield significantly different lifecycle GHG impacts depending on the composition of their respective national electricity mixes" (Kim, 2025).

Table 38 Regional Electricity Grid Emission Factors

Region	Dominant Generation Source	Emission Factor (kg CO2-eq/kWh)
Australia	Hard coal (44.6%)	0.981
Japan	Natural gas (39.2%)	0.632
EU-28	Nuclear (25.9%), diversified	0.386

The 2.5-fold difference between Australia and EU-28 emission factors demonstrates that electric vessel environmental performance is inseparable from regional energy infrastructure. A vessel operating identically but charging in Australia rather than the EU would exhibit substantially higher lifecycle emissions solely due to grid composition (Kim, 2025).

2.7.6 Paradigm Shift in Environmental Assessment

The integration of digital twin technology with lifecycle assessment represents a fundamental methodological advancement. "Such a paradigm shift from static to simulation-based dynamic LCA is not merely a technical enhancement but a necessity for the accurate and reliable assessment of lifecycle GHG intensity for marine electric vessels" (Kim, 2025).

Key capabilities enabled by this approach include: - **Dynamic emission limit enforcement:** Real-time identification of compliant versus non-compliant fuel pathways against specified thresholds - **Electrical system monitoring:** Power, voltage, and current analysis for stability assessment and blackout prevention - **Predictive modelling:** Shore-based simulation for operational optimisation before voyage execution - **Fleet-level assessment:** Aggregated environmental performance monitoring across multiple vessels

Over a 30-year vessel lifespan, fuel pathway selection can result in emission differences exceeding 50,000 tonnes CO2-eq, underscoring the importance of accurate, dynamic assessment capabilities (Kim, 2025).

2.8 Comparative LCA for Maritime Component Design

2.8.1 Lightweight Design and Fuel Efficiency

Life cycle assessment provides a systematic framework for evaluating trade-offs between production impacts and operational benefits of alternative design solutions. The relationship between vessel mass and fuel consumption creates opportunities for lifecycle emission reduction through lightweight design, even when the production phase of lighter materials incurs higher environmental burdens.

Del Pero et al. (2024) demonstrate this principle through comparative assessment of yacht superstructure designs: Glass Fiber reinforced Vinylester-isophthalic Resin (GFVR) versus Carbon Fiber reinforced Epoxy Resin (CFER). Despite carbon fiber's substantially higher production energy intensity, "the innovative solution allows achieving a significant quota of GWP over the entire LC (more than 16%), which is mainly associated with decreased amount of fuel needed and lowered CO2 exhaust emissions during operation."

The mass reduction from 9.9 tonnes (GFVR) to 5.5 tonnes (CFER)—a 44-45% decrease—translates directly to proportional reductions in operational fuel consumption and emissions, establishing the operational phase as the primary determinant of lifecycle environmental performance.

2.8.2 Lifecycle Stage Contribution Analysis

Table 39 GWP Distribution by Lifecycle Stage

Stage	GFVR (Reference)	CFER (Lightweight)
Production	22%	49%
Use	74%	49%
End-of-Life	4%	3%

For the reference GFVR design, the use phase dominates environmental impact at 74%, driven by 25,000 operating hours consuming approximately 54,700 litres of diesel over the 25-year lifetime. The CFER design's reduced mass shifts the distribution, with production and use phases contributing equally (49% each), reflecting both the reduced operational burden and the higher energy intensity of carbon fiber production (Del Pero et al., 2024).

The dramatic difference in specific GWP between material systems explains this shift:

Table 40 Specific GWP by Material Type

Material	Specific GWP (kg CO2-eq/kg)
Carbon fiber reinforced resin	23
Glass fiber reinforced resin	4
Carbon fiber production alone	20
Glass fiber production alone	1.7

Carbon fiber production requires energy-intensive stabilisation, carbonisation, and heat treatment (graphitisation) processes to convert polyacrylonitrile precursor fibers, resulting in specific impacts approximately 12 times higher than glass fiber (Del Pero et al., 2024).

2.8.3 Break-Even Point Analysis

Despite higher production impacts, the CFER design achieves environmental superiority over the lifecycle through accumulated operational savings. The break-even point—where production disadvantages are offset by operational benefits—occurs at 12,700 operating hours, representing 51% of the reference 25,000-hour lifetime.

Table 41 Break-Even Point Sensitivity to Fuel Consumption

Hourly Consumption (l/h)	Break-Even Point (hours)
40 (minimum)	25,305
60	~19,000
80 (reference)	12,700
100	~10,000
120 (maximum)	8,435

Higher consumption rates accelerate the break-even, with a threefold reduction in payback time (25,305 to 8,435 hours) as consumption increases from 40 to 120 l/h. This relationship indicates that "an increase in yacht consumption makes bigger the influence of use stage on the overall LC GWP, with also increased environmental benefits achievable through lightweight design" (Del Pero et al., 2024).

2.8.4 Scenario Analysis and Design Recommendations

Analysis across 35 consumption-duration scenario combinations reveals that the CFER design delivers environmental benefits in 27 scenarios (77%), with GWP variation ranging from +25% (minimum consumption and duration) to -30% (maximum consumption and duration). This indicates that lightweight design strategies require careful consideration of expected operational profiles to ensure environmental benefits materialise.

Design guidance for lightweight solutions: - Favour lightweight design when: High fuel consumption levels expected, long operational lifetimes anticipated, intensive operational profiles planned - **Exercise caution when:** Short operational lifetimes limit payback period, fuel consumption levels expected to be low, uncertainty exists regarding operational profiles

"Lightweight design is the main effective strategy for impact reduction, since it allows to take advantage from both primary mass reduction (reduced weight of components) and secondary mass reduction (powertrain resizing)" (Del Pero et al., 2024).

For vessels with operational profiles exceeding 30,000 hours or consumption rates above 100 l/h, lightweight composite solutions provide consistent lifecycle benefits regardless of other operational variables. This finding supports strategic investment in advanced composite materials for high-utilisation commercial vessels where operational savings compound over extended service lives.

2.9 Methodological Review of Maritime Fuel LCA Studies

2.9.1 State of the Art Assessment

A systematic review of 43 peer-reviewed LCA articles on maritime fuels, encompassing 429 individual case studies published between 2011 and 2023, reveals significant gaps in methodology, transparency, and fuel coverage that limit the utility of existing research for decision-making (Roux et al., 2024). "Current LCA studies of maritime fuels are unable to provide clear guidance on the potential environmental impacts of maritime fuels, in particular those relating to emerging fuel types."

Table 42 Fuel Type Coverage in Maritime LCA Literature

Fuel Type	% of Articles	% of Case Studies	Key Gap
LNG	63%	21%	Most studied but transition fuel only
HFO	47%	-	Reference baseline
MGO	42%	-	Conventional fuel
Biofuels	33%	-	72% first-generation
Hydrogen	33%	-	56% electrolysis-based
Methanol	26%	-	Only 7% e-methanol
Ammonia	21%	-	Least studied despite industry interest

Despite growing industry interest in ammonia as a future fuel, it remains the least-studied alternative in the peer-reviewed literature, while methanol from electrolysis—identified as a key potential fuel for 2050—is investigated in only 7% of methanol case studies (Roux et al., 2024).

2.9.2 Documentation and Transparency Gaps

The review identified critical deficiencies in LCA documentation that undermine reproducibility and cross-study comparison:

Table 43 Documentation Gaps in Maritime Fuel LCAs

Element	% Adequately Documented	Implication
Full WtW inventory	19%	Limited reproducibility
Vessel type	Variable (17-58%)	Unclear applicability
Engine type	Better than vessels	Comparison difficulties
Electricity input for LNG	10%	Unknown production impacts
Temporal scope	35%	Technology mismatch risk
Geographical scope	65%	Limited regional applicability

"There is a lack of transparent disclosure of the methodological choices and assumptions… making it difficult to reproduce studies and validate results" (Roux et al., 2024).

2.9.3 Impact Category Limitations

The overwhelming focus on climate change impacts—with 39% of studies reporting only GWP100—creates significant risks of burden-shifting and incomplete environmental assessment:

Table 44 Impact Category Coverage in Maritime Fuel LCAs

Impact Category	% of Articles	Relevance
GWP 100 years	>90%	Standard but incomplete
Acidification	~40%	SOx/NOx emissions
PM formation	~36%	Human health
Eutrophication	~40%	Marine impacts
GWP 20 years	13%	Methane short-term effects
Marine eutrophication	9%	Scrubber discharges
Land use change (dLUC)	37% (biofuels)	Carbon stock changes
Land use change (iLUC)	22% (biofuels)	Market-mediated effects

"The focus on carbon emissions may limit the options for identifying burden-shifting and effects on other types of impacts, which ultimately represents a limited basis for decision-making" (Roux et al., 2024).

For biofuels, the exclusion of land use change dramatically underestimates environmental impacts. When indirect land use change is included, soybean biodiesel GWP increases from 38.4 to 135 gCO2-eq per MJ—a factor of 3.5 increase (Roux et al., 2024).

2.9.4 Uncertainty and Sensitivity Analysis Deficiencies

The review reveals alarming gaps in uncertainty treatment, particularly critical for emerging technologies:

Table 45 Uncertainty Analysis Practice in Maritime Fuel LCAs

Analysis Type	% of Articles	Adequacy
Sensitivity analysis	33%	Insufficient
Uncertainty analysis	16%	Critical gap
Scenario analysis	12%	Limited
Monte Carlo simulation	9%	Rare
Data quality assessment	2%	Almost absent

"Uncertainty analyses, which are a key methodological element of LCAs and particularly relevant for emerging fuels and technologies, are only included in 16% of the reviewed articles" (Roux et al., 2024).

This deficiency is particularly problematic when comparing fuels at different technology readiness levels (TRLs). E-fuel engines such as ammonia fuel cells (TRL 1-4) and ammonia gas turbines (TRL 4-6) cannot be fairly compared with mature methanol technologies (TRL 7-9) without appropriate upscaling methods and uncertainty quantification.

2.9.5 Fugitive Emissions and Methane Slip

The treatment of fugitive emissions, particularly methane slip from LNG, varies substantially across studies with significant impact implications:

- **Processing-related methane emissions:** Included in only 32% of LNG case studies
- **Combustion methane slip:** Reported in only 57% of LNG case studies
- **Impact of omission:** Up to 24% difference in GWP scores

"For smaller vessels such as ferries, LNG burnt in medium and high speed engines can have a higher climate change impact than HFO due to methane slip" (Roux et al., 2024).

The reported methane slip from LNG combustion varies dramatically—from 0.009 to 14.5 g CH4/kWh—reflecting different engine types, operating conditions, and measurement methodologies. This variation, combined with frequent omission of slip entirely, introduces substantial uncertainty into LNG environmental assessments.

2.9.6 Impact Score Variability

The wide variation in reported environmental impacts for the same fuels illustrates the consequences of methodological inconsistency:

Table 46 GWP100 Impact Score Ranges from Reviewed Studies

Fuel Type	Range (gCO2-eq/MJ)	Spread	Case Studies
HFO	74-197	2.7×	30
LNG	66-242	3.7×	38
Biofuels (excl. LUC)	-58 to 148	Variable	40

"Such variations hence lead to inability to draw conclusions as to which fuel alternatives perform better for climate change" (Roux et al., 2024).

Critically, LNG scores overlap substantially with HFO, suggesting that "switching to LNG could be more detrimental than beneficial" depending on specific conditions and methodological choices.

2.9.7 Recommendations for Improved Practice

Based on the systematic review, the following methodological requirements are essential for decision-relevant maritime fuel LCAs:

Fuel and Technology Coverage: - Prioritise second-generation biofuels and electro-fuels - Include feedstock availability constraints - Address technology readiness level differences through upscaling - Consider fuel-engine compatibility explicitly

System Boundaries and Inventory: - Apply well-to-wake boundaries including capital goods - Document complete life cycle inventories normalised to functional unit - Include fugitive emissions throughout fuel lifecycle - Ensure temporal alignment between foreground and background data

Impact Assessment: - Include multiple relevant impact categories beyond GWP100 - Consider GWP20 for fuels with methane emissions - Include land use change for biofuels (both direct and indirect) - Develop maritime-specific characterisation factors

Uncertainty Treatment: - Conduct sensitivity analyses on key parameters - Provide data quality assessment using pedigree matrices - Perform Monte Carlo simulations for quantitative uncertainty - Document all assumptions and methodological choices transparently

"In order to make informed decisions regarding fuel choices for the future fleet and avoid burden shifting, there is the need for considerable improvement of maritime fuel LCAs to support informed decision-making regarding future fuel choice" (Roux et al., 2024).

CHAPTER 3

Digital Technologies and Smart Shipping

3.1 Digital Twins in Maritime Operations

Digital twins enable real-time performance monitoring, predictive analytics, and system optimization, enhancing fuel efficiency and operational effectiveness (Sadiq et al., 2025).

3.2 IoT-Based Monitoring Systems

IoT-based systems can monitor vessel performance, fuel consumption, and emissions, enabling operators to optimize maritime operations. These tools provide actionable insights for reducing emissions and improving fuel performance (Sadiq et al., 2025).

3.3 Predictive Analytics and AI Applications

Predictive maintenance powered by artificial intelligence and machine learning can enhance operational efficiency and reliability (Sadiq et al., 2025).

3.3a Big Data Analytics and Machine Learning for Fuel Efficiency

The application of big data analytics (BDA) and machine learning (ML) to maritime operations represents a key Fourth Industrial Revolution technology for achieving fuel efficiency and emission reduction. Harbour craft vessels (HCV)—including tugboats, patrol vessels, and ferries—present particular opportunities for ML-driven efficiency improvements, with Singapore allocating dedicated funding for harbour craft digitalisation initiatives (Tay et al., 2021).

Digitalization Framework:

ML with BDA for fuel efficiency involves four interconnected components: telemetry (sensors and data acquisition), vessel monitoring systems (continuous operational condition monitoring), network middleware (data communication and management), and the ML/BDA system itself. The analytical process operates in two stages: Stage 1 (Descriptive Analytics) establishes patterns and correlations between the Energy Efficiency Index (EEI), vessel speed, displacement, fuel consumption, and environmental conditions; Stage 2 (Predictive/Prescriptive Analytics) predicts vessel behaviour under different scenarios and provides decision support for optimised speed and route selection (Tay et al., 2021).

Energy Efficiency Index:

Ship energy efficiency can be measured through the Energy Efficiency Index (EEI):

$$EEI = \frac{\Delta^{2/3} \cdot V^3}{FC}$$

Where Δ represents ship displacement, V the vessel speed, and FC the fuel consumption. For harbour craft vessels where draft and trim variations are minimal due to vessel scale, speed adjustment represents the primary parameter for improving EEI (Tay et al., 2021).

Data Acquisition Technologies:

Accurate fuel consumption measurement requires Coriolis mass flowmeters—made mandatory by Singapore Maritime Port Authority from 1 July 2019—which achieve measurement accuracy of ±0.2% with no moving parts and built-in temperature, pressure, and density sensors. Complementary sensors include ultrasonic wind sensors (real-time wind speed and direction without moving parts), acoustic Doppler profilers (current flow measurement), and driveshaft RPM sensors for categorising operational activities (Tay et al., 2021).

Table 47 Data Filtering Techniques for Maritime Operational Data

Method	Advantages	Limitations
Control Chart Technique (CCT)	Intuitive, preserves time information	Only for normally distributed data without noise
Haar Wavelet Transform (HWT)	Computationally efficient, handles sudden transitions	Shift sensitivity, lacks phase information
Fast Fourier Transform (FFT)	Filters varying frequencies, converts discrete to continuous	Loses time information, computationally expensive
Kalman Filter (KF)	Preserves time information, fast, light on memory	Requires known initial state probability function

Machine Learning Model Performance:

Comparative analysis of ML techniques for fuel consumption prediction reveals significant performance differences:

Table 48 Machine Learning Model Performance Comparison (R Values)

Model Type	Configuration	R Value	Computation Time
ANN (Exponential sigmoid)	7-4-5-1	0.9636	0.52 s
ANN (Tangent sigmoid)	—	0.9383	0.46 s
ANN (ReLU)	—	0.8790	0.54 s
Support Vector (Quadratic)	—	0.4810	380.99 s
Regression (Full Quadratic)	—	0.3582	0.24 s
LSTM Combined	—	~1.0	—

The Artificial Neural Network (ANN) model with exponential sigmoid activation achieves the highest accuracy among single-model approaches, with R values exceeding 0.96. However, the Long Short-Term Memory (LSTM) model—particularly when combined with autoencoder ensemble learning—outperforms conventional methods when handling time-series data with missing values, achieving R^2 approaching 1.0. A critical finding indicates that data pre-processing is more important than hyperparameter tuning for improving prediction accuracy (Tay et al., 2021).

Grey Box Model Approach:

When limited historical operational data is available, the Grey Box Model (GBM)—a hybrid of white-box (simulated) and black-box (historical) models—provides improved prediction accuracy. By incorporating domain knowledge of vessel characteristics through simulated ship resistance data alongside historical operational records, GBM achieves comparable precision to black-box models whilst reducing data requirements significantly. This approach proves particularly valuable during early-stage digitalisation when historical datasets remain limited (Tay et al., 2021).

Quantified Digitalization Benefits:

The economic and environmental benefits of BDA and ML implementation are substantial:

- Predictive maintenance reduces unexpected failures by 55%
- Maintenance costs reduced by estimated 25–30%
- 10–35% more cost-effective operations through optimised fuel consumption
- Maersk reported 13% fuel consumption reduction through BDA implementation (Tay et al., 2021)

These findings underscore the dual benefits of digitalisation: operational cost reduction and environmental impact mitigation through improved fuel efficiency and reduced emissions.

Implementation Challenges:

Despite the significant benefits, maritime digitalisation faces substantial implementation barriers:

Data Acquisition Challenges: - High capital, operation, and maintenance costs for sensor systems - Installation must accommodate busy operational schedules of harbour craft vessels - Intermittent sensor malfunctions may occur without warning signals - Inclement marine weather conditions limit onshore troubleshooting opportunities - Research experiments on vessels may interfere with commercial operations (Tay et al., 2021)

Data Transmission Challenges: - Vessels frequently operate outside shore station coverage - Unstable network connections in offshore areas - Large file synchronisation issues between vessel and shore systems - Potential for duplicate data and time lapse between machines - Reliance on costly satellite communications for offshore operations (Tay et al., 2021)

Cyber Security Concerns: The conventional approach to ship cyber-security—keeping systems isolated from Internet and intranets—is challenged by digitalisation requirements. Cyber-attack vulnerabilities include potential triggering of ecological disasters through remotely-controlled discharge valves, or malicious GPS signal manipulation causing groundings or accidents.

Companies must invest substantially in cyber security infrastructure, as incidents could severely undermine environmental protection efforts (Tay et al., 2021).

Fourth Industrial Revolution Context:

The shipping industry has evolved through successive industrial revolutions—from steam engines in the First, electrical and combustion engines in the Second, digital transformation in the Third—and now enters the Fourth Industrial Revolution focusing on smart shipping through IoT integration, intelligent systems, and innovative solutions. Major industry players including Rolls-Royce and Wärtsilä have established research centres exploring remote and autonomous shipping, though overall digitalisation adoption remains slower than in other industries (Tay et al., 2021).

3.3b AI Technology Taxonomy in Maritime Engineering

Systematic review of AI applications in ocean and maritime engineering reveals a diverse ecosystem of techniques deployed across seven principal application domains. A comprehensive analysis of 270 research papers following PRISMA guidelines identifies distinct methodological clusters and their evolution from early applications in the 2000s to the current state-of-the-art (Portillo Juan et al., 2025).

AI Technique Classification:

Five principal AI technique categories dominate maritime applications, each with distinct characteristics and optimal use cases:

Table 49 AI Technique Categories for Maritime Applications

Category	Key Techniques	Primary Applications
Optimization Algorithms	GA, GP, PSO, ACO, HS, FMM	Route planning, feature selection, path optimization
Supervised Learning	ANNs, SVM, SVR, LR, RF, GMDH	Wave prediction, structural analysis, regression
Unsupervised Learning	K-Means, Spectral Clustering, HMM	Traffic classification, state transitions
Reinforcement Learning	Q-Learning, Deep RL, Policy Gradient	Autonomous control, collision avoidance, real-time decisions
Fuzzy Logic	FL, ANFIS	Uncertainty handling, hybrid systems

GA = Genetic Algorithm; GP = Genetic Programming; PSO = Particle Swarm Optimization; ACO = Ant Colony Optimization; HS = Harmony Search; FMM

= Fast Marching Method; GMDH = Group Method of Data Handling; HMM = Hidden Markov Models; ANFIS = Adaptive Neuro-Fuzzy Inference System

Neural Network Architectures:

Different neural network architectures demonstrate varying suitability for maritime applications:

Table 50 Neural Network Types and Maritime Suitability

Network Type	Architecture Characteristics	Best Applications	Performance Notes
FFNN	Simple, shallow, forward-only	Wave characterization	Limited data scenarios
RBF	Basis function combination	Non-linear relationships	Complex input-output
CNN	Convolutional layers	Flood mapping, beaches	Spatial feature extraction
RNN	Internal loops, delayed activation	Short-term forecasting	Time-series, noisy data
LSTM	Long/short-term memory cells	Long-term prediction	Best for delays
Transformers	Self-attention mechanisms	Global temporal relationships	Emerging state-of-the-art

Publication Growth and Adoption Trends:

AI adoption in maritime engineering has experienced exponential growth, particularly since 2018:

Table 51 AI Publication Growth in Maritime Engineering (2010-2022)

Period	Publications/ Year	Growth Factor	Key Developments
2010-2013	~20	Baseline	Initial adoption
2015-2017	~50	2.5×	Growing interest
2018	179	3.6×	Tipping point—computational maturity
2019	395	2.2×	Smart ships emergence
2020	535	1.4×	Continued expansion
2021	672	1.3×	Deep learning dominance
2022	1329	2.0×	Exponential growth (6.6× vs 2018)

The inflection point around 2018 reflects convergence of three factors: computational power reaching feasibility thresholds for complex deep learning, emergence of smart and autonomous ship technologies requiring adaptive AI models, and increased availability of maritime operational data through sensor networks and satellite systems (Portillo Juan et al., 2025).

Application Domain Distribution:

The distribution of AI research across maritime application domains reveals both established areas and underexplored opportunities:

Table 52 Maritime AI Application Domains by Research Volume

Application Domain	Studies	Dominant Techniques	Development Stage
Vehicle control & route optimization	82	RL, OA, ANNs	Most advanced (post-2018)
Ships & underwater vehicles	46	SVM, ANNs, UL, OA	Diverse and mature
Wave climate characterization	31	ANNs (in 25/26 studies)	Pioneer field (since 2000s)
Nature-based studies & energy	31	ANNs, RL, RF, GPR	Transformers emerging
Beach & flooding studies	30	CNNs, RF, Deep Learning	Image-based methods
Fault detection	28	LSTM, CNN, SVM	Emerging (since 2015)
Structural studies	22	GP, GA, ANFIS, SVM	Most underexplored

Vehicle control and route optimization dominates recent research activity, driven by autonomous vessel development requirements. Wave climate characterization represents the pioneering subfield where AI techniques were first applied in the 2000s, establishing methodological foundations for subsequent expansion (Portillo Juan et al., 2025).

Reinforcement Learning Transformation:

The most significant methodological development is the transformative impact of Reinforcement Learning (RL) on maritime applications. Unlike supervised learning that requires predefined input-output mappings, RL enables systems to learn through trial-and-error interactions with dynamic environments—essential for ship control and navigation operating in constantly changing marine conditions: “The advantage of RL over SL techniques is its ability to interact with a dynamic environment, which allows learning from it. Ship control and navigation systems, operating in an ever-changing environment, require AI techniques capable of dynamic interaction and information assimilation, making RL a fitting choice" (Portillo Juan et al., 2025).

Research Gaps:

The systematic review identifies significant underexplored areas. Structural studies remain the least developed subfield due to challenges including high-dimensional design spaces, nonlinear fluid-structure interactions, and uncertain boundary conditions. Hybrid AI models combining optimization algorithms with deep learning present a promising solution: "Optimization techniques help navigate large solution spaces efficiently, while deep learning models can capture complex physical behaviours from simulation or experimental data" (Portillo Juan et al., 2025).

3.4 Real-Time Emission Monitoring

[Content to be added with additional sources]

3.5 Marine Autonomous Surface Ships (MASS)

The maritime industry is undergoing a transformation in which automation and digitalisation play a critical role in achieving environmental sustainability. Marine Autonomous Surface Ships (MASS) are viewed as a potential game-changer, facilitating new business models for goods and passenger transport whilst providing services to harbour and offshore industries (Palaniappan & Vedachalam, 2022).

Significant technological milestones have been achieved in MASS development:

Table 53 Marine Autonomous Surface Ship Development Milestones

Year	Project/Vessel	Achievement
2012-2015	MUNIN (EU)	Unmanned/autonomous vessel technology development
2017	Sisu (Rolls-Royce/ Svitzer)	First remotely operated commercial vessel
2018	Falco (Rolls-Royce/ Finferries)	First fully autonomous ferry demonstration
2018	IMO MSC	Approved MASS regulatory scoping framework
2019	IMO MSC	Interim guidelines for MASS trials
2021	IMO MSC	Regulatory scoping exercise outcome approved
2022	Yara Birkeland	All-electric autonomous container ship (80m, 7 MWh, 120 TEU)

The Yara Birkeland represents a landmark in autonomous shipping, designed as an all-electric container vessel with operational specifications of 6 knots service speed, 12 knots maximum speed, and 120 TEU cargo capacity. The vessel demonstrates the convergence of zero-emission propulsion and autonomous operation technologies (Palaniappan & Vedachalam, 2022).

Regulatory development has progressed in parallel with technological advancement. The IMO's Maritime Safety Committee has established a framework and methodology for regulatory scoping exercises on MASS, addressing human elements, safety, security, liability, compensation for damage, port interactions, pilotage, incident response, and marine environmental protection. Classification by Lloyd's Register, Bureau Veritas, the Norwegian Forum for Autonomous Ships (NFAS), and other agencies considers three dimensions: the degree of advanced functions, the location where supporting functions are provided, and the degree of human involvement (Palaniappan & Vedachalam, 2022).

Artificial intelligence with continuous machine learning for situation awareness and collision avoidance represents a critical enabling technology for commercial MASS deployment. Computer systems that partially or fully replace human operators must demonstrate total compliance with existing international regulations including the International Regulations for Preventing Collisions at Sea (COLREGS). The integration of multiple technologies—route planning, route sharing, situational awareness sharing, dynamic risk assessment, and risk-based navigation—is required to achieve comprehensive autonomous operation across normal and abnormal scenarios. Based on current development trajectories and strategic plans proposed by multiple agencies, the global ecosystem favours deployment of commercially viable MASS by 2025 (Palaniappan & Vedachalam, 2022).

3.5a AI Navigation Decision-Support Systems

Autonomous shipping systems require sophisticated navigation decision-support capabilities that ensure compliance with international maritime regulations while enhancing operational safety. The NAVDEC (NAVigation DECision support system) represents the world's first comprehensive navigation tool combining informational functions with decision-support capabilities, developed at the Maritime University of Szczecin and commercialised by Sup4Nav (Durlik et al., 2024).

System Capabilities:

Unlike conventional navigation systems that merely provide situational awareness, NAVDEC integrates knowledge of the International Regulations for Preventing Collisions at Sea (COLREGS), best seamanship practices, and criteria used by experienced navigators. The system operates in real-time, observing the vessel and surrounding environment, identifying and assessing navigational situations, and developing solutions to ensure safe navigation (Durlik et al., 2024).

Table 54 NAVDEC System Functional Capabilities

Function	Description	Benefit
Situation identification	Classifies encounter situations per COLREG	Standardised regulatory interpretation
Right-of-way determination	Identifies which vessel has priority	Reduces decision ambiguity
Maneuver recommendation	Proposes course/speed adjustments	Evidence-based collision avoidance
Alternative solutions	Provides range of compliant options	Operational flexibility
Rationale provision	Explains reasoning for proposed actions	Decision transparency and crew confidence

The system analyses navigational situations concerning all nearby vessels within a configurable radius (default 8 nautical miles), classifying each encounter according to COLREG provisions and determining appropriate responses. When collision scenarios are identified, NAVDEC calculates safe maneuvers including timing and parameters, presenting both primary recommendations and alternative regulation-compliant options (Durlik et al., 2024).

Industry Adoption:

NAVDEC has achieved commercial deployment across multiple European shipping companies, demonstrating practical viability:

Table 55 NAVDEC Commercial Deployments

Shipowner	Fleet Type	Deployment Status
Unity Line	Ferry operations	Operational
Polska Żegluga Morska (PŻM)	Mixed cargo	Operational
Euroafrica	General cargo	Operational
Unibaltic	Shipping services	Operational
Polferries	Ferry operations	Operational

The integration of AI navigation systems with port operations represents a future development pathway. Autonomous ships communicating with port authorities could streamline docking and cargo-handling processes, reducing waiting times and improving operational efficiency. This coordination capability remains largely theoretical but represents significant potential for comprehensive autonomous maritime logistics (Durlik et al., 2024).

Collision Avoidance Evolution:

The future development trajectory for AI anti-collision systems includes potential ship-to-ship communication protocols for intention-sharing regarding collision avoidance maneuvers, and remote human oversight models where shore-based operators supervise AI-managed vessel navigation. Both approaches seek to balance autonomous decision-making efficiency with appropriate levels of human oversight for safety-critical operations (Durlik et al., 2024).

3.6 Competitive Dynamics of Digital Technology Adoption

The strategic decision to invest in digital technologies for emission reduction creates complex competitive dynamics among shipping companies. Game-theoretic analysis reveals that technology adoption decisions are interdependent, with outcomes depending not only on a firm's own investment choices but critically on competitors' responses (Wu et al., 2025).

Digital Technology Impact Pathways:

Digital technologies contribute to decarbonisation through multiple mechanisms: route optimisation algorithms reduce fuel consumption and transit times, delivering lower CO_2 per voyage; digital platform coordination minimises waiting times and port congestion, decreasing auxiliary engine emissions; IoT-based monitoring provides real-time energy consumption feedback enabling optimised operating parameters; and blockchain documentation eliminates paper-based delays, reducing supply chain emissions (Wu et al., 2025).

Quantitative modelling indicates digital technology adoption can achieve 40% reduction in transit time and 50% reduction in carbon emissions compared to traditional operations. However, the magnitude of competitive advantage depends critically on cost structures: when unit operating costs and installation costs remain below critical thresholds, digital adoption conveys significant market share gains; above these thresholds, the economic case for adoption weakens substantially (Wu et al., 2025).

Industry Milestone Events:

Recent developments illustrate the acceleration of digitalisation across the shipping value chain:

Table 56 Recent Maritime Digitalisation Industry Milestones

Date	Development	Significance
November 2021	SMASH Dutch smart shipping roadmap	Defined 5 application scenarios, 10 R&D priority areas
November 2023	ZeroNorth acquisitions (Clearlynx, Prosmar Bunkering, BTS)	Integrated shipping fuel value chain digitalisation
March 2024	Hapag-Lloyd partnership with Ankeri	Digital fleet data infrastructure for optimisation
March 2024	Neptune Robotics hull cleaning services	Reduced navigation resistance, fuel consumption
February 2025	PG Ship Management + SDARI carbon monitoring	Fleet-wide emission tracking from data entry

These deployments demonstrate that digitalisation extends beyond individual vessel efficiency to encompass fleet-wide coordination, fuel supply chain management, and regulatory compliance monitoring (Wu et al., 2025).

Winner-Takes-All Dynamics:

When technology costs are favourable, first-mover advantages emerge strongly. The technologically advanced firm captures market share through superior service quality (faster transit, lower emissions), while competitors face declining profitability. This "winner-takes-all" phenomenon creates incentives for pre-emptive investment but also risks regarding technology lock-in and stranded assets if cost assumptions prove incorrect (Wu et al., 2025).

Addressing these competitive dynamics requires coordinated approaches that balance competitive incentives with collective decarbonisation objectives. Mandatory data-sharing platforms, industry consortia for infrastructure development, and green shipping corridor initiatives represent governance mechanisms capable of transforming competitive technology races into collaborative transitions.

3.7 Blockchain Technology in Transportation and Maritime Logistics

Blockchain technology represents a cornerstone of Industry 4.0 transformation in transportation systems, offering fundamental capabilities that address long-standing inefficiencies in logistics networks. By digitizing trust and enabling secure data sharing among untrusted parties, blockchain addresses critical issues including tampered records, delayed payments, and inadequate tracking that have historically plagued maritime supply chains (Neumannová & Repková Štofková, 2026).

3.7.1 Blockchain Core Characteristics and Transportation Applications

Blockchain's suitability for transportation stems from three fundamental characteristics: decentralization eliminates single points of control and reduces data manipulation risks; transparency enables all authorized participants to access shared ledger information, fostering trust and accountability; and immutability ensures recorded data cannot be altered, creating tamper-proof transaction records (Neumannová & Repková Štofková, 2026).

Table 57 Blockchain Core Characteristics and Transportation Benefits

Characteristic	Description	Transportation Benefit
Decentralization	Operates on distributed network without single controlling authority	Reduces data manipulation risk, democratic data management
Transparency	All authorized participants access shared ledger	Fosters trust and accountability among stakeholders
Immutability	Recorded data cannot be altered or deleted	Ensures integrity and reliability of transaction records

These features make blockchain particularly suitable for addressing transportation sector challenges. The technology enhances transparency across logistics networks, automates processes through smart contracts, and ensures traceability and authenticity of shipments. Smart contracts—self-executing agreements with predefined conditions—automatically release payments upon delivery confirmation, reducing delays and eliminating intermediaries (Neumannová & Repková Štofková, 2026).

3.7.2 Industry Case Studies and Implementation Results

Real-world implementations demonstrate blockchain's transformative potential across diverse transportation contexts, though they also reveal the challenges of achieving widespread adoption.

Table 58 Blockchain Implementation Case Studies in Transportation

Organization	Application	Results/Outcomes
Walmart	Food supply chain traceability	Contaminated produce trace time reduced from 7 days to 2.2 seconds
TradeLens (Maersk-IBM)	Shipping industry digitization	Real-time shipping data access; discontinued 2023 due to insufficient global adoption
DHL	IoT temperature monitoring	Real-time monitoring for pharmaceuticals/food; regulatory compliance; spoilage reduction
FedEx	Smart contracts for disputes	Automated dispute resolution; eliminated lengthy verification processes

The Walmart implementation represents a landmark achievement, demonstrating that blockchain integration can reduce tracing time for contaminated produce origins from approximately seven days to just 2.2 seconds, significantly enhancing food safety and transparency. Conversely, the TradeLens discontinuation in 2023 illustrates that even well-resourced initiatives require broad industry participation to achieve network effects necessary for platform viability (Neumannová & Repková Štofková, 2026).

3.7.3 Blockchain-IoT-AI Integration Synergies

When combined with Internet of Things (IoT) sensors and Artificial Intelligence (AI) analytics, blockchain unlocks advanced capabilities enabling predictive decision-making and creating smarter, more adaptive transportation networks. IoT devices collect real-time shipment data including temperature, location, and condition; blockchain provides secure, immutable storage ensuring data integrity; and AI algorithms optimize routes and predict disruptions (Neumannová & Repková Štofková, 2026).

This integration represents particular value for cold chain logistics in maritime shipping, where DHL has deployed IoT sensors to monitor temperature of sensitive goods such as pharmaceuticals and food products. The blockchain layer ensures data cannot be retroactively altered, providing verifiable compliance records for regulatory purposes and reducing spoilage through real-time alerts (Neumannová & Repková Štofková, 2026).

3.7.4 Implementation Challenges and Adoption Strategies

Despite transformative potential, blockchain adoption in transportation faces significant barriers requiring strategic approaches to overcome.

Key Implementation Challenges: - **High Costs:** Infrastructure requirements and training costs create barriers particularly for small and medium enterprises - **Scalability:** Transportation networks generate vast data volumes that can overwhelm blockchain platforms, causing inefficiencies - **Regulatory Barriers:** Inconsistent regulations across jurisdictions complicate global logistics operations - **Resistance to Change:** Stakeholder reluctance slows integration into existing systems (Neumannová & Repková Štofková, 2026)

Strategic Adoption Framework: - **Pilot Projects:** Small-scale implementations assess feasibility and return on investment before large-scale adoption - **Stakeholder Collaboration:** Engagement with regulators, industry leaders, and technology providers fosters standardized frameworks - **Phased Implementation:** Gradual integration minimizes disruption and builds stakeholder confidence - **Educational Initiatives:** Training programs and awareness campaigns address resistance and demonstrate blockchain value (Neumannová & Repková Štofková, 2026)

3.7.5 Blockchain Contributions to Maritime Sustainability

Blockchain supports sustainability objectives by optimizing logistics operations, reducing waste, and lowering emissions. End-to-end visibility ensures compliance with environmental regulations and encourages eco-friendly practices. Specific applications include carbon footprint monitoring, energy consumption tracking, resource usage optimization, and route optimization for fuel consumption reduction (Neumannová & Repková Štofková, 2026).

The technology's ability to enhance transparency, streamline processes, and promote sustainable practices establishes it as a cornerstone for the future of logistics within Industry 4.0 paradigms. As transportation systems evolve toward Industry 5.0 with its emphasis on human-machine collaboration and resilient supply chains, blockchain provides foundational infrastructure for trusted, automated, and environmentally responsible operations (Neumannová & Repková Štofková, 2026).

3.7.6 Blockchain Limitations and Comparison with Centralized Systems

Despite blockchain's transformative potential, critical assessments reveal significant limitations that warrant consideration before large-scale maritime deployment. Blockchain technology remains at an early experimental stage in the maritime sector, with research primarily based on qualitative analysis lacking concrete quantitative validation. Key obstacles include insufficient high-level support, weak coordination mechanisms, absence of trust frameworks, and high implementation costs (Xu & Chen, 2025).

The scalability of blockchain systems is significantly constrained by energy-intensive consensus mechanisms such as Proof of Work (PoW). Even when adopting lightweight protocols such as Proof of Stake (PoS) or Proof of Authority (PoA), inherent trade-offs persist between scalability, security, and decentralisation. Critically, while blockchain applications in shipping may increase transparency, they are outperformed by centralised systems such as the IMO Data Collection System (IMO DCS) regarding regulatory efficiency, system maturity, and scalability (Xu & Chen, 2025).

Table 59 Blockchain vs. Centralized Systems for Maritime Applications

Criterion	Blockchain Systems	Centralized Systems (e.g., IMO DCS)
Regulatory efficiency	Lower	Higher
System maturity	Early experimental	Mature, operational
Scalability	Constrained by consensus	Well-established
Transparency	High (distributed ledger)	Moderate (single authority)
Energy consumption	High (PoW) or moderate (PoS)	Low
Implementation cost	High	Lower

Future research directions include effective integration of lightweight consensus mechanisms with maritime regulatory frameworks and construction of trustworthy multi-party data sharing platforms to support port carbon footprint monitoring and low-carbon trade settlement (Xu & Chen, 2025).

3.8 Sixth Generation Ports and Future Port Evolution

With ports increasingly developing into highly energy-intensive hubs, the sixth generation port (6GP) model has emerged as an integrated framework addressing digital transformation, low-carbon development, and system resilience. The 6GP concept emphasises integration of intelligent technologies with green infrastructure, platform-based collaboration, governance capacity enhancement, and comprehensive system resilience (Xu & Chen, 2025).

6GP represents a fundamental reconfiguration of comprehensive governance logic rather than merely a functional upgrade from fifth-generation ports (5GP). Integrated technologies—artificial intelligence, blockchain, Internet of Things, and cloud systems—form the foundation for resilient logistics networks and sustainable operational mechanisms. The transition from 5GP to 6GP requires institutional coordination between centralised governance and diverse regional demands, representing a critical issue for future port policymaking (Xu & Chen, 2025).

Table 60 Sixth Generation Port (6GP) Characteristics

Dimension	6GP Features
Technology Integration	AI, blockchain, IoT, cloud systems
Green Infrastructure	Renewable energy, low-carbon operations
Platform Collaboration	Multi-stakeholder digital coordination
Governance Capacity	Enhanced adaptive management
System Resilience	Crisis response, supply chain adaptability

In major Chinese container ports, the 6GP model has demonstrated initial success in enhancing intelligence levels, improving green operational performance, and boosting regional coordination efficiency. The COVID-19 pandemic accelerated convergence of digitalisation and low-carbon initiatives, exposing weaknesses in existing port system resilience while establishing urgency for frameworks capable of addressing external uncertainties (Xu & Chen, 2025).

3.9 AI and Machine Learning Research Trends in Maritime Power Systems

Bibliographic analysis of AI and ML applications in maritime power systems reveals significant evolution in research focus and geographic distribution. Analysis of IEEE Transactions on Industry Applications publications (1990-2025) identifies 121 relevant papers, with publication rates surging dramatically after 2015—reflecting growing recognition of AI's potential for fuel efficiency enhancement, autonomous vessel operations, and renewable energy integration (Sadiq et al., 2025b).

Table 61 AI/ML Maritime Research Publication Trends

Period	Research Activity	Key Development
Pre-2015	Limited publications	AI/ML not central to maritime energy systems
2015-2023	Significant expansion	Growing focus on fuel optimization, energy management
2024	Peak output	Maximum research publications
2025+	Sustained growth	Continued trajectory expected

Research contributions demonstrate distinct international patterns, with the United States, Germany, and China leading in AI-driven maritime technology development. European nations including the United Kingdom, France, and Italy contribute significantly, whilst Taiwan has emerged as a notable contributor focusing on hybrid maritime systems and AI-based optimisation models for renewable energy integration and propulsion efficiency (Sadiq et al., 2025b).

Table 62 AI Application Domains in Maritime Power Systems

Application Domain	AI/ML Technique	Documented Benefit
Fuel consumption optimization	Predictive analytics, advanced control	Significant reduction in hybrid systems
Port microgrid management	Deep Reinforcement Learning (DRL)	Enhanced renewable energy integration
Cybersecurity	AI-powered detection systems	Improved resilience of maritime infrastructure
EV charging at ports	Stochastic optimization	Better grid balancing, sustainable operations
Predictive maintenance	Digital twin technology	Reduced downtime and maintenance costs
Microgrid scheduling	AI-driven algorithms	Enhanced energy sustainability and efficiency

Keyword co-occurrence analysis reveals distinct research clusters: a primary cluster centred on AI and ML advancing fuel optimisation, autonomous navigation, and energy management; a secondary cluster highlighting renewable energy and sustainable maritime operations; and interdisciplinary connections with smart grid technologies addressing energy efficiency and decarbonisation convergence (Sadiq et al., 2025b).

Future research directions emphasise development of robust AI algorithms for real-time operational optimisation under unpredictable conditions (severe weather), improved integration of hybrid energy systems, and advancement of AI-based smart port technologies. Critical challenges include adapting AI-driven systems to variable maritime conditions, addressing legal and regulatory concerns regarding AI decision liability, mitigating increased cybersecurity risks from embedded AI systems, and developing fault-tolerant AI capable of maintaining accuracy despite data quality inconsistencies (Sadiq et al., 2025b).

3.10 AI Implementation Challenges and Industry Opportunities

Despite demonstrated benefits, AI adoption in the maritime industry faces systemic barriers that require coordinated responses from industry stakeholders, technology providers, and regulatory bodies. Conversely, emerging technological capabilities and collaborative frameworks present significant opportunities for accelerating sustainable maritime transformation (Durlik et al., 2024).

Implementation Barriers:

Table 63 Barriers to AI Adoption in Maritime Industry

Challenge Category	Description	Impact
High implementation costs	Significant investment required for AI infrastructure, sensors, data storage, computing power, and skilled personnel	Deters small-to-medium enterprises; slows adoption rate
Legacy system integration	Many maritime operations depend on outdated systems incompatible with modern AI technologies	Requires substantial technical overhaul and investment
Data quality and availability	Data often fragmented, inconsistent, and unavailable due to remote and diverse nature of maritime operations	Affects AI accuracy and system effectiveness
Connectivity issues	Remote maritime operations have limited connectivity affecting real-time data transmission	Hinders deployment of AI requiring continuous data processing
Data privacy and security	Handling of sensitive operational and proprietary data requires robust protection	Compliance complexity; cyberattack vulnerability
Skilled personnel shortage	Lack of professionals with expertise in AI, data science, and machine learning	Limits deployment and maintenance capabilities

Challenge Category	Description	Impact
Regulatory complexity	Variability in international regulations and lack of AI technology standardisation	Increases compliance burden; interoperability challenges
Resistance to change	Cultural hesitancy regarding job displacement and technology uncertainty	Delays adoption; reduces implementation effectiveness

The reliance on legacy systems represents a particularly significant barrier. Maritime operations frequently depend on equipment and software designed decades ago, creating substantial technical debt when integrating modern AI capabilities. The high costs associated with both hardware upgrades and organisational change management can deter adoption, particularly among smaller operators lacking economies of scale (Durlik et al., 2024).

Industry Opportunities:

Table 64 Opportunities for AI Adoption in Maritime Industry

Opportunity Area	Description	Potential Impact
Advanced ML algorithms	Enhanced prediction and decision-making through deep learning, reinforcement learning, neural networks	Optimised operations, improved safety margins
IoT integration	Real-time data from ships, ports, and cargo containers enabling interconnected systems	Comprehensive operational visibility; predictive capabilities
Edge computing	Local data processing addressing connectivity limitations	Real-time decision-making in remote environments
Green technology enablement	AI-driven optimisation of alternative fuels, hybrid propulsion systems	Accelerated decarbonisation; regulatory compliance
Circular economy support	AI-optimised resource use, waste management, and material recycling	Environmental sustainability; economic efficiency
Long-term cost savings	Significant reduction in operational expenses through efficiency gains	Compelling ROI case for investment
Industry collaboration	Shared knowledge, best practices, and standards through public-private partnerships	Accelerated technology maturation and deployment

Edge computing presents particular promise for addressing connectivity challenges. By processing data locally on vessels or at port facilities rather than relying on continuous cloud connectivity, edge computing enables real-time AI decision-making even in remote maritime environments. This architectural approach enhances reliability while reducing dependency on potentially expensive satellite communications (Durlik et al., 2024).

Case Study Evidence:

Industry case studies demonstrate measurable returns from AI implementation:

- **Maersk Line:** AI-driven fuel optimisation and predictive maintenance achieved reduced fuel consumption, lowered CO_2 emissions, and improved maintenance practices across the fleet
- **Port of Rotterdam:** AI-powered air and water quality monitoring enabled enhanced environmental monitoring, rapid response to pollution events, and improved regulatory compliance (Durlik et al., 2024)

Collaborative Pathways:

Maximising AI opportunities requires coordinated stakeholder collaboration encompassing shipping companies, port operators, technology providers, and regulatory bodies. Essential mechanisms include:

- Public-private partnerships facilitating funding, research, and development
- Government incentives (tax breaks, grants) offsetting high initial implementation costs
- Industry consortia driving standardisation and best-practice sharing
- Academic partnerships building skilled workforce capabilities
- International regulatory harmonisation reducing compliance complexity (Durlik et al., 2024)

The convergence of declining technology costs, maturing AI capabilities, and increasing regulatory pressure for decarbonisation creates favourable conditions for accelerated AI adoption. First-mover advantages may emerge for organisations that establish AI competencies early, positioning them to capture efficiency gains and meet tightening environmental requirements while competitors face catch-up investments.

CHAPTER 4

Regional Perspectives and Case Studies

4.1 Global Research Landscape

Bibliographic analysis reveals significant regional disparities in maritime decarbonization research, with developed regions leading and limited contributions from developing nations (Sadiq et al., 2025).

Research Output by Region:

Table 65 Maritime Decarbonisation Research Output by Region

Country/Region	Publications
United States	88
China	50
Australia	27
European Union (Germany, Norway, Netherlands)	Leading contributors

4.1a Bibliometric Mapping of Decarbonisation Technologies

Systematic bibliometric analysis of 210 papers published between 2011 and 2024 reveals the thematic structure of maritime decarbonisation research. Using VOSviewer clustering analysis, seven distinct research themes emerge, reflecting the multifaceted nature of technological approaches to reducing shipping emissions (Tran et al., 2025):

Table 66 Thematic Clusters in Maritime Decarbonisation Research (2011-2024)

Cluster	Research Theme	Key Finding
A	LNG and ammonia fuels	Growing since 2019; 10 papers in 2024; ammonia emerging post-2019
B	Electricity and hybrid systems	19 papers concentrated 2019-2023
C	Renewable energy applications	Emerging cluster with growth since 2021
D	Engine efficiency optimisation	Established theme focusing on fuel consumption
E	System integration	Bridge cluster connecting multiple themes
F	Carbon capture and storage	12 papers with attention since 2021
G	Ship-network optimisation	Largest cluster (50 papers): speed and route optimisation

Technology Distribution in Published Research:

Table 67 Distribution of Decarbonisation Technologies in Scopus Literature

Technology Category	Papers	Percentage
Alternative Fuels	86	40.95%
Mixed Methods	46	21.90%
Ship Design	26	12.38%
Ship-Network Optimisation	19	9.05%
Carbon Capture	12	5.71%
Ship Engine Optimisation	11	5.24%
Renewable Energy	10	4.76%

The dominance of alternative fuels research—accounting for more than two-fifths of the literature—reflects industry and regulatory prioritisation of fuel pathway transitions. The relatively modest attention to carbon capture (5.71%) and renewable energy integration (4.76%) suggests potential underexplored research areas (Tran et al., 2025).

Leading Contributing Countries:

Table 68 Top Contributing Countries to Maritime Decarbonisation Research

Rank	Country	Publications
1	China	45
2	Italy	15
3	United Kingdom	15
4	Norway	13
5	Germany	11

China's leadership in publication output reflects substantial government investment in maritime technology research and the scale of its shipbuilding and shipping industries. European countries collectively represent a significant research cluster, driven by ambitious regulatory frameworks and funding programmes such as Horizon Europe.

Research Gap Identification:

The bibliometric analysis identifies a critical underexplored research area: "While novel technologies like AI and blockchain have been integrated into various sectors, there is a dearth of papers within the ship-network optimization domain that leverage AI or blockchain to optimize shipping routes" (Tran et al., 2025). This gap represents an opportunity for interdisciplinary research combining maritime operations with emerging digital technologies.

4.2 United States Initiatives

The United States leads global research output with 88 publications, driven by extensive federal funding, government-backed programs (e.g., U.S. Department of Energy hydrogen programs), and strong academia-industry collaboration (Sadiq et al., 2025).

4.2a Pacific Northwest to Alaska Green Shipping Corridor

The Pacific Northwest to Alaska Green Shipping Corridor represents the world's first cruise-focused GSC, spanning approximately 950 nautical miles through one of the most sensitive marine ecosystems in the Northern Hemisphere. This initiative addresses the disproportionate environmental impact of cruise operations along the route linking Vancouver, Seattle, Prince Rupert, and Juneau—ports serving the iconic Alaska cruise market (Dolatabadi et al., 2025).

Port Infrastructure and Shore Power Deployment:

The four corridor ports demonstrate varying levels of infrastructure readiness, with Vancouver and Seattle leading in shore power deployment while Prince Rupert and Juneau face infrastructural challenges:

Table 69 Pacific Northwest Corridor Port Shore Power Infrastructure

Port	Year Introduced	Capacity	2024 Utilization
Vancouver	2009	12–14 MW	80%
Seattle	2005	Up to 16 MW	66%
Prince Rupert	2023	7.5 MW (container)	N/A
Juneau	2001	7–11 MW	N/A

Vancouver became the third port globally and first in Canada to provide shore power for cruise vessels (2009), with two of three cruise jetties now equipped with up to 14 MW capacity. The port offers a 75% discount on harbour dues for vessels using shore power, contributing to cumulative GHG reductions of up to 45,000 tonnes since 2009. Seattle has established itself as a policy frontrunner, becoming the first US port to mandate 100% shore power use for homeported cruise ships, accelerating the original 2030 target to 2027. Juneau pioneered cruise ship shore power globally when it introduced the technology in 2001, though utilization data remains limited (Dolatabadi et al., 2025).

Cruise Traffic Concentration:

Cruise operations constitute a significant but varying share of port activity along the corridor:

Table 70 Pacific Northwest Corridor Cruise Traffic Share (2023)

Port	Total Port Calls	Cruise Calls	Cruise Share
Vancouver	5,296	333	13.9%
Seattle	4,108	361	30.7%
Prince Rupert	61 cruise calls	61	11.4%
Juneau	1,361	775	98.5%

Juneau's near-exclusive dependence on cruise traffic (98.5% of port calls) creates both concentrated environmental pressures and strong economic incentives for decarbonisation investments. The port welcomes over 1.5 million cruise passengers annually, positioning tourism as the dominant economic driver (Dolatabadi et al., 2025).

Port Emission Reduction Commitments:

Table 71 Pacific Northwest Port Emission Reduction Targets

Port	2030 Target	2050 Target
Vancouver	40% GHG intensity reduction (vs 2010)	Net-zero
Seattle	50% GHG reduction (vs 2007)	Carbon neutral
Prince Rupert	30% GHG intensity reduction (vs 2018)	Net-zero
Juneau	N/A	N/A

Seattle has adopted additional progressive targets including net-zero emissions from controlled and indirect sources by 2040, and zero-emission trucks and cargo equipment by 2035. Maritime emissions account for approximately 3.5% of Seattle's total GHG emissions (~180,000 metric tonnes in 2020) (Dolatabadi et al., 2025).

Cross-Border Regulatory Challenges:

The corridor's spanning of US-Canada jurisdiction creates regulatory harmonisation challenges. Canada maintains a national carbon pricing mechanism while the United States lacks equivalent federal frameworks, resulting in state-led maritime decarbonisation approaches that vary by region. Vancouver operates under voluntary incentive systems for shore power, whilst Seattle has enacted mandatory requirements. Different emission reporting standards and absence of standardised alternative fuel benchmarks across jurisdictions complicate coordinated corridor development. The Inflation Reduction Act (US) and Low Carbon Fuel Standard (Canada) provide disparate financial incentive structures for green fuel adoption (Dolatabadi et al., 2025).

Green Fuel Infrastructure Development:

Prince Rupert's strategic advantages position it as a potential renewable fuel hub for the corridor. The port benefits from the deepest natural harbour in North America and 500 nautical miles shorter voyage time to Asia compared to other Pacific Northwest ports. Planned green fuel production facilities in nearby Prince George include the Tumbler Ridge Methanol project (0.17 Mt green plus 1.58 Mt blue methanol annually from 2028) and the Fortescue Coyote Project (140 kt hydrogen plus 700 kt ammonia annually). Direct rail connections between Prince George and Prince Rupert could enable efficient fuel distribution throughout the corridor (Dolatabadi et al., 2025).

However, alternative fuel bunkering infrastructure remains limited across the corridor. Vancouver and Seattle lack robust LNG and biofuel availability, while Prince Rupert and Juneau lack comprehensive bunkering capabilities. The seasonal concentration of cruise traffic—driven by the May-September Alaska cruise season—limits year-round fuel demand that could justify substantial infrastructure investments (Dolatabadi et al., 2025).

Strategic Assessment:

With appropriate strategic initiatives and investments, the Pacific Northwest to Alaska GSC has potential to serve as a global model for cruise-focused sustainable maritime transportation. Key success factors include policy harmonisation between Canadian and US jurisdictions, expansion of shore power infrastructure to achieve universal cruise berth coverage, development of green fuel bunkering capabilities leveraging Prince Rupert's strategic position, and collaborative stakeholder engagement encompassing cruise lines, port authorities, and environmental organisations (Dolatabadi et al., 2025).

4.3 European Union Strategies

EU countries benefit from funding programs like Horizon 2020 and Horizon Europe, enabling collaborative projects in hydrogen, renewable energy, and decarbonization technologies aligned with ambitious climate targets (Sadiq et al., 2025).

4.3.0 EU Maritime Policy Process and Stakeholder Dynamics

The development of EU maritime decarbonisation policy illustrates the complex interplay between institutional actors, industry interests, and civil society advocacy. Analysis of the FuelEU Maritime legislative process reveals two competing coalitions with divergent problem framings and policy preferences (von Malmborg, 2025).

Incumbent Industry Coalition: The European Commission's initial proposal was significantly influenced by established maritime and fossil fuel industry actors, including the European Community Shipowners' Association (ECSA), FuelsEurope, International Chamber of Shipping, World Shipping Council, and major oil companies including Shell and BP. These incumbents advocated for: - Technology-neutral, goal-based regulation without fuel-specific mandates - Moderate emission reduction targets preserving competitive position - Continued viability of LNG as a transitional fuel - Preference for global governance through the IMO rather than unilateral EU action - Concerns regarding high costs of RFNBOs and risk of technology lock-in

Progressive Coalition: Transport & Environment, the European green mobility federation, led an alternative coalition comprising environmental organisations (Seas at Risk, Clean Air Task Force, Environmental Defense Fund), the Getting to Zero Coalition, and progressive industry players including Maersk, Siemens, and Hydrogen Europe. This coalition advocated for: - Technology-specific measures including RFNBO subquotas and multipliers - 100% emission reduction target by 2050 - First-mover advantage in the hydrogen economy - Strategic autonomy in zero-carbon fuel production

Transport & Environment recommended a minimum 6% RFNBO share by 2030, a multiplier of 5 for RFNBOs (versus the eventual multiplier of 2), and 18% RFNBOs by 2030 with 85% by 2040. Although the final regulation adopted more moderate provisions, the progressive coalition successfully shifted outcomes beyond the Commission's initial proposal (von Malmborg, 2025).

Member State Positions: A progressive coalition within the Council—comprising Austria, Belgium, Denmark, Germany, Ireland, Luxembourg, the Netherlands, and Sweden—advocated for higher ambition and RFNBO subquotas. Shipping-dependent Mediterranean member states (Cyprus, Greece, Malta) initially resisted ship operator obligations, preferring requirements on fuel suppliers only, but ultimately accepted compromise provisions. 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, 2025).

This case demonstrates that economically weaker policy entrepreneurs advocating transformative change can overcome resistance from dominant incumbents if they successfully couple attractive problem framings with viable policy solutions and a responsive political environment (von Malmborg, 2025).

4.3.0a Scandinavian Leadership in Maritime Decarbonisation

Denmark, Norway, and Sweden have emerged as frontrunners in the transition to sustainable shipping, having implemented more ambitious decarbonisation targets and policies than those established by the IMO. These nations have demonstrated active and influential participation during IMO negotiations, consistently advocating for stricter GHG regulation (Bach & Hansen, 2023). The Scandinavian approach reflects a broader pattern wherein progressive member states and external actors have developed complementary initiatives in response to perceived insufficient progress at the IMO level, including industry frameworks such as the Poseidon Principles for responsible ship finance and the Clydebank Declaration establishing green shipping corridors (Bach & Hansen, 2023).

4.3.1 Port of Rotterdam Case Study

The Port of Rotterdam exemplifies responsiveness to energy transition challenges with comprehensive sustainability initiatives. The port currently hosts 70 sustainability-related projects, comprising 19 operational initiatives, 15 works in progress, and 36 projects in preparation. The port's energy transition strategy towards a circular and carbon-neutral operation by 2050 encompasses three phases (Profumo et al., 2025):

Phase 1: Infrastructure development, including heating networks and CO_2 emission capture systems.

Phase 2: Energy system transformation through green electricity generation via wind and solar installations, combined with hydrogen production and import capabilities.

Phase 3: Replacement of fossil fuels with green hydrogen, biomass, and recycled materials.

Rotterdam aims to function as an international hub for hydrogen production, import, application, and transfer to neighbouring countries. The port is progressing toward a large-scale hydrogen network with dedicated green hydrogen production facilities. Additionally, Rotterdam is developing carbon capture, utilisation, and storage infrastructure enabling CO_2 storage in depleted gas fields beneath the North Sea (Profumo et al., 2025).

4.3.2 Northern European Port Investments

Northern Range ports are investing substantially in sustainability through construction of ammonia and methanol production facilities proximate to port areas. This strategic positioning enables refuelling and storage infrastructures to serve as foundation points for networks utilising ammonia and methanol as shipping fuels, thereby reducing last-mile distribution costs (Profumo et al., 2025).

4.4 China's Maritime Decarbonization Efforts

China's 50 publications reflect growing focus on clean energy adoption and maritime infrastructure investment to meet carbon neutrality goals by 2060 (Sadiq et al., 2025).

4.4.1 Policy Framework Characteristics

Comparative analysis of maritime decarbonisation governance reveals distinctive characteristics of China's policy approach. Chinese maritime decarbonisation policies demonstrate a strong emphasis on command-control instruments relative to market-based mechanisms, reflecting the broader governance model prevalent in the Chinese regulatory system. Policy Mix Consistency analysis indicates scores ranging from 6.0 to 8.0 for Chinese maritime policies, suggesting moderate to high internal coherence but with greater variability than observed in IMO or EU frameworks (Lin et al., 2025).

China has implemented its carbon emission trading system across seven pilot industries, with significant progress achieved in market-oriented green technology innovation and green finance development (Huang et al., 2025). The expansion of carbon trading mechanisms provides a potential foundation for future inclusion of the maritime sector within the Chinese carbon market framework.

The distribution of policy instruments across jurisdictions illustrates fundamental differences in governance approaches: the IMO relies on moderate command-control and high supportive/voluntary measures with limited economic/market-based mechanisms; the EU employs moderate command-control instruments with high economic/market-based mechanisms (EU ETS, FuelEU Maritime) and moderate supportive measures; China demonstrates high command-control instruments with moderate economic/market-based and supportive measures, reflecting its "1+N" policy system approach (Lin et al., 2025).

4.4.2 Shanghai Port Green Methanol Initiative

Shanghai Port, the world's largest container port, signed an agreement with Maersk in March 2023 to develop cooperation on green methanol bunkering, with fuel utilisation commencing from 2024. Under this arrangement, the port provides bunkering infrastructure for green methanol while Maersk has ordered 19 bi-fuel methanol vessels. The initial phase involves ship-to-ship refuelling and in-port fuel tank storage, with subsequent phases exploring strategic partnership expansion upstream in the green methanol industrial chain (Profumo et al., 2025).

4.4.3 Fiscal Policy Effectiveness in China's Shipping Industry

Empirical analysis of fiscal policy effects across 22 Chinese provinces from 2007 to 2022 reveals non-linear relationships between policy instruments and low-carbon transition outcomes. Panel regression models demonstrate distinctive patterns for tax-based policies (TBP) and transfer payment policies (TPP) in promoting shipping decarbonisation (Hu & He, 2024).

Tax-Based Policy Effects:

Tax policies exhibit an inverted U-shaped relationship with low-carbon transition, indicating that an optimal taxation level exists beyond which additional taxes yield diminishing or negative returns:

Table 72 Tax-Based Policy Effects on Low-Carbon Transition

Parameter	Value	Interpretation
Optimal TBP level	2.77	Peak effectiveness point
Primary coefficient	-0.1754	Initial emission reduction effect
Square coefficient	0.0317	Diminishing returns above optimum
Optimal TBP with digital tech	2.57	Lower threshold with technology adoption

When tax levels exceed the saturation point, shipping enterprises become less sensitive to tax incentives, and governmental regulations must become stricter to maintain emission reduction momentum (Hu & He, 2024).

Transfer Payment (Subsidy) Policy Effects:

Subsidy policies demonstrate a more complex N-shaped relationship with two inflection points. The first inflection occurs at TPP level 4.1 where initial positive effects transition to negative; the second inflection at TPP level 17.56 marks where negative effects return to positive. With digital technology adoption, these thresholds shift: the first inflection delays to TPP level 5.1 whilst the second accelerates to TPP level 16.33. The N-shaped pattern emerges because initial subsidies stimulate rapid technology investment, but resource constraints subsequently force enterprises to prioritise business expansion over further low-carbon investment. Continued subsidy increases eventually enable breakthrough technologies that restore positive emission reduction effects (Hu & He, 2024).

Sectoral Variations:

Policy effectiveness varies significantly across shipping segments, with container shipping demonstrating highest sensitivity to fiscal interventions:

Policy effectiveness varies significantly across shipping segments, with optimal tax-based policy (TBP) levels demonstrating sensitivity rankings: container shipping is most sensitive (optimal TBP 2.55), followed by liquid shipping (optimal TBP 2.64), passenger shipping at moderate sensitivity (optimal TBP 3.03), and dry bulk shipping as least sensitive (optimal TBP 3.21). International shipping reaches optimal tax levels at TBP = 2.43, while domestic shipping requires higher levels (TBP = 3.16), reflecting differences in vessel technology sophistication and management efficiency (Hu & He, 2024).

Digital Technology Moderation:

Digital technology application plays a significant moderating role, strengthening positive policy effects and weakening negative effects. The combination of low-carbon technologies and digital technologies—including intelligent navigation, hull monitoring, engine room automation, and energy efficiency management systems—enhances policy effectiveness by enabling precise ship scheduling, improved energy utilisation, and accelerated pollution control technology deployment (Hu & He, 2024).

4.5 Mediterranean and Middle East Initiatives

Egypt has progressively strengthened its role in the green economy transition by increasing investments in renewable energy sources. The Egyptian government has allocated resources toward green port development to reduce environmental impact and curb emissions. The Port of Alexandria has implemented green measures including electric vehicle deployment and photovoltaic lighting systems, while the Port of Sokhna has installed solar-powered electricity systems capable of covering one-fifth of the port's energy requirements (Profumo et al., 2025).

The memorandum of understanding between Egypt and the European Union, signed at COP-27 in Sharm el-Sheikh, establishes a strategic partnership on climate, energy, and energy transition with prospects for a Mediterranean Hydrogen Partnership. In 2021, the Suez Canal Zone signed a contract to develop the Port of Sokhna with estimated investment of approximately $1.27 billion (Profumo et al., 2025).

4.6 Challenges for Developing Regions

Regions such as Africa, South America, and parts of Asia-Pacific show minimal research activity due to limited funding, technological constraints, and lack of international collaboration. Addressing these gaps requires fostering technology transfer and capacity-building initiatives (Sadiq et al., 2025).

4.7 Asia-Pacific and United Kingdom Maritime Policies

4.7.1 Japan: Technology-Led Safety Standards

Japan's regulatory framework is characterised by technological leadership and rigorous safety standards. The Classification Society Nippon Kaiji Kyokai (ClassNK) has developed comprehensive guidelines for alternative fuel vessels. In April 2016, ClassNK issued the Guidelines for Gas-fueled Ships (4th Edition), followed by Guidelines for Fuel Cell Systems Onboard Ships (1st Edition) in June 2019. The Guidelines for Ships Using Alternative Fuels, Version 3.0 (May 2024) introduces safety requirements for hydrogen-fueled vessels and comprehensively specifies safety measures including installation, control, and safety systems (Wang, Liu, Zhang et al., 2025).

Japan's strength lies in providing globally trusted technical specifications and safety protocols, particularly for high-risk fuels such as ammonia and hydrogen. However, the approach results in slower commercial deployment rates compared to markets with more aggressive policy incentives.

4.7.2 Singapore: Hub-Based Pragmatic Strategy

As the world's largest bunkering hub, Singapore focuses on maintaining its central role in international shipping through pragmatic and open strategies. The Maritime Singapore Green Initiative (MSGI), renewed in 2020 and extended to December 2024, encompasses four key programmes: Green Ship, Green Port, Green Energy and Technology, and Green Awareness. Updated Green Port Programme (GPP) and Green Ship Programme (GSP) entered into effect on 1 January 2025, providing port tax incentives for low- and zero-emission vessels using renewable fuels and advanced energy systems (Wang, Liu, Zhang et al., 2025).

Singapore established the Global Centre for Maritime Decarbonisation (GCMD) on 1 August 2021 as the central driving force for maritime decarbonisation initiatives. The Maritime Singapore Decarbonisation Blueprint: Working Towards 2050 (March 2022) identifies seven key focus areas including future marine fuels, bunkering standards and infrastructure, carbon awareness, carbon accounting, and green financing. The Singapore-Rotterdam Memorandum of Understanding (August 2022) establishes the world's longest green and digital shipping corridor (Wang, Liu, Zhang et al., 2025).

4.7.3 South Korea: Industry-Competitive Export Strategy

South Korea's policy approach is distinctly driven by industrial competition, with the core objective of consolidating its dominant position in global shipbuilding. In July 2022, the Ministry of Trade, Industry and Energy and Ministry of Oceans and Fisheries announced investment of approximately USD 200 million over ten years to advance eco-friendly ship technologies (Wang, Liu, Zhang et al., 2025).

Table 73 South Korea Green Ship Fuel Supply Chain Targets

Metric	2027 Target	2030 Target
Green fuel supply share	10% (1.34 Mt)	30% (4.02 Mt)
Green-fueled container ship calls (by GT)	10%	20%
Total port storage capacity	400,000 t	1,000,000 t
LNG storage capacity	-	600,000 t
Methanol storage capacity	-	200,000 t
Ammonia storage capacity	-	200,000 t

Source: Wang, Liu, Zhang et al. (2025)

4.7.4 United Kingdom: Innovation-Focused Strategic Incubation

The United Kingdom released Maritime 2050 in February 2019, followed by the Clean Maritime Plan in July 2019, which sets the pathway to zero-emission shipping and stipulates that all new vessels ordered for operation in UK waters from 2025 onwards should be designed with zero-emission technologies (Wang, Liu, Zhang et al., 2025).

The Clean Maritime Demonstration Competition (CMDC), launched in March 2021, allocated over £23 million to support the design and development of zero-emission vessel technologies, with 55 projects receiving funding. The second round (March 2022) provided £12 million for pre-deployment trials and feasibility studies.

On 25 March 2025, the UK announced the Maritime Decarbonisation Strategy with targets to reduce greenhouse gas emissions by 30% by 2030, 80% by 2040, and achieve net zero by 2050. Shipping will be incorporated into the UK Emissions Trading Scheme (UK ETS). On 25 April 2025, the Maritime and Coastguard Agency (MCA) issued guidelines for the use of ammonia as a marine fuel, marking a critical step toward widespread adoption of alternative fuels in the UK maritime sector (Wang, Liu, Zhang et al., 2025).

On 25 March 2025, the UK announced the Maritime Decarbonisation Strategy with progressive targets: 30% greenhouse gas emission reduction by 2030, 80% reduction by 2040, and achievement of net zero by 2050. Shipping will be incorporated into the UK Emissions Trading Scheme (UK ETS) (Wang, Liu, Zhang et al., 2025).

4.7.5 Malaysia: Trilateral Stakeholder Dynamics in Maritime Decarbonisation

Malaysia's maritime industry occupies a strategic position along the Strait of Malacca—one of the world's busiest shipping lanes—with major ports including Port Klang (ranked among the top 20 globally) and Tanjung Pelepas serving as key transit hubs for international trade. However, the sector faces distinctive challenges in implementing emission reduction strategies, requiring coordinated approaches among government, port authorities, and shipping companies (Ruslan et al., 2025).

Socio-Economic Constraints:

Several factors shape the feasibility and pace of emission reduction efforts within Malaysia's maritime sector. Economic dependence on maritime trade generates revenue from port activities that poses financial challenges for transitioning toward green port infrastructure, as such investments may disrupt existing economic flows. Unlike leading maritime nations, Malaysia offers limited green subsidies or financial support mechanisms, making it difficult for shipping companies to adopt low-emission technologies or modernise their fleets. Notable disparities exist between major ports and smaller regional ports, with the latter often lacking the capacity and resources to implement sustainability initiatives effectively (Ruslan et al., 2025).

Regulatory Landscape:

Malaysia adheres to IMO regulations, particularly MARPOL Annex VI mandating sulfur emission reductions. However, the country's regulatory framework lacks a clear carbon pricing mechanism comparable to the EU Emissions Trading System. Government strategies can be characterised as either passive (weak enforcement, voluntary compliance) or active (strict penalties, financial incentives), with current approaches tending toward voluntary participation. Green Port initiatives at Port Klang and Tanjung Pelepas have implemented Environmental Ship Index (ESI) incentive programmes offering port fee reductions for low-emission vessels, though participation remains voluntary (Ruslan et al., 2025).

Operational Challenges:

Infrastructure limitations constrain emission reduction capacity: most Malaysian ports lack adequate shore power facilities, resulting in ships relying on auxiliary engines whilst at berth; the fleet composition is dominated by older, less fuel-efficient vessels; and regional ports continue to face difficulties upgrading facilities and adopting sustainable technologies. LNG bunkering initiatives at Johor Port and Port Klang support the transition to alternative fuels, though local shipping companies have been slower to transition than international operators due to cost concerns and uncertainty in long-term fuel pricing (Ruslan et al., 2025).

Game-Theoretic Analysis:

Evolutionary game analysis of trilateral stakeholder interactions reveals that Malaysia's government faces a critical decision between active regulation (imposing stricter emission limits, offering incentives) and passive approaches (relying on voluntary compliance). Port authorities must evaluate whether incremental benefits from green infrastructure investments outweigh modernisation costs—a calculation heavily dependent on shipping company alignment with green practices. Shipping companies bear significant financial burdens including ship renovation costs, new vessel development, and technical personnel training, with fleet retrofitting costs estimated at approximately $1.5 million for comprehensive upgrades (Ruslan et al., 2025).

Policy Recommendations:

Game model findings suggest several strategic interventions for Malaysia's maritime industry: financial subsidies for port infrastructure upgrades can reduce investment barriers and encourage green technology adoption; grants supporting shipping companies' transition to low-emission technologies address capital constraints; tiered regulatory mechanisms reflecting varying investment capacities across operators can ensure equitable compliance pathways; and coordination between ports and shipping companies through public-private partnerships can distribute costs whilst maximising collective benefits. Gradual subsidy phase-out rather than abrupt termination produces smoother convergence toward active emission reduction strategies without destabilising strategic equilibria (Ruslan et al., 2025).

4.8 Global Standards Coordination and Alternative Fuel Transition

4.8.1 Alternative Fuel Adoption Acceleration

The year 2024 marks a pivotal milestone in the maritime industry's fuel transition. Alternative-fuel vessels accounted for over 50% of global newbuilding orders by deadweight tonnage for the first time, while orders for conventionally fueled vessels have shrunk to nearly zero. Beginning in 2025, the application of marine clean alternative fuels in shipping has entered a new stage of rapid development (Wang, Liu, Zhang et al., 2025).

Alternative fuel vessel adoption has accelerated dramatically: 209 alternative fuel vessels were ordered in 2020, rising to 449 vessels in 2021; by Q1 2022, alternative fuels represented 61% of newbuild orders by gross tonnage; and the alternative fuel fleet share by deadweight tonnage increased from 41.2% in 2023 to 43.2% in 2024, with January–April 2025 newbuild orders reaching 63% alternative fuel share (Wang, Liu, Zhang et al., 2025).

In the container segment, LNG-powered vessels maintained a leading share of 58% among 2024 newbuild orders, followed by methanol-powered vessels at 30%, with conventionally fueled ships nearly phased out. Leading shipping companies such as Maersk and CMA CGM have cumulatively ordered over 100 methanol-fueled vessels. For roll-on/roll-off vessels and ferries, 45% of newbuilding orders utilise battery/hybrid propulsion systems, supported by 60% shore power coverage at Nordic ports. Ammonia-ready designs comprise 6% of new ship orders (45 confirmed orders plus 303 options), with ammonia-related technology patents increasing annually by 37% (Wang, Liu, Zhang et al., 2025).

Bulk carriers and tankers exhibit slower transition rates, with conventional fuels still accounting for 83% of new orders in these segments. The main bottleneck lies in infrastructure gaps: only 18% of global ports are equipped with green fuel bunkering capabilities, methanol bunkering is available at just 35 ports worldwide, and ammonia/hydrogen fueling infrastructure has yet to reach significant scale (Wang, Liu, Zhang et al., 2025).

4.8.2 Technology Readiness and Emission Reduction Potential

Comprehensive evaluation of marine clean alternative fuels reveals significant variation in technology readiness and emission reduction potential. Using the Technology Readiness Level (TRL) scale, LNG has reached full commercialisation (TRL 9), while methanol is in quasi-commercialisation (TRL 8) with dual-fuel engines having accumulated over 1.5 million operating hours. Ammonia fuel storage and leakage monitoring technologies remain under development (TRL 5), while hydrogen is in engineering verification stage (TRL 5) with orders concentrated in cruise/ferry segments (Wang, Liu, Zhang et al., 2025).

Emission reduction potential varies significantly by alternative fuel type relative to the IMO (2023) HFO carbon emission intensity baseline of 94 gCO_2eq/MJ: LNG achieves 10–25% CO_2 reduction limited by methane slip; methanol achieves 85–95% reduction dependent on biomass carbon source sustainability; ammonia achieves 92–98% reduction with electrolytic energy consumption as the key limiting factor; and hydrogen achieves 96–99% reduction constrained by liquefaction efficiency losses (Wang, Liu, Zhang et al., 2025).

LNG can reduce CO_2 emissions by 15-20%, cut SOx emissions by more than 98%, and lower NOx emissions by approximately 85-90%. However, methane slip during combustion—whereby unburned methane escapes into the atmosphere—remains a primary reason environmental organisations question LNG's environmental performance (Wang, Liu, Zhang et al., 2025).

Alternative fuel cost multiples and technology readiness levels demonstrate significant variation: LNG has reached TRL 9 with cost multiples of 1.8–2.2× versus HFO (including fuel and vessel modifications); methanol has achieved TRL 8 with cost multiples of 2.3–2.8× (higher fuel price plus engine modifications); ammonia remains at TRL 5 with cost multiples of 3.5–4.5× (storage tanks representing 60% of modification cost); and hydrogen is at TRL 5 with orders comprising less than 1% of the market, concentrated in cruise and ferry segments (Wang, Liu, Zhang et al., 2025).

4.8.3 IMO Net-Zero Framework and Global Carbon Pricing

The 83rd Marine Environment Protection Committee (MEPC 83), held in London on 7-11 April 2025, approved draft amendments to MARPOL Annex VI, establishing the world's first regulatory framework combining mandatory emission limits with greenhouse gas pricing for the shipping industry. This milestone framework represents a crucial step toward achieving net-zero carbon emissions in international shipping around 2050 (Wang, Liu, Zhang et al., 2025).

The framework establishes a regulatory system based on greenhouse gas fuel intensity (GFI), with two compliance targets: direct compliance and base target. Ships failing to meet emission reduction targets will incur carbon emission costs. On 11 April 2025, IMO member states reached global agreement approving the first global carbon tax for international shipping—

the first carbon revenue system of any kind managed by the United Nations (Wang, Liu, Zhang et al., 2025).

The agreement sets global standards for progressively reducing the greenhouse gas intensity of ship fuels, covering the entire lifecycle of shipping fuels. Using standardised standards and universal certification schemes ensures that the global shipping market maintains a level playing field regardless of where fuel is produced, transported, or used. Companies receive incentives for investing in zero-emission and near-zero-emission marine clean fuels such as renewable methanol and ammonia (Wang, Liu, Zhang et al., 2025).

4.8.4 Green Shipping Corridors

Green shipping corridors refer to zero-emission trade routes between major port hubs, requiring collaboration of port authorities, shippers, carriers, fuel suppliers, and other stakeholders to jointly advance full lifecycle decarbonisation operations. During COP26 in 2021, 22 countries signed the Clydebank Declaration on Green Shipping Corridors, pledging to establish at least six green corridors by 2025 and to further scale up by 2030 (Wang, Liu, Zhang et al., 2025).

Green shipping corridor development has accelerated substantially since the 2021 Clydebank Declaration: 22 countries signed the declaration at COP26 pledging to establish at least six green corridors by 2025, with subsequent scaling by 2030; by November 2024, 62 global corridor initiatives had been announced, with European corridors comprising approximately 33% and North/Asia-Pacific corridors approximately 40% of the total, and 18 new corridors launched during 2024 (Wang, Liu, Zhang et al., 2025).

The World Shipping Council has identified green shipping corridors as one of the six key pathways to achieve zero-carbon maritime transport. Building such corridors enables the earliest commercial deployment of low- and zero-carbon fuels, attracts green finance, improves supply chains and supporting port infrastructure, and advances digitalisation of shipping (Wang, Liu, Zhang et al., 2025).

4.8.5 Challenges in Global Standards Harmonisation

Geopolitical Competition and Standards Fragmentation:

The harmonisation of international technical standards and regulations extends beyond technical issues to encompass strategic competition and geopolitical rivalry. Countries vie for dominance in standard development to secure first-mover advantage and path dependency in global markets.

This “national champion” model, treating standards as strategic tools, leads countries to prioritise promoting standards favourable to their own interests in international forums, rather than seeking technically optimal solutions. Negotiations feature game-playing and compromise, delaying formation of globally unified consensus (Wang, Liu, Zhang et al., 2025).

During the second special committee meeting of the IMO Marine Environment Protection Committee (October 2025), representatives from 135 member states engaged in discussions revealing fundamental divisions. Developing countries emphasised challenges regarding food security, accessibility of green fuels and emission reduction technologies, and capacity-building. Countries including Saudi Arabia, United States, and Russia argued that current proposals fail to genuinely reflect multilateralism. EU countries, the United Kingdom, Pacific small island nations, and some African countries voiced support for adoption (Wang, Liu, Zhang et al., 2025).

Technology-Regulation Gap:

Standards development organisations face inherent challenges keeping pace with rapid technological innovation. For ammonia fuel, there is a lack of detailed bunkering procedures and no mandatory, globally recognised training and operational certification system for crew members. For hydrogen fuel, no globally accepted and transparent certification standards exist for assessing full lifecycle carbon emissions. For biofuels and blended fuels, authoritative standards are missing regarding long-term stability and maximum permitted blending ratios (Wang, Liu, Zhang et al., 2025).

Common But Differentiated Responsibilities (CBDR):

Within IMO negotiations, the CBDR principle remains a focal point of contention between developed and developing countries. Major shipping nations and developed economies emphasise “globally unified standards” to ensure environmental integrity and maintain level playing fields. Developing countries insist that historical emissions and existing capacity inequalities must be considered, seeking to ensure they are not forced out of the global shipping system due to transition costs. These fundamental differences make IMO negotiations slow and fraught with compromise (Wang, Liu, Zhang et al., 2025).

Table 74 Comparative Regulatory Framework Approaches

Country/ Region	Policy Approach	Key Mechanisms	Strengths	Challenges
China	Top-down, systematic	"1+N" policy system	Rapid implementation, strong government support	Limited market-driven flexibility
EU	Regulatory coercion	EU ETS, FuelEU Maritime, AFIR	Leverages single market for compliance	Complex compliance, high costs
Japan	Technology-led, safety-focused	ClassNK guidelines	High safety credibility globally	Slower commercial deployment
Singapore	Hub-based, pragmatic	MSGI, GCMD, green corridors	Flexibility, international cooperation	Limited domestic manufacturing
South Korea	Industry-competitive	R&D funding, supply chain plan	Strong shipbuilding leverage	Export market dependency
UK	Innovation-focused	CMDC, UK ETS, MCA guidelines	Strong R&D ecosystem	Post-Brexit influence reduced

Source: Wang, Liu, Zhang et al. (2025)

There is no one-size-fits-all perfect regulatory framework. China's systematic approach, the EU's regulatory coercion, Japan's technological rigour, Singapore's hub-based flexibility, South Korea's industry-led competitiveness, and the UK's innovation-oriented strategy collectively form a multi-driven landscape for global shipping decarbonisation. The future trend involves mutual learning and integration of these models, ultimately leading to a multi-layered global governance system balancing policy constraints, market incentives, technological innovation, and international cooperation (Wang, Liu, Zhang et al., 2025).

4.9 Southern African Development Community (SADC) Transport Transition

The Southern African Development Community provides a critical case study in regional transport decarbonisation, illustrating the interplay between power sector transformation, vehicle fleet electrification, and modal shifting in achieving ambitious emission reduction targets. Energy systems modelling of the SADC region reveals distinctive challenges and opportunities for developing economies pursuing Paris Agreement-aligned transitions (Ahjum, 2020).

4.9.1 Regional Emissions Profile and South African Dominance

SADC accounts for approximately 2-3% of global greenhouse gas emissions from fossil fuel combustion, with South Africa exercising disproportionate influence over regional outcomes. The concentration of emissions in a single dominant economy creates both challenges and opportunities for coordinated regional decarbonisation (Ahjum, 2020).

Table 75 SADC Transport Emissions and Energy Profile

Metric	Value	Notes
SADC Emissions (2014)		
Total fuel combustion CO_2	567 Mt	Regional total
Transport sector share	17% (94 Mt CO_2)	Road transport primary contributor
SADC share of global emissions	2-3% (594 $MtCO_2e$)	
South Africa Dominance		
Share of SADC GHG emissions	82%	Fuel combustion
Share of SADC road fleet	60%	
Share of SADC transport fuel demand	60% (1190 PJ in 2018)	
Share of SADC GDP	50%	
Domestic transport emissions share	14% of national energy-related CO_2	
Road transport share of domestic emissions	90%	
Power Sector (SAPP)		
South Africa capacity share	81% (48,467 MW of 59,991 MW)	
Grid emissions intensity	~1 kg CO_2eq/kWh	Declining to 139 g/kWh by 2050
Population Projections		
SADC 2020	363 million	
SADC 2050 projection	>700 million	Near doubling
South Africa 2020	57-60 million	16% of SADC
South Africa 2050 projection	75 million	10% of SADC

Source: Ahjum (2020)

South Africa's regional dominance reflects its coal-intensive economy, which generates electricity for both domestic consumption and the Southern African Power Pool (SAPP). The SAPP transmission network connects sixteen member countries, with South Africa responsible for 90% of regional generation and 85% of demand. This concentration creates both path dependency risks—where South Africa's energy choices constrain regional options—and transformation opportunities through coordinated infrastructure investment (Ahjum, 2020).

Angola represents the second largest SADC emitter at 8% of regional total, driven primarily by petroleum production and processing. Angola's 90% dependence on petroleum product exports for national revenue positions it as the SADC member most at risk from transport electrification transitions, necessitating economic diversification strategies to maintain fiscal stability during the global energy transition (Ahjum, 2020).

4.9.2 Vehicle Fleet and Motorisation Dynamics

The SADC vehicle fleet demonstrates significant variation in motorisation rates, reflecting income disparities across member states. In 2015, the regional fleet totalled approximately 16 million vehicles, with passenger vehicles comprising 65% of the total. South Africa accounts for 60% of this fleet, creating analytical conditions where South African transport policy decisions effectively determine regional emissions trajectories (Ahjum, 2020).

Motorisation Rate Comparisons (vehicles per 1000 persons): - SADC excluding South Africa: ~40 - Continental average: ~40 - Global average: 180 - South Africa: 120-130 (2013-2018) - Europe average: 470 - United States: 820

South Africa's motorisation rate increased by 6% between 2013 and 2018, indicating a trend toward private vehicle ownership that, if replicated across the region as incomes rise, would dramatically increase transport energy demand and emissions. The SADC population projection of 700 million by 2050—nearly doubling from 363 million in 2020—amplifies the urgency of establishing low-carbon transport pathways before motorisation patterns become locked into fossil fuel dependence (Ahjum, 2020).

4.9.3 SATIM Scenario Analysis

The South Africa TIMES (SATIM) full-sector energy model was employed to assess four transport pathways to 2050, evaluating combinations of vehicle technology choice and modal shifting interventions. The analysis assumes average GDP growth of approximately 3% annually and population reaching

75 million by 2050, with no economy-wide emissions constraint applied to isolate transport-specific impacts (Ahjum, 2020).

Table 76 South African Transport Scenario Outcomes (2050)

Scenario	Energy Demand (PJ)	Change vs Fossil-Car	GHG Emissions ($MtCO_2eq$)	Change vs Fossil-Car	Key Characteristics
Baseline (2015)	897	-	60	-	Reference year
Fossil-Car	1117	-	65	-	ICE/Hybrid dominance, no modal shift
Fossil-Efficiency	894	-20%	50	-23%	Hybrid-ICE + 70% rail freight + TOD
Electric-Car	578	-48%	9	-86%	EV cost parity by 2030, no modal shift
Eco-Mobility	508	-55%	9	-86%	EV + modal shift + TOD; lowest energy demand

Source: Ahjum (2020)

The Eco-Mobility scenario—combining electric vehicle adoption with modal shifting and transit-oriented development—achieves the most substantial reductions in both energy demand and emissions. Electric vehicles alone (Electric-Car scenario) deliver 86% emission reductions compared to business-as-usual, but the additional 12% energy demand reduction from modal shifting and transit-oriented development in the Eco-Mobility scenario represents significant avoided infrastructure investment and resource consumption (Ahjum, 2020).

Residual emissions under the electric scenarios (9 $MtCO_2eq$) derive entirely from aviation (9 $MtCO_2eq$) and maritime transport (0.08 $MtCO_2eq$), as road vehicles achieve zero tailpipe emissions through complete electrification. This result underscores the particular challenges facing aviation decarbonisation relative to ground transport, where electric propulsion technology has matured sufficiently for comprehensive deployment (Ahjum, 2020).

4.9.4 Power Sector and Infrastructure Requirements

Transport electrification creates substantial additional demand for electricity generation capacity. Under the Eco-Mobility scenario, an additional 95 TWh of electricity—representing a 20% increase over non-transport baseline demand—

would be required by 2050, necessitating 41 GW of additional generation capacity. Without modal shifting (Electric-Car scenario), requirements increase to 102 TWh and 45 GW (Ahjum, 2020).

Table 77 SADC E-Mobility Transition Requirements

Requirement	Eco-Mobility	Electric-Car	Notes
Power Sector (2050)			
Additional electricity demand	+95 TWh (+20%)	+102 TWh	vs non-transport baseline
Additional generation capacity	+41 GW	+45 GW	Wind, Solar PV, gas, storage
RE share of generation	76%	76%	By 2050
Grid emissions intensity	139 g/kWh	139 g/kWh	Down from 1141 g/kWh (2015)
Vehicle Fleet (2050)			
Private passenger fleet	8 million	13 million	Modal shift reduces fleet size
Public transport fleet	225,000	250,000	
Modal Shift Targets			
Freight road-to-rail	70%	-	vs 15% baseline
Public transport modal share	50%	-	
TOD demand reduction	10%	-	Motorised travel reduction
Hydrogen (v-km share)			
Freight fuel cell share	6%	13%	HFCVs for corridor freight
Refinery Investment			
New capacity required	None	None	EV scenarios avoid refinery investment
Fossil scenarios	300,000 bbl/day	-	New refinery needed by 2050

Source: Ahjum (2020)

Cost-optimal power sector expansion would result in rapid decarbonisation post-2030, with renewable energy sources—wind, solar PV, and gas with battery storage—comprising 76% of generation capacity by 2050. Grid emissions intensity would decline from 1141 g CO_2eq/kWh in 2015 to 139 g CO_2eq/kWh by 2050, an 88% reduction that enables transport electrification to deliver genuine emission reductions rather than simply shifting emissions to the power sector (Ahjum, 2020).

The SAPP transmission network provides a crucial enabling infrastructure for coordinated regional decarbonisation. The network's expansion to connect diverse renewable resources across member states—including substantial solar potential in Botswana and Namibia, hydropower in the Democratic Republic of Congo and Mozambique, and geothermal resources in Tanzania—could establish a multi-corridor renewable energy SAPP facilitating SADC-wide e-mobility transition (Ahjum, 2020).

4.9.5 Regional Value Chain Opportunities

SADC member states possess substantial mineral endowments relevant to electric vehicle and hydrogen fuel cell manufacturing, creating potential for regional automotive value chains that capture greater shares of transition-related economic activity. South Africa holds approximately 80% of the world's known platinum reserves, essential for fuel cell catalysts, while the Democratic Republic of Congo and Zambia maintain global monopolies on cobalt and copper production critical for battery manufacturing. Zimbabwe possesses lithium resources increasingly important for battery production (Ahjum, 2020).

The existing South African automotive manufacturing sector—responsible for 7.5% of GDP including multipliers and employing 113,532 workers—provides an industrial foundation for EV production transition. Current reciprocal trade in vehicles and components between South Africa and SADC neighbours could expand under the SADC Green Economy Strategy and Action Plan (GESAP) framework to encompass electric vehicle assembly, battery manufacturing, and fuel cell component production (Ahjum, 2020).

Hydrogen fuel cell heavy vehicles (HFCVs) present particular opportunities for corridor freight applications where battery electric vehicles face range limitations. Under the Eco-Mobility scenario, hydrogen fuel cell vehicles would account for 6% of freight vehicle-kilometres by 2050; without modal shifting, this rises to 13-17%. Integration of hydrogen production with South Africa's existing coal-to-liquids (CTL) infrastructure—currently emitting approximately 55 $MtCO_2eq$ annually—could enable green hydrogen production through carbon capture and utilisation, potentially extending facility operational life while reducing emissions (Ahjum, 2020).

4.9.6 Policy Framework Alignment

The GESAP provides the central framework for SADC's green industrialisation agenda, with transport identified as vital for regional economic integration. Three transport-specific strategies address climate-resilient infrastructure, green public transport and multimodal systems, and regional low-emitting vehicle trade. Short-term priorities include public-private partnerships for green transport systems and public transport access for marginalised populations; medium-term objectives encompass harmonised vehicle emissions regulations and reduced fossil fuel subsidies; long-term investments target green ports, railways, and inland waterways (Ahjum, 2020).

However, potential contradictions exist between GESAP objectives and complementary regional strategies. The Regional Indicative Strategic Development Plan (RISDP) 2020-30 prioritises transport infrastructure investment but also includes conventional oil and gas infrastructure development that may defer or preclude investment in zero-emission alternatives through technology and supply chain lock-in. Resolving these tensions requires explicit prioritisation of climate-aligned investment consistent with member states' Nationally Determined Contributions under the Paris Agreement (Ahjum, 2020).

South Africa's Green Transport Strategy targets a 5% reduction in transport GHG emissions by 2050, alongside 30% freight shift from road to rail, 20% passenger shift from private to public transport, and 5% conversion of public and national sector fleets to clean alternatives by 2025. These targets, while ambitious relative to business-as-usual trajectories, remain modest compared to the 86% emission reduction potential identified through comprehensive electrification scenarios (Ahjum, 2020).

4.9.7 Transition Risks and Opportunities

The SADC transport transition presents differentiated risks and opportunities across member states, reflecting their varied positions in energy commodity trade and industrial development:

Transition Risk Assessment: - **Angola (High Risk):** 90% export revenue from petroleum products; direct exposure to reduced oil demand from transport electrification; requires economic diversification strategy leveraging renewable energy potential - **Mozambique (Moderate Risk):** Natural gas exports could serve as hydrogen production feedstock during transition; carbon capture and utilisation essential for maintaining export viability - **DRC and Zambia (Opportunity):** Global monopolies on cobalt and copper position for battery manufacturing value chains; electrification increases mineral demand - **South**

Africa (Dual): Dominant regional economy with automotive manufacturing base; transition from CTL and petroleum processing to green hydrogen and EV production; R417 billion road maintenance backlog incentivises modal shift to rail

E-micromobility—including electric bicycles and scooters—presents particular opportunities for rural mobility where motorised alternatives are limited by infrastructure and fuel supply constraints. Integration with minigrid electrification could address both transport access and energy poverty simultaneously, particularly in DRC and Tanzania where electrification rates remain below 50% (Ahjum, 2020).

4.10 Capital Investment Constraints in Developing Economies

Beyond sector-specific challenges, developing countries face fundamental macroeconomic constraints during the low-carbon transition that extend across all transport modes, including maritime shipping. The transition requires substantial investments in capital goods—from port infrastructure and vessels to fuel production facilities and bunkering systems—yet capital goods production is concentrated predominantly in advanced economies. This structural asymmetry creates balance-of-payments pressures that may constrain the pace and depth of developing country decarbonisation efforts (Tausch & Magacho, 2024).

4.10.1 Import Dependency of Green Investment

Analysis of capital-use matrices for six Latin American and Caribbean countries reveals that the low-carbon transition generates substantial demand for imported capital goods. For every dollar invested to maintain productive capacity, on average more than 45% leaks directly and indirectly to foreign producers through imports. This represents a significant macroeconomic constraint for developing countries pursuing decarbonisation strategies (Tausch & Magacho, 2024).

Table 78 Import Leakage from Investment by Country

Country	Import Leakage (% of Investment)	Interpretation
Honduras	55.8%	Highest constraint
Mexico	53.6%	High constraint
Costa Rica	52.1%	High constraint
Colombia	~45%	Moderate constraint
Peru	~45%	Moderate constraint
Dominican Republic	27.8%	Lower constraint
Sectoral Maximum	~80%	Electrical Equipment, Electronics

The sectoral variation is substantial: import-intensive sectors such as Telecommunications, Transportation, Construction, and Electronics experience leakages as high as 80%, meaning that for every dollar invested in these transition-critical sectors, only approximately 20 cents stimulates domestic economic activity (Tausch & Magacho, 2024).

4.10.2 Structural Asymmetry in Capital Goods Production

The concentration of capital goods manufacturing in advanced economies creates structural constraints for developing countries pursuing decarbonisation. Eighty percent of capital goods are produced by only ten countries, and green capital goods essential for decarbonisation tend to have higher technological content, further disadvantaging developing economies that lack productive capabilities in these industries (Tausch & Magacho, 2024).

Table 79 Capital Asset Import Characteristics

Capital Asset Type	Direct Import Share	Domestic Production Share	Notes
Machinery & Equipment	>50%	<50%	Highest direct import dependency
Building Construction	<1%	>99%	Primarily domestic, but embedded imports
Civil Engineering Construction	<1%	>99%	Primarily domestic, but embedded imports
Other (Cultivable, Manufactures)	15-20%	80-85%	Moderate import dependency

While Building Construction and Civil Engineering Construction are produced predominantly domestically (>99%), they incorporate substantial embedded imports—inputs and capital goods required to produce the domestic capital stock. In some countries, up to 50% of domestically produced capital stock depends on imported inputs and capital goods. This means infrastructure investment in port facilities, railways, and transport systems generates significant foreign exchange requirements even when the construction itself is domestic (Tausch & Magacho, 2024).

4.10.3 Capital Intensity of Transition-Critical Sectors

Sectors essential to the low-carbon transition demonstrate particularly high capital-output ratios, indicating they require substantial investment per unit of economic activity generated.

Most Capital-Intensive Sectors: - Government Services - Utilities (Waste, Water, Gas, Electricity) - Transportation - Education - Information and Communications Technology (Telecommunications, Information Services)

These sectors are characterised not only by high capital intensity but also by extreme import intensity and limited positive effects on domestic employment multipliers. This creates a challenging combination for developing countries: the sectors most requiring transformation also generate the greatest balance-of-payments pressure while providing limited domestic employment benefits from investment (Tausch & Magacho, 2024).

Maritime Transport Implications:

The Transport sector specifically demonstrates: - High capital-output ratio across analysed countries - Strong dependence on Machinery & Equipment capital assets - Very high import intensity of investment - Limited positive effects on domestic employment multipliers

This pattern implies that maritime decarbonisation investments in developing countries—including vessel retrofits, alternative fuel systems, port infrastructure, and bunkering facilities—will generate substantial import requirements while providing limited domestic employment stimulation (Tausch & Magacho, 2024).

4.10.4 Balance-of-Payments Constraints

The theoretical framework underlying these constraints derives from balance-of-payments constrained growth models (Thirlwall, 1979). Developing countries occupy subordinated positions in international technological, productive, and financial hierarchies. They tend to specialise in low-value-added industries while requiring imports of technology-intensive goods, creating high income elasticity of imports combined with low export elasticity (Tausch & Magacho, 2024).

Key Structural Characteristics: - **High import elasticity:** Economic growth requires proportionally higher imports of capital goods - **Low export elasticity:** Exports concentrated in primary commodities with weak global demand growth - **Currency hierarchy:** Subordinated position in international financial system limits capacity to finance imports through foreign savings - **Survival constraint:** Constant need to attract capital inflows to pay for essential imports

As developing countries embark on low-carbon transitions, they create large demands for imported capital goods—both advanced capital goods directly and green infrastructural goods indirectly. This deepens the external constraint, with domestic capital accumulation suppressed by the constant need to attract foreign currency for capital goods imports (Tausch & Magacho, 2024).

4.10.5 Employment Effects and Socio-Economic Imbalances

Green investment in developing countries produces positive employment effects across the economy. However, the socio-economic benefits of this investment are partially absorbed by capital goods-exporting countries rather than fostering domestic employment creation.

Employment Dynamics: - Direct employment intensities are largest across most sectors - Embodied employment in capital tends to equal or exceed embodied employment in inputs - High levels of imported content mean most demand for capital goods leaks to foreign producers - Positive domestic employment generation effects are limited

The transition also creates structural employment challenges: job creation in low-emitting (sunrise) sectors may be offset by job destruction in high-emitting (sunset) industries, potentially producing socio-economic imbalances particularly in economies with concentrated employment in carbon-intensive activities (Tausch & Magacho, 2024).

4.10.6 Policy Implications for Maritime Decarbonisation

These macroeconomic constraints have significant implications for maritime decarbonisation strategies in developing countries:

Ineffective Strategies: 1. **Intensifying primary commodity exports:** Perpetuates environmental inequalities and delays decarbonisation 2. **Sole reliance on technological transfer through trade:** Deepens structural dependence on foreign-produced capital goods 3. **Technology transfer through FDI alone:** Limited spillover to non-export industries

Recommended Strategies: 1. **Increase export elasticity:** Diversify and sophisticate export structure to generate foreign exchange for capital goods imports 2. **Develop productive capabilities:** Build domestic capacity for capital goods production where feasible 3. **Strategic revenue allocation:** Direct revenues from emission-intensive exports toward export diversification rather than intensification 4. **Labour market resilience:** Develop resilient labour markets capable of absorbing transition restructuring 5. **Economic preparation:** Position economies for declining fossil fuel demand

Technology transfer for maritime decarbonisation should be viewed as a step-by-step process whereby countries develop capabilities to adapt and absorb foreign technology, gradually reducing technological gaps and moving toward more diversified, sustainable productive structures. Direct technology transfer without capability development risks permanent dependence on foreign suppliers (Tausch & Magacho, 2024).

4.10.7 Green Complexity and Maritime Transition

The concept of "Green Complexity" (Mealy and Teytelboym, 2022) provides a framework for understanding developing country positions in green technology value chains. Countries with higher Green Complexity possess strengthened capabilities to competitively export green, technology-intensive inputs and capital goods—including those relevant to maritime decarbonisation such as propulsion systems, fuel cells, and alternative fuel handling equipment (Tausch & Magacho, 2024).

For maritime sector stakeholders in developing economies, these findings suggest:

For Port Authorities: Infrastructure investments will generate substantial import requirements; planning should incorporate foreign exchange implications

For National Maritime Administrations: Regulatory frameworks should account for balance-of-payments constraints when setting transition timelines

For Shipowners in Developing Countries: Vessel retrofitting and newbuilding will face financing constraints related to import dependency; regional cooperation may mitigate individual country constraints

For International Policy: IMO regulatory frameworks should incorporate Common But Differentiated Responsibilities principles that acknowledge structural investment constraints faced by developing maritime nations

The SADC case study (Section 9.9) illustrates these dynamics in practice, where regional value chain opportunities in minerals and manufacturing provide potential pathways for capturing greater shares of transition-related economic activity. Similar strategies may be applicable in other developing regions with relevant resource endowments and industrial capabilities (Tausch & Magacho, 2024).

4.11 Collaborative Governance for Maritime Decarbonisation

The transition to low-carbon shipping requires coordinated action among diverse actors at multiple governance levels. A systematic review of 60 empirical studies on collaborative governance in marine and coastal settings provides valuable lessons for structuring maritime decarbonisation efforts (Asio et al., 2026).

4.11.1 Collaborative Governance Framework

Collaborative governance refers to "decentralised, multi-actor decision-making processes where different levels of government, communities, and civil society collectively achieve goals that could not be accomplished by individual actors alone" (Asio et al., 2026). This framework is particularly relevant to maritime decarbonisation given:

- **Multi-jurisdictional nature:** Flag state, port state, and coastal state interests intersect
- **Diverse stakeholder involvement:** Shipowners, port authorities, fuel suppliers, labour unions, coastal communities
- **Technical complexity:** Requires integration of scientific, engineering, and operational knowledge
- **Long-term horizon:** Transition timelines extend across decades, requiring sustained commitment

The systematic review identified that while collaborative governance involves diverse actors, "power remains unevenly distributed, often concentrated within the state" (Asio et al., 2026). This finding has direct implications for international maritime governance.

4.11.2 Actor Roles in Maritime Governance

Table 80: Actor Types in Collaborative Governance (Asio et al., 2026)

Actor Category	Frequency in Studies	Maritime Equivalent
National-level agencies	n=59 (98%)	Maritime administrations, environment ministries
Fishing/user communities	n=36 (60%)	Seafarers, port workers, coastal communities
BINGOs/development NGOs	n=35 (58%)	Clean Shipping Coalition, Sustainable Shipping Initiative
Collaborative committees	n=28 (47%)	IMO committees (MEPC, MSC), regional MOUs
Community-based organisations	n=22 (37%)	National shipowner associations, port community groups
External funders/donors	n=11 (18%)	World Bank, regional development banks, GCF

The predominance of national-level agencies in 98% of studies reflects the central role of flag states and port states in maritime regulation. However, the review emphasises that when "governments managed marine extractive reserves, positioning them as central actors upon whom others depended" (Asio et al., 2026), this creates power asymmetries that can undermine effective collaboration.

4.11.3 Barriers to Collaborative Maritime Governance

The systematic review identified eight barrier categories across 55 of 60 studies. Applied to maritime decarbonisation:

Table 81: Barriers to Collaborative Governance (Asio et al., 2026)

Barrier	Frequency	Maritime Application
Tokenistic engagement	n=22 (37%)	Developing country participation in IMO without substantive influence
Low non-state participation	n=21 (35%)	Limited industry/labour voice in regulatory development
Lack of funding/ personnel	n=24 (40%)	Capacity constraints in developing country administrations
Inefficient coordination	n=12 (20%)	Fragmented fuel standards across jurisdictions
Rule violations	n=11 (18%)	Non-compliance with emission regulations

Barrier	Frequency	Maritime Application
Resource access conflicts	n=11 (18%)	Competition for limited green bunkering facilities
Absence of legal authority	n=11 (18%)	Unclear governance for new fuel types

The review finds that "decision-making processes are often centralised, with limited involvement of key actors, particularly those most affected and vulnerable" (Asio et al., 2026). In maritime contexts, this manifests in concerns that IMO regulatory processes may not adequately incorporate perspectives from:

- Small Island Developing States particularly vulnerable to climate impacts
- Seafarers and port workers facing transition-related employment changes
- Developing country shipowners with limited access to green finance
- Coastal communities affected by port infrastructure development

4.11.4 Enabling Conditions for Collaboration

The review identified six opportunity categories across 53 of 60 studies:

Table 82: Opportunities for Collaborative Governance (Asio et al., 2026)

Opportunity	Frequency	Maritime Application
Social networks	n=36 (60%)	Industry associations, regional cooperation frameworks
Regular meetings	n=17 (28%)	IMO committee cycles, regional MOU meetings
Commitment among actors	n=15 (25%)	Industry decarbonisation pledges, national NDCs
Local knowledge integration	n=14 (23%)	Operational insights from seafarers, port operators
Legal agreements/ policies	n=13 (22%)	IMO conventions, regional regulations (EU ETS)
Strong leadership	n=11 (18%)	Progressive flag states, industry first-movers

Bridging Actors: The review highlights that "grassroots CSOs and BINGOs often served as bridging actors…linking fishers and government agencies" (Asio et al., 2026). In maritime governance, organisations such as the Global Maritime Forum, International Transport Workers' Federation, and Clean Shipping Coalition serve analogous bridging functions between industry, labour, and regulatory bodies.

Legitimacy: The review emphasises that "legitimacy, defined by balanced representation and the perception that actors receive a 'fair hearing' in decision-making, is essential for sustaining collaboration. Without legitimacy, CG arrangements are likely to collapse" (Asio et al., 2026). This underscores the importance of:

- Inclusive consultation processes at IMO
- Technical assistance programmes for developing country participation
- Recognition of diverse stakeholder interests in regulatory design
- Transparent decision-making procedures

4.11.5 Outcomes and Measurement Challenges

Only 31 of 60 studies (52%) explicitly reported governance outcomes. Social outcomes were more frequently cited than ecological outcomes:

Table 83: Collaborative Governance Outcomes (Asio et al., 2026)

Outcome Type	Category	Frequency
Positive social	Community empowerment	n=12
Positive social	Knowledge sharing	n=7
Positive social	Enhanced social capital	n=7
Positive ecological	Perceived resource improvements	n=7
Positive social	Conflict resolution	n=5
Implementation	Policy impacts	n=5

The review identifies a critical gap: "while half of the reviewed studies mentioned collaborative outcomes, only a few employed standardised measures to link CG to those outcomes explicitly" (Asio et al., 2026). For maritime decarbonisation governance, this suggests need for:

- Clear metrics for evaluating governance effectiveness
- Systematic tracking of both emission reductions (ecological) and stakeholder participation (social)
- Longitudinal assessment of collaborative arrangement sustainability
- Transparent reporting on decision-making inclusivity

4.11.6 Implications for Maritime Decarbonisation Policy

The systematic review offers four principal recommendations applicable to maritime governance:

Power Sharing: "Power should be considered at the outset of any CG initiative…the CG initiators, typically the government or external donors, must actively design and facilitate inclusive processes" (Asio et al., 2026). For IMO processes, this implies:

- Enhanced technical assistance for developing country delegations
- Structured mechanisms for industry and civil society input
- Recognition of structural inequalities in decision-making capacity
- Joint management approaches for regionally-shared infrastructure

Legitimacy: "Policies and agreements should clearly articulate the decision-making rights, roles, and responsibilities of all actors involved" (Asio et al., 2026). This requires:

- Transparent regulatory development procedures
- Clear stakeholder participation pathways
- Explanation of how input influences final decisions
- Regular feedback mechanisms on implementation

Bridging Actors: "Involving CSOs may enhance policy legitimacy and improve local knowledge integration" (Asio et al., 2026). Maritime governance should:

- Strengthen observer organisation participation at IMO
- Support industry knowledge-sharing platforms
- Facilitate dialogue between regulators and operational stakeholders
- Encourage regional cooperation mechanisms

Financial Sustainability: "Governments should institutionalise funding and capacity-building mechanisms that promote continuity and strengthen local ownership of collaborative efforts" (Asio et al., 2026). This encompasses:

- Sustained technical cooperation programmes
- National budget allocations for maritime administration capacity
- Long-term funding for developing country participation
- Incentives enhancing inclusivity and actor diversity

4.11.7 Governance Lessons for Regional Implementation

The collaborative governance literature provides specific guidance for regional maritime decarbonisation efforts:

Regional Cooperation Frameworks: The establishment of collaborative committees such as "Local Fishery Councils" that provide "a space for dialogue, conflict resolution, and information-sharing among fishers and state actors" (Asio et al., 2026) suggests value in regional maritime coordination bodies focused on:

- Green corridor development and governance
- Harmonised bunkering standards and safety protocols
- Shared infrastructure investment planning
- Workforce transition support mechanisms

Community Engagement: Studies finding that "fishing communities contributed by sharing traditional ecological knowledge, participating in rule co-development, and engaging in enforcement activities" (Asio et al., 2026) indicates importance of:

- Port community involvement in alternative fuel facility siting
- Seafarer input on operational implications of new fuels
- Local stakeholder consultation on shore power infrastructure
- Labour organisation engagement on just transition measures

Capacity Building: Given that "once project funding ends, essential activities such as planning, regulatory updates, and rights allocation often discontinue, particularly when governments remain passive" (Asio et al., 2026), regional programmes should ensure:

- Institutionalised training and knowledge-sharing mechanisms
- Permanent technical secretariats for regional cooperation
- Sustainable funding models beyond initial project cycles
- Government ownership of collaborative arrangements

These governance insights complement the technical and economic considerations examined in preceding chapters, emphasising that successful maritime decarbonisation requires not only appropriate technologies and market mechanisms, but also inclusive, legitimate, and sustainable governance arrangements that enable coordinated action across diverse stakeholder groups and jurisdictional boundaries.

4.12 China-Pacific Island Maritime Cooperation and the UN Ocean Decade

The UN Decade of Ocean Science for Sustainable Development (2021-2030) provides a framework for advancing maritime cooperation between major maritime powers and Small Island Developing States (SIDS). Analysis of the China-Pacific Island Countries relationship illustrates how science and technology diplomacy can support maritime sustainability transitions in vulnerable island nations (Mao & Zhang, 2024).

4.12.1 Historical Cooperation Framework

The China-Pacific Island Countries relationship has evolved through three distinct phases, establishing an institutional foundation for maritime cooperation (Mao & Zhang, 2024):

Table 84: Evolution of China-Pacific Island Countries Relations

Phase	Period	Key Developments	Cooperation Scope
Diplomatic Establishment	1970s	China's UN seat restoration; PIC independence movements	Initial diplomatic relations (Fiji, 1975)
Institutionalised Development	2000s	Economic Development Cooperation Forum (2006)	20+ fields including marine environment, disaster prevention
Strategic Partnership	2014-2022	Comprehensive strategic partnership (2018); Community with Shared Future (2022)	Blue Partnership, Belt and Road MoUs

The institutionalisation of bilateral cooperation expanded from initial diplomatic exchanges to encompass "trade and investment, marine environment protection, disaster prevention and mitigation, poverty alleviation and health care" across more than twenty fields of engagement (Mao & Zhang, 2024).

4.12.2 Economic Complementarity in Maritime Development

The bilateral relationship demonstrates significant economic growth potential for maritime cooperation:

Table 85: China-Pacific Island Countries Economic Indicators

Indicator	Value	Period
Trade volume (start)	US$153 million	1992
Trade volume (end)	US$5.3 billion	2021
Average annual growth rate	13%	1992-2021
China gross ocean product	>9 trillion yuan	2021
Ocean product GDP contribution	8.0%	2021
Cooperation fields	20+ areas	Current

The economic complementarity derives from contrasting resource endowments: "There is a high degree of complementarity between the tropical maritime economies of Pacific Island countries and the continental natural endowments of China's economic structure" (Mao & Zhang, 2024). Pacific Island Countries benefit from UNCLOS provisions granting "an exclusive economic zone of 200 nautical miles" containing "abundant biological and mineral resources" (Mao & Zhang, 2024).

4.12.3 UN Ocean Decade and Maritime Sustainability

The UN Ocean Decade framework (2021-2030) provides an organising structure for maritime scientific cooperation:

Vision: "The science we need for the ocean we want"

Key Objectives: - Reverse decline in ocean health - Unite stakeholders for ocean governance - Achieve sustainable development through science-based solutions - Prioritise SIDS, LDCs, and landlocked developing countries

The compatibility between the UN Ocean Decade and China's "Community with a Shared Future" concept reflects their shared emergence from "the era of globalization" with converging development visions focused on "creating a mutually beneficial and sustainable future" (Mao & Zhang, 2024).

4.12.4 Challenges for Pacific Island Maritime Development

Pacific Island Countries face distinctive vulnerabilities affecting maritime development:

Environmental Challenges: - Sea level rise threatening island existence - Tropical cyclones and marine heatwaves - Ocean acidification impacts - Tourism and fishery dependence on marine conditions - "A single large-scale catastrophe can result in damages of nationally significant proportions" (Mao & Zhang, 2024)

Governance Challenges: - Political instability affecting policy continuity - Multiple stakeholder interests in foreign cooperation - Colonial exploitation legacy - Geopolitical competition among major powers

The Boe Declaration recognises that "climate change is the greatest single threat to the survival of island nations, and solutions to ocean problems will depend on the speed of development of ocean science" (Mao & Zhang, 2024).

4.12.5 Science and Technology Diplomacy Pathways

Three pathways for maritime science cooperation emerge from the analysis:

Innovation Cooperation Platforms: - Macro-level planning for cooperation direction - Scientific and technological information resource bases - Incentive policies with funding and technical support - Industry-academia partnerships for technology transformation

Capacity Building and Technology Transfer: - Technology application for climate adaptation - Capacity development for SIDS sustainable development - International obligation fulfilment contributing to UN Ocean Decade vision - China's island and reef construction technology transfer potential

Civil Science and Technology Exchanges: - Complementing official diplomacy through civil society engagement - Young scientist exchange programmes - Overseas Chinese communities as exchange bridges - Private sector participation through strategic incentives

4.12.6 Institutional Frameworks for Maritime Cooperation

Multiple institutional mechanisms support China-Pacific Island maritime cooperation:

International Legal Framework: - UNCLOS Parts 13 and 14: Freedom of marine scientific research - International cooperation and technology transfer principles - Capacity building mandates for developing countries

Bilateral Platforms: - China-Pacific Forum Cooperation Fund - China-Pacific Island Countries Cooperation Center on Climate Change - China-Pacific Island Countries Fisheries Cooperation and Development Forum - Pingtan Declaration (Blue Partnership)

Strategic Initiatives: - Belt and Road Initiative / 21st Century Maritime Silk Road - "2050 Strategy for the Blue Pacific Continent" alignment - Blue economy development cooperation

4.12.7 Implications for Maritime Decarbonisation

The China-Pacific Island cooperation model offers broader implications for maritime decarbonisation:

For Major Maritime Powers: - Science and technology diplomacy as engagement pathway - Capacity building responsibilities toward SIDS - Technology transfer mechanisms within international frameworks - Civil society and private sector mobilisation

For Small Island Developing States: - Leveraging international partnerships for maritime technology access - Regional unity (Blue Pacific Continent) for negotiating strength - Climate adaptation integration with maritime development - Indigenous knowledge integration with modern marine science

For Global Maritime Governance: - South-South cooperation models complementing North-South assistance - UN Ocean Decade as coordinating framework for bilateral/multilateral action - UNCLOS implementation through practical cooperation programmes - Integration of climate and maritime development agendas

The China-Pacific Island case illustrates how science and technology diplomacy can advance maritime sustainability transitions through institutional frameworks that connect major economies with vulnerable island nations, potentially serving as a model for other regional partnerships addressing maritime decarbonisation in the context of climate vulnerability.

4.13 Norwegian Ferry Electrification: Multi-System Transition Dynamics

Norway represents a global frontrunner in maritime electrification, with its ferry sector providing critical insights into the challenges and dynamics of building connections between the maritime transport system and electricity system during low-carbon transitions. By late 2022, 63 electric ferries were operating on 44 of Norway's 133 near-shore car ferry routes, representing the world's most advanced electric ferry deployment (Andersen et al., 2023).

4.13.1 Policy Context and Deployment Timeline

The Norwegian government introduced ambitious climate targets in the early 2010s, including reducing greenhouse gas emissions by at least 40% by 2030. Because Norway already had a low-carbon electricity system with renewables accounting for approximately 98% of electricity generation, policymakers targeted emission reductions in transport and industry via electrification (Andersen et al., 2023).

Table 86 Norwegian Electric Ferry Deployment Timeline

Year	Key Development
2011	NPRA introduces innovation tender for low-carbon ferries
2011-2014	Ampere demonstration project (single pilot)
2015	Parliamentary decision: all ferries zero-emission by 2025
2015-2018	Early deployment phase (tensions emerge)
2018	DSO revenue model review initiated
2018-2022	Diffusion phase with asymmetric adjustments
2021	Grid Development Commission launched
2022	63 electric ferries on 44 of 133 routes

The Ampere demonstration project (2011-2014) used regulatory exemptions and a stationary battery system, avoiding the interface challenges that would later characterise wider deployment. Following its success, the 2015 parliamentary decision demanding all ferries be zero-emission by 2025 led to rapid implementation of emission requirements in procurement tenders (Andersen et al., 2023).

4.13.2 Multi-System Interface Tensions

The transition from diesel to electric ferries required building new nexuses with the electricity system to enable charging of electric ferries. Analysis reveals four dimensions of system interface tensions that emerged during early deployment (2015-2018):

Technology Tensions: Electric ferry charging presents significant technical challenges. Ferry quays are often in remote areas with weak grids, yet require substantial electricity flows—typically 2-4 MW average, sometimes up to 10 MW, over periods of 5-15 minutes. Ferry operators initially preferred direct fast charging from the grid, while Distribution System Operators (DSOs) recommended stationary onshore battery systems to avoid expensive grid upgrades (Andersen et al., 2023).

Significant variation emerged in charging interface technologies: - Automated docking: mechanical, vacuum, and magnetic options - Charging connections: different vessel locations, plug types, and pantographs - Charging technologies: direct fast charging versus stationary battery systems

This lack of standardisation created uncertainties, forcing site-specific solutions with only approximately 3 years from contract award to operational deadline for designing, ordering, and building electric ferries, charging configurations, and grid connections (Andersen et al., 2023).

Institutional Tensions: The DSO revenue model, designed to maximise customers served while minimising capital costs, disincentivised engagement with ferry electrification requiring expensive grid upgrades for few customers. Maritime actors traditionally focused on issues at sea, with the ferry and quay institutionally and organisationally separated—an approach that proved inadequate for the emerging green transformation (Andersen et al., 2023).

Different time frames created additional friction: DSOs operated in multi-year procedures with rigorous cost-efficiency assessments, while maritime actors faced political urgency to meet decarbonisation targets. Regulatory institutions further complicated matters, as ferry operators could only formally order electricity after winning contracts, by which point proper grid planning was often no longer feasible (Andersen et al., 2023).

Actor Coordination Tensions: Ferry operators lacked electricity-related competencies and perceived the charging interface as risky territory. Disagreements emerged over roles and responsibilities: ferry operators thought DSOs should own and operate battery packs as grid extensions, while DSOs showed no interest in operating battery equipment beyond the distribution grid. Limited coordination among 124 regional DSOs led to diverging views on technical specifications, timelines, and feasibility, forcing larger ferry operators to negotiate in parallel with multiple DSOs holding different demands (Andersen et al., 2023).

4.13.3 Asymmetric Adjustments and Workaround Solutions

The diffusion phase (2018-2022) was characterised by adjustment efforts that proved asymmetrical, with maritime actors making significantly more amendments than electricity system actors:

Table 87 Adjustments by System During Ferry Electrification Diffusion Phase

Adjustment Type	Maritime System Actions	Electricity System Actions
Institutional	NPRA changed procurement procedures; lengthened timelines 3→4 years; timetable adjustments	Revenue model review initiated but ongoing; clarification of regulations
Technical	Accepted workarounds (stationary batteries, floating batteries, battery-swapping)	Technical guide development; standards work (slow progress)
Competence	All operators developed electric system competencies; NPRA hired consultants	Limited learning about maritime actors
Coordination	Engaged with DSO procedures; cross-system conferences	Guidelines for large customers (one-directional)

The asymmetry resulted from several factors: the nexus building demand originated from the maritime system under political pressure to achieve decarbonisation goals; DSOs increasingly faced grid connection demands from multiple electrifying sectors, seeing ferry operators as merely one customer among many; and DSOs possessed monopoly power with obligations focused on cost-efficient grid operation rather than rapid nexus building (Andersen et al., 2023).

Because tensions remained unresolved, maritime actors implemented workaround solutions: - Stationary battery pack systems at quays - Floating battery systems where quay space was limited - Battery-swapping experiments (since 2020) - Timetable adjustments—slower sailing and extended charging times to reduce power demands - Scheduling multiple vessels to avoid simultaneous docking and charging

As noted in 2020, "the ship-to-shore [i.e., charging] is the weakest link in the chain for electric ferries" (Andersen et al., 2023).

4.13.4 Implications for Maritime Transitions Theory

The Norwegian ferry electrification case reveals that multi-system interface dynamics differ fundamentally from "normal" transition patterns. In typical transitions, technological variety and disagreement are initially high but reduce through learning and social interactions. However, in multi-system interfaces, tensions are initially low (when symbiotic potential motivates actors) but subsequently grow as the focal innovation diffuses and system interface needs increase (Andersen et al., 2023).

The case also challenges transition theory's assumption that alignment challenges are resolved before mass diffusion. The rapid deployment following only one pilot project (Ampere) compressed the experimentation phase, limiting trial-and-error learning and requiring ferry operators to include immature and uncertain technologies in bids. This temporal compression merged competitive procurement procedures and innovation processes, creating high risks and proposals based on incorrect assumptions about the charging interface (Andersen et al., 2023).

4.13.5 Policy Lessons for Multi-System Nexus Building

The Norwegian experience provides critical lessons for policymakers addressing multi-system interactions in low-carbon transitions:

1. **Anticipate interface importance:** System interfaces become increasingly important as niche innovations diffuse and require more resources from other systems
2. **Enable early learning:** Multiple pilot projects support learning-by-doing before mandating rapid deployment
3. **Address power asymmetries:** If institutions or power imbalances hamper particular actors, consider regulatory or incentive adjustments
4. **Dedicate resources early:** Political attention and investment in interface challenges should precede rather than follow mounting problems
5. **Recognise asymmetry dynamics:** Understand that actors under greater external pressure will likely bear disproportionate adjustment burdens (Andersen et al., 2023)

These findings hold broader relevance beyond ferries, as at least four of six core IEA pathways for net-zero transitions involve extensive multi-system interactions: electrification of transport and industry, alternative fuels for aviation and shipping, carbon capture and storage, and behaviour change including circular economy systems (Andersen et al., 2023).

CHAPTER 5

Future Pathways and Conclusions

5.1 Research Trends and Emerging Topics

Analysis of publication trends from 2000 to 2024 reveals growing research interest in hydrogen and ammonia as maritime fuels, driven by evolving regulatory frameworks and technological advancements. A significant acceleration occurred post-2015, with peak activity in 2023 exceeding 80 publications (Sadiq et al., 2025).

5.2 Fleet Transition Trends and Replacement Challenge

The global shipping fleet is undergoing substantial transformation toward alternative fuel capability. As of 2024, the world fleet comprises approximately 109,000 ships exceeding 100 gross tonnes, of which the vast majority remain reliant on conventional fossil fuels. Alternative fuel propulsion remains limited: 1,239 vessels operate on LNG, 139 on LPG, 35 on methanol, 3 on hydrogen, and only 1 on ammonia (Zincir, 2025). The global cargo-carrying capacity reached 12,292 million tonnes in 2023, representing a 2.4% increase from 2022, with heavy fuel oil (HFO) still commanding approximately 79% of marine fuel consumption (Zincir, 2025).

As of June 2023, vessels capable of operating on alternative fuels account for 5.5% of the in-water fleet by gross tonnage, while representing 47.7% of the global orderbook. The year 2022 witnessed sustained growth in orders for alternative fuel vessels, accounting for 60% of total capacity ordered (Profumo et al., 2025).

Despite these orderbook trends, the current operational fleet remains predominantly reliant on conventional fuels. As of early 2024, only approximately

14% of newly delivered vessels were equipped with alternative fuel capability, highlighting the substantial gap between orderbook composition and actual fleet turnover rates (Lin et al., 2025). This disparity underscores the extended timeframes required for fleet transformation given typical vessel operating lifespans of 15-40 years (Bach & Hansen, 2023). The extended service life of maritime vessels creates path dependencies that render near-term investment decisions critical for achieving mid-century decarbonisation targets; vessels ordered or built today will remain operational through 2050 and beyond.

Current newbuilding rates present a fundamental constraint on transition timelines. In 2022, newbuildings represented only 1.5% of the global fleet of approximately 90,000 large commercial ships, implying that more than 50 years would be required to replace the current fleet at prevailing construction rates (Mahmoudi et al., 2024). This creates a significant gap between the urgency of climate action—with IMO targets requiring substantial emission reductions by 2050—and the historical observation that radical change in socio-technical systems typically requires approximately 50 years. Retrofitting existing vessels with low-emission technologies represents a critical strategy for accelerating the transition without dependence on fleet replacement through newbuilding alone (Mahmoudi et al., 2024).

The scale of required retrofitting is substantial. Approximately 35,000 vessels are projected to undergo retrofits by 2046, with approximately 55,000 ships equipped with two-stroke engines and 30,000 with four-stroke engines requiring conversion to meet evolving regulatory requirements. Risk-based cost-benefit analysis indicates that optimal retrofitting age for VLSFO-to-LNG conversion ranges from 12 to 22 years depending on cost consequence scenarios and vessel CII rating targets. When retrofitting time and shipyard scheduling constraints are considered, optimal retrofit timing extends to 15–22 years for most scenarios (Garbatov et al., 2023).

Optimal retrofitting ship age for dual-fuel conversion (VLSFO to LNG) varies by cost scenario: under low cost scenarios, optimal age is 12 years without retrofit time consideration but extends to 15–17 years when retrofit time is considered; moderate cost scenarios indicate 12–13 years but extend to 16–18 years; high cost scenarios suggest 12–14 years extending to 18–20 years; and extreme cost scenarios indicate 12–15 years extending to 20–22 years when retrofit scheduling constraints are incorporated. Dual-fuel conversion costs approximately €12 million ($12M USD), with the retrofit cost threshold established at no more than 25% of newbuild value (Garbatov et al., 2023).

The evolution of fleet capacity toward alternative fuels demonstrates accelerating transformation: from negligible green and alternative fuel fleet shares in 2009, green fleet share increased to 18% and alternative fuel fleet share to 3% by 2019, with projections indicating 32% green fleet share and 5% alternative fuel fleet share by 2024 (Profumo et al., 2025).

In the container segment, the transformation is particularly pronounced, with 92% of the 2023 orderbook comprising vessels with alternative fuel capability. Only 8% of capacity ordered in the first half of 2023 was allocated to conventionally propelled vessels, down from 14% in the second half of 2022 (Profumo et al., 2025).

The 2023 alternative fuel vessel orderbook demonstrated significant momentum: methanol-powered vessels dominated with 138 orders (concentrated in containerships), ammonia-powered vessels achieved 11 orders (marking the first year with significant ammonia orders), and hydrogen-powered vessels received 5 orders primarily for fuel cell auxiliary power applications (Profumo et al., 2025).

More recent data from the January–October 2024 orderbook period reveals continued acceleration, with 229 LNG-powered vessels, 162 methanol-powered vessels, 47 LPG-powered vessels, 19 ammonia-ready vessels, and 7 hydrogen-powered vessels ordered—demonstrating both the continued prominence of LNG as a transitional fuel and the rapid growth of methanol adoption (Zincir, 2025).

The dominance of methanol in the 2023 orderbook reflects its higher technology readiness level (TRL 9 for two-stroke engines) and more established bunkering infrastructure compared to ammonia (TRL 5–6) and hydrogen (TRL 4). Hydrogen-powered vessels remain limited to fuel cell applications for auxiliary power on cruise ships and main propulsion for short-sea shipping, where range limitations are less constraining (Semchukova et al., 2025).

5.3 Investment Requirements

Decarbonisation of the maritime sector necessitates substantial capital investment. Financing requirements for the fuel transition are projected to increase significantly over coming decades (Profumo et al., 2025):

Table 88 Maritime Decarbonisation Investment Requirements

Period	Annual Investment	Cumulative Investment
2012-2022	~$92 billion/year	-
2023-2033	~$150 billion/year	>$1.7 trillion
To 2050	-	$4.4 trillion

Total investment required to achieve comprehensive industry decarbonisation is estimated at $3 trillion (Drewry, 2023, cited in Profumo et al., 2025).

Systematic review provides additional investment estimates. Achieving a 50% reduction in shipping emissions by 2050 will require an estimated USD 1.4 trillion in total investment. Annual investments in new fuel and engine technologies are projected at USD 8–28 billion, while onshore fuel infrastructure will require USD 28–90 billion annually. The IMO's 2030 target—requiring 5–10% of maritime energy from zero or near-zero emission sources—will necessitate approximately 17 million metric tons of carbon-neutral fuel, representing 30–40% of current global production capacity and emphasising the urgent need for infrastructure scaling (Vakili et al., 2025).

These investment requirements underscore the challenges facing Small Island Developing States (SIDS) and Least Developed Countries (LDCs), where fragmented fleets, thin markets, and limited credit access hinder investment readiness. Blended finance instruments, public-private partnerships, and climate finance mechanisms such as the Green Climate Fund are essential for de-risking investments and supporting infrastructure development in emerging maritime regions (Vakili et al., 2025).

5.4 Key Barriers to Overcome

The transition to low-carbon maritime transport faces several interrelated barriers requiring coordinated attention from industry stakeholders and policymakers. Retrofit costs for existing vessels present a particularly significant challenge; for example, conversion of a 15,000 TEU container vessel to LNG propulsion requires capital expenditure of approximately USD 25-30 million (Lin et al., 2025). These substantial capital requirements, combined with uncertainty regarding future fuel availability and regulatory trajectories, create substantial investment hesitancy among shipowners.

Governance coordination challenges further complicate the transition pathway. The fragmented nature of maritime regulation—spanning international (IMO), regional (EU), and national jurisdictions—creates potential for policy misalignment and regulatory arbitrage. Comparative analysis indicates that while individual policy frameworks demonstrate reasonable internal consistency (PMC scores of 7.6-8.0), inter-jurisdictional coordination mechanisms remain underdeveloped (Lin et al., 2025). Enhanced coordination between international organisations, regional bodies, and national authorities is essential for creating a coherent global framework that provides clear investment signals to industry participants.

The lack of robust bunkering infrastructure remains a significant obstacle compounding the challenges of large-scale deployment of alternative fuels (Sadiq et al., 2025). Current production methods for hydrogen and ammonia rely heavily on fossil fuels, which undermines their net-zero potential until green production capacity scales sufficiently (Sadiq et al., 2025).

Hydrogen infrastructure development faces specific threshold requirements that influence investment decisions. Analysis indicates that permanent hydrogen infrastructure becomes financially justifiable when daily fuel demand exceeds 1,400 kg, with broader supply chain infrastructure investments warranted as demand approaches 5,000 kg per day. On-site electrolysis becomes cost-effective compared to truck delivery when daily consumption exceeds 800 kg/day. A hydrogen refuelling station capable of dispensing 5,000 kg per day requires initial investment of approximately $7.5 million. Hydrogen fuel prices are projected to decline to $4/kg by the mid-2030s, potentially improving economic viability for marine applications (Semchukova et al., 2025).

Green hydrogen production costs demonstrate substantial regional variation, ranging from $3–6 per kilogram globally in 2023. Cost projections indicate potential reduction to below $2 per kilogram by 2030 in regions with favourable renewable energy resources, driven by declining electrolyser capital costs and improved capacity factors. Maritime hydrogen transportation costs are projected to decline from $2.5–4.5/kg (2030) to $0.7–1.6/kg (2050) per 10,000 km of seaborne transport, with pipeline transportation remaining most economical at distances below 500 km at less than $0.1/kg. The convergence of production and transportation cost reductions is essential for achieving commercial viability of hydrogen as a maritime fuel (Jayabal, 2025).

Port-based hydrogen applications demonstrate varying levels of readiness. Fuel cell electric trucks (FCETs) for drayage operations have achieved TRL 7–8, with demonstrated ranges up to 450 miles and refuelling times of 15–20 minutes. Hydrogen-powered cargo-handling equipment remains at earlier stages: terminal tractors and reach stackers at TRL 7, container handlers at TRL 6, and straddle carriers at TRL 5. The first hydrogen fuel cell tugboat is estimated to cost approximately $41.8 million, compared to $20.9 million for conventional diesel—a cost premium expected to decrease to $32.77 million by the 20th vessel through learning curve effects (Semchukova et al., 2025).

5.4a Critical Success Factors for Green Ammonia Adoption

Empirical analysis of expert opinion (n=48) across major maritime stakeholder categories has identified ten critical success factors (CSFs) for green ammonia adoption, revealing structural relationships that indicate which factors must be addressed first to enable achievement of others. Using Interpretive Structural Modelling (ISM), these factors are organised into a five-level hierarchical model based on their driving power and dependency characteristics (Balci et al., 2024):

Level V (Antecedent Factors) – Must Be Addressed First: - Stakeholder support and collaboration - Carbon taxation mechanisms - Public awareness of shipping emissions - Early practical actions by leading companies

Level IV (Linkage Factors) – Bridge Between Antecedents and Outcomes: - R&D in green ammonia - Safety regulations for ammonia as marine fuel

Level III (Secondary Transition Factors): - Development of ammonia-fuelled propulsion systems - Maximising availability of green ammonia supply

Level II (Third-Degree Transition Factor): - Reducing the cost of green ammonia

Level I (Consequent Factor) – Dependent on All Others: - Development of port infrastructure for ammonia supply and delivery

This hierarchical structure reveals that cost reduction—frequently cited as the most important barrier in alternative fuel studies—is actually a dependent factor contingent upon eight antecedent and linkage factors being addressed first. Similarly, port infrastructure development represents the final stage, requiring industry conviction that ammonia represents a viable fuel option before significant port investments can be justified. Green ammonia port infrastructure investments are inherently costly and difficult to reverse due to limited space availability and construction challenges (Balci et al., 2024).

The International Energy Agency projects that ammonia may power up to 45% of shipping by 2050 in a net-zero scenario. Green ammonia is anticipated to become cost-competitive from 2030, with production costs projected at €300–350 per tonne. The Port of Rotterdam plans to establish an import terminal capable of handling 2.5 million tonnes of green ammonia annually from 2024 (Balci et al., 2024).

Engine development progress supports near-term ammonia adoption. MAN Energy Solutions has targeted commercialisation of two-stroke ammonia engines by 2024, while Wärtsilä completed the world's first full-scale ammonia engine test in 2020 through collaboration with Knutsen Shipping, Kelson, the Sustainable Energy Catapult Centre, and the Norwegian Research Council (Balci et al., 2024).

5.4b Technology and Fuel Cost Benchmarks

Comprehensive cost analysis across emission mitigation technologies reveals substantial variation in capital intensity, influencing adoption pathways for different vessel categories and operator types. Technology installation costs demonstrate wide ranges reflecting vessel size, retrofit complexity, and regional factors (Zincir, 2025):

Efficiency Technology Installation Costs:

Table 89 Efficiency Technology Installation Costs

Technology	Cost Range	Notes
Shaft generator	~$400/kW	Moderate cost with fuel savings offset
Propeller optimization	$250,000–$400,000	Implemented during drydocking
Engine modifications	$60,000–$3,000,000	Highly variable by scope
Hull optimization	$150,000–$500,000	Part of scheduled drydock activities
Air lubrication system	€800,000–€2,000,000	Retrofitting varies by hull design
WHRS	$150–$200/kW	Capital-intensive with long-term savings
SCR system	$45/kW	Expensive urea operational costs
Sulfur scrubber	$2–$8 million	Enables continued HFO use
CCS installation	~$660/kW	Very high capital and operational cost
Cold ironing (port berth)	€7.4 million/berth	Requires port-side infrastructure
Renewable energy systems	$200–$600/kW	Wind rotors, kites, solar panels

Alternative Fuel Engine Costs:

Table 90 Alternative Fuel Engine Installation Costs

Engine Type	Installed Cost
Hydrogen ICE	$323/kW
Ammonia engine	$579/kW
Hydrogen fuel cell (with battery)	$719/kW
Methanol engine	$820/kW
LNG engine	$1,268/kW
Small nuclear reactor	$2,850/kW

Current Fuel Prices (2024–2025):

Table 91 Current Marine Fuel Prices (2024–2025)

Fuel Type	Price
Methanol	\$500/ton
Biofuels	\$500–\$1,500/ton
Conventional ammonia	\$600/ton
LNG	\$600/ton
E-LNG	\$1,350–\$3,500/ton
E-methanol	\$1,400/ton
E-diesel	\$1,600/ton
Green hydrogen	\$10,416/ton

These cost differentials fundamentally shape the economics of fuel selection decisions. Alternative fuels produced via renewable electrolysis (e-fuels) command substantial premiums over conventionally produced alternatives—e-methanol at \$1,400/ton versus conventional methanol at \$500/ton represents a 180% premium that must be offset through carbon pricing mechanisms or regulatory mandates to achieve market uptake. Green hydrogen's extreme cost position (\$10,416/ton) explains its current limitation to niche applications despite superior environmental performance (Zincir, 2025).

5.4c Technology Readiness and Cost-Effectiveness by Vessel Size

Technology readiness levels and cost-effectiveness metrics vary significantly across decarbonisation measures, with vessel size determining optimal technology selection. Systematic analysis reveals distinct pathways for different fleet segments (RobaloCabrera2025):

Technology Readiness and Payback by Measure:

Table 92 Technology Readiness and Cost-Effectiveness by Vessel Size

Technology	TRL	CAPEX	Payback	Large (>20k GT)	Medium	Small (<5k GT)
LNG dual-fuel	9	Low–Medium	Short	★★★	★★★	★★
Biodiesel	9	Low	Short	★★★	★★★	★★★
Bio-methanol	7–8	Medium	Medium	★★★	★★★	★★
Green ammonia	5–6	High	Long	★★★	★★	★

Technology	TRL	CAPEX	Payback	Large (>20k GT)	Medium	Small (<5k GT)
Green hydrogen	5–6	High	Long	★★	★★★	★★★
Post-combustion CCS	6–7	High	Long	★★	★★★	★★
Battery-electric	8–9	High	Medium	★	★★	★★★

Cost-effectiveness ratings: ★★★ = High, ★★ = Moderate, ★ = Limited

Operational measures demonstrate immediate applicability across all vessel sizes with minimal capital requirements:

Table 93 Operational Measure Technology Readiness and Applicability

Operational Measure	TRL	CAPEX	Payback	Applicability
Slow steaming	9	N/A	Immediate	All vessel sizes
Route optimisation	9	Low	Short	All vessel sizes
Just-in-time arrival	8	Low	Short	All vessel sizes
Adaptive pitch control	8	Medium	Medium	Medium–Large

Slow steaming delivers proportionally significant emission reductions: 10% speed reduction achieves 16.9–27% emission reduction at $121.2 per tonne CO_2 avoided, while 40% speed reduction achieves 78.4% emission reduction at $287.5 per tonne CO_2 avoided—demonstrating favourable cost-effectiveness compared to fuel switching (RobaloCabrera2025).

Energy efficiency technologies offer the most favourable payback periods among capital-intensive measures. Waste heat recovery systems achieve 16.6% annual fuel reduction, while organic Rankine cycle integration delivers 15–22% efficiency improvements. Air lubrication systems reduce hull-water friction substantially, with fuel savings justifying installation costs over typical operational periods. Battery hybrid systems demonstrate 8.6–20.7% emission reductions for medium vessels when combined with grid charging at ports (RobaloCabrera2025).

Critical implementation gaps persist between technological capability and operational deployment. While 51% of vessels on order incorporate dual-fuel or alternative-fuel capability, this does not guarantee proportional emission reductions without corresponding investments in green fuel supply chains and energy efficiency applications. The review concludes that decarbonisation pathways must be tailored to specific vessel types and operational profiles, as no single solution suits all applications (RobaloCabrera2025).

5.5 Development Timeline and Leading Industry Players

The transition trajectory for maritime decarbonisation spans three temporal phases characterised by distinct fuel and technology priorities (Wang et al., 2024):

Short-term (2018–2030): - Internal combustion engines remain dominant with low-carbon fuels (LNG, LPG, methanol, biofuels) - Experimentation with fuel cell ships and all-electric ships - Initial emission reductions achieved through fuel switching - Focus on mature technologies with established infrastructure

Medium-term (2030–2050): - Expanded low-carbon fuel utilisation with renewable sustainable energy (RSE) production - Increased development of hydrogen and ammonia zero-carbon fuels - Exploration of FC-hybrid and ammonia-hybrid ICE power systems - Growing market share for hydrogen-ammonia pathways

Long-term (after 2050): - Mature zero-carbon fuel power systems achieving complete lifecycle carbon neutrality - Diversification of ship fuels with zero-carbon transition complete - Transition from mechanical propulsion to electric or hybrid propulsion dominant

Regional Leadership:

Regional leadership in maritime decarbonisation demonstrates distinct specialisations: Europe and the US lead in diesel engine expertise, LNG development, and methanol engine technology (MAN, Wärtsilä product lines); Nordic countries specialise in LNG as ship fuel with comprehensive bunkering networks; Japan focuses on hydrogen-diesel dual-fuel systems (exemplified by the Hydro BINGO ferry launched in 2021); South Korea advances pure electric hydrogen vessels such as the Gold Green HYGEN; and the United States develops ammonia-fuelled vessels including the Amogy ammonia tugboat (Wang et al., 2024).

5.5a Green Methanol Cost Competitiveness Timeline

Projections for green methanol production costs indicate substantial reduction potential through technological learning and scale advantages. Average levelised costs for offshore wind-powered green methanol production are projected to decline by more than 50% between 2025 and 2050 (Du et al., 2025):

Green methanol cost projections demonstrate substantial reduction potential, with levelised costs expected to decline by more than 50% between 2025 and 2050: Pure Scenario I (OWF-E + DAC) moves from 1,123.70 €/t in 2025 to 560.07 €/t by 2050 (50.1% reduction), while Mix Scenario III (Grid-E + DAC) declines from 1,077.43 €/t to 529.74 €/t (50.8% reduction) (Du et al., 2025).

This cost trajectory, combined with escalating GHG emission costs for conventional fuels under EU ETS and FuelEU Maritime regulations, creates a convergence point where green methanol achieves cost parity with VLSFO plus associated carbon costs. Analysis indicates green methanol can become cost-competitive with conventional fuels after 2030 and is expected to be uniformly less expensive by 2035 (Du et al., 2025).

Notably, direct air capture (DAC) technology for carbon sourcing is projected to become more cost-effective than industrial carbon capture (ICC) before 2030, despite higher initial capital costs. Under EU regulatory frameworks (CDR II), ICC from power generation combustion is permitted only until 2036, while DAC remains permanently permitted for RFNBO production. This regulatory timeline, combined with cost convergence, favours a hybrid carbon sourcing strategy: utilising ICC as a transitional source (2025–2030) while scaling DAC infrastructure for long-term operations.

Alternative fuel vessels represented 41% of total tonnage in H1 2024 global new orders, with 49 methanol-powered ships ordered during this period. The first green methanol-fuelled container ship refuelling occurred at the Port of Rotterdam on 29 August 2023, marking a milestone in commercial green methanol bunkering operations (Du et al., 2025).

5.5b MCFC Technology Cost Evolution

Molten carbonate fuel cell (MCFC) technology demonstrates significant cost reduction trajectories relevant to maritime carbon capture applications. Analysis of MCFC-based onboard carbon capture systems indicates that MCFC stack costs as a proportion of total system CAPEX have declined from 74% in 2021 to 49% in current estimates—a reduction of one-third reflecting ongoing manufacturing scale-up and technology maturation. This cost trajectory parallels earlier adoption curves observed in PEMFC and SOFC technologies, suggesting continued reductions as production volumes increase (Berry et al., 2025).

The economic case for MCFC-based carbon capture systems strengthens under projected future conditions. System economics are projected to improve with anticipated green methanol price reductions (from current levels around

175 €/MWh toward production cost parity with fossil methanol), increasing carbon prices under EU ETS and emerging carbon pricing mechanisms, and rising demand for high-purity CO_2 streams for carbon utilisation pathways. The MCFC's inherent carbon concentrating capability—achieving 93.2% capture without energy-intensive solvent regeneration—positions this technology favourably compared to conventional post-combustion capture approaches for maritime applications (Berry et al., 2025).

5.5c Technological Innovation Systems for Maritime Decarbonisation

The transition to low- and zero-carbon (LoZeC) maritime technologies requires more than technological advancement—it depends on the formation and functioning of complete innovation systems around new technologies. The Technological Innovation Systems (TIS) framework provides analytical tools for understanding how new technologies develop, diffuse, and overcome barriers to widespread adoption. Applied to maritime battery-electric and hydrogen solutions in Norway, this approach reveals distinct patterns of innovation system maturity and identifies specific weaknesses requiring policy attention (Bach et al., 2020).

TIS Functions Framework:

Innovation systems are evaluated across seven key functions that collectively determine whether a new technology can progress from experimental status to commercial viability:

Table 94 Technological Innovation System Functions

Function	Description	Key Indicators
Knowledge Development & Diffusion	Broadening knowledge base; sharing between actors	R&D projects, publications, patents, network collaborations
Entrepreneurial Experimentation	Real-world trial-and-error testing	Pilot projects, demonstration vessels, business model innovation
Market Formation	Opening space for commercial exchange	Orders, contracts, infrastructure investment
Influence on Direction of Search	Mechanisms guiding resource allocation	Policy targets, regulations, first-mover actions
Resource Mobilisation	Acquisition of capital, competence, assets	Public funding, private investment, workforce development

Function	Description	Key Indicators
Legitimation	Gaining regulatory, normative, cognitive acceptance	Safety approvals, standards development, public acceptance
Development of Positive Externalities	Creating shared system-level utilities	Pooled labour markets, specialised suppliers, shared infrastructure

Norwegian Maritime Sector Context:

Norway's coastal shipping sector provides an instructive case study due to unique geographic circumstances, abundant renewable electricity, and strong policy commitment to maritime decarbonisation. The sector comprises approximately 6,400 vessels—300 freight, 5,000 fishing, 600 offshore supply, and 500 coastal passenger vessels—and accounts for 19% of domestic transport GHG emissions and 10% of national total emissions. The 20,000 km coastline along fiords makes coastal passenger transport essential for connectivity, placing substantial public procurement power in the hands of authorities who can specify emission requirements in tender contracts (Bach et al., 2020).

Battery-Electric TIS Assessment:

The Norwegian battery-electric TIS has matured rapidly, with most innovation system functions now assessed as "strong." Following the 2015 operational debut of M/F Ampere—the world's first full battery-electric car/passenger ferry—70 BE ferries were ordered within five years. Norway now accounts for approximately 40% of global maritime battery installations, with battery module factories established by Corvus and Siemens (combined capacity ~800 MWh) indicating confidence in continued market growth (Bach et al., 2020).

Table 95 Battery-Electric TIS Function Assessment

Function	Assessment	Strengths	Weaknesses
Knowledge Development	Intermediate	Strong national/regional networks; competition drives innovation	Further development needed; upscaling required
Direction of Search	Strong	Clear political goals; renewable electricity access; first movers inspire	Risk of technology lock-in from procurement specifications
Entrepreneurial Experimentation	Strong	Wide-ranging experiments by multiple actor types	—
Market Formation	Strong	Emissions regulations; segment-specific incentives	High risk in long-term procurement contracts
Legitimation	Strong	Successful implementations; relatively complete regulatory framework	Technological uncertainties; standardisation gaps
Resource Mobilisation	Strong	Substantial public and private investment	Complex funding applications; education needs
Positive Externalities	Intermediate	Late-mover advantages; specialised supplier entry	Lack of standards for charging infrastructure

Core strengths enabling BE TIS development include legitimacy derived from successful operational experience, strong political direction through climate policy, substantial market formation through public procurement, and significant resource mobilisation including 1.5 billion NOK from Enova (public support agency) for ship technology plus 665 million NOK for charging infrastructure. The historical precedent of diesel-electric propulsion—in operation since the early 1900s—established technological familiarity that facilitated acceptance of battery-electric systems (Bach et al., 2020).

Hydrogen TIS Assessment:

The hydrogen TIS remains less mature, with all functions assessed as “weak to intermediate.” However, development is accelerating, with development contracts for hydrogen-powered ferries creating momentum analogous to the earlier BE trajectory. High-speed passenger ferries are identified as suitable entry points due to their high energy demands and stringent emission compliance requirements (Bach et al., 2020).

Table 96 Hydrogen TIS Function Assessment

Function	Assessment	Strengths	Weaknesses
Knowledge Development	Intermediate	Regional/national/international network collaboration; increasing R&D	Weak knowledge base; development and upscaling needed
Direction of Search	Intermediate	Political goals; renewable electricity access	Dependent on competing technology status; parallel development hesitance
Entrepreneurial Experimentation	Intermediate	Increasing pilot testing via development contracts	Few actors involved; high development contract risk
Market Formation	Weak	Potential road transport synergies	High fuel prices; limited availability; investment risk
Legitimation	Intermediate	Important actor investments; lobbying; road transport developments	Insufficient rules/regulations; safety classification issues
Resource Mobilisation	Intermediate	Increasing public and private capital	Lack of external investors; personnel education needs
Positive Externalities	Weak	Development contracts implemented	Early phase; non-existent maritime fuel infrastructure

The principal hydrogen TIS weakness is absence of accessible bunker infrastructure. Two development pathways are under consideration: local production at harbours enabling ship-owner fuel self-sufficiency, or large-scale centralised production requiring extensive distribution infrastructure. The lack of safety classifications specific to maritime hydrogen applications increases design costs and certification complexity, as hydrogen vessels automatically receive the strictest security classification due to regulatory gaps (Bach et al., 2020).

Policy Instruments and Their Effects:

Development contracts—state-initiated arrangements providing extra funding for innovation in combination with winning tenders—have proven particularly influential in both TIS. The 2013 development contract leading to M/F Ampere catalysed the BE TIS by demonstrating feasibility and creating operational experience that subsequent entrants could observe. Similar effects are anticipated from hydrogen development contracts targeting operational vessels by 2021 (Bach et al., 2020).

Green public procurement enables public authorities to include emission standards in specifications for ferry tenders, forcing innovation among bidding shipowners who must meet requirements to win contracts. This mechanism has been crucial for the car/passenger ferry segment and could be extended to other segments such as cargo shipping through requirements for LoZeC transport of goods.

Table 97 Norwegian Public Funding for Maritime LoZeC Technologies

Funding Source	Amount	Purpose
Enova	1.5 billion NOK	Ship technology
Enova	665 million NOK	Charging infrastructure
Enova	518 million NOK	Onshore power supply
NOx-fund	119 million NOK	BE and hydrogen technology (prioritised)

The NOx-fund prioritises battery-electric and hydrogen technology when allocating support, providing higher support rates for technologies with greater emission reduction potential. Lower support rates apply to mature technologies such as catalytic systems, whilst full electrification (battery or hydrogen) receives highest support rates (Bach et al., 2020).

Shared System Weaknesses and Policy Recommendations:

Both TIS share several weaknesses requiring coordinated policy attention: (1) continued need for technology development and upscaling; (2) high perceived investment risk among shipowners; (3) potential for technology lock-in from overly specific procurement requirements; (4) limited interaction between BE and hydrogen TIS despite complementary characteristics; and (5) insufficient education for onboard personnel operating new systems (Bach et al., 2020).

Policy recommendations emerging from TIS analysis include: maintaining and expanding funding mechanisms; implementing market stimulation through fossil fuel subsidy removal and CO_2 taxation; designing procurement requirements that minimise negative lock-in effects; creating synergies between BE and hydrogen pathways through joint R&D programmes; developing educational policies for vocational training and on-the-job skill development; and for hydrogen specifically, considering temporary permission for fossil-based hydrogen to increase fuel availability during the transition period (Bach et al., 2020).

Supranational Implications:

The Norwegian experience demonstrates that national policy can drive substantial maritime decarbonisation when sufficient policy leverage exists—particularly through public procurement of domestic transport services. However, national measures alone are insufficient for international shipping. TIS analysis supports recommendations that IMO include CO_2 in coastal emission control areas alongside existing NOx and SOx regulations, and that EU guidelines for green public procurement be extended to include ships alongside other transport modes (Bach et al., 2020).

5.5d Maritime Shipping Decarbonization Roadmap

Alongside technology innovation system analyses, comprehensive roadmapping exercises provide crucial guidance for the maritime sector's transition to zero-emission operations. The development of realistic decarbonization scenarios requires integration of regulatory timelines, technological readiness levels, fuel availability projections, and industry implementation capacity—recognising that shortages in manufacturing, commercialization, and supply of low and zero-emission fuels represent the main obstacles hampering achievement of shipping industry decarbonization targets (Grzelakowski et al., 2022).

Maritime Transport's Global Significance:

Maritime transport constitutes the backbone of the global economy, handling over 82% of world trade volume when measured by tonnes and 92% of global transport performance when accounting for average distances (5,230 nautical miles per tonne). In 2021, approximately 11.1 billion tonnes of goods were carried by sea—representing a 40.5% increase compared to 2010 and nearly 3.9 times the 1990 volume. Seaborne trade has grown at more than 2% annually since 1970, outpacing both global GDP and OECD industrial production growth rates. The sector accounts for approximately 66% of total maritime trade value (USD 14.7 trillion in 2020), with European Union ports processing 90% of EU external freight and embarking/disembarking over 400 million passengers annually (Grzelakowski et al., 2022).

Despite this economic significance, shipping produces only 2.3% of global GHG emissions (0.947 billion tonnes CO_2) and contributes less than 12% of the global transport sector's GHG emissions—which total approximately 7.9 billion tonnes CO_2. This relatively modest contribution, compared to other transport modes, results partly from maritime transport's inherent efficiency. However, projections indicate that without intervention, shipping could represent up to 10% of all global emissions by 2050 (Grzelakowski et al., 2022).

Regulatory Framework Comparison:

The decarbonization pathway is shaped by complementary but distinct regulatory requirements from the IMO and European Union.

Table 98 IMO and EU Regulatory Targets for Maritime Shipping

Regulatory Body	Target Date	Reduction Target	Baseline Year	Additional Specifications
IMO	2030	30% CO_2 reduction	2008	Per transport work basis
IMO	2050	70% CO_2 reduction	2008	Per transport work basis
IMO	2050	50% GHG equivalent	2008	Total emissions basis
EU	2030	55% GHG reduction	1990	European Climate Law target
EU	2050	Climate neutrality	N/A	Net-zero GHG emissions
EU Transport	2050	90% GHG reduction	1990	All transport sector

The IMO has implemented six mandatory requirements addressing GHG emissions: the Energy Efficiency Design Index (EEDI) for newbuilts; the Ship Energy Efficiency Management Plan (SEEMP) for all vessels above 400 GT; the Fuel Oil Consumption Data Collection System (DCS); the Energy Efficiency Existing Ship Index (EEXI) effective from January 2023; the Carbon Intensity Indicator (CII); and strengthened SEEMP with mandatory content for achieving CII targets. The CII rating system operates on a scale from A (best) to E (worst), with vessels receiving D or C ratings for two consecutive years required to achieve at least category C in the following year, facing potential detention if they fail to comply (Grzelakowski et al., 2022).

EEDI Phase-In Timeline:

Phase	Period	Required CO_2 Reduction
Phase 1	2015-2020	10%
Phase 2	2020-2025	20%
Phase 3	2025-2030	30%

Given average ship ages of 24-26 years and EEDI's application only to newbuilts, full fleet coverage under this mechanism will not occur until approximately 2040. Research indicates that EEDI-driven improvements have often been achieved through hull design changes and conventional equipment optimisation rather than through adoption of innovative electrical and mechanical technologies, limiting the mechanism's transformative potential (Grzelakowski et al., 2022).

The EU's "Fit for 55" package (July 2021) establishes more stringent targets. The FuelEU Maritime initiative specifically addresses maritime sector requirements, with proposals for a Renewable and Low-Carbon Fuels Value Chain Alliance (RLCFVCA) to complement the European Clean Hydrogen Alliance and European Battery Alliance. These collaborative platforms aim to integrate shipping representatives, industry actors, public authorities, and civil society in promoting renewable and low-carbon fuel adoption (Grzelakowski et al., 2022).

Classification of Decarbonization Measures:

Decarbonization measures can be classified into three primary categories: technological, operational, and alternative fuels/energy. Each category offers distinct potential for emission reductions, though application varies depending on vessel size, segment, operational profile, and route characteristics.

Table 99 Technological Measures and Potential Fuel Savings

Measure	Potential Savings (%)	Implementation Notes
Light materials	0-10	Material substitution in construction
Slender design	10-15	Up to 25% at 15-16 knots; requires length-hull fullness optimisation
Propulsion improvement devices	1-25	Propeller and appendage optimisation
Bulbous bow	2-7	Hull hydrodynamic improvement
Air lubrication and hull surface	2-9	Active air injection and surface coatings
Waste heat recovery	0-4	Heat exchanger systems

Slender hull designs, characterised by lower block coefficients, can achieve fuel consumption reductions of 10-15% at lower speeds and up to 25% per nautical mile at 15-16 knots. However, this requires altering ship length-to-hull fullness ratios, which can limit operator willingness to undertake such renovations due to expense (Grzelakowski et al., 2022).

Table 100 Operational Measures and CO_2 Reduction Potential

Measure	Potential Reduction (%)	Implementation Characteristics
Speed reduction	0-60	Highest single-measure potential; affects transit time
Ship size optimisation	0-30	Also functions as technical measure; affects capacity utilisation
Ship-port interface	1	Operational coordination improvements
Onshore power (cold ironing)	0-3	Eliminates auxiliary engine emissions at berth

The speed-power relationship follows a cubic function, with power demand proportional to the third power of vessel speed. Halving vessel speed theoretically reduces power demand eightfold, though actual fuel savings are typically 1.8-3.3 times due to other operational factors. This relationship underpins the slow steaming argument: a 20% reduction in ship speeds can save approximately 32-40% of CO_2 emissions and fuel consumption (Grzelakowski et al., 2022).

However, systematic review indicates that the traditionally assumed cubic relationship between ship speed and fuel consumption is not entirely accurate—the actual speed–power exponent is typically lower than 3, suggesting that slow steaming emission reduction benefits may be less significant than anticipated. Precise speed optimisation models incorporating weather forecast information achieve 7.34% fuel consumption reduction compared to constant-speed strategies, with dynamic integration of meteorological data enhancing both practicality and predictive accuracy of operational planning (Xu & Chen, 2025).

Table 101 Alternative Fuels and Energy Sources: Emission Reduction Potential

Fuel/Energy Source	Potential CO_2 Reduction (%)	Remarks
Advanced biofuels	25-100	Depends on feedstock and production pathway
LNG	0-20	Transitional fuel; methane slip concerns
Hydrogen	0-100	100% only if produced from renewable energy
Ammonia	0-100	100% only if “green” ammonia
Fuel cells	2-20	Efficiency gains in energy conversion
Electricity	0-100	100% only if from renewable sources

Fuel/Energy Source	Potential CO_2 Reduction (%)	Remarks
Wind assistance	1-32	Route and weather dependent
Solar	0-12	Limited by vessel surface area
Nuclear	0-100	Regulatory and public acceptance barriers

The 100% reduction potential for synthetic fuels and electricity can only be achieved when produced from renewable energy sources. Current low-carbon fuel penetration remains minimal: only 0.1% of energy consumed in shipping comes from low-carbon sources according to the International Energy Agency. Projections indicate that alternative fuels may comprise less than 3% of shipping energy by 2030 and less than 33% by 2050—far below requirements for achieving net-zero targets (Grzelakowski et al., 2022).

Fuel Energy Density and Storage Implications:

A critical factor in fuel transition is the significantly different energy densities and storage requirements of alternative fuels compared to conventional marine fuels. These differences directly impact vessel design, particularly for ocean-going ships requiring 30-45 days of operational autonomy.

Table 102 Marine Fuel Energy Capacity Comparison (HFO = 1.0)

Fuel Type	Density (kg/m³)	LHV (MJ/kg)	Energy Capacity Factor	Factor with Tank Insulation*
Heavy Fuel Oil (HFO)	940	39	1.000	—
Marine Diesel Oil (MDO)	870	41.5	1.015	—
Marine Gas Oil (MGO)	840	43	1.015	—
Biodiesel	880	37.2	1.120	—
Renewable diesel	780	44.1	1.066	—
FAME	765	43	1.206	—
Methanol	794	22	2.099	—
Ethanol	789	28	1.660	—
Ammonia	682	18.6	2.890	3.468
Propane (LPG)	493	46.6	1.596	2.075
Methane (LNG/SNG)	460	50	1.594	2.551
Liquid hydrogen	71	120	4.303	8.606

Thermal insulation multipliers: ammonia ×1.2; propane ×1.3; methane ×1.6; hydrogen ×2.0

The energy capacity factor indicates the relative tank volume required to store equivalent energy compared to HFO. For liquid hydrogen, the energy capacity factor reaches 8.606 when accounting for tank insulation and shape requirements—meaning hydrogen storage requires approximately 8.6 times the volume of HFO for equivalent energy content. These storage requirements present fundamental design challenges for vessel retrofit and newbuild programmes (Grzelakowski et al., 2022).

Global Fuel Demand Equivalents:

Current global bunker demand approximates 370 million tonnes annually. Meeting equivalent energy requirements with alternative fuels would require:

Alternative Fuel	Required Volume (Million Tonnes)	Current Global Production	Production Gap
LNG	324	Adequate	Infrastructure-limited
LPG	338	Adequate	Limited maritime application
Methanol	777	~100 Mt	Significant gap
Ethanol	600	~100 Mt	Significant gap
Ammonia	835	144 Mt (2020)	Severe gap (6× production needed)

Ammonia presents a particularly challenging case: global production in 2020 totalled only 144 million tonnes (38 million tonnes in China), produced mainly from natural gas. Current ammonia production accounts for approximately 1% of global CO_2 emissions. Producing 835 million tonnes of ammonia for shipping using current production technology would generate 5.8% of global emissions—more than double shipping's current total contribution (Grzelakowski et al., 2022).

R&D Investment Trends and Gaps:

Corporate R&D investment in innovative maritime technologies has declined significantly, from USD 2.7 billion in 2017 to USD 1.6 billion in 2019. This trend has prompted proposals for an IMO Maritime Research Fund (IMRF) of USD 5 billion, raised through mandatory R&D contributions from shipping companies starting from 2023. The proposed fund could triple current R&D spending levels and create opportunities for enhanced public-private partnerships in developing zero-carbon emission technologies (Grzelakowski et al., 2022).

Industry Expert Perspectives:

Consultations with maritime industry experts using the Delphi technique—involving representatives from leading container shipping companies and the Polish Ship Classification Society (PRS)—revealed significant uncertainty regarding optimal decarbonization pathways. Key findings include:

1. Individualized approaches to decarbonization among shipowners, with significant differences in preferred pathways
2. High investment risk in tonnage renewal and propulsion source selection
3. Inability to develop long-term decarbonization strategy given current fuel availability uncertainties
4. Expert consensus that LNG and methanol represent the most effective and promising transition fuels through 2030-2035
5. Agreement that both operational/technical measures AND alternative fuels are necessary (Grzelakowski et al., 2022)

Industry Case Studies:

Leading container operators demonstrate varying approaches to decarbonization targets:

Maersk (March 2022): Established strategic partnerships with six companies to acquire green methanol (bio-methanol and e-methanol) at scale. Targets include 700,000 tonnes of green methanol by 2025 and 1.2 million tonnes beyond 2025. However, context is important: if all shipping converted to methanol, approximately 777 million tonnes would be required—far exceeding projected production capacity (Grzelakowski et al., 2022).

MSC: Outlined three decarbonization routes in response to the European Green Deal: - Fleet management and voyage plan optimisation: up to 5% reduction - Machinery efficiency and wind assistance: up to 30-55% reduction - Alternative fuels: LNG (up to 10%), biodiesel (up to 100%), electric battery/hydrogen fuel cells (up to 100%), ammonia/hydrogen (up to 100%)

These industry commitments, while ambitious, highlight the gap between operator aspirations and the fuel supply infrastructure required to achieve them (Grzelakowski et al., 2022).

2050 Fuel Scenario Projections:

Based on expert consultations and market analysis, a potential roadmap for marine fuel distribution through 2050 suggests:

Period	Conventional Fuels	LNG/Bio-LNG	Methanol/ Bio-Methanol	Ammonia	Hydrogen	Electricity
2020 (baseline)	~97%	~3%	Minimal	Minimal	Minimal	Minimal
2030	Declining	Growing significantly	Emerging	First applications	Pilots	Short-sea only
2040	Reduced	Substantial	Growing	Commercial deployment	Beginning commercial	Expanding
2050	Substantially reduced	Mature	Mature	Significant share	Significant share	Established

However, projections indicate alternative fuels may still comprise less than 33% of total shipping energy by 2050—substantially below requirements for achieving climate neutrality. Neither the IMO nor any other international organization has specified a definitive route for the transition to alternative and target fuels, leaving shipowners to assume investment risk without certainty regarding the correct pathway (Grzelakowski et al., 2022).

Critical Success Factors:

Achievement of decarbonization targets will require: 1. Integration of multiple measure types—no single measure can achieve required reductions alone 2. Enhanced public-private partnerships for technology development and deployment 3. Coordination among all parties in the fuel production and distribution chain 4. Alignment with circular economy principles for sustainable supply chain transformation 5. Regulatory clarity from IMO and regional authorities on preferred transition pathways 6. Massive scaling of alternative fuel production capacity 7. Development of global bunkering infrastructure for new fuel types 8. Resolution of vessel design challenges for low-energy-density fuels

The roadmap analysis demonstrates that while technical solutions exist, the primary constraint on maritime decarbonization lies in the manufacturing, commercialization, and supply of low and zero-emission fuels to the shipping market. Coordinated policy action across multiple jurisdictions, combined with unprecedented levels of investment in fuel production infrastructure, will be essential to overcome these obstacles (Grzelakowski et al., 2022).

5.6 Recommended Policy Actions

A collaborative, multi-stakeholder approach involving policymakers, industry leaders, and academia is essential for addressing decarbonization challenges. Investments in infrastructure, safety protocols, and hybrid systems, along with international collaboration and targeted funding, can accelerate the transition to zero-carbon fuels (Sadiq et al., 2025).

Game Theory-Based Policy Design:

Evolutionary game analysis of trilateral interactions among governments, port authorities, and shipping companies provides evidence-based guidance for policy formulation. Key recommendations emerging from game-theoretic studies include:

Subsidy Design and Phase-Out Strategy: Government subsidies prove critical in offsetting initial high costs and shifting stakeholder behaviour toward active emission reduction strategies. However, the manner of subsidy adjustment significantly affects policy outcomes. Gradual subsidy phase-out produces smoother convergence toward active strategies, minimising disruption and sustaining momentum in green investment. Abrupt subsidy termination introduces sudden cost burdens causing temporary destabilisation of strategic equilibria, with delayed or reduced convergence toward active emission reduction—particularly among shipping companies with capital constraints (Ruslan et al., 2025).

Penalty Mechanism Effectiveness: Dynamic penalty mechanisms demonstrate significantly greater influence on shipping company transition decisions than subsidy mechanisms alone. Regulatory frameworks combining adaptive penalty structures with targeted subsidies achieve superior outcomes compared to either approach in isolation. Penalty intensity should vary with enterprise transition behaviour, producing spiral convergence toward evolutionarily stable strategies regardless of initial conditions (He et al., 2024; Ruslan et al., 2025).

Stakeholder Coordination Requirements: The interdependence of government actions, port operations, and shipping company decisions necessitates coordinated approaches. Port authorities must align infrastructure investments with shipping company operational strategies, whilst governments provide regulatory certainty and financial support mechanisms. Public-private partnerships facilitate shared investments in infrastructure projects, technology upgrades, and regulatory compliance measures—distributing costs effectively whilst maximising collective environmental and economic benefits (Ruslan et al., 2025).

Economies of Scale Encouragement: Cost functions incorporating economies of scale [$C(n) = C_0 \times n\,\hat{}\,(-\alpha)$] reveal that per-unit costs decline as adoption expands. Policies should therefore prioritise early adoption incentives to trigger cost reduction cascades, recognising that initial investments generate compounding benefits as market scale increases. This approach reflects empirical trends in LNG bunkering, shore power facilities, and alternative fuel vessel retrofitting where infrastructure development leads to progressive cost reductions (Ruslan et al., 2025).

Tiered Regulatory Mechanisms: Developing maritime nations face greater financial constraints than established shipping centres, requiring tiered regulatory approaches that reflect varying investment capacities and infrastructure readiness. Phased transitions from voluntary to mandatory compliance can accommodate economic development disparities whilst maintaining progress toward emission reduction objectives (Ruslan et al., 2025).

5.7 Transition Scenario Projections

Agent-based modelling of shipping industry transitions provides insight into potential decarbonisation pathways under different policy scenarios. The MATISSE-SHIP model, which simulates technology diffusion based on the Multi-Level Perspective framework, evaluates how retrofitting strategies could accelerate the transition from conventional propulsion to low-carbon alternatives (Mahmoudi et al., 2024).

Simulation results indicate that the effectiveness of retrofitting varies substantially across policy scenarios:

Table 103 Transition Scenario CO_2 Savings Projections

Scenario	CO_2 Savings (2015-2050)	Key Characteristics
Business as Usual	3.3 billion tonnes	No global measures; HFO/diesel below 50% share three years earlier
Out of Control	2.3 billion tonnes	Climate initially ignored; wind eventual growth
Regulation-Driven	9.3 billion tonnes	Aggressive policy action; highest savings; wind-assisted reaches 28% share
Radical Change	7.2 billion tonnes	Strong international response; HFO/diesel below 50% six years earlier

The regulation-driven scenario demonstrates the highest emission reduction potential because retrofitting represents a supply-oriented solution that aligns effectively with supply-side policy measures. Under this scenario, stringent GHG regulations and carbon taxation on fossil fuels reduce the market share of conventional low-sulphur diesel after initial adoption as a transitional measure. Wind-assisted and power-to-liquid (PtL) technologies gain increasing market share, while LNG competitiveness diminishes due to volatile gas market prices that have increased production costs for non-diesel fuels since 2020 (Mahmoudi et al., 2024).

These findings underscore that policy design significantly influences transition pathways. Geopolitical risks affecting the accessibility and affordability of alternative fuels must be considered in policy formulation, and sufficient incentives are required to develop reliable alternative fuel supply chains (Mahmoudi et al., 2024).

5.8 Vision for Sustainable Maritime Transport

The pathway to maritime decarbonisation remains characterised by uncertainty, with technology, regulation, and geopolitical factors all influencing outcomes. Unlike road and rail transport where electrification pathways are relatively clear, maritime transport case scenarios are less predictable. Multiple solutions are being studied and refined, though none offers certainty regarding long-term applicability. Different pathways will emerge depending on traffic patterns and contingent circumstances, with strong initial dependence on bunkering facilities available at ports of call (Profumo et al., 2025).

Projections for the 2050 marine fuel mix indicate continued diversity of energy sources rather than convergence on a single solution. Liquid fuels are expected to contribute more than 40% of marine energy requirements through 2050, whilst ammonia and hydrogen combined are projected to provide approximately 40% of requirements by mid-century. This diversified fuel landscape reflects the varying operational requirements across vessel types and trade routes, as well as regional variations in fuel availability and infrastructure development (Palaniappan & Vedachalam, 2022).

Industry surveys of senior shipping leaders reveal temporal priorities in fuel switching strategies. In the near term (next 5 years), LNG/LPG/CNG ranks first, followed by biofuels, battery packs, and shore power. In the medium term (next 10 years), hydrogen and ammonia are expected to rise in importance, with hydrogen ranking third and ammonia fourth among preferred fuel options. This progression reflects both the current state of technology readiness and anticipated infrastructure development trajectories (Palaniappan & Vedachalam, 2022).

Global methanol production capacity is projected to expand substantially in support of the maritime energy transition. According to Methanol Institute projections, production capacity is expected to reach 500 million tonnes by 2050, with approximately 80% comprising synthetic green methanol and bio-methanol (Meyer-Larsen & Schories, 2025). This expansion from current predominantly fossil-based production to renewable feedstocks represents a fundamental shift in the methanol supply chain necessary to realise the fuel's decarbonisation potential.

The transition requires investment of approximately US$1.5 trillion through 2050, encompassing sustained innovation in fuel production and handling systems, policy frameworks that provide clear investment signals, vessel adaptation costs, and development of global bunkering infrastructure. Realising the transition will depend upon effective coordination among regulatory agencies, classification societies, ship designers and builders, fuel producers, port operators, and vessel operators. While some fuels currently under development may prove to be intermediate solutions, they remain essential components of the industry's journey toward a carbon-neutral future (Palaniappan & Vedachalam, 2022).

Alongside slow steaming, retrofitting with energy-saving technologies, fleet renewal, and route optimisation, the role of alternative fuels will constantly increase. The transition to zero-impact fuels has commenced, requiring coordinated efforts among the various players in the maritime and port cluster to address the challenges of a scenario characterised by multiple uncertainties (Profumo et al., 2025).

5.9 Sustainable Maritime Transport Optimization: State of Research

A systematic review of sustainable maritime transport optimization and operations research reveals the multidimensional nature of the decarbonisation challenge across technology, management, and policy domains (Xu & Chen, 2025). Analysis of 202 publications from 2015-2025 demonstrates that technical studies comprise approximately 45% of the literature, management studies approximately 37%, and policy studies approximately 17%, reflecting the continued emphasis on technological solutions while management and policy research remains comparatively underdeveloped.

5.9.1 Alternative Fuel Technology Assessment

Comprehensive assessment of alternative marine fuels reveals significant trade-offs across energy density, cost, technical maturity, and infrastructure requirements:

Table 104: Alternative Marine Fuel Characteristics

Fuel Type	Energy Density (kWh/kg)	Cost Level	Technical Maturity	Key Emission Characteristics
LNG	13.9–15.6	Medium (economies of scale potential)	Mature, widely commercialised	CO2 ~20-25% lower than HFO; methane fugitive issues
Methanol	5.5–6.1	Moderate, easy transport	High commercial maturity	Green methanol carbon neutral; fossil methanol not zero-carbon
Hydrogen	33.3	High (LCOH EUR 16.77/kg for green LH2)	Pilot phase; storage/ combustion challenges	Zero carbon combustion; NOx risk
Green Ammonia	5.2–5.5	High; requires policy support	Maturing; combustion control issues	Zero CO2; combustion produces NOx
Blue Ammonia	5.2–5.5	Medium to high	Relatively mature pathway	Reductions depend on CCS effectiveness

Hydrogen cost projections demonstrate significant variability depending on production technology: proton exchange membrane electrolysis ranges from USD 5.3 to USD 9.29 per kilogram, alkaline electrolysers from USD 7.49 to USD 7.59 per kilogram, and solid oxide electrolysers from USD 6 to USD 9.34 per kilogram with potential future reduction to USD 1.9 per kilogram (Xu & Chen, 2025). Wind speed and other environmental parameters significantly affect cost fluctuations, with levelised cost of hydrogen potentially ranging from USD 1.7 to USD 40.0 per kilogram depending on conditions.

Methanol demonstrates compliance limitations: while meeting EEDI and CII requirements through 2025, compliance "will expire around 2028" without renewable pathway support (Xu & Chen, 2025). This highlights the transitional nature of some alternative fuel solutions.

5.9.2 Energy Efficiency and Operational Optimization

Research on ship fuel consumption prediction has evolved through three modelling approaches: - **White Box Models:** Physics-based with good interpretability but poor adaptability under complex sea conditions - **Black Box Models:** Data-driven with enhanced accuracy but dependent on data quality and lacking interpretability - **Grey Box Models:** Combining physics and data approaches to achieve both accuracy and interpretability

A significant finding challenges conventional assumptions about speed optimization: "The traditionally assumed cubic relationship between ship speed and fuel consumption is not entirely accurate. The actual speed–power exponent is typically lower than 3, suggesting that the emission reduction benefits of slow steaming may be less significant than anticipated" (Xu & Chen, 2025). This has important implications for emissions reduction strategies relying on speed reduction.

Table 105: Operational Optimization Achievements from Literature Review

Optimization Area	Achievement	Method
Shore power pollutant reduction	7.31%	NSGA-III + TOPSIS
Shore power operational efficiency	11.46% improvement	Multi-objective optimization
Hybrid RTG emissions	Up to 82.17% reduction vs diesel	Energy recovery systems
Fuel consumption (weather-integrated)	7.34% reduction	Dynamic meteorological integration
Port delay (ballast water integration)	20.84% reduction	Integrated vessel traffic scheduling
Port stay time	9.42% reduction	Intermediate pumping strategy

5.9.3 Policy Framework Evolution

The regulatory landscape has intensified with multiple overlapping mechanisms: - **EEXI and CII:** Effective from 1 January 2023, with stricter CII requirements leading to "reduced cargo loads, shorter ballast voyages, and slower speeds, resulting in lower CO2 emissions but also decreased total profits" (Xu & Chen, 2025) - **EU ETS:** Maritime transport included from 2024, with potential side effects including detours that could increase overall emissions - **Flexible Compliance Mechanism (FCM):** Scheduled for 2027, allowing emissions offset through Flexible Compliance Units

Market-based measure research indicates that "taxation on emissions exceeding threshold outperforms carbon-based taxation" (Xu & Chen, 2025). However, policy effectiveness varies significantly by maritime route and vessel type, with progressive taxation promoting green maritime transport more effectively than fixed taxation in some contexts while showing limited applicability in others.

Government subsidy research using evolutionary game analysis demonstrates that "regardless of initial strategies, ports were inclined to adopt shore power facilities when incentivized by subsidies" (Xu & Chen, 2025). However, information asymmetry and inadequate policy stability may weaken subsidy effectiveness, requiring greater policy transparency and coordination.

5.9.4 Future Research and Technology Directions

Three emerging technology areas offer potential for advancing sustainable maritime transport:

Blockchain Technology: - Applications include transaction record keeping, supply chain traceability, and blockchain-driven incentive systems - Challenges include "insufficient high-level support, weak coordination mechanisms, the absence of trust frameworks, and high costs" (Xu & Chen, 2025) - Scalability constraints due to energy-intensive consensus mechanisms remain significant barriers

Big Data Analytics: - Applications span shipping management, vessel scheduling, safety assurance, and port operations - Challenges include lack of technical standards, data barriers, and insufficient coordination mechanisms - Potential for enhanced accident response transparency and collective situational awareness

Sixth-Generation Ports (6GP): - Key enabling technologies: AI, blockchain, Internet of Things, and cloud systems - Focus areas: digital transformation, low-carbon development, and system resilience - Transition from 5GP to 6GP forms foundation for resilient logistics networks and sustainable operations

5.9.5 Research Gaps and Synthesis

The literature review identifies critical gaps requiring attention:

Technical Level: - No unified modelling paradigm or evaluation framework for sustainable maritime transport technologies - Limited system integration studies, particularly for coupling alternative fuels with navigation strategies, port scheduling, and energy management - Most studies assume deterministic conditions with inadequate uncertainty modelling

Management Level: - Theoretical framework for sustainable maritime operations management remains preliminary - Green management treated primarily as extension of operational optimization rather than systematic mechanism construction - Limited introduction of fuzzy parameters or stochastic optimization in decision-making models

Policy Level: - Focus primarily on short-term effects on individual firms or specific technologies - Limited systematic investigations of multi-level policy synergies - Insufficient structural comparisons addressing diverse vessel types, routes, and supply chain configurations

Emerging Technology Integration Gaps:

Bibliometric analysis of 210 papers (2011-2024) reveals significant underexploration of emerging digital technologies within maritime decarbonisation research. While ship-network optimisation represents the largest thematic cluster with 50 papers, the integration of advanced digital technologies remains limited: "While novel technologies like AI and blockchain have been integrated into various sectors, there is a dearth of papers within the ship-network optimization domain that leverage AI or blockchain to optimize shipping routes" (Tran et al., 2025). This gap represents a critical opportunity for interdisciplinary research combining maritime operational efficiency with digital transformation capabilities.

The distribution of research attention across technology categories also reveals potential blind spots. Alternative fuels dominate with 40.95% of publications, while carbon capture technologies receive only 5.71% and renewable energy applications only 4.76%—despite their potential contribution to transition pathway diversification. LNG research should be viewed as transitional, with longer-term focus shifting towards synthetic fuels, ammonia, and hydrogen (Tran et al., 2025).

The collaborative governance system model—integrating "government regulation—corporate responsibility—social supervision"—emerges as essential for achieving systematic decarbonisation. Success depends on cooperation among governments as policymakers, ports as supply chain nodes, vessel operators optimizing operations, industry associations representing corporate interests, NGOs providing cross-sector data, and technical standard-setting institutions promoting emerging technologies (Xu & Chen, 2025).

5.9.6 Artificial General Intelligence Governance for Maritime Systems

As artificial intelligence systems evolve towards artificial general intelligence (AGI) and become increasingly embedded in maritime technologies, new ethical, legal, and operational challenges emerge that require proactive governance frameworks (Portillo Juan et al., 2025). A comprehensive review of 270 maritime AI papers reveals the sector stands at a critical juncture where governance mechanisms must anticipate rather than merely respond to technological advancement.

Governance Framework Components:

Table 106: AGI Governance Framework for Maritime Systems

Governance Element	Implementation Requirements	Stakeholders
Regulatory Standardization	Clear guidelines for AGI development, deployment, and operation; certification requirements; performance benchmarks	IMO, regional regulators, classification societies
Human Oversight Mechanisms	System design preventing "black box" decision-making; human-in-the-loop validation for critical decisions; override capabilities	Ship operators, crew, safety authorities
Explainable AI (XAI) Implementation	Interpretable outputs for safety-critical operations; transparent reasoning for collision avoidance, fault detection, autonomous routing	System developers, certification bodies
Ethical Frameworks	Guidelines accounting for maritime-specific moral dilemmas; autonomous vessel collision scenarios; liability allocation	Maritime law bodies, insurers, operators
Adaptive Governance	Regular reviews and updates as technology evolves; international harmonization; flexible regulatory mechanisms	IMO, national administrations, industry associations

The International Maritime Organization, in collaboration with regional regulators and classification societies, should assume a leading role in formulating AGI standards for maritime applications. For AI to be trusted and deployed in safety-critical maritime operations—including collision avoidance, fault detection, and autonomous vessel routing—systems must provide interpretable outputs that enable human oversight (Portillo Juan et al., 2025).

Future AI Technology Trajectories:

Table 107: Emerging AI Directions for Maritime Decarbonisation

Technology Direction	Maritime Applications	Decarbonisation Contribution
Hybrid AI Models	Combining physics-based models with data-driven approaches; enhanced prediction accuracy	Optimised fuel consumption through improved weather routing and voyage planning
Advanced Reinforcement Learning	Autonomous navigation, vessel control, real-time operational optimization	Continuous efficiency improvements; adaptive speed optimization
Transformers and Attention Networks	Sequential data analysis, predictive maintenance, demand forecasting	Reduced unplanned maintenance; optimised fleet deployment
Digital Twin Integration	Real-time vessel simulation, predictive analytics, scenario testing	Virtual testing of efficiency measures; reduced physical prototyping
Federated Learning	Distributed model training across fleets; privacy-preserving data sharing	Industry-wide efficiency gains without compromising commercial sensitivity

The trajectory from narrow AI applications towards more generalised systems represents both opportunity and challenge for maritime decarbonisation. Reinforcement learning has emerged as particularly transformative for autonomous navigation and vessel control, enabling real-time optimization that traditional algorithmic approaches cannot achieve. However, realising this potential requires governance frameworks that balance innovation with safety, transparency, and accountability (Portillo Juan et al., 2025).

5.9.7 Global Research Landscape and Implementation Barriers

Bibliometric analysis of 714 publications on ship emission reduction technologies (2000-2024) reveals substantial growth in research activity and distinct geographic patterns of intellectual contribution. Publication volumes maintained steady upward trends from 2009 to 2016, accelerating significantly from 2017 onwards following the IMO's 2016 confirmation of the 2020 global sulfur limit. The period 2021-2024 accounts for approximately 60% of total research output, indicating intensified academic attention as policy deadlines approached (Bai et al., 2025).

Table 108: Global Research Productivity in Ship Emission Reduction Technologies

Country	Publications	Share (%)	Cooperation Network
China	287	40.20%	24 countries, link strength 94
South Korea	58	8.12%	Regional focus
United Kingdom	44	6.16%	12 countries (8 European)
United States	43	6.02%	16 countries, link strength 34
Sweden	39	5.46%	16 countries, link strength 32

China's research dominance reflects "strategic support and policy drive at the national level, as well as the deep cooperation between universities and enterprises, forming a complete chain of 'university technology research - enterprise engineering application'" (Bai et al., 2025). However, cooperation patterns reveal regional clustering: European countries maintain closer intra-regional collaboration, while intercontinental partnerships remain underdeveloped outside China's extensive network.

Implementation Barriers:

Table 109: Barriers to Ship Emission Reduction Technology Deployment

Barrier Category	Magnitude	Implications
Investment requirement	~$2 trillion (Citibank estimate)	Significant burden for shipping companies; delayed technology adoption
Infrastructure vicious cycle	<200 of 6,000 ports provide shore power	No investment → No infrastructure → No adoption loop
Talent shortage	Global shipbuilding sector	Insufficient composite talent combining manufacturing and green technology skills
Technology uncertainty	Multiple competing pathways	Companies wait for cost reduction and maturity before adoption

The infrastructure investment challenge creates a self-reinforcing barrier: "If companies do not use new technologies, ports are also reluctant to invest in infrastructure that matches these new technologies, and the lack of infrastructure further discourages companies from investing, creating a vicious cycle" (Bai et al., 2025).

Technology Prioritization Framework:

Research synthesis identifies green power technologies as highest priority due to their direct pathway to IMO 2050 carbon neutrality goals, low technological lock-in risk, and significant long-term benefits. Digital intelligence technologies receive moderate prioritization—optimizing existing system efficiency yields quick short-term results but cannot independently resolve the emission problem. Emission reduction technologies (scrubbers, shore power, carbon capture) similarly receive moderate priority as end-of-pipe control measures effective for retrofitting existing fleets but potentially subject to obsolescence with the energy transition (Bai et al., 2025).

Financing mechanisms offer potential solutions to overcome investment barriers. Green credit, green bonds, and other financial instruments can provide shipping companies with diversified financing channels and reduced financing costs. In June 2022, the International Finance Corporation (IFC) reached a cooperation agreement with Qingdao Bank in China to provide a $150 million blue syndicated loan specifically for marine-friendly projects—demonstrating demand for alternative financing mechanisms that support low-carbon retrofitting processes (Bai et al., 2025).

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_2eq	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 (NH_3) 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 CO_2, 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 CO_2 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 CO_2) 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 CO_2 or CO_2-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 CO_2 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 CO_2 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 (H_2) 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 (≤0.50% globally, ≤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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