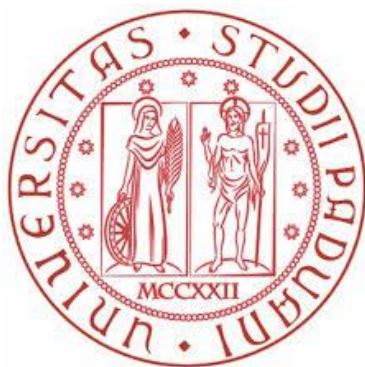




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**CORSO DI LAUREA MAGISTRALE IN SUSTAINABLE CHEMISTRY AND
TECHNOLOGIES FOR CIRCULAR ECONOMY**

TESI DI LAUREA MAGISTRALE

**Towards Zero-Emission Shipping: Emerging Innovations
and Regulatory Frameworks Supporting Sustainable
Development in the Maritime Sector**

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ANNO ACCADEMICO 2025/2026

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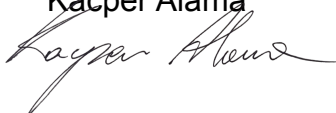
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ABSTRACT

This thesis examines the global maritime industry's green transition as it rapidly shifts from a fossil-fuel-dependent transport model to a decarbonized future. Driven by stringent environmental mandates like the European Union's Emissions Trading System, the FuelEU Maritime regulation, and the International Maritime Organization's Net-Zero Framework, the sector is accelerating its adoption of sustainable, zero-emission technologies. To achieve these ambitious climate targets and legally comply with strict limits on fuel carbon intensity, major shipping lines are investing heavily in alternative clean energy solutions, including green methanol, dual-fuel engines, and wind-assisted propulsion. However, the research also highlights the uneven pace of this ecological shift, noting that smaller regional vessels face significant infrastructural and spatial barriers to integrating green technology. Ultimately, this thesis demonstrates how the maritime green transition is fundamentally reshaping fleet operations, necessitating massive global investments in alternative fuel infrastructure to successfully build a sustainable, net-zero supply chain.

Keywords: Green shipping, Alternative fuels, Maritime, Sustainability, EU ETS

LIST OF ABBREVIATIONS

ADA: Alternative Design Approval

AROS: Autonomous and Remotely Operated Ships

BRI: Belt and Road Initiative

BWM: Ballast Water Management

CAPEX: Capital expenditure

CEF: Connecting Europe Facility

CII: Carbon Intensity Indicator

DCS: Data Collection System

DWT: Deadweight tonnage

ECA: Emission Control Area

EEXI: Energy Efficiency Existing Ship Index

EGR: Exhaust Gas Recirculation

EMSA: European Maritime Safety Agency

EU ETS: European Union Emissions Trading System (or Scheme)

FLL: Fuel Lifecycle Labels
GFI: Greenhouse Gas Fuel Intensity
GHG: Greenhouse Gas
GT: Gross tonnage
HDI: Human Development Index
HFO: Heavy Fuel Oil
IACS: International Association of Classification Societies
IMO: International Maritime Organization
LNG: Liquefied Natural Gas
MASS: Maritime Autonomous Surface Ships
MEPC: Marine Environment Protection Committee
MLC: Maritime Labour Convention
MRV: Monitoring, Reporting and Verification
MSC: Mediterranean Shipping Company
Mtoe: Million tonnes of oil equivalent
NOx: Nitrogen oxides
NVOCCs: Non-Vessel Operating Common Carriers
NZF: Net-Zero Framework
OCCS: Onboard Carbon Capture and Storage
ONE: Ocean Network Express
OSVs: Offshore Support Vessels
PdM: Predictive maintenance
PM: Particulate matter
PPPs: Public-private partnerships
PSA: Port of Singapore Authority
PSC: Port State Control
RED III: Renewable Energy Directive
Reefers: Refrigerated vessels
RFNBOs: Renewable Fuels of Non-Biological Origin
Ro-Ro: Roll-On/Roll-Off
ROs: Recognized Organizations
RUs: Remedial Units
SCR: Selective Catalytic Reduction
SDGs: Sustainable Development Goals
SFCS: Sustainable Fuels Certification Scheme

SOx: Sulfur oxides

STCW: Standards of Training, Certification, and Watchkeeping

SUs: Surplus Units

TEU: Twenty-Foot Equivalent Units

TFEU: Treaty on the Functioning of the European Union

ULCC: Ultra-large crude carrier

ULCVs: Ultra-large container vessels

UNFCCC: United Nations Framework Convention on Climate Change

URN: Underwater Radiated Noise

VLOC: Very Large Ore Carrier

VLSFO: Very Low Sulphur Fuel Oil

WAPS: Wind-Assisted Propulsion Systems

WCED: World Commission on Environment and Development

WtW: Well-to-Wake

Introduction

Maritime transport serves as the foundational backbone of the modern global economy, enabling the large-scale movement of raw materials, energy resources, and manufactured goods across ocean basins. Operating under the economic principle of derived demand, the sector exploits unparalleled economies of scale to drastically reduce the economic friction of geographic distance, thereby integrating regional markets into global value chains. Historically evolving from early transoceanic routes to the mid-20th-century advent of containerization, the maritime industry has continuously adapted to maximize cost efficiency and structural capacity. Today, highly specialized merchant fleets navigate high-density global corridors and strategic geographic chokepoints to sustain international commerce.

However, this massive global scale generates profound environmental externalities. The maritime sector's deep-seated reliance on conventional fossil fuels fundamentally clashes with contemporary international mandates designed to mitigate global climate change and atmospheric pollution. Realigning this sector with sustainable principles requires a holistic transformation to balance the industry's economic vitality with rigorous environmental protection. Frameworks established by the International Maritime Organization (IMO) and the European Union are actively converting technical environmental obligations into strict corporate financial liabilities. This shift necessitates a heavy reliance on alternative low-carbon marine fuels, advanced propulsion systems, and digital operational optimizations.

Navigating this complex intersection of microeconomic volatility, stakeholder coordination, and sustainable development forms the core focus of this research. Therefore, this thesis investigates the overarching topic of the maritime industry's green transition amidst tightening international environmental governance. Specifically, the central thesis question asks: How do emerging environmental regulatory frameworks and sustainable technological innovations influence the global maritime industry? By examining the regulatory maturation of emissions trading, statutory liability shifts, and the technical horizon of decarbonization, this study aims to synthesize the strategic future outlook for a sector striving to achieve net-zero carbon shipping without compromising its role as an indispensable driver of global trade.

1. The Economic Evolution of Maritime Trade: Frameworks, Markets and Stakeholders Ecosystem

1.1 Derived demand, economies of scale, and global economic integration

Accounting for the vast majority of international merchandise trade by volume, the maritime sector provides an indispensable infrastructure characterized by unparalleled economies of scale, high energy efficiency per ton-mile, and extensive geographical reach. At its core, maritime transport operates under the economic principle of derived demand. Shipping services are rarely demanded for their intrinsic utility, rather demand for ocean freight is directly generated by international market demand for the underlying commodities, raw materials, and finished consumer goods being transported. From a macroeconomic perspective, maritime logistics functions as the physical infrastructure that operationalizes international trade theories, turning comparative advantage into real-world supply chain flows (Stopford, 2009).

The economic viability of maritime transport relies heavily on its capacity to exploit scale economies. By deploying increasingly massive vessels (capable of multiple containers or hundreds of thousands of tons of bulk cargo in a single transit) shipping operators achieve a low unit transport cost per ton-mile. This cost compression drastically reduces the economic friction of geographic distance, enabling regional markets to integrate into global value chains. Industries such as manufacturing, heavy metallurgy, agriculture, and energy depend fundamentally on these low-cost logistics to remain internationally competitive (Stopford, 2009).

Furthermore, maritime transport serves as a primary vector for global economic convergence. High maritime connectivity correlates directly with reduced trade costs, expanded export opportunities, and accelerated domestic financial growth (Notteboom & Rodrigue, 2005). Modern port infrastructure and multimodal transport networks—comprising rail, inland waterways, and highway systems—extend the economic reach of sea routes deep into inland hinterlands, transforming coastal gateways into national economic engines.

1.2 Historical Milestones in Maritime Industry

The contemporary maritime logistics network is the product of centuries of technological and organizational evolution. Since antiquity, maritime corridors have served as primary conduits for the exchange of goods, culture, and technology. A notable historic precursor to modern global networks was the "Maritime Silk Road," which linked the economies of East Asia, South Asia, the Middle East, and the Mediterranean basin in a complex trade web (Frankopan, 2015).

The Age of Discovery in the 15th and 16th centuries marked a significant structural expansion in global shipping. Maritime exploration enabled European powers to establish transoceanic trade routes, securing direct access to valuable commodities such as spices, precious metals, and textiles (Parry, 1981). Advancements in naval architecture, navigation, and cartography during this era established shipping as a primary driver of colonial economies and international commerce (Parry, 1981).

The Industrial Revolution of the 18th and 19th centuries fundamentally altered maritime operations through the introduction of steam propulsion. Replacing sail power with steam engines significantly reduced transit times, eliminated total reliance on seasonal wind patterns, and exponentially expanded vessel load capacities (Stopford, 2009). This era witnessed the formalization of scheduled liner services, the establishment of global shipping enterprises, and the construction of vital artificial waterways. The opening of the Suez Canal in 1869 and the Panama Canal in 1914 restructured global geography by eliminating thousands of nautical miles from interoceanic voyages (Stopford, 2009).

In the mid-20th century, maritime freight underwent its most radical structural transformation with the advent of containerization. Pioneered in the 1950s, the standardization of intermodal shipping containers revolutionized cargo handling by facilitating seamless transfers between ships, trucks, and trains (Levinson, 2016). By replacing manual, labor-intensive break-bulk loading with mechanized crane operations, containerization drastically reduced port turnaround times, minimized cargo loss and damage, and lowered freight costs (Levinson, 2016). This technological leap catalyzed

modern globalization, enabling the spatial fragmentation of manufacturing processes across multiple continents (Levinson, 2016). Today, the industry continues to evolve through digitalization, automated port operations, and green technologies designed to meet stringent global sustainability mandates (UNCTAD, 2023)

Ancient Era	Maritime Silk Road that connected trade between Asia, Middle East and Europe
15th-16th Century	Age of Discovery that established transoceanic colonial trade
18th - 19th Century	Industrial Evolution introduced steamships and canals
Mid-20th Century	Containerization standardized intermodal cargo transport
21st Century	Era of digitalization, mega-vessels, autonomous shipping and green AI

Table 1. Summary of Historical Milestones in Maritime Industry

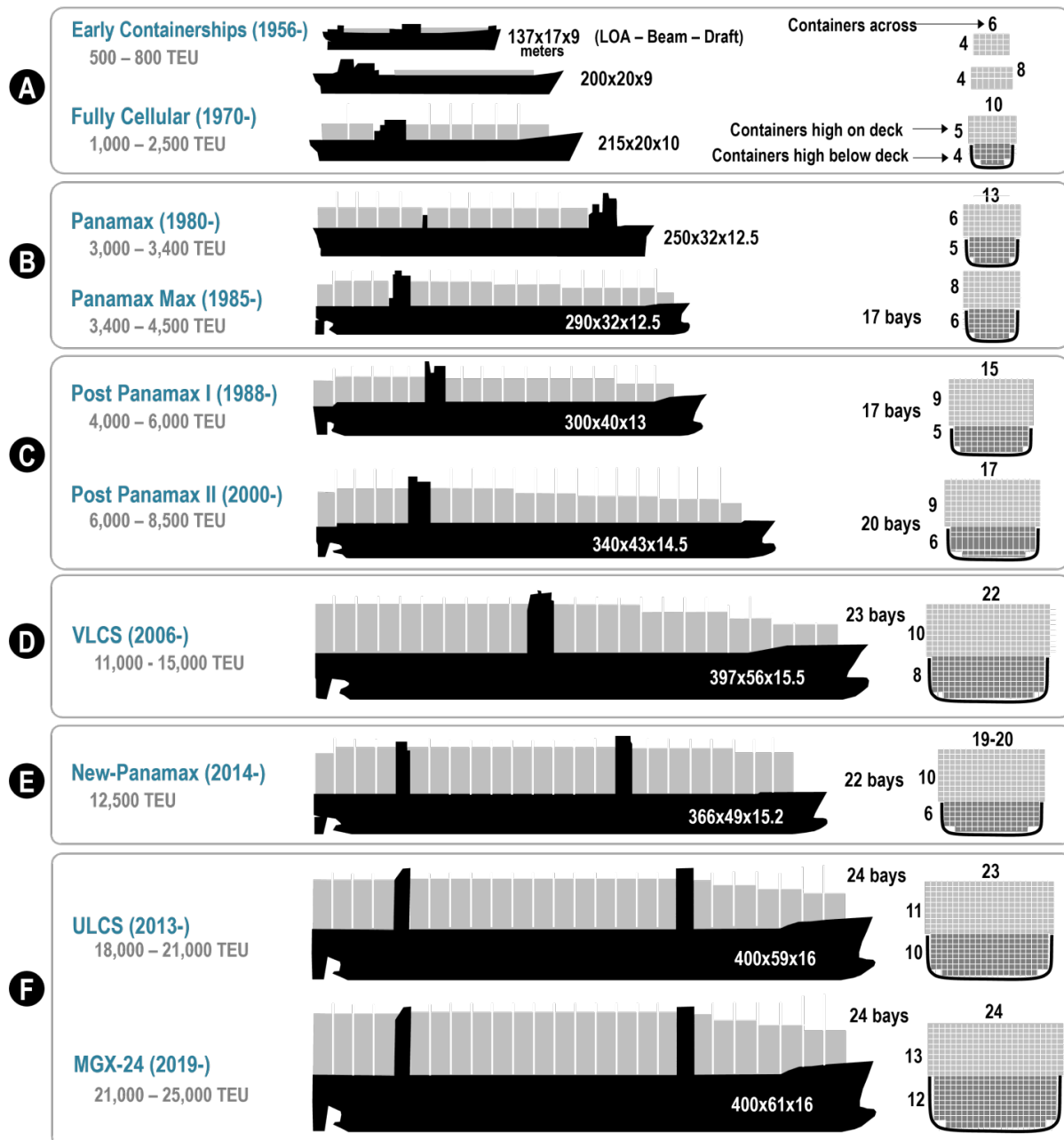
1.3 Typology of Maritime Freight and Fleet Specialization

1.3.1 General Cargo and Intermodal Container Shipping

The modern merchant fleet is highly specialized, categorized according to cargo characteristics, handling techniques, and operational schedules. Among these classifications, container shipping represents the backbone of global trade in manufactured, semi-manufactured, and consumer goods. Container ships are designed to optimize space utilizing standard intermodal containers, measured primarily in Twenty-Foot Equivalent Units (TEU).

The evolution of container vessel capacity reflects a continuous push toward maximum economies of scale. Early container vessels carried a few hundred units, whereas modern ultra-large container vessels (ULCVs) exceed 20,000 TEU. Notable examples illustrate this structural progression. The „Emma Maersk” was an influential early super-container ship that set new design benchmarks for long-haul routes. Pushing boundaries further, the „MSC Irina” was engineered to carry over 14,000 TEU, providing massive transport capacity on major East-West corridors. Today, mega-containerships like the Ever Ace boast capacities exceeding 23,000 TEU, demonstrating the extreme scale required to service high-density trade lanes such as Asia–Europe. like the Ever Ace

boast capacities exceeding 23,000 TEU, demonstrating the extreme scale required to service high-density trade lanes such as Asia–Europe.



Picture 1. Evolution of Containerships

Source: Rodrigue, J.-P. (2024). *The Geography of Transport Systems* (6th ed.). Routledge. <https://doi.org/10.4324/9781003343196>

1.3.2 Bulk Transport Dynamics: Dry Bulk and Liquid Energy Carriers

Bulk transport represents the non-containerized segment of maritime freight, divided into dry bulk commodities and liquid energy bulk. Dry bulk vessels carry unpackaged, homogeneous raw materials in large cargo holds equipped with wide hatches to facilitate high-speed loading and discharge. These vessels are vital to heavy industrial supply chains, carrying iron ore for steel production, thermal and metallurgical coal for energy and manufacturing, and agricultural grains to ensure food security. Key specialized dry bulk carriers include the MS Berge Stahl, historically one of the world's largest dry bulk carriers engineered to haul massive shipments of iron ore from deep-water ports in Brazil to industrial hubs in Europe and Asia. Similarly, the MS Vale Brasil is a Very Large Ore Carrier (VLOC) designed to maximize energy efficiency and cargo volume when moving iron ore between South America and East Asian markets.



Picture 2. MS BERGE STAHL

Source: photo by Dave van Spronsen <https://www.shipspotting.com/photos/2644249?navList=gallery&imo=8420804&page=2&viewType=normal&sortBy=newest>



Picture 3. MS VALE BRASIL

Source: photo by Tommy Chia <https://www.shipspotting.com/photos/1505536?navList=gallery&imo=9488918&page=1&viewType=normal&sortBy=newest>

Liquid bulk tankers are purpose-built to move liquid cargoes, including crude oil, refined petroleum products, liquid chemicals, and Liquefied Natural Gas (LNG). These vessels feature segregated tanks, sophisticated pumping systems, and specialized safety features to manage hazardous or volatile materials. Prominent energy tankers include the Knock Nevis, historically the largest vessel ever constructed, which showcased the maximum physical boundaries of maritime bulk capacity. Modern advancements are seen in the Hellenic Spirit, a modern double-hulled ultra-large crude carrier (ULCC) featuring advanced internal coatings, inert gas protection systems, and environmental safety measures to minimize catastrophic pollution risks. Bridging containerization and alternative fuel technology, the CMA CGM Jacques Saade is an ultra-large container ship powered by Liquefied Natural Gas (LNG), reducing carbon intensity and localized atmospheric emissions.



Picture 4. CMA CGM JACQUES SAADE

Source: photo by Wolfgang Fricke <https://www.shipspotting.com/photos/3962456?navList=gallery&imo=9839179&page=1&viewType=normal&sortBy=newest>

1.3.3 Specialized Vessel Architectures: Ro-Ro, Reefer, Heavy-Lift, and Hybrid Carriers

Beyond standard container ships and bulk carriers, maritime transport relies on specialized vessel architectures tailored to unique cargo profiles. Roll-On/Roll-Off (Ro-Ro) vessels, such as the massive MV Tonsberg, are designed with internal ramps and multi-deck structures allowing wheeled vehicles, automobiles, and heavy industrial machinery to drive directly on and off, serving as a primary link in the global automotive supply chain. Refrigerated vessels (Reefers), like the MV Seatrade Orange, feature high-precision temperature-controlled cargo holds to transport perishable agricultural commodities and tropical fruits across intercontinental trade routes.



Picture 5. MV TONSBERG

Source: photo by Geir Vinnes <https://www.shipspotting.com/photos/3801038?navList=gallery&imo=9216999&page=1&viewType=normal&sortBy=newest>

For oversized and ultra-heavy industrial components such as offshore oil rigs and wind turbine blades, specialized heavy-lift ships are deployed. The MV Blue Marlin, a semi-submersible heavy-lift ship, can submerge its main deck to load massive marine structures, primarily serving the energy and infrastructure sectors. In response to strict environmental regulations, hybrid and wind-assisted vessels have also emerged. The MV Beluga SkySails combined traditional marine engines with automated towing kites to harness high-altitude wind power, effectively reducing operational fuel burn. Lastly, regional connectivity is maintained by Ro-Pax ferries and short-sea vessels like the Stena Ebba, which operate across waters like the Baltic Sea to connect land transit networks and sustain regional trade integration.



Picture 6. MV STENA EBBA

Source: photo by Kevin Gothe [https://www.shipspotting.com/photos/4009436?](https://www.shipspotting.com/photos/4009436?navList=gallery&imo=9863003&page=1&viewType=normal&sortBy=newest)

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Picture 7. MV Blue Marlin

Source: photo by Kyle Stubbs [https://www.shipspotting.com/photos/2229305?](https://www.shipspotting.com/photos/2229305?navList=gallery&imo=9186338&page=4&viewType=normal&sortBy=newest)

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1.4 Global Shipping Routes, Strategic Chokepoints, and Geographic Disparities

1.4.1 Comparative Analysis of Core Global Shipping Corridors

The global maritime network consists of high-density trunk routes connected to regional feeder networks. The economic density, vessel size, and commodity composition vary across these maritime pathways:

Primary Maritime Route	Annual Trade Volume (Est. TEU / DWT / MT)	Key Chokepoints Crossed	Dominant Cargo Categories	Primary Risks
Asia - Europe	~24M TEU / 1.2B MT	Strait of Malacca, Bab el-Mandeb, Suez Canal	Manufactured consumer goods, apparel, electronics, crude oil, components	Geopolitical instability (Red Sea), Suez Canal capacity/ blockages, piracy
Trans-Pacific (Asia - North America)	~28M TEU / 850M MT	Strait of Malacca (for SEA origins), Panama Canal	Consumer electronics, machinery, furniture, agricultural exports (return leg)	Panama Canal draft restrictions (drought), extreme weather (Typhoons in Pacific)
Middle East - Asia	Minimal TEU / ~1.8B MT (Liquid/ Bulk)	Strait of Hormuz, Strait of Malacca	Crude oil, LNG (Liquefied Natural Gas), refined petroleum products	High geopolitical risk (Strait of Hormuz closure), regional conflicts
Trans-Atlantic (Europe - North America)	~8M TEU / 400M MT	Dover Strait, St. Lawrence Seaway	Automobiles, pharmaceuticals, heavy machinery, specialty chemicals	Severe winter storms (North Atlantic), port congestion
Intra-Asia	~45M TEU / 2.5B MT	Taiwan Strait, Strait of Malacca, South China Sea	Intermediate manufactured components, raw materials, coal, iron ore	Geopolitical tensions (South China Sea, Taiwan Strait), seasonal typhoons
South America - Asia	Minimal TEU / ~900M MT (Dry Bulk)	Panama Canal, Strait of Magellan / Cape Horn	Iron ore, soybeans, copper, agricultural commodities	Long transit times, weather rounding Cape Horn, Panama Canal bottlenecks

Table 2. Overview of Primary Maritime Routes

The **Far East–Europe** maritime corridor is widely regarded as one of the highest-volume and most economically vital trade routes in the world. Connecting East Asian

manufacturing powerhouses (China, South Korea, Japan, Taiwan) with Western European consumer markets, this route handles immense volumes of containerized consumer goods, electronics, industrial machinery, and textiles. Operating primarily through the South China Sea, the Strait of Malacca, the Indian Ocean, the Arabian Sea, the Red Sea, the Suez Canal, and the Mediterranean Sea before entering Northern European ports like Rotterdam, Antwerp, and Hamburg, this corridor demands the deployment of the largest Ultra-Large Container Vessels (ULCVs) afloat to maintain cost efficiency.

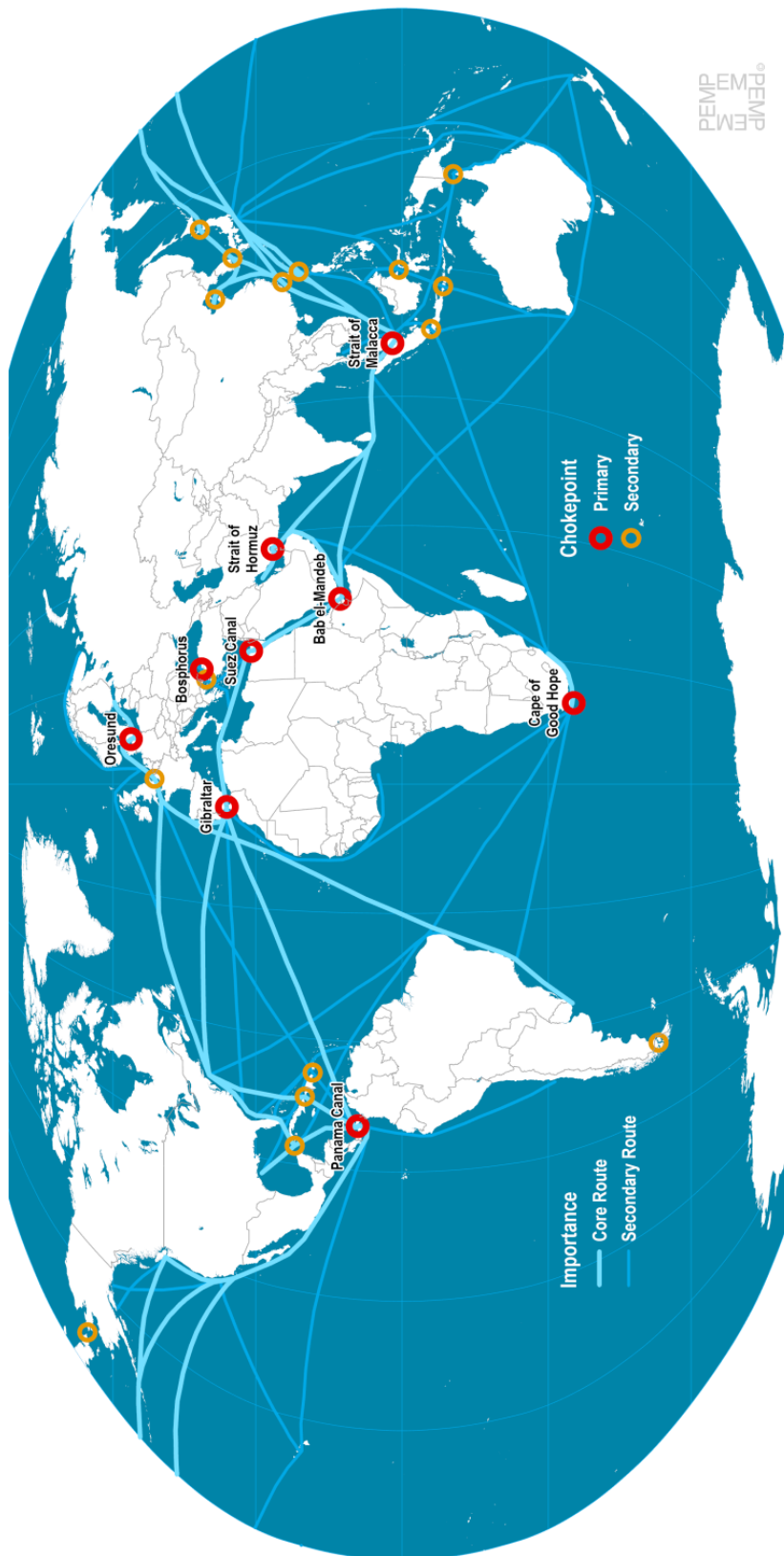
The Transpacific Route connects Asia directly with the West Coast of North America (primarily the ports of Los Angeles, Long Beach, Oakland, and Prince Rupert), serving as the primary conduit for East Asian exports to North American consumer markets. Transpacific trade is heavily asymmetrical, characterized by high-value, containerized manufactured imports heading eastward, balanced by lower-volume, lower-value agricultural products, raw materials, and waste paper heading westward.

The Transatlantic Route connects North American East Coast ports with Western European gateways, standing as one of the oldest and most stable corridors in international shipping. Unlike the heavily consumer-focused Far East lanes, Transatlantic shipping features a balanced exchange of high-value industrial goods, specialized machinery, automotive parts, chemicals, and processed agricultural commodities.

Finally, **Intra-Asian** routes represent a dense web of short-sea shipping corridors connecting manufacturing hubs across East Asia, Southeast Asia, and South Asia. Driven by regional trade agreements and localized supply chain integration, these routes handle both raw material inputs and semi-finished components moving between factories, as well as final consumer goods. Feeder vessels playing these short routes collect cargo from smaller regional ports and consolidate it at mega-hub ports like Singapore, Shanghai, and Busan for transshipment onto mainline ocean carriers.

1.4.2 Strategic Maritime Chokepoints and Vulnerabilities

Global maritime routes rely on narrow geographic passages known as chokepoints, which are natural or artificial waterways representing critical bottlenecks where high traffic density, physical restrictions, or regional instability pose operational risks to international trade.



Picture 8.

Main Maritime Shipping Routes and Chokepoints

(Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2026) Port Economics, Management and Policy, 2nd Edition, New York: Routledge, 734 pages / 232 illustrations. ISBN 9781032955339. doi.org/10.4324/9781003585367)

The **Suez Canal** in Egypt connects the Red Sea to the Mediterranean Sea, providing the shortest sea route between Europe and Asia. By bypassing the African continent, it saves thousands of nautical miles and reduces transit times by up to two weeks. Any disruption to the Suez Canal—whether caused by physical blockages, weather events, or geopolitical conflict—forces fleet reroutings around the Cape of Good Hope, inflating ton-mile demand, fuel consumption, and insurance premiums.

Similarly, the **Panama Canal** connects the Atlantic and Pacific Oceans across the Isthmus of Panama, making it vital for Transpacific trade destined for the US East and Gulf Coasts, as well as South American trade routes. The expansion of the canal through new locks introduced the "Neo-Panamax" vessel standard, allowing larger containerships and bulk carriers to pass. However, draft restrictions caused by regional droughts highlight the climate vulnerability of freshwater-fed canal systems.

In Southeast Asia, the **Strait of Malacca** is situated between the Malay Peninsula and the Indonesian island of Sumatra, serving as the primary sea lane connecting the Indian Ocean to the Pacific Ocean. Handling a massive portion of global oil shipments and container traffic, it is a critical chokepoint for energy security in East Asia. This high traffic density requires vigilant maritime safety management to mitigate collision and piracy risks.

1.4.3 Regional Disparities, Landlocked Economies, and Infrastructure Deficits

The economic benefits of maritime transport are unevenly distributed across the globe. Geographical access, port infrastructure quality, regulatory frameworks, and capital investments determine a nation's level of integration into maritime trade networks. Advanced economies in Northern Europe and East Asia have built smart ports equipped with automated container gantry cranes, digital tracking platforms, and multimodal rail links. Port complexes like Rotterdam, Hamburg, Antwerp, Shanghai, and Singapore set global benchmarks for container handling efficiency, turnaround speed, and environmental compliance (Ferrari & Tei, 2020).

In contrast, many developing nations face severe structural barriers. Outdated port infrastructure, shallow harbor depths, manual cargo handling, and inefficient customs procedures result in severe port congestion, long vessel dwell times, and inflated freight rates. These infrastructure deficits restrict market competitiveness and perpetuate economic isolation. Landlocked countries face acute challenges, lacking direct ocean access and depending entirely on transit corridors through neighboring coastal states. Landlocked developing nations rely on cross-border rail, river, and highway networks to reach seaport gateways. In Europe, nations like Austria and Hungary utilize the Danube River inland waterway system alongside cross-border rail connections to access global sea routes, demonstrating the importance of integrated multimodal logistics systems (Ferrari & Tei, 2020).

International development initiatives aim to bridge these infrastructure gaps. The Connecting Europe Facility (CEF) is a European Union funding mechanism supporting cross-border infrastructure projects, port modernization, and multimodal transport links. CEF investments strengthen regional cohesion by linking peripheral and landlocked areas to main European shipping corridors. Additionally, the Belt and Road Initiative (BRI) is a multi-billion-dollar global infrastructure initiative led by China, funding port developments, logistics hubs, and maritime connectivity across Asia, Africa, Europe, and Latin America to facilitate international trade flows (Herrero & Xu, 2017).

1.4.4 Regional Focus Example: European and Baltic Maritime Ecosystems

Europe's geography, bounded by the Atlantic Ocean, the Baltic Sea, the North Sea, and the Mediterranean Sea, makes maritime transport vital to its economic integration. Within the European Union, maritime trade drives both inter-state commerce and external international trade. Coastal nations leverage strategic locations to support significant maritime industries. Greek shipowners, for example, control a major share of the global merchant fleet, particularly in dry bulk carriers and liquid tankers, exerting significant influence over world trade flows. In Croatia, ports along the Adriatic Sea, such as Rijeka, serve as sea gateways for landlocked Central European markets. Furthermore, Poland, located on the Baltic Sea, has actively expanded its port hubs at Gdansk, Gdynia, and Szczecin-Swinoujscie. The Port of Gdansk features deep-water container terminals capable of handling direct ocean calls by ultra-large container ships from East Asia, firmly establishing Poland as a key logistics hub for Central and Eastern Europe.



Picture 9. Port of Gdansk

Source: <https://www.portgdansk.pl/port/terminale-i-nabrzeza/terminal-kontenerowy-baltic-hub/>

1.5 The Maritime Stakeholder Landscape

The execution of global ocean freight requires structured coordination across a diverse ecosystem of commercial, operational, and regulatory entities.

Shipowners hold physical title to maritime vessels and bear capital investment risks, vessel maintenance, insurance, and compliance costs, often leasing vessels to operating shipping lines or charterers. Prominent examples include Zodiac Maritime alongside private shipowning groups in Greece. Shipping lines (carriers) are companies that operate these fleets to offer ocean cargo transport services. Industry leaders such as MSC (Mediterranean Shipping Company), Maersk, CMA CGM, COSCO, Evergreen, and Hapag-Lloyd operate globally, providing scheduled liner services and managing container fleets (Notteboom et al., 2026).

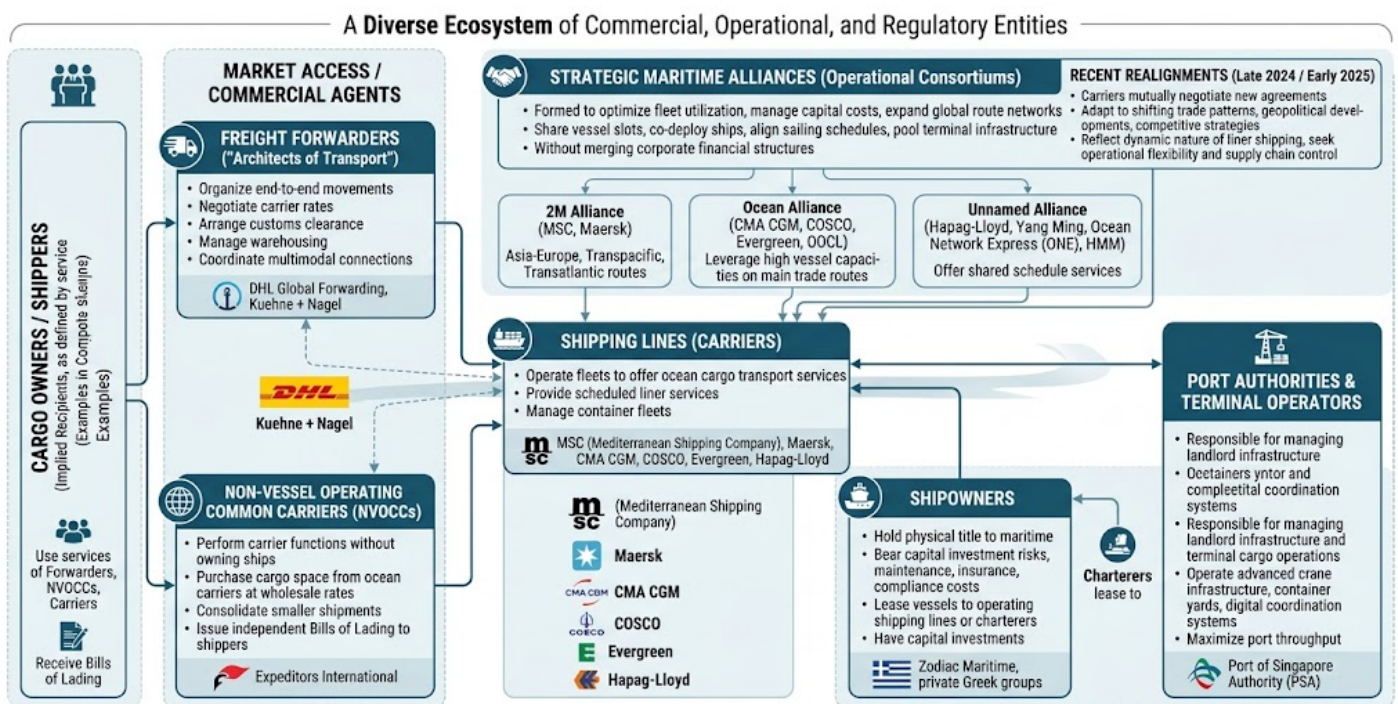
Freight forwarders, often referred to as "architects of transport," organize end-to-end freight movements for cargo owners. Entities like DHL Global Forwarding and Kuehne + Nagel negotiate carrier rates, arrange customs clearance, manage warehousing, and coordinate multimodal connections. Similarly, Non-Vessel Operating Common Carriers (NVOCCs), such as Expeditors International, perform carrier functions without owning physical ships. NVOCCs purchase cargo space from ocean carriers at wholesale rates, consolidate smaller shipments, and issue independent Bills of Lading to shippers. Overseeing the physical infrastructure are Port Authorities and Terminal Operators, entities responsible for managing landlord infrastructure and terminal cargo operations. Organizations like the Port of Singapore Authority (PSA) operate advanced crane infrastructure, container yards, and digital coordination systems to maximize port throughput (Notteboom et al., 2026).

To optimize fleet utilization, manage capital costs, and expand global route networks, major container shipping lines have historically formed strategic maritime alliances. These operational consortiums enable carriers to share vessel slots, co-deploy ships, align sailing schedules, and pool terminal infrastructure without merging corporate financial structures (UNCTAD, 2024).

For many years, the global container market was dominated by three major operational alliances. The 2M Alliance was an operational agreement between MSC and

Maersk, focusing heavily on Asia-Europe, Transpacific, and Transatlantic routes. The Ocean Alliance comprised CMA CGM, COSCO, Evergreen, and OOCL, leveraging high vessel capacities on main trade routes. Moreover, an alliance formed by Hapag-Lloyd, Yang Ming, Ocean Network Express (ONE), and HMM offered shared schedule services across global networks. By late 2024 and early 2025, these strategic alliances underwent major realignments. Ocean carriers mutually negotiated new operational agreements to adapt to shifting trade patterns, geopolitical developments, and competitive strategies, reflecting the dynamic nature of liner shipping as carriers seek greater operational flexibility and supply chain control (Notteboom et al., 2026; UNCTAD, 2024)

MARITIME STAKEHOLDER LANDSCAPE & THE ECOSYSTEM FOR GLOBAL OCEAN FREIGHT EXECUTION



Graph 1 Maritime Stakeholder Landscape & The Ecosystem For Global Ocean Freight Execution
Source: AI-assisted and generated graph based on the Chapter 1.5 input; corrected manually; AI tool used - Google Gemini

1.6 Capacity Management, Freight Volatility, and Microeconomic Dynamics

The microeconomics of ocean freight are fundamentally characterized by high cyclicalities and extreme freight rate volatility, a condition stemming directly from a structural mismatch between supply and demand elasticity. On the supply side of the market, marine vessel construction requires long lead times, frequently spanning two to three years from the initial shipyard contract to the vessel's physical delivery (Kalouptside, 2014). This structural rigidity prevents shipping lines from rapidly scaling up fleet capacity during sudden surges in global cargo demand. Kalouptside (2014) identifies this time lag in shipbuilding as a primary catalyst for the boom-and-bust cycles inherent to maritime economics. Conversely, the massive fixed capital costs associated with vessel ownership mean that carriers incur significant financial losses when these ships sit idle during economic downturns. On the demand side, the need for ocean shipping fluctuates much more rapidly, driven by shifting macroeconomic conditions, consumer spending habits, seasonal inventory cycles, and sudden changes in international trade policy.

When capacity growth inevitably exceeds this fluctuating cargo demand, the resulting structural overcapacity heavily depresses freight rates across global trade lanes. To maintain operational margins during these market downturns, shipping lines are forced to employ aggressive tactical capacity management strategies. The most prominent of these tactics is the implementation of blanked, or canceled, sailings. In this scenario, scheduled vessel voyages (or specific port calls within a rotation) are temporarily canceled by the carrier to artificially reduce active market capacity. As highlighted by Cariou and Guillotreau (2021), blank sailings have evolved from a desperate crisis-response measure into a standardized, proactive capacity management strategy utilized by major carrier alliances to artificially tighten space and stabilize freight rates during seasonal demand dips.

In conjunction with blank sailings, carriers frequently utilize slow steaming, a tactic involving intentionally operating vessels at cruising speeds significantly lower than their designed maximum capacity. Because fuel consumption is a non-linear function of vessel speed, speed reductions yield disproportionate savings in bunker fuel while drastically lowering daily operational costs (Mohammed, 2023; Song, 2021). Furthermore, by stretching the physical duration of a voyage, carriers can effectively absorb excess vessel

capacity across longer route transit times, keeping ships active without oversupplying destination ports. Finally, when low-demand cycles are exceptionally prolonged, operators may resort to absolute capacity reductions through vessel scrapping and lay-ups, permanently retiring older, inefficient tonnage or temporarily mooring inactive ships until market conditions improve (Song, 2021).

2. Environmental Governance and Sustainable Development in Maritime Shipping

2.1 Frameworks of Sustainable Development

The paradigm of sustainable development remains one of the most pervasive, yet intricately complicated, frameworks in modern global policy, carrying massive weight in areas of environmental regulation, economic structuring, and social equity. The contemporary understanding of this concept was largely constructed in 1987 with the World Commission on Environment and Development (WCED) publication of *Our Common Future*, which characterized sustainable progress as fulfilling current societal necessities without jeopardizing the capacity of subsequent generations to fulfill their own (WCED, 1987). While this foundational definition is universally recognized, it frequently fails to encapsulate the inevitable friction that occurs when institutions attempt to harmonize ecological, economic, and social ambitions. The enduring power of this framework lies in its normative ambition: securing human prosperity without overstepping planetary boundaries or deepening societal divides (Rockström et al., 2009). Nevertheless, the inherent fluidity of the concept makes it susceptible to a wide array of interpretations, political maneuvering, and academic critique.

The ideological roots of this movement trace back to the surge in ecological consciousness during the latter half of the twentieth century. Throughout the 1960s and 1970s, unchecked industrial expansion, rapid population surges, and aggressive resource extraction prompted severe global anxieties, famously articulated in watershed publications like Rachel Carson's *Silent Spring* (Carson, 1962) and the Club of Rome's *The Limits to Growth* (Meadows et al., 1972). These texts successfully elevated the dangers of ecological overreach into the public consciousness. By the 1980s and 1990s, these concerns transitioned into actionable international policy, marked by the WCED's emphasis on the nexus between ecological decay and social disparity, and culminating in

the 1992 Earth Summit in Rio de Janeiro, which produced Agenda 21 (United Nations, 1992). This trajectory continued with the 2000 Millennium Development Goals, which targeted extreme poverty and health crises, and eventually the 2015 adoption of the 2030 Agenda and its 17 Sustainable Development Goals (SDGs), which broadened the focus to include climate intervention, inequality reduction, and cyclical consumption paradigms (United Nations, 2015).

Fundamentally, the architecture of sustainable development relies on three interdependent dimensions (Purvis et al., 2019). The first, environmental sustainability, demands the preservation and rehabilitation of the biosphere, emphasizing biodiversity conservation, pollution mitigation, and strict adherence to planetary ecological limits. The second, economic sustainability, envisions systems capable of generating wealth and innovation without depleting natural or social capital. It advocates for inclusive growth and challenges the traditional capitalistic assumption that infinite economic expansion is viable on a planet with finite resources. The third, social sustainability, champions equitable human advancement, focusing on human rights, universal access to healthcare and education, and the protection of marginalized demographics. These pillars are deeply interconnected, meaning policy shifts in one domain inevitably generate ripple effects across the others.

Despite its widespread acceptance, the concept is fraught with contention. Proponents of "green growth" assert that technological leaps can successfully sever the link between economic expansion and environmental harm, whereas critics maintain that modern consumption patterns are fundamentally irreconcilable with ecological survival (Hickel & Kallis, 2020). The ambiguity of sustainability has also given rise to "greenwashing," where entities employ eco-friendly rhetoric to mask policies that ultimately harm the environment or exacerbate inequality. Furthermore, geopolitical tensions persist between the Global North and the Global South - developing nations frequently argue for their right to economic maturation, insisting that wealthier, industrialized nations (who hold historical responsibility for the bulk of global emissions) must bear the brunt of climate mitigation efforts.

Academically, sustainability is often visualized through competing structural models. The traditional three-pillar model depicts the economy, society, and environment as overlapping circles or the legs of a stool, though critics argue this falsely implies the three

dimensions are structurally equal. Conversely, the nested model illustrates the economy operating strictly within the bounds of human society, which itself exists entirely within the absolute limits of the natural environment (Giddings et al., 2002). This theoretical landscape is further divided by the concepts of weak sustainability, which posits that natural capital can be technologically replaced, and strong sustainability, which insists that certain ecological baselines are irreplaceable and cannot be breached under any circumstances (Neumayer, 2013). Measuring these states relies on diverse tools like the Human Development Index (HDI) and the Ecological Footprint, though their exact methodologies invite continuous debate.

Translating these theories into reality is hindered by rampant policy inconsistencies, short-term political and corporate planning driven by election cycles and profit margins, and a severe lack of robust data in developing regions. Moreover, critical academic frameworks continuously challenge mainstream approaches. Degrowth theorists argue that genuine sustainability requires a managed reduction of energy and material throughput in wealthy nations (Kallis, 2011).

2.2 The Strategic Imperative for Eco-Friendly Innovations

Integrating sustainable solutions has become the cornerstone of contemporary environmental defense strategies, particularly within resource-intensive sectors. These innovations are designed to blunt the destructive impact of industrial activity by weaving cyclical, sustainable practices and cutting-edge technologies into standard operations. Among global industries, maritime transport is notably infamous for its colossal resource consumption and pollution outputs, making it a prime candidate for sweeping eco-friendly overhauls.

In the broader context of global ecological fragility, green solutions serve as the primary defense against climate destabilization, habitat eradication, and the rapid depletion of natural resources. They represent a strategic balancing act, engineered to protect the biosphere without triggering total economic collapse. The overarching goals of these interventions are clear: drastically curtailing greenhouse gas outputs, safeguarding fragile biodiversity, optimizing resource utilization to drive down both waste and operating costs, and fortifying societal infrastructure against the inevitable shocks of a changing climate.

Failing to institutionalize these green paradigms presents catastrophic risks to ecological stability, economic continuity, and public health. If heavy industries continue their reliance on fossil fuels, the resulting surge in emissions will inevitably accelerate global warming, triggering catastrophic weather anomalies, devastating sea-level rises, and unparalleled losses in biodiversity. Economically, recalcitrant industries face the looming threat of crippling regulatory fines, legal battles, and a massive erosion of consumer trust as global markets increasingly penalize unsustainable behavior.

The localized failures of environmental management carry severe global consequences. As localized habitats degrade, disrupting regional agriculture and water security, the threat of climate-driven mass migration escalates, paving the way for geopolitical instability and fierce conflicts over dwindling essential resources. Within the marine environment specifically, the continued neglect of sustainable practices threatens to unravel oceanic ecosystems. Coral reefs, already battered by rising ocean temperatures and acidification, face total collapse under the added pressures of industrial pollution and overfishing, which would subsequently decimate global fish populations and critical human food supplies.

Equally alarming is the disruption of the global hydrological cycle. Industrial runoff and maritime pollution introduce massive quantities of toxins into the hydrosphere, overwhelming the natural filtration capacities of crucial ecosystems like wetlands. Once degraded, these wetlands lose their ability to sequester carbon, filter waterborne diseases, and buffer coastal communities against flooding. Furthermore, the melting of polar ice and shifts in oceanic salinity threaten to permanently alter global weather systems and ocean currents, creating cascading failures across the entire terrestrial and aquatic biosphere. Counteracting this looming reality requires immense coordinated action, integrating public awareness campaigns, targeted financial incentives like tax relief for green investments, and long-term infrastructural planning to foster a resilient, low-carbon global economy.

2.3 Sustainability Dynamics in Maritime Shipping

The ecological footprint of global maritime transport has drawn intense international scrutiny due to its massive contributions to marine degradation, atmospheric pollution, and climate change. The industry's deep-seated reliance on conventional fossil fuels

fundamentally clashes with international mandates designed to curb global carbon emissions. Realigning this sector with sustainable principles requires a holistic transformation that satisfies the United Nations 2030 Agenda by balancing the industry's economic vitality with rigorous environmental protection and social accountability.

Central to this transformation are the regulatory frameworks established by the International Maritime Organization (IMO). The IMO has mandated a stringent reduction of maritime greenhouse gas emissions by a minimum of 50 percent by 2050 compared to 2008 benchmarks, a target designed to align with the Paris Agreement's goal of capping global temperature increases at 1.5°C. Furthermore, the IMO 2020 sulfur cap has already forced a drastic reduction in the sulfur content of marine fuels, yielding immediate benefits for global air quality. However, achieving true sustainability in shipping goes far beyond simple regulatory compliance; it involves navigating a labyrinth of technological, economic, and socio-political hurdles.

One of the most formidable technical challenges is the industry's pivot toward zero-carbon and low-carbon propulsion systems. While liquefied natural gas (LNG), biofuels, and hydrogen offer promising pathways, their widespread adoption is severely bottlenecked. Hydrogen, for instance, demands incredibly complex storage solutions—either at extreme pressures or cryogenic temperatures—which exponentially inflates operational costs. Furthermore, retrofitting older, fossil-fuel-dependent fleets to accommodate these volatile new energy sources is often prohibitively expensive. Regulatory fragmentation also plagues the sector; discrepancies between global IMO standards and regional policies, such as the European Union's Emissions Trading Scheme (EU ETS), create a chaotic compliance landscape that drives up administrative and operational costs for international shipping entities.

Financing this monumental green transition presents another massive barrier. Overhauling global fleets and modernizing port infrastructure requires staggering capital investments. Unfortunately, financial institutions frequently categorize green maritime projects as high-risk, leading to a lack of accessible funding, particularly for smaller operators and developing nations. To bridge this gap, the industry must heavily rely on public-private partnerships (PPPs), green bonds, and robust international financial support to ensure smaller economies are not economically marginalized.

The human and social dimensions of this transition are equally critical but often sidelined. The rapid influx of automation and digitalization threatens the job security of thousands of seafarers, necessitating massive global reskilling initiatives. Furthermore, crews operating advanced vessels face new occupational hazards and intense mental health pressures, requiring stringent safety protocols and adherence to the labor protections outlined in the Maritime Labour Convention (MLC). Addressing the industry's historical gender imbalance is also paramount; initiatives like the IMO's "Women in Maritime" program seek to dismantle systemic barriers and promote female leadership within the sector. At the community level, port developments must be meticulously managed to ensure that local populations benefit economically from the green transition without suffering from the localized costs of shifting supply chains.

Ultimately, mitigating the industry's environmental impact requires tackling multiple fronts simultaneously. Beyond carbon emissions, the sector must confront underwater noise pollution, which severely disorients marine mammals, through the deployment of quieter propulsion technologies and mandatory slow-steaming zones. The ecological threat of invasive species spread via ballast water is being combated through advanced onboard UV and filtration treatments, while stringent enforcement of the MARPOL Convention seeks to eradicate oil spills and marine litter. Moving forward, the fusion of intelligent AI-driven route optimization, blockchain-secured supply chains, and sweeping international cooperation will dictate the maritime industry's ability to evolve into a truly sustainable conduit of global trade.

2.4 The Global Catalyst: The Paris Agreement

To understand the maritime industry's transition toward decarbonization, we must first examine the hierarchical construction of environmental law, which begins at the global level. The ultimate catalyst for this shift is the Paris Agreement, which binds nations to strict macro-climate goals. Specifically, Article 2(1)(a) establishes the legal baseline of holding the increase in the global average temperature to well below 2°C above pre-industrial levels, while Article 4(1) binds parties to reach a global peaking of greenhouse gas emissions as soon as possible (United Nations Framework Convention on Climate Change [UNFCCC], 2015). Because the International Maritime Organization (IMO) requires consensus from over 170 Member states, translating these global targets into

international shipping baselines is a slow process. This regulatory lag has forced ambitious regional bodies to create strict vanguard laws to enforce these global climate objectives.

2.5 Translating Global Goals to Regional Law: The "Fit for 55" Package

Rather than relying on slow international consensus, the European Union has established a comprehensive and legally binding ecosystem for maritime decarbonization known as the "Fit for 55" package. The foundation of this system is accurate data, governed by Regulation (EU) 2015/757 (the MRV Regulation). This framework was recently amended by Regulation (EU) 2023/957, which, under Article 1, explicitly expands the scope of mandatory monitoring beyond carbon dioxide to include highly potent greenhouse gases, specifically methane and nitrous oxide (European Union, 2023b).

Once these emissions are accurately reported, they are subject to strict financial penalties under the European Union Emissions Trading System (EU ETS). Directive (EU) 2023/959 amended the original EU ETS framework (Directive 2003/87/EC) to capture maritime transport (European Union, 2023a). The microeconomic impact of this inclusion is codified in Article 3ga, which establishes a strict phase-in period for the surrender of emissions allowances: shipping companies are legally required to surrender allowances for 40% of their verified emissions in 2024, scaling up to 70% in 2025, and reaching 100% by 2026. Failure to surrender these allowances triggers severe penalties under Article 16 of the consolidated directive, imposing an excess emissions penalty of 100 EUR per tonne of carbon dioxide equivalent emitted, alongside a continuing obligation to surrender the missing allowances.

While the EU ETS penalizes the absolute volume of emissions on a Tank-to-Wake basis, Regulation (EU) 2023/1805, known as FuelEU Maritime, regulates the physical quality of the fuel itself across its entire lifecycle (Well-to-Wake). Article 4(2) of this regulation sets binding, gradual limits on the greenhouse gas intensity of energy used on board ships. The legal limit requires a 2% reduction by 2025, scaling aggressively to a 14.5% reduction by 2035, and an 80% reduction by 2050 (European Union, 2023c). If a vessel fails to meet these intensity limits, Article 20 dictates the calculation of a financial FuelEU penalty which acts as a deficit-close cost for non-compliance.

Finally, to ensure that the maritime industry actually has access to sustainable fuels, Directive (EU) 2023/2413 (RED III) forces the supply chain to adapt. By amending the Renewable Energy Directive, RED III specifically targets fuel suppliers (European Union, 2023d). Article 25 introduces a 1.2% sub-target for the supply of Renewable Fuels of Non-Biological Origin (RFNBOs) to the transport sector, while offering a 1.5x multiplier for these advanced fuels when supplied to the hard-to-abate aviation and maritime sectors, heavily incentivizing the market production of e-methanol and e-ammonia.

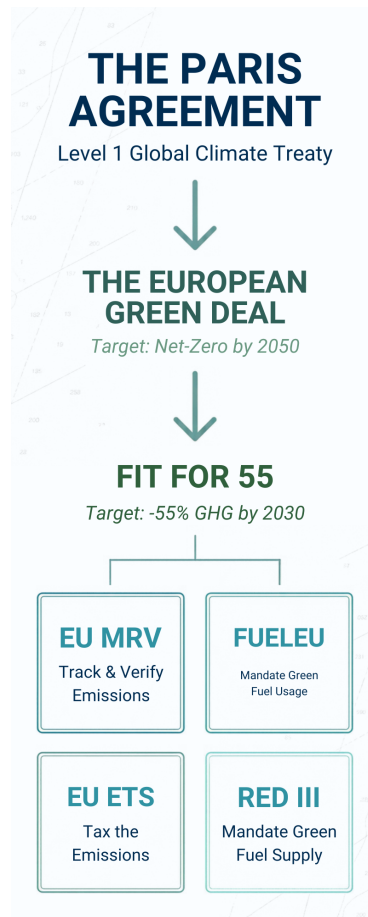
2.6 Discussion on Feasibility of Legal Frameworks

The European Union's "Fit for 55" framework marks a major shift in how shipping emissions are regulated, moving from non-binding international agreements to a set of three clear, legally enforceable policies. Together, these rules address the industry's environmental impact from energy production to vessel exhaust. The EU Emissions Trading System (ETS) forces shipping companies to pay for their direct emissions by purchasing carbon allowances, putting a clear price tag on pollution. At the same time, FuelEU Maritime sets strict limits on the overall carbon intensity of fuels used on ships, pushing the industry away from traditional fossil fuels. To ensure green fuels are actually available, the Renewable Energy Directive (RED III) targets fuel producers, setting minimum supply goals and incentives for advanced green hydrogen fuels like e-methanol and e-ammonia.

As these rules take effect, the cost of pollution will become part of normal shipping expenses. Shippers and consumers should expect a lasting increase in freight costs, as shipping lines pass down the added expenses of buying carbon allowances and purchasing expensive green fuels. This financial pressure is intentionally designed to make cheap, dirty heavy fuel oil too costly to use, narrowing the price gap between traditional fuels and zero-carbon alternatives.

Looking at whether these targets are achievable reveals a clear difference between the near future and the long term. In the short term, the initial goal of reducing fuel carbon intensity by 2% by 2025 is very manageable. Ship operators can easily meet this requirement using current technology, such as sailing at slower speeds, making ship hulls more efficient, and blending in small amounts of biofuels. However, the long term targets, a 14.5% cut by 2035 and an 80% cut by 2050, present a much bigger challenge. Meeting

these deep cuts depends almost entirely on whether RED III succeeds in building up green fuel supplies. Without massive investments in clean electricity, green hydrogen plants, and port fueling infrastructure, the shipping industry will face severe fuel shortages, making the 2050 climate goals nearly impossible to reach.



Graph 2 Scheme of Environmental Legal Acts and their Main Use
Source: AI Generated and manually corrected using chapter 2.6; AI tool used - Canva AI

2.7 The Microeconomic Reality of Compliance

The combination of these legal acts forces a fundamental shift in maritime microeconomics by internalizing environmental externalities according to the Polluter Pays Principle, as codified in Article 191(2) of the Treaty on the Functioning of the European Union (TFEU). If a shipowner ignores sustainable development, they face a dual financial liability. They must simultaneously purchase EU ETS allowances for their absolute

emissions while risking deficit penalties under FuelEU Maritime if their fuel mix remains highly carbon-intensive. Consequently, the hierarchy of European environmental law acts as a direct catalyst for physical engineering changes. These interconnected legal mechanisms make green shipping and technological retrofitting an unavoidable economic necessity rather than a theoretical corporate social responsibility goal.

2.8 Example: Contractual Transfer of Liability and Pooling Mechanics

To illustrate the commercial mechanics of modern European maritime directives, consider a scenario involving a Panamanian-flagged container ship, owned by a Greek shipowner, but leased under a multi-year time charter to a Danish logistics operator.

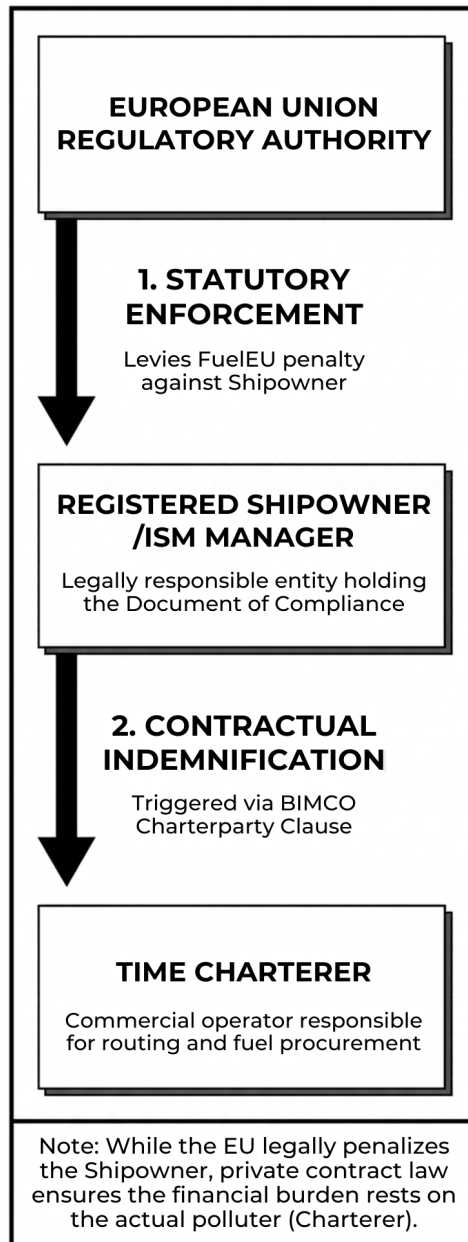
The Compliance Deficit: Under the FuelEU Maritime framework, the time charterer procures traditional high-carbon fuel rather than compliant biofuels, generating a verified compliance deficit by the end of the reporting period.

Statutory Enforcement: The European Union regulatory authority issues a formal statutory financial penalty notice directly to the Greek shipowner, as the shipowner holds the Document of Compliance.

Contractual Indemnification: Because the charterparty contract incorporates the BIMCO FuelEU Maritime Clause, the shipowner legally compels the Danish time charterer to fully reimburse the financial penalty amount.

Alternative Pooling Strategies: To mitigate these exposures, the companies may enter a contractual "Compliance Pool," combining a green vessel's surplus with a legacy vessel's deficit to neutralize statutory penalties entirely.

Graph presented on next page give an insight and visualize the process of the contractual liability. Worth mentioning is note incorporated in graph at the bottom, which showcase who is actually responsible for penalties related to caused pollution.



Graph 3. Visualization of provided example

Source: AI Generated and manually corrected using chapter 2.8; AI tool used - Canva AI

2.9 The Role of Classification Societies in Regulatory Enforcement and Standardization

The global maritime governance architecture relies on a complex, tripartite institutional system to ensure the safety of life at sea and the protection of the marine

environment. At the macroscopic level, the International Maritime Organization (IMO) serves as the primary standard-setting body, developing overarching international conventions. Sovereign Flag States are legally responsible for ratifying and enforcing these conventions across their registered fleets, while Port State Control (PSC) regimes act as a secondary safety net to inspect foreign-flagged vessels entering sovereign waters.

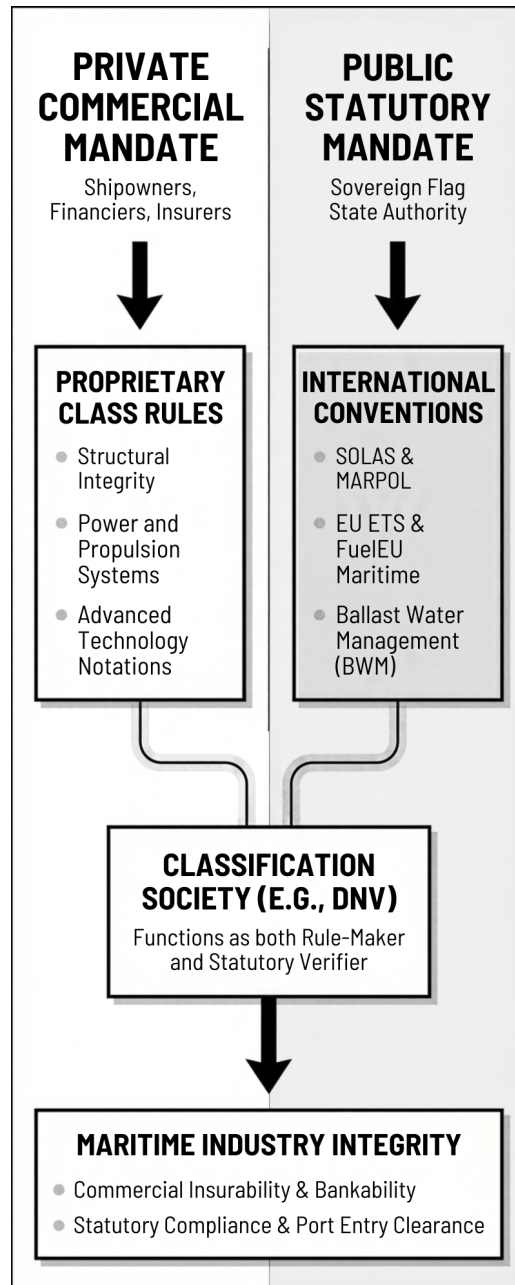
Within this intricate matrix, classification societies occupy a uniquely influential and structurally indispensable position. Originally established as independent technical bodies to assess ship structural integrity for marine insurance underwriters, their function has evolved significantly. Today, the modern classification society is the central techno-regulatory nexus of the maritime industry, bridging the gap between high-level political agreements and actionable marine engineering.

Classification societies govern global shipping through a distinct "dual function" paradigm, operating simultaneously as private engineering authorities and as delegated extensions of sovereign state power.

- **Private Capacity (Class Rules):** In their independent capacity, classification societies formulate highly prescriptive, proprietary engineering standards known as "Class Rules". These rules govern structural scantlings, hull strength, and machinery reliability, ensuring that vessels are fit for commercial operations and insurable by the private market.
- **Public Capacity (Recognized Organizations):** Under the IMO RO Code, flag state administrations explicitly delegate statutory oversight capabilities to qualified classification societies, designating them as Recognized Organizations (ROs). Because flag states often lack the expansive technical networks required to physically survey vessels globally, ROs are legally authorized to verify compliance with major conventions like SOLAS and MARPOL, and subsequently issue statutory safety certificates on the state's behalf.

The maritime industry is currently facing profound structural and operational disruption driven by the imperative to achieve net-zero greenhouse gas (GHG) emissions by 2050. Navigating maritime decarbonization is a highly complex challenge characterized by immense dynamic uncertainty regarding regulatory timelines, fuel availability, and

technological readiness. Regulators such as the IMO and the European Union (EU) have fundamentally altered the compliance landscape, transitioning from traditional pollution containment to strict life-cycle emission reductions.



Graph 4. Visualization of the Place and Role of Classification Society within Maritime Legal Framework

Source: AI Generated and manually corrected using chapter 2.9; AI tool used - Canva AI

The introduction of regional frameworks, such as the EU Emissions Trading System (ETS) and the FuelEU Maritime regulation, imposes severe financial penalties on high-intensity emission profiles. These regulations necessitate a comprehensive well-to-wake assessment of a ship's environmental footprint, accounting for GHG emissions generated from the extraction of raw materials through to onboard combustion. In this environment, the statutory function of classification societies has expanded into advanced emissions auditing. Serving as accredited verifiers, these organizations monitor complex energy efficiency metrics (such as the IMO DCS and EU MRV data), validating compliance deficits and auditing multi-vessel carbon pooling agreements to ensure absolute adherence to state-level environmental law.

2.9.1 DNV as a Regulatory Pioneer

International maritime regulations frequently lag behind technological advancements, as amending foundational IMO treaties like the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) requires lengthy geopolitical consensus among Member states. To prevent a regulatory vacuum that would otherwise stifle the green transition, leading classification societies actively formulate preemptive standards ahead of international law.

Det Norske Veritas (DNV) provides a paramount example of this proactive techno-regulatory governance. By developing robust engineering frameworks, DNV de-risks capital investments for shipowners and provides flag states with the technical basis necessary for statutory approvals.

- **Pioneering Alternative Fuel Standards:** DNV became the first classification society globally to class a ship fueled by liquefied hydrogen, and similarly certified the first oceangoing vessel fueled by ammonia.
- **Bridging the IMO Gap:** While the IMO only approved its first non-mandatory interim guidelines for ammonia in late 2024 and mandatory regulations are still years away, DNV proactively developed highly prescriptive classification rules for ammonia and hydrogen fuels.

- **Streamlining Statutory Approval:** Compliance with these DNV rules is sufficient for the classification certificate to be issued. Furthermore, subject to the flag administration's acceptance, DNV's proprietary rules serve directly as the state's approval basis, significantly reducing the bureaucratic complexity of introducing novel zero-carbon fuels to the global fleet.
- **Digitalization and Autonomy:** Beyond decarbonization, classification societies are tasked with mitigating the risks of digital transformation. By developing goal-based frameworks for Maritime Autonomous Surface Ships (MASS) and regulating the deployment of predictive maintenance (PdM) sensor architectures, societies like DNV ensure that cyber-resilience and operational safety evolve alongside computational capabilities.

International maritime regulations frequently lag behind technological advancements, as amending foundational IMO treaties like the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) requires lengthy geopolitical consensus among Member states. In practice, this means that until the IGF Code itself is amended with mandatory chapters for ammonia and hydrogen, a change not expected before 2028 at the earliest, every such vessel must instead pass through the IMO's risk-based Alternative Design Approval (ADA) procedure, which requires a bespoke hazard identification and risk assessment for each ship (DNV, 2025b). To prevent a regulatory vacuum that would otherwise stifle the green transition, leading classification societies actively formulate preemptive standards ahead of international law.

Det Norske Veritas (DNV) provides a paramount example of this proactive techno-regulatory governance. DNV's authority to do so rests on a dual mandate that predates the current energy transition by more than a century: on one hand it is a private technical body that writes and enforces its own class rules governing ship design, construction and maintenance, and on the other it acts, once individually authorized, as a Recognized Organization (RO) performing statutory tasks on behalf of flag administrations. This second, delegated function is itself governed internationally by the IMO's RO Code, set out in Resolutions MSC.349(92) and MEPC.237(65), which fixes the minimum quality and independence standards a society must meet before a government may transfer survey and certification work to it. The precise scope of what is delegated, however, still varies from one flag state to the next: some administrations hand over nearly the entire statutory

function, while others, retain narrowly defined duties for their own inspectors (Maritime Page, 2024). By developing robust engineering frameworks, DNV de-risks capital investments for shipowners and provides flag states with the technical basis necessary for statutory approvals. The society states that it is currently authorized by more than 130 flag administrations to carry out statutory certification on their behalf, and that roughly 85 per cent of the DNV-classed fleet is now covered by flag acceptance of fully electronic class and statutory certificates, a digitalization DNV presents as reducing the administrative burden on flag and port state authorities alike while making certificate fraud harder (DNV, n.d.-c, n.d.-d, n.d.-e).

- **Pioneering Alternative Fuel Standards** - DNV became the first classification society globally to class a ship fueled by liquefied hydrogen, and similarly certified the first oceangoing vessel fueled by ammonia. These milestones rested on rule sets developed years ahead of the incidents themselves: DNV published the first edition of its classification notation for ammonia-fuelled ships in 2021, and followed with a dedicated notation for hydrogen-fuelled ships in July 2024, both of which have since been revised annually to keep pace with technological change and emerging international guidance (DNV, 2024, 2025a).
- **Bridging the IMO Gap** - While the IMO only approved its first non-mandatory interim guidelines for ammonia in late 2024 and mandatory regulations are still years away, DNV proactively developed highly prescriptive classification rules for ammonia and hydrogen fuels. DNV's own literature frames these prescriptive notations explicitly as a way of narrowing the scope of the hazard identification and risk assessment that the ADA process otherwise requires case by case, so that compliance with the notation substitutes for much of the bespoke engineering justification a shipowner would otherwise have to commission independently (DNV, 2025c).
- **Streamlining Statutory Approval** - Compliance with these DNV rules is sufficient for the classification certificate to be issued. Furthermore, subject to the flag administration's acceptance, DNV's proprietary rules serve directly as the state's approval basis, significantly reducing the bureaucratic complexity of introducing novel zero-carbon fuels to the global fleet. This mechanism is not unique to alternative fuels, academic and industry commentary describe it as a general feature of the sector. Because statutory conventions typically state only a high-level safety objective without

specifying the calculations, safety margins, or component tolerances an engineer must use to satisfy it, class societies fill that gap with their own technical rules, and flag state statutory law frequently references those rules directly rather than restating them in national legislation (The Liquid Grid, 2026). Scholars who have studied classification societies as organizations note that this arrangement places them in a dual, at times paradoxical, position - at the national level they perform classification and statutory certification functions delegated by individual governments, while at the supranational level, largely through the International Association of Classification Societies (IACS), they participate in drafting the unified interpretations that other societies and, indirectly, the IMO itself subsequently rely on (Fulconis & Lissillour, 2021).

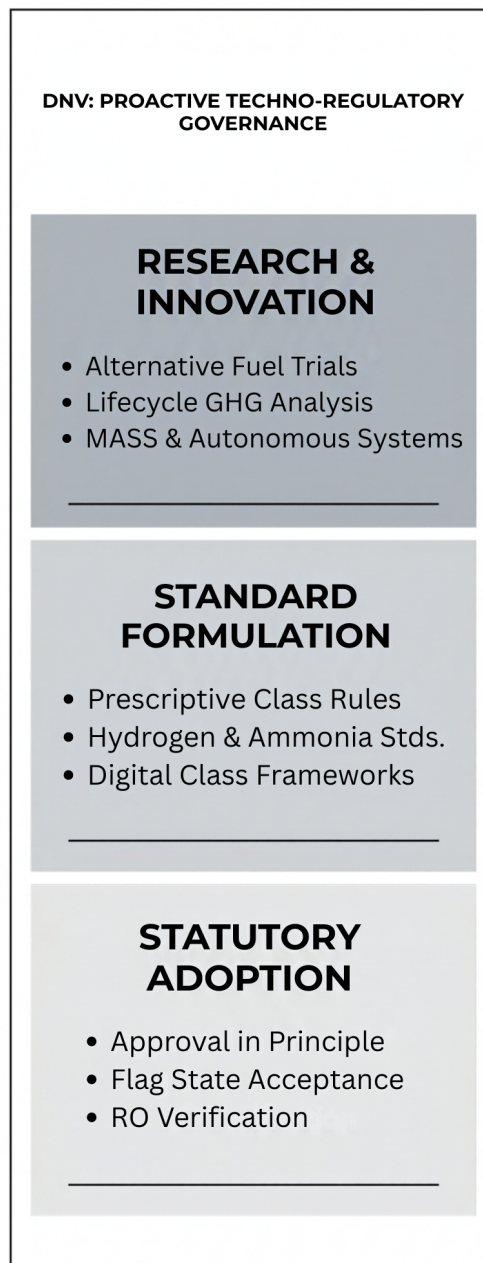
- **Digitalization and Autonomy** - Beyond decarbonization, classification societies are tasked with mitigating the risks of digital transformation. By developing goal-based frameworks for Maritime Autonomous Surface Ships (MASS) and regulating the deployment of predictive maintenance (PdM) sensor architectures, societies like DNV ensure that cyber-resilience and operational safety evolve alongside computational capabilities. DNV's response, its Autonomous and Remotely Operated Ships (AROS) family of class notations, was built for the same structural reason as its fuel rules: the IMO's forthcoming MASS Code is expected to remain voluntary from 2025 and is not due to become mandatory before 2032, leaving a multi-year gap that an internationally binding instrument does not yet fill. DNV states that the notations were developed in close cooperation with flag and coastal states, which retain ultimate approval responsibility, while the class society supplies the underlying functional requirements and risk-assessment methodology that individual administrations can then adopt as their own approval basis (DNV, 2025d).

The relationship between DNV, administering authorities, the Union Registry and governmental bodies is most clearly illustrated outside classification proper, in the European Union's greenhouse gas legislation, where the society's regulatory role continues past ship construction into ongoing environmental compliance. Under the EU Monitoring, Reporting and Verification (MRV) Regulation and the EU Emissions Trading System (ETS), DNV is formally accredited as an independent verifier of shipowners' emissions data, a function distinct from, though administratively adjacent to, its work as a classification society. Each shipping company is first assigned to a single Administering Authority, a competent body located in one EU member state, determined either by the

company's own country of registration or, for non-EU operators, by whichever member state has received the greatest number of the company's historical port calls (European Commission, n.d.; Lloyd's Register, n.d.). DNV, in its capacity as verifier, reviews and endorses the company's monitoring plan and its annual emissions report before that data moves forward; the Administering Authority is the governmental body that then accepts the verified report, oversees the opening of the company's Maritime Operator Holding Account, and ultimately requires that a corresponding number of EU allowances be surrendered by 30 September of each year. The Union Registry is the electronic ledger underlying this whole exchange: it is the EU's central database in which allowances are issued, held and surrendered, and a shipping company must apply through its Administering Authority's national registry administrator to open a holding account in it before any allowance can be bought, sold or surrendered (European Commission, n.d.; Eagle.org, n.d.). DNV therefore sits between the shipowner and the state apparatus without displacing either body - it does not issue allowances, open registry accounts, or impose penalties, all of which remain the Administering Authority's and, ultimately, the European Commission's prerogative, but its independent verification is a precondition the Administering Authority relies on before acting on the figures recorded in the Union Registry. A comparable structure has since been extended to the United Kingdom, where the UK ETS relies on accredited verifiers such as DNV to check operators' Annual Emissions Reports while national regulators approve monitoring plans and the UK ETS Registry, administered separately, records the resulting allowance transactions (DNV, 2026).

A structurally similar, though narrower, form of governmental oversight applies to DNV's core classification work. Within the European Union, a classification society may only be delegated statutory survey and certification tasks by a member state once the European Commission has recognised it under Regulation (EC) No 391/2009 and Directive 2009/15/EC, and the Commission's maritime safety agency, EMSA, reassesses each recognised organisation roughly every two years to confirm that recognition remains warranted (EMSA, n.d.). Flag states outside the European Union authorise DNV bilaterally, and the extent of the mandate granted is set out in individual agreements rather than a single harmonized instrument, which is consistent with the earlier observation that delegation can range from nearly the entire statutory function to a short list of specifically named duties. Taken together, these arrangements suggest that DNV, like other IACS members, functions less as an ordinary private contractor to shipowners and more as an intermediary technical authority: governmental bodies retain the sovereign functions of

recognition, enforcement and penalty, while DNV supplies the standing engineering capacity, digital infrastructure and, in the case of EU and UK climate legislation, independent verification, that a purely governmental structure would otherwise need to build and staff on its own (Clear Seas, 2022; Maritime Page, 2024).



Graph 5. Summary of DNV's Techno-Regulatory Governance
Source: AI Generated and manually corrected using chapter 2.9.1; AI tool used - Canva AI

2.9 Sustainability Dynamics in Maritime Shipping

The ecological footprint of global maritime transport has drawn intense international scrutiny due to its massive contributions to marine degradation, atmospheric pollution, and climate change (Psaraftis & Kontovas, 2009). The industry's deep-seated reliance on conventional fossil fuels fundamentally clashes with international mandates designed to curb global carbon emissions. Realigning this sector with sustainable principles requires a holistic transformation that satisfies the United Nations 2030 Agenda by balancing the industry's economic vitality with rigorous environmental protection and social accountability (UNCTAD, 2023).

Central to this transformation are the regulatory frameworks established by the International Maritime Organization (IMO). The IMO has mandated a stringent reduction of maritime greenhouse gas emissions, aiming for alignment with the Paris Agreement's climate targets (Faber et al., 2020). Furthermore, the IMO 2020 sulfur cap has already forced a drastic reduction in the sulfur content of marine fuels, yielding immediate benefits for global air quality. However, achieving true sustainability in shipping goes far beyond simple regulatory compliance; it involves navigating a labyrinth of technological, economic, and socio-political hurdles.

One of the most formidable technical challenges is the industry's pivot toward zero-carbon and low-carbon propulsion systems. While liquefied natural gas (LNG), biofuels, and hydrogen offer promising pathways, their widespread adoption is severely bottlenecked (DNV, 2025). Hydrogen, for instance, demands incredibly complex storage solutions—either at extreme pressures or cryogenic temperatures—which exponentially inflates operational costs. Furthermore, retrofitting older, fossil-fuel-dependent fleets to accommodate these volatile new energy sources is often prohibitively expensive. Regulatory fragmentation also plagues the sector; discrepancies between global IMO standards and regional policies, such as the European Union's Emissions Trading Scheme (EU ETS), create a chaotic compliance landscape that drives up administrative and operational costs for international shipping entities.

Financing this monumental green transition presents another massive barrier. Overhauling global fleets and modernizing port infrastructure requires staggering capital investments. Unfortunately, financial institutions frequently categorize green maritime projects as high-risk, leading to a lack of accessible funding, particularly for smaller operators and developing nations. To bridge this gap, the industry must heavily rely on public-private partnerships (PPPs), green bonds, and robust international financial support to ensure smaller economies are not economically marginalized.

The human and social dimensions of this transition are equally critical but often sidelined. Rapid influx of automation and digitalization threatens the job security of thousands of seafarers, necessitating massive global re-skilling initiatives. Furthermore, crews operating advanced vessels face new occupational hazards and intense mental health pressures, requiring stringent safety protocols and adherence to the labor protections outlined in the Maritime Labour Convention. Addressing the industry's historical gender imbalance is also paramount; initiatives like the IMO's "Women in Maritime" program seek to dismantle systemic barriers and promote female leadership within the sector. At the community level, port developments must be meticulously managed to ensure that local populations benefit economically from the green transition without suffering from the localized costs of shifting supply chains.

Ultimately, mitigating the industry's environmental impact requires tackling multiple fronts simultaneously. Beyond carbon emissions, the sector must confront underwater noise pollution, which severely disorients marine mammals, through the deployment of quieter propulsion technologies and mandatory slow-steaming zones. The ecological threat of invasive species spread via ballast water is being combated through advanced onboard UV and filtration treatments, while stringent enforcement of the MARPOL Convention seeks to eradicate oil spills and marine litter. Moving forward, the fusion of intelligent AI-driven route optimization, blockchain-secured supply chains, and sweeping international cooperation will dictate the maritime industry's ability to evolve into a truly sustainable conduit of global trade (Psaraftis & Kontovas, 2009).

3. Ecological Externalities and Green Transition

The global maritime industry generates a complex array of ecological externalities that extend far beyond greenhouse gas emissions. While climate change rightly dominates global regulatory discussions, ocean shipping simultaneously drives severe systemic degradation across local marine ecosystems. Despite this broad spectrum of environmental damage, decarbonization remains the overriding priority within the modern statutory frameworks governing the sector. Carbon dioxide (CO₂), along with methane and nitrous oxide, presents an urgent, systemic threat to global climate stability. Because of this, the legal texts analyzed throughout this work, most notably the EU Emissions Trading System (EU ETS), FuelEU Maritime, and the IMO Net-Zero Framework, are specifically structured around greenhouse gas mitigation rather than holistic marine conservation.

3.1 Environmental Impact Pathways of Ocean Freight

While maritime transport remains the most carbon-efficient method for moving heavy cargo on a per-ton-mile basis, its massive global scale creates significant environmental externalities. Mitigating this footprint requires international regulatory frameworks, primarily overseen by the International Maritime Organization (IMO), alongside stringent regional policies and technological innovations.

Environmental Impact & Hazard	Description & Ecological Threat	Regulatory Frameworks	Mitigation Technologies & Actions
Atmospheric Emissions (GHG, CO₂, SO_x, NO_x, PM)	Contributes to global climate change and degrades local air quality in coastal and port communities.	IMO Global Sulphur Cap (0.50%), EEXI, CII, EU ETS	Shift to Very Low Sulphur Fuel Oil (VLSFO), alternative fuels (LNG), exhaust gas cleaning systems ("scrubbers"), and carbon pricing.
Ballast Water & Biological Invasions	Discharging untreated water introduces invasive organisms (e.g., zebra mussels, comb jellies) that disrupt local food webs and native fisheries.	Ballast Water Management (BWM) Convention	Installation of approved treatment systems utilizing mechanical filtration, UV irradiation, or chemical disinfection.

Environmental Impact & Hazard	Description & Ecological Threat	Regulatory Frameworks	Mitigation Technologies & Actions
Marine Litter & Microplastics	Discarded packaging, lost containers, and plastic waste (<5mm) accumulate in biological food chains and ocean habitats.	MARPOL Annex V	Strict prohibitions on discharging garbage and plastics into the ocean; public-private initiatives to remove ocean gyre waste.
Oil Pollution	Oil pollution originating from tankers and vessel machinery spaces.	MARPOL Annex I	International controls established to prevent oil pollution from commercial vessels.
Acoustic Pollution & Physical Risks	Low-frequency engine/propeller noise disrupts marine mammal acoustic communication and navigation; high-density lanes pose physical vessel strike hazards.	None explicitly identified in the provided text.	None explicitly identified in the provided text.

Table 3. Summary of Environmental Hazards Imposed on Maritime Industry with Relation to Regulatory Frameworks and Possible Solutions

Atmospheric Emissions and GHG Reduction

The global fleet is responsible for approximately 2.5% of worldwide greenhouse gas (GHG) emissions. Heavy Fuel Oil (HFO) combustion releases carbon dioxide, sulfur oxides (SOx), nitrogen oxides (NOx), and fine particulate matter, contributing to climate change and degrading coastal air quality. To combat this, the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) mandate continuous energy efficiency improvements, grading ships annually to incentivize reductions. Concurrently, the EU Emissions Trading System (EU ETS) applies a direct carbon price on European maritime emissions. Meeting the IMO's Net-Zero 2050 Strategy requires shifting to alternative fuels (LNG, methanol, ammonia, hydrogen), wind-assisted propulsion, and slow steaming.

SOx and NOx Controls

The IMO Global Sulphur Cap limits marine fuel sulfur content to 0.50% globally, driving the adoption of Very Low Sulphur Fuel Oil (VLSFO) and exhaust gas cleaning systems ("scrubbers"). In designated Emission Control Areas (ECAs), this limit drops strictly to 0.10%. Furthermore, MARPOL Annex VI enforces Tier III nitrogen oxide standards,

pushing the industry to adopt Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR) technologies.

Ballast Water and Biological Invasions

Ships take on ballast water to maintain stability, but discharging it untreated introduces invasive species—such as the zebra mussel in North America and the comb jelly in the Black Sea—disrupting local food webs and native fisheries. The Ballast Water Management (BWM) Convention and its rigorous D-2 standards mandate that ships install approved treatment systems using mechanical filtration, ultraviolet (UV) irradiation, or electro-chlorination to neutralize organisms prior to discharge.

Marine Litter and Oil Pollution

Operations generate marine debris, lost cargo containers, and plastic waste. Microplastics pose long-term threats to marine life by accumulating in biological food chains. MARPOL Annex V enforces strict prohibitions on discharging plastics anywhere at sea, supported by onboard compactors and port reception facilities. Simultaneously, public-private initiatives collaborate with industry stakeholders to extract floating plastic waste from ocean gyres. For acute hazards, MARPOL Annex I establishes strict international controls to prevent oil pollution from tankers and machinery spaces.

Underwater Acoustic Pollution and Physical Risks

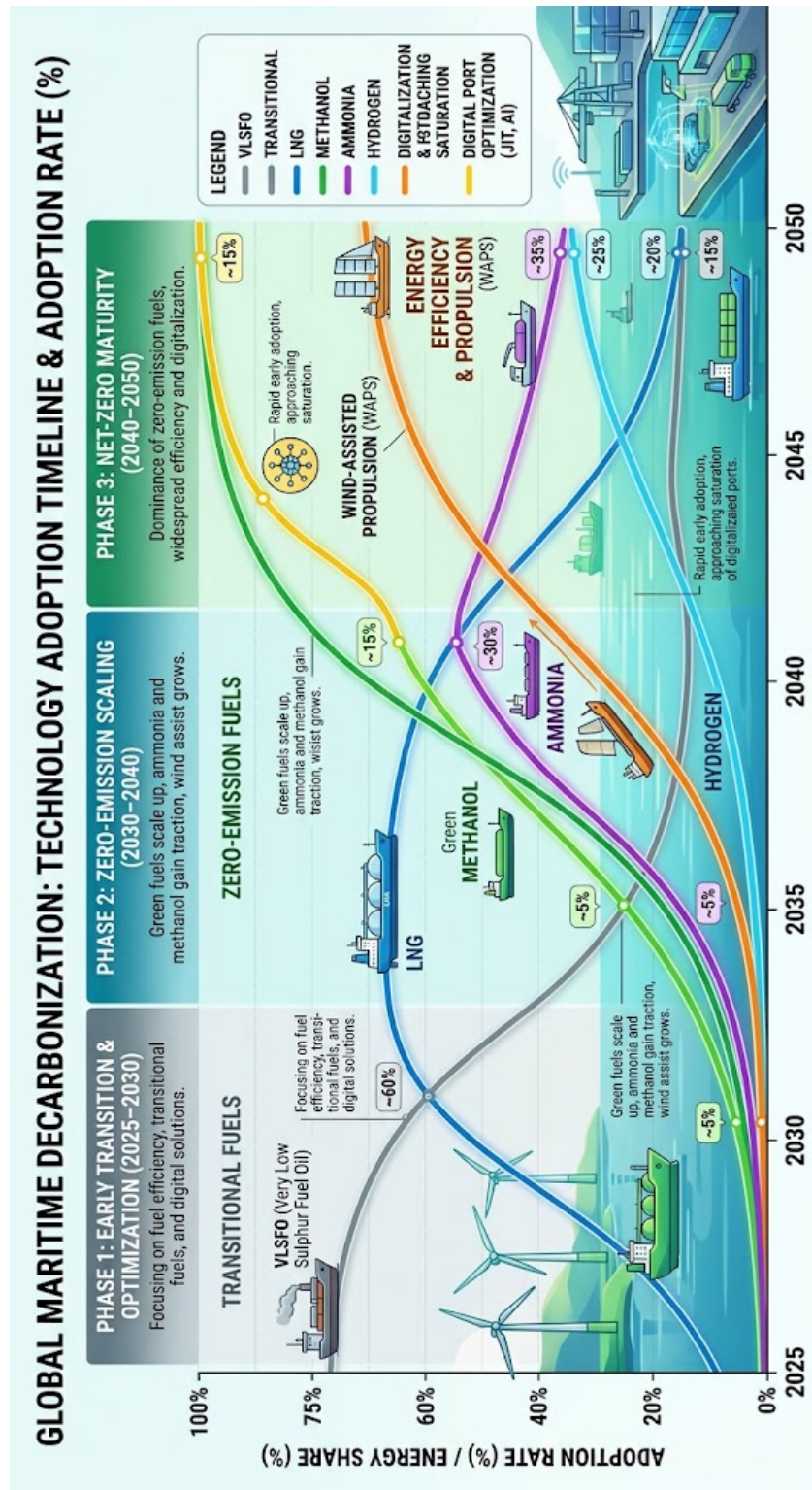
Low-frequency noise from engine vibration and propeller cavitation interferes with the acoustic communication, navigation, and foraging behavior of marine mammals. Additionally, vessel strikes present physical hazards in high-density shipping lanes. Mitigation is advancing through the IMO Revised Guidelines for Underwater Radiated Noise (URN), which encourage optimized propeller designs, machinery vibration isolation, and port-level incentive programs for quieter vessels.

3.2 Technical Innovations and the Decarbonization Horizon

Achieving net-zero carbon shipping requires a comprehensive shift toward alternative energy sources, innovative propulsion systems, and digital optimization tools. Shipping companies are investing heavily in vessels powered by alternative low-carbon marine fuels. Liquefied Natural Gas (LNG) currently serves as an immediate transitional

fuel, reducing sulfur and particulate emissions. Long-term decarbonization targets focus heavily on green methanol, zero-carbon green ammonia, and liquid hydrogen propulsion (DNV, 2025) .

Wind-assisted propulsion technology is also re-emerging as a viable supplement to commercial marine engines. Rigid sails, rotor sails, and automated towing kites (pioneered by vessels like the MV Beluga SkySails) capture wind energy to reduce engine load, lowering fuel burn and carbon emissions by up to 10–30% depending on route weather conditions. Beyond physical engineering, digitalization and operational efficiency are critical to modern logistics. Real-time voyage optimization, AI-driven weather routing, and speed reduction ("slow steaming") deliver immediate fuel savings. Additionally, blockchain technology and electronic documentation streamline administrative processes, reduce port dwell times, and enhance supply chain transparency (DNV, 2025) .



Graph 6. Global Maritime Decarbonization Technology Adoption Timeline & Adoption Rate

Source: DNV. (2025). Maritime forecast to 2050. Det Norske Veritas. <https://www.dnv.com/maritime/publications/maritime-forecast-2050/> ; AI Generated visualization using previously mentioned source and manual input; AI tool used - Google Gemini

3.3 Current Shipping Decarbonization Influence & Future Outlook

The global maritime industry entered a transformative regulatory era in April 2025, when the International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC 83) approved the Net-Zero Framework (NZF) as a new Chapter 5 in MARPOL Annex VI (DNV, 2025). Scheduled for formal adoption in late 2025 and enforcement starting March 2027, the NZF establishes the first global pricing mechanism for greenhouse gas (GHG) emissions alongside mandatory Well-to-Wake (WtW) GHG fuel intensity (GFI) reduction targets starting January 1, 2028. This sub-chapter is a generous sum up of the key information on current state and future outlook on shipping innovations based on DNV Maritime Forecast 2025 (DNV, 2025).

3.3.1 The Regulatory Framework and Financial Mechanisms

The NZF mandates annual Well-to-Wake GFI baseline reductions calculated against a 2008 benchmark of 93.3g CO₂eq/MJ across all commercial vessels over 5,000 gross tonnage (GT). The framework implements a dual-target compliance mechanism alongside a two-tier remedial fee structure.

Compliance Target / Metric	2028 Benchmark	2030 Target	2035 Target	2040 Target	Compliance Mechanism / Penalty
Base Target (GFI Reduction)	4.0%	8.0%	30.0%	65.0%	Tier 1 Remedial Units (RUs): \$100/tCO ₂ eq
Direct Compliance Target	17.0%	21.0%	43.0%	Undefined	Tier 2 Remedial Units (RUs): \$380/tCO ₂ eq
Zero/Near-Zero (ZNZ) Threshold	<19 gCO ₂ eq/MJ	<19 gCO ₂ eq/MJ	<14 gCO ₂ eq/MJ	<14 gCO ₂ eq/MJ	Eligible for Net-Zero Fund Rewards

Table 4. Future Outlook on Compliance Targets

Source: DNV. (2025). Maritime forecast to 2050. Det Norske Veritas. <https://www.dnv.com/maritime/publications/maritime-forecast-2050/>

Under this framework, ships achieving an attained GFI below the Direct Compliance target generate Surplus Units (SUs) that can be banked for two reporting periods or transferred once to balance Tier 2 deficits of other vessels (DNV, 2025). Ships falling between the Base and Direct targets incur Tier 1 compliance deficits payable at \$100 per tonne of CO₂eq, while deficits exceeding the Base target trigger Tier 2 penalties at \$380 per tonne of CO₂eq.

The IMO Net-Zero Fund is projected to collect between \$10 billion and \$15 billion annually from these remedial payments (DNV, 2025). Concurrently, regional policies have tightened: FuelEU Maritime became effective on January 1, 2025, imposing non-compliance penalties of approximately €650/tCO₂eq (~\$730/tCO₂eq), alongside the full integration of shipping into the EU Emissions Trading System (EU ETS) requiring allowance surrenders in 2025 for 2024 emissions (DNV, 2025).

3.3.2 Fleet Technology Transition and Innovation Adoption

The operational fleet currently consumes approximately 1 million tonnes of oil equivalent (Mtoe) of low-GHG fuels annually against a total global fleet energy consumption of 280 Mtoe (DNV, 2025). To meet the IMO NZF 2030 Base target, maritime consumption of low-GHG fuels must reach 25 Mtoe per year—representing 25% to 35% of the total projected global low-GHG fuel production across all industrial sectors (70–100 Mtoe) (DNV, 2025).

While alternative fuel capabilities account for only 8.9% of gross tonnage in the operating fleet, they comprise 51.1% of gross tonnage in the active order book as of late 2025.

- **Container Vessels** accounted for the fastest technology transition; 76% of containerships over 2,000 TEU on order are dual-fuel capable (50% LNG, 25% methanol).
- **Tankers** and **Bulkers** showed slower adoption rates;

- **Dual-fuel ships** represented 18% of tanker orders (>45,000 DWT) and 5.2% of bulk carrier orders (>40,000 DWT) due to unpredictable chartering routes and lower asset valuations.

Order Book Distribution by Vessel Capability:

LNG Dual-Fuel - 1,539 ships operating; 966 on order,

Methanol Dual-Fuel - 70 ships operating; 336 on order,

LPG Dual-Fuel - 159 ships operating; 128 on order,

Ammonia Dual-Fuel - 3 ships operating; 38 on order,

Hydrogen Fuel Cell/Internal Combustion - 8 ships operating; 33 on order,

Battery-Hybrid Systems - 1,072 ships operating; 440 on order.

In parallel, energy-efficiency retrofits have expanded rapidly. Wind-Assisted Propulsion Systems (WAPS) (including rotor sails, suction sails, and wing sails) are installed on 64 operating vessels (56 retrofitted or built after 2020) with 84 additional vessels on order, delivering verified annual fuel savings between 5% and 20%. Rotor sails currently dominate the market with a 50% share across bulkers and tankers. Furthermore, Onboard Carbon Capture and Storage (OCCS) modeling demonstrates that deploying CO₂ offloading infrastructure at the 20 largest global ports would enable carbon capture on large container, bulker, and tanker fleets, reducing world fleet CO₂ emissions by 9% (75 million tonnes of CO₂), equivalent to replacing 25 Mtoe of fossil energy with low-GHG fuels (DNV, 2025).

3.3.3 Compliance Challenges for Small Tonnages and Offshore Support Vessels

Although current IMO NZF and FuelEU Maritime regulations set an initial applicability threshold of 5,000 GT, small tonnages (400–5,000 GT) and Offshore Support Vessels (OSVs) face imminent regulatory inclusion. The IMO's scheduled 2032 review explicitly considers expanding the NZF scope down to 400 GT, while the European Union and UK ETS Authorities are currently evaluating the feasibility of lowering their threshold to include vessels under 5,000 GT.

The extension of mandatory emission reporting, Data Collection System (DCS) monitoring, and fuel intensity targets to small tonnages and OSVs creates acute operational, structural, and financial bottlenecks for operators:

Volumetric and Space Constraints - Unlike large ocean-going containerships or bulk carriers, OSVs, tugs, and coastal traders suffer from severe deck and engine-room spatial limitations. Installing alternative fuel containment—such as insulated cryogenic tanks for LNG/hydrogen, or double-walled fuel lines and safety buffer zones for toxic fuels like ammonia and low-flashpoint methanol—drastically reduces operational deck cargo area and payload capacity.

Capital Cost versus Asset Valuation - The high capital expenditure (CAPEX) associated with dual-fuel machinery, battery hybridization, or OCCS retrofits cannot be easily amortized over small vessel asset values. Furthermore, small vessel operators typically lack access to green financing mechanisms or long-term charter premiums (e.g., ZEMBA buyers' alliances) available to multi-national container lines.

Bunkering and Supply Chain Localization - Small tonnages and OSVs operate primarily in regional, coastal, or non-linear off-shore service routes. Current alternative fuel bunkering infrastructure is disproportionately concentrated in major global hubs—such as Singapore (holding 10 methanol bunker barges) and Rotterdam. Accessing certified bio-LNG, e-methanol, or green hydrogen in secondary or offshore ports remains geographically impractical.

Administrative Overhead and Verification Burden - Compliance requires verifying well-to-wake emissions through a recognized Sustainable Fuels Certification Scheme (SFCS) and maintaining Fuel Lifecycle Labels (FLL). Small fleet operators lacking dedicated sustainability departments face disproportionate administrative costs to implement digital monitoring, report granular operational data, and avoid Tier 2 non-compliance fees.

Human Factor and Crew Certification Deficits - Transitioning to alternative propulsion across specialized small vessels presents severe safety management challenges. Across the global fleet, approximately 33,000 additional seafarers require specialized alternative fuel training by 2028. The lack of formalized STCW (Standards of

Training, Certification, and Watchkeeping) model courses for methanol, ammonia, and hydrogen forces smaller offshore operators to develop custom, flag-approved competence schemes at significant expense.

The alignment of global pricing mechanisms under the IMO NZF and regional frameworks like FuelEU Maritime marks a decisive shift from voluntary decarbonization to mandatory economic penalties. While high-volume commercial shipping segments are rapidly adopting LNG and methanol dual-fuel capabilities, the transition for smaller tonnages and offshore vessels remains hindered by spatial constraints, high relative CAPEX, localized infrastructure shortages, and rigorous verification requirements. Addressing these structural barriers will require tailored regulatory adaptations, expanded regional bunkering networks, and flexible mass-balance Chain of Custody models to ensure a balanced transition across all vessel classes.

Summary

The central objective of this thesis was to examine how emerging environmental regulatory frameworks and sustainable technological innovations are reshaping the global maritime industry. The findings demonstrate that these combined forces are fundamentally altering shipping from a purely cost-driven sector into one governed by carbon accountability. This shift is changing commercial contracts, driving a clear split in how different vessel types adopt new technology, and redefining how companies invest capital for the long term.

Ocean shipping carries more than 80 percent of global trade by taking advantage of massive scale. Ultra-Large Container Ships and specialized bulk carriers significantly lower transport costs per ton. However, the industry remains vulnerable to severe market swings because building new ships takes years. This rigid supply capacity means that when trade demand shifts or drops, operators must use operational tactics—such as reducing vessel speeds or canceling sailings—to protect their profit margins. Historically, fuel selection was treated strictly as an operational expense. Today, because ocean shipping generates roughly 2.5 percent of global greenhouse gas emissions, fuel choice has become the central strategic and financial issue for the industry.

To address these emissions, regulatory bodies have shifted from voluntary targets to legally binding financial penalties. The European Union has led this effort through policies like the EU Emissions Trading System and FuelEU Maritime, which require operators to pay for their carbon output and steadily reduce the lifecycle emissions of their fuel. On a global scale, the International Maritime Organization's Net-Zero Framework enforces similar targets using financial fees that hold polluters responsible for excess emissions. These regulations directly influence commercial maritime law. Because authorities fine registered shipowners for non-compliance, companies use standardized contract clauses, such as BIMCO provisions, to pass these carbon costs down to the charterers who decide ship routes and buy the fuel. Operators can also use compliance pooling to combine emissions data across a fleet, balancing cleaner vessels against older ones to meet overall targets.

These regulatory pressures have created a clear divide in how different maritime sectors adopt new technology. Large container lines are rapidly ordering dual-fuel engines capable of running on alternative fuels like LNG or green methanol, while also adopting wind-assisted sails and AI-powered route optimization. Conversely, smaller cargo ships and offshore support vessels face serious barriers. Their smaller size leaves little room for bulky alternative fuel tanks, retrofit costs are difficult to recover, green fuels are scarce outside major ports, and there is a growing shortage of seafarers trained to handle alternative fuels safely. Classification societies act as essential bridges through this transition. By establishing technical safety standards for new fuels like ammonia and hydrogen, while auditing official emissions data, these organizations provide the operational certainty required to guide the global fleet toward net-zero emissions.

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