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FROM EMISSIONS TO SOLUTIONS: DECARBONIZING GLOBAL SHIPPING

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ABSTRACT

Climate change presents a dual challenge for the shipping industry. While it enables nearly 90% of global trade, the sector contributes about 3% of global greenhouse gas (GHG) emissions—comparable to a major industrialized nation (IMO Fourth GHG Study, 2020). At the same time, shipping is highly exposed to climate risks: rising sea levels threaten ports, extreme weather disrupts routes, droughts impair canals, and shifting baselines under UNCLOS raise legal uncertainties. Without intervention, emissions could rise by 50% by 2050, undermining the Paris Agreement's 1.5°C goal. International law provides guiding principles—state responsibility, environmental protection, and sustainable development—embedded in UNCLOS (1982) and the Paris Agreement (2015). Regulatory tools such as MARPOL Annex VI, with measures like the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), and the 2020 sulphur cap, have pushed progress.

The IMO's Revised GHG Strategy (2023) sets net-zero by 2050, with interim cuts of 20–30% by 2030 and 70–80% by 2040, while complementary initiatives like the UN High Seas Treaty and the EU's Fit for 55 strengthening the momentum. The urgency is clear that shipping emissions rose from 977 million tonnes in 2012 to over 1 billion in 2018, with continued growth projected. Decarbonization requires investment of \$200–350 billion annually, or up to \$1.4 trillion by 2050. Promising innovations include zero-emission fuels, AI-enabled route

optimization, and market-based measures, though challenges remain in technology, enforcement, and equity. At this crossroads, integrating legal reform, technological innovation, and sustainable practices—aligned with SDGs 13 and 14—is vital to achieving resilient, net-zero shipping.

INTRODUCTION

Shipping is the backbone of global trade, carrying nearly 90% of international commerce. Yet, this vital sector is also a significant contributor to climate change, responsible for about 2.9–3% of global anthropogenic CO₂ emissions—comparable to those of a major industrialized nation. Without urgent interventions, emissions could increase by 50% or more by 2050, jeopardizing the Paris Agreement’s 1.5°C target. The industry faces a dual challenge: while it drives climate change, it is also highly vulnerable to its impacts. Rising sea levels threaten ports, extreme weather disrupts routes, droughts reduce canal traffic, and Arctic melting opens contested new passages. These changes also complicate maritime boundaries and legal rights under the United Nations Convention on the Law of the Sea (UNCLOS, 1982).

Legally, the question is whether current frameworks can address such climate-induced disruptions. UNCLOS obliges states to protect the marine environment but does not directly regulate greenhouse gas emissions. The Paris Agreement, though ambitious, excludes international shipping, leaving responsibility to the International Maritime Organization (IMO). Through MARPOL Annex VI and later strategies, the IMO has introduced measures to curb sulphur and nitrogen oxides, improve ship efficiency, and pursue net-zero emissions “by or around 2050.” However, enforcement, equity, and adequacy remain unresolved concerns. Decarbonization requires transitioning to low- and zero-carbon fuels such as hydrogen, ammonia, and biofuels, along with improved ship designs and operational efficiency. These measures involve heavy costs—estimated at \$1.4 trillion by 2050—posing particular challenges for developing nations and small island states. Ensuring fairness in this transition is critical, aligning with global commitments under the Sustainable Development Goals (SDG 13: Climate Action and SDG 14: Life Below Water).

Judicial and arbitral precedents, such as the *South China Sea Arbitration (2016)* and the *Trail Smelter Case (1941)*, highlight evolving interpretations of environmental obligations and state responsibility. Principles like the Polluter Pays Principle, the Precautionary Principle, and

Common but Differentiated Responsibilities (CBDR) provide a foundation for addressing emissions equitably.

Ultimately, the path to net-zero shipping lies in a multi-layered approach: reforming international law, advancing technological solutions, securing financial mechanisms, and fostering global cooperation. Only through such integrated efforts can the sector continue to power trade while safeguarding the planet's future.

CLIMATE CHANGE AND THE SHIPPING INDUSTRY

The shipping industry today faces a paradoxical situation: it is both a major contributor to the global greenhouse gas (GHG) emissions and one of the most vulnerable sectors to the adverse consequences of climate change. This dual challenge underscores the urgency of adopting sustainable solutions within the sector, combining legal reform, technological innovation, and global cooperation.

Shipping as a Major Polluter

Maritime transport is the backbone of the global economy, carrying approximately 90 percent of international trade. However, its carbon footprint is significant. The International Maritime Organization's (IMO) Fourth GHG Study (2020) estimated that shipping accounted for about 2.89% of global anthropogenic CO₂ emissions, releasing over 1 billion tonnes of CO₂ in 2018 alone¹. This figure is comparable to the emissions of a major industrialized nation such as Japan or Germany.

Key pollutants include:

Emissions are projected to increase from about 90% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios. (FIGURE 1).²

Revenues from carbon pricing taxes and Emissions Trading Systems (ETS) have



¹ Fourth Greenhouse Gas Study 2020 - <https://share.google/wctEnst18oNVyAFv7>

² Fourth Greenhouse Gas Study 2020 - <https://share.google/wctEnst18oNVyAFv7>

reached a record high, about \$95 billion, finds the World Bank's annual "State and Trends of Carbon Pricing" report. This is despite the challenging context for governments facing high inflation, fiscal pressures, and energy crises.³

If unchecked, emissions from international shipping are projected to increase by 50% by 2050, driven by the continued growth of global trade. This would directly undermine the Paris Agreement's goal of limiting temperature rise to 1.5°C, pushing the world toward more dangerous climate tipping points. Despite progress in fuel efficiency and regulations under MARPOL Annex VI, the industry remains highly dependent on fossil-based bunker fuels. The scale of shipping emissions demands urgent attention, particularly because they are largely generated in international waters, complicating regulatory enforcement. If shipping was to fully decarbonize by 2050, this would require extra investments of approximately USD 400 billion over 20 years, making the total investments needed between USD 1.2-1.6 trillion dollars. The estimate of investments required is based on ammonia (NH₃) being the primary zero carbon fuel choice adopted by the shipping industry as it moves towards zero carbon fuels. Under different assumptions, hydrogen, synthetic methanol, or other fuels may displace ammonia's projected dominance, but the magnitude of investments needed will not significantly change for these other fuels.⁴

Research on the historical trends in ship design efficiency shows that vessels constructed in the early 2000s were generally less fuel-efficient compared to those produced during the 1990s. Evidence further reveals that bulk carriers, tankers, and container ships delivered in 2013 consumed about 10% more fuel on average than ships built 25 years earlier. These results challenge the industry's common claim of continuous progress in environmental performance.⁵

E-fuels are likely to be the best bet in the long run due to their high emissions reduction potential and scalability. Because scaling up the use of e-fuels will take a long time, targeted investments should be made now to increase production capacity in time, establish global supply chains, and facilitate consistent access to e-fuels at strategically important bunkering hubs. This transition to e-fuels requires large-scale investments from shipowners, fuel producers, ports,

³ State and Trends of Carbon Pricing 2023 <https://www.worldbank.org/en/news/press-release/2023/05/23/record-high-revenues-from-global-carbon-pricing-near-100-billion#>

⁴ The scale of investment needed to decarbonize international shipping | Global Maritime Forum <https://share.google/jVIYWQosAFP8caK4z>

⁵ Climate impact of shipping | T&E – <https://www.transportenvironment.org/topics/ships/climate-impact-shipping>

and charters/cargo owners. A fixed levy on GHG emissions with rewards for e-fuels is the only policy option that can make e-fuels competitive with other fuel pathways.⁶ Revenues collected from economic measures should be purposefully directed toward assisting lower-income nations in their shift to cleaner energy. Such support may involve financing zero-emission fuel production, building necessary infrastructure, training the workforce, and advancing broader climate adaptation efforts to ensure all countries progress inclusively.⁷

Shipping as a Victim of Climate Change

While contributing significantly to global warming, the shipping industry is simultaneously one of its greatest victims. Severe weather encompasses a range of adverse weather conditions that pose risks to navigation safety, maritime operations and the wellbeing of persons at sea⁸. Climate-related impacts manifest across multiple dimensions:



1. Rising Sea Levels and Port Infrastructure

Ports, shipyards, and coastal terminals are highly vulnerable to sea-level rise. According to the IPCC Special Report on the Ocean and Cryosphere (2019), global mean sea levels could rise by up to one meter by 2100 if emissions continue unabated. Such an increase would inundate low-lying port cities, causing billions of dollars in damages and disrupting international trade routes.

2. Extreme Weather Events

The intensity and frequency of cyclones, hurricanes, and typhoons are increasing due to climate change. These events cause significant disruptions to maritime transport,

⁶ IMO policy measures: Ensuring certainty for shipping's energy transition | Global Maritime forum- <https://share.google/Eh9rgZ3cMBRDw34Pk>

⁷ Ibid

⁸ Climate change, severe weather, impact on shipping | Britannia P&I – <https://share.google/97K7Km9UZL6qmGDuQ>

delaying shipments, damaging vessels, and increasing insurance costs. Cargo losses from extreme storms are becoming more frequent, raising questions about liability and insurance adequacy under maritime law.

3. Droughts and Canal Operations

Climate-induced droughts threaten the functionality of major canals. The Panama Canal, which depends on freshwater reservoirs, has already experienced reduced water levels, limiting the tonnage of ships able to pass through. Similarly, the Suez Canal and other chokepoints could face operational challenges as climate variability alters hydrological conditions.

4. Shifts in Maritime Routes

Melting Arctic ice has opened new northern shipping routes. While this reduces travel time between Asia and Europe, it poses serious environmental risks, including threats to fragile ecosystems and increased geopolitical competition in the Arctic region

5. Human Security and Seafarers

Rising sea temperatures and harsher weather conditions also affect seafarers' safety, leading to more accidents, mental health pressures, and occupational hazards. Ensuring safe working conditions in such circumstances presents an additional challenge for regulators and industry stakeholders.

Overall, severe weather at sea encompasses a range of hazardous conditions and meteorological phenomena that require careful monitoring, risk assessment, and response measures to ensure maritime safety and mitigate potential impact. Although these phenomena are not new, their influence on the shipping industry is expected to grow and intensify as climate change advances. Sadly, there are many examples of severe weather contributing to serious incidents resulting in loss of life and ships. Some of them led to introducing new regulatory requirements and industry practices as lessons were learned. Examples of these widely publicised incidents include:

- The grounding of the container ship **Ever Given in 2021**, which resulted in the obstruction of the Suez Canal was attributed to high winds during a sandstorm as one of the direct causes. The absence of fatalities did not prevent the incident from having a severe economic impact and generating extensive claims.
- Sinking and the loss of 33 crew members of the cargo ship **El Faro (2015)**, where the key causes included a failure to avoid the tropical storm and handle the ship against it, whilst relying on outdated weather sources⁷

- Sinking of the ferry **Estonia (1994)** with the loss of 852 lives, attributed to the failure of bow door and ramp in heavy weather⁸
- Sinking of the **OBO carrier Derbyshire** during Typhoon Orchid in 1980 with the loss of 44 lives, caused by water ingress to forward section of the ship, ultimately resulting in structural failure. Subsequent investigations indicated that the ship may have encountered a super rogue wave.⁹

With climate change, the risk of severe weather-related incidents increases if a ship owner is not duly prepared. This emphasizes the necessity of keeping systematic reviews current and fostering knowledge sharing so that hazards are detected early and risks are managed proactively, rather than only after accidents or losses occur. Hence, building resilience in advance through a structured and business-oriented approach becomes essential. The shipping sector now stands at a critical crossroads. It must either fast-track its transition toward sustainability—leveraging AI and alternative fuels to cut emissions—or risk intensifying climate change while enduring its most severe consequences. The challenge is not only technical but also deeply legal and ethical, requiring global cooperation and equitable burden-sharing.

INTERNATIONAL LEGAL FRAMEWORK

The governance of shipping and its environmental impacts is shaped by a complex web of international treaties, customary principles, and institutional mechanisms. While shipping is indispensable to the functioning of the global economy, its regulation is fragmented across instruments that were developed in different contexts and for varying purposes. At the center lies the United Nations Convention on the Law of the Sea (UNCLOS, 1982), often described as the “constitution for the oceans.” Complementing it are specialized environmental agreements, such as the Paris Agreement (2015) and the International Maritime Organization’s MARPOL Convention (1973/1978). More recently, the IMO’s Revised GHG Reduction Strategy (2023) and the UN High Seas Treaty (2023) reflect efforts to update governance to match contemporary climate challenges.

➤ **UNITED NATIONS CONVENTION ON THE LAW OF THE SEA (UNCLOS, 1982): The foundational treaty**

UNCLOS, often described as the “constitution for the oceans,” provides a comprehensive legal framework for maritime governance. Adopted in 1982, it codifies

⁹ Ibid

a wide range of issues, including navigation rights, maritime zones, seabed mining, and environmental protection.

- Environmental Obligations (Arts. 192–196):

Article 192 imposes a general duty on states to “protect and preserve the marine environment”¹⁰. Articles 194 and 195 specify obligations to prevent, reduce, and control pollution from any source, including vessels. These fundamental obligations reflect customary international law and is considered *erga omnes*, meaning it applies to all states in the international community.

Although UNCLOS does not explicitly mention greenhouse gas emissions, these provisions provide a legal basis for extending the definition of marine pollution to include climate-related emissions.

- Pollution from Vessels:

Article 211 recognizes the special competence of the IMO in regulating vessel-source pollution, linking UNCLOS obligations to MARPOL. The Article addresses pollution from vessels, establishing that states must adopt laws to prevent, reduce and control such pollution for ships flying their flag. It mandates the creation of international standards through competent international organization to ensure a balance between global navigation integrity and the environmental protection interests of coastal states.

- Baselines and Rising Sea Levels:

Maritime zones under UNCLOS—such as territorial seas (12 nm), exclusive economic zones (200 nm), and continental shelves—are measured from coastal baselines defined at the low-water mark. Rising sea levels threaten to submerge or shift these baselines, creating legal uncertainty. Should maritime zones be fixed based on historic baselines, or should they shift as coastlines change? This unresolved issue has sparked debate among scholars and states, raising the risk of maritime boundary disputes.

- Dispute Settlement Mechanisms:

UNCLOS provides mechanisms such as the International Tribunal for the Law of the Sea (ITLOS) and arbitral tribunals (Annex VII) for resolving disputes. However, their adequacy in addressing climate-induced disputes remains untested.

¹⁰ PREAMBLE TO THE UNCLOS – <https://share.google/hPfDnqPsffu6fPnW3>

The **South China Sea Arbitration (Philippines v. China, 2016)** demonstrated the tribunal's willingness to enforce environmental protection duties under UNCLOS, potentially extending to climate-related harms. While the case primarily addressed sovereignty, the tribunal emphasized on states have duties under UNCLOS to protect fragile marine ecosystems, including coral reefs, and found China in breach of these obligations, showing a readiness to extend such reasoning to broader harms, potentially including climate change. This demonstrates the "green potential" of UNCLOS, suggesting its principles could evolve to address climate-related environmental harms in future disputes.¹¹

➤ **THE PARIS AGREEMENT (2015): Indirect Influence**

The Paris Agreement, adopted on December 12, 2015 under the UN Framework Convention on Climate Change (UNFCCC), is the central global instrument on climate change. Its primary goal is to hold global temperature rise to well below 2°C above pre-industrial levels, while also pursuing efforts to limit it to 1.5°C, which aims to prevent dangerous climate change impacts and promote resilience.¹²

• **Nationally Determined Contributions (NDCs):**

NDCs are each country's self-defined climate action plans under the Paris Agreement, outlining their targets for reducing greenhouse gas emissions and adapting to climate impacts. States must submit NDCs every five years outlining emission reduction efforts with increased ambition to achieve the Paris Agreement's goal.

NDCs are the main vehicle for countries to collectively address climate change. Countries are required to pursue domestic emissions reductions with the aim to meeting their NDC targets over the next 10 years¹³. However, international shipping is excluded from NDCs, reflecting the difficulty of attributing emissions to specific states.

• **Indirect Impact on Shipping:**

While shipping is not directly regulated, the Paris Agreement exerts pressure on states to push the IMO and national governments to create and implement

¹¹ David Freestone, "The South China Sea Arbitration: Environmental Law in the South China Sea", 110 AJIL (2016) 290

¹² The Paris Agreement | UNFCCC – <https://share.google/saFMyuB9m3t3YUH2r>

¹³ World Resources Institute – <https://www.wri.org/insights/nationally-determined-contributions>

stricter emission reduction targets, driving the development and adoption of new green technologies and fuels, creating incentives for the shipping industry to invest in sustainable practices, and raising consumer and investor pressure for the sector to decarbonize¹⁴. Thus, it acts as a political driver, if not a legal one.

- Sustainable Development and Equity:

Article 4 of the Agreement stresses equity and reflects the principle of “**Common But Differentiated Responsibilities and Respective Capabilities**” (CBDR-RC) by allowing countries to determine their own actions based on national circumstances, while developed countries have a leading role in providing financial and other support to developing countries.¹⁵

➤ **MARPOL Convention (1973/1978): Regulating Vessel Emissions**

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the primary IMO treaty regulating vessel-source pollution. While initially designed to tackle oil pollution, it has evolved to address air pollution and GHGs.

- Annex VI (1997, effective 2005):

The MARPOL Annex VI is an international treaty under IMO that sets regulations to prevent air pollution from ships, specifically limiting emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) from ship exhausts.

It regulates air pollution from ships by defining Emission Control Areas (ECAs) with stricter limits. Ships must use these requirements by using low-sulphur fuels, installing exhaust gas cleaning systems or implementing other approved technologies.¹⁶ It introduced the mandatory Energy Efficiency Design Index (EEDI, 2011) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for existing vessels, targeting to reduce greenhouse gas emissions from international ships.

- 2020 Global Sulphur Cap:

The 2020 Global Sulphur Cap, known as IMO 2020, reduced the maximum sulphur content in ships' fuel oil from 3.5% to 0.5% starting January 1, 2020. This regulation under the MARPOL Convention significantly decreases sulphur

¹⁴ Full speed ahead with climate-change measures at IMO following Paris Agreement – <https://share.google/1AqUFZovVEUOkvyyB>

¹⁵ Key aspects of the Paris Agreement | UNFCCC – <https://share.google/ZHbXG2Kt2xztui4xL>

¹⁶ Key requirements in MARPOL Annex VI – <https://share.google/csSXau0HskvE9rXL>

oxide (Sox) emissions, leading to better air quality and human health by reducing respiratory and cardiovascular diseases. Within designated Sulphur Emission Control Areas (SECAs), the limit remained 0.1%.

- Carbon Intensity Indicators (CII):

Recently introduced to measure and rank ships' efficiency. It rates the operational efficiency of ships in reducing carbon emissions. Ships with lower ratings must develop and implement corrective action plans to improve their carbon efficiency, while boundary requirements become more stringent each year.¹⁷ These metrics are meant to incentivize cleaner practices, although enforcement remains inconsistent.

➤ **IMO's Revised GHG Reduction Strategy (2023)**

On 7 July 2023, the IMO adopted a Revised GHG Strategy, which represents a historic turning point in maritime climate governance by setting a new ambition for net-zero GHG emissions from international shipping "close to 2050".

- Interim Checkpoints:

2030: At least 20% reduction (striving for 30%) in GHG emissions relative to 2008 levels.

2040: At least 70% reduction (striving for 80%) in GHG emissions relative to 2008 levels

- Basket of Candidate Measures:

Technical element: A goal-based marine fuel standard will regulate the phased reduction of the marine fuel's GHG intensity, focusing on well-to-wake emissions.

Economic element: A maritime GHG emissions pricing mechanism will be developed and implemented.

This strategy, while ambitious, faces criticism for vagueness in enforcement and its reliance on voluntary compliance by flag states.

¹⁷ Rules on ship carbon intensity and rating system enter into force – <https://share.google/BMVbxXfOSj1THnBaX>

➤ **THE UN HIGH SEAS TREATY (2023): Filling Regulatory Gaps**

The Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Treaty),



of Areas Beyond National Jurisdiction (BBNJ Treaty), adopted in 2023 is a legally binding international agreement to protect marine life in the open ocean and addresses governance gaps in the high seas. While not focused specifically on shipping, it:

Its emphasis on coordination and sustainability may indirectly strengthen legal approaches to shipping emissions, particularly in areas beyond national jurisdiction where enforcement has historically been weak.

➤ **REGIONAL LEGAL INITIATIVES**

Regional frameworks complement global treaties by enforcing more ambitious or localized measures:

• **European Union “Fit for 55” package:**

1. Includes shipping in the EU Emission Trading System (ETS).
2. Targets 55% reduction in emissions by 2030 compared to 1990 levels.
3. Promotes green shipping corridors to incentivize low-emission fuels.
4. Core part of the European Green Deal.
5. Aims to put the EU on a path to becoming climate-neutral by 2050.

• **North American and Asia-Pacific initiatives:**

North America is also developing strategies like those focused on clean energy mobility and exploring new technologies such as wind propulsion. In the Asia-Pacific region, focus is on integrating sustainable transport solutions, including the scaling of electric mobility and investing in renewable energy infrastructure to address rapidly growing freight and passenger transport demands. These initiatives often serve as models for international regulation, demonstrating practical pathways to reduce emissions. Despite these developments, challenges persist. Enforcement is often inconsistent, particularly among “flags of convenience” states that apply

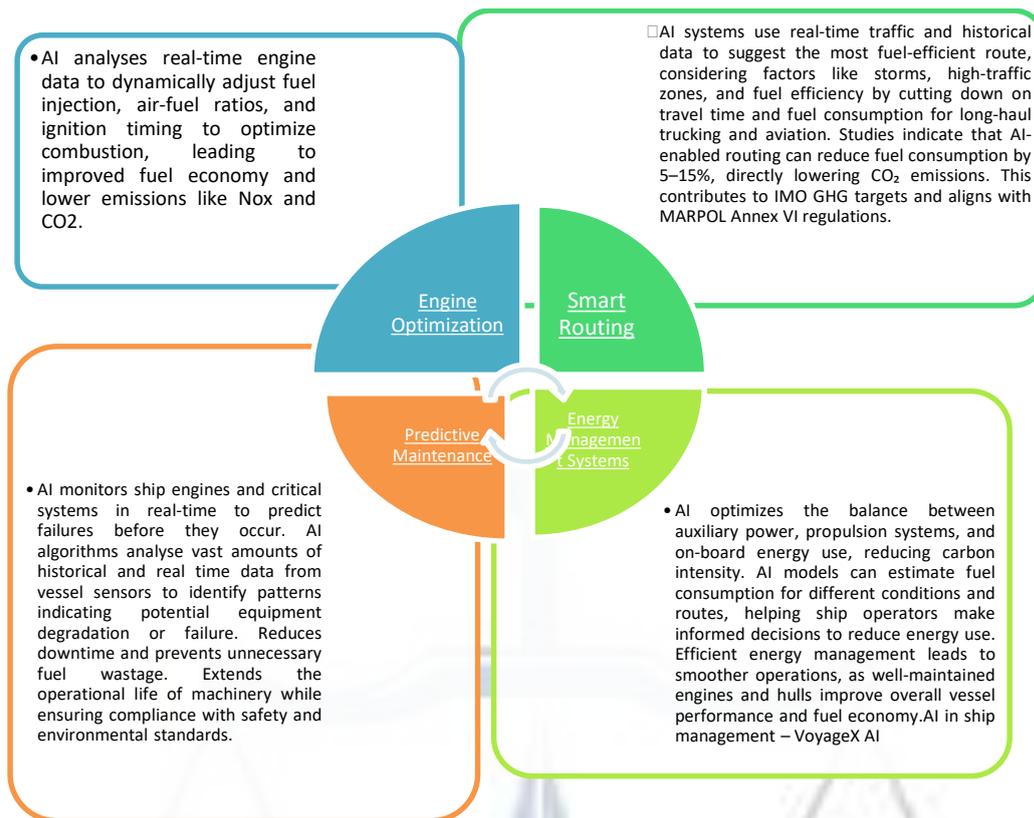
laxer standards. Furthermore, legal frameworks remain fragmented, with overlaps and gaps that complicate compliance. In sum, the international legal framework for climate change and shipping is evolving but remains incomplete. While UNCLOS, the Paris Agreement, MARPOL, and the IMO provide the foundation, stronger enforcement, clearer obligations, and deeper integration of sustainability principles are needed to achieve the 2050 net-zero target.

AI AND TECHNOLOGICAL INNOVATIONS IN SHIPPING

The shipping industry is at the crossroads of technological transformation, with artificial intelligence (AI) emerging as a key enabler of sustainability and climate resilience. As global trade volumes continue to grow, shipping faces the dual challenge of reducing emissions and adapting to climate-induced disruptions. AI offers opportunities to optimize operations, enhance safety, and comply with international legal obligations while supporting decarbonization goals.

AI for Fuel Efficiency and Emission Reduction: One of the most immediate applications of AI in shipping is fuel optimization. Fuel consumption represents the largest contributor to GHG emissions in maritime transport. AI-based solutions, such as machine learning algorithms and predictive analytics, allow shipping operators to optimize engine performance and vessel speed according to weather, sea currents, and cargo load.





AI in Weather Forecasting and Risk Mitigation

Climate change has increased the frequency and intensity of extreme weather events, which disrupt maritime trade and increase insurance and operational costs. AI-driven weather modelling allows vessels to anticipate storms, high waves, and hurricanes:

- **Predictive Analytics for Storm Avoidance:** AI models, such as WoFS Cast, learn the intricate physics of storms, including updrafts and cold air pockets, to better predict their evolution and movement. Ships can re-route dynamically to avoid severe weather, reducing the risk of cargo loss and fuel wastage.
- **AI in Canal Operations:** AI and stimulation modelling are used to analyse historical data and predict future conditions, such as those related to canal expansion and water salinity, to inform operational decisions. Forecasting low water levels or congestion in key passages like the Panama Canal enhances planning and efficiency.
- **Integration with Digital Twins:** Digital twin simulations of ships and port operations, powered by AI, allow operators to test multiple scenarios for climate-related risks and analyse complex data and take predictive decisions for improved operational efficiency, risk reduction and innovation.

This predictive capability not only improves safety but also ensures shipping complies

with state obligations under UNCLOS Articles 192–196, which require environmental protection and disaster prevention measures.

Alternative Fuels and AI Optimization

The transition to low- and zero-emission fuels is central to decarbonizing shipping. AI optimizes alternative fuels by predicting performance, enabling real-time adjustments to fuel mixes for improved efficiency and reduced emissions, and accelerating the design of novel fuels through advanced computational modeling and inverse design techniques.

- **Hydrogen, Ammonia, and LNG:** AI predicts energy demand, prevents hydrogen levels, optimizes combustion parameters for ammonia-diesel blends, and helps integrate these alternative fuels into existing energy systems for a more sustainable future.
- **Biofuels and Synthetic Fuels:** AI optimizes waste-to-fuel technologies and synthetic biology processes for enhanced CO₂ absorption and yield in biofuel production. AI predicts engine performance and emission profiles, ensuring compliance with MARPOL and IMO emission standards.
- **Fuel Blending:** AI algorithms can suggest optimal blends of conventional and alternative fuels to reduce emissions without compromising vessel performance. AI algorithms, such as Artificial Neural Networks (ANNs) and Random Forests, are trained on experimental and simulation data to accurately predict fuel properties and engine performance characteristics¹⁸. These algorithms understand complex non-linear relationships in fuel blends, accelerating development and supporting the adoption of sustainable, next-generation fuels.

The adoption of these fuels is critical to meeting IMO's 2023 Revised GHG Strategy, which calls for net-zero emissions by 2050 with interim reductions of 20–70% by 2030–2040.

Port Operations and Supply Chain Optimization

Ports and maritime logistics also benefit from AI applications:

- **AI-Enabled Port Management:** AI can optimize berthing schedules, cargo handling, and crane operations to minimize waiting times and fuel consumption. This transforms ports into smart hubs, improving overall supply chain visibility and enhancing competitiveness.

¹⁸ A case study on Integrating an AI system into the fuel blending process – <https://share.google?L2JDNh1J101QVwVDU>

- **Smart Supply Chains:** Predictive algorithms improve inventory management and reduce unnecessary voyages, decreasing emissions. By predicting demand, optimizing logistics, monitoring product quality, and improving real-time visibility, the advanced AI systems create more agile, sustainable, and resilient supply networks.
- **Green Shipping Corridors:** AI helps coordinate routes where low- or zero-emission fuels are used, supporting regional sustainability initiatives like the EU's green corridor projects. Machine learning models use Automatic Identification System (AIS) data to predict vessel arrival times, thereby, improving energy efficiency in ports and monitoring emissions, thus, accelerating the transition to sustainable shipping.
By integrating AI into port management, operators can reduce the carbon footprint of shipping at multiple nodes in the supply chain.

AI in maritime navigation brings vast opportunities but also raises legal challenges such as liability in case of collisions, compliance verification for emissions, cybersecurity risks to ships and ports, and concerns over data protection and transparency. Existing frameworks like UNCLOS, SOLAS, and MARPOL may require amendments to address these issues.

Way forward: The regulatory framework must evolve to clearly allocate liability, establish AI-based compliance standards, strengthen cybersecurity measures, and ensure transparent data-sharing—so AI can function as both a compliance tool and a driver of safe, sustainable maritime operations.

SUSTAINABILITY AND EQUITY CHALLENGES IN SHIPPING

Achieving sustainability in the shipping industry is not only a technological or regulatory challenge but also a question of equity and fairness. As shipping moves toward decarbonization and climate resilience, significant disparities emerge between developed and developing nations, large and small shipping companies, and coastal versus landlocked states. Thus, sustainability and equity emerge as the central challenges that must guide maritime regulation and industry practices.

Sustainability Challenges: -

(a) **High Emission Footprint**

Despite energy efficiency measures, emissions continue to rise due to expanding global trade. Traditional fuels like heavy fuel oil emit SO_x, NO_x, and particulate matter,

worsening air pollution and marine degradation.¹⁹

(b) Technological Barriers

Zero- and low-emission fuels—such as green hydrogen, ammonia, and biofuels—face challenges of scalability, safety, and cost. Storage facilities, bunkering infrastructure, and retrofitting of vessels require enormous investment. Implementing new technologies such as AI, automation, and internet of things (IoT) systems involve significant upfront costs for hardware, software, and training.²⁰

(c) Regulatory Gaps

The MARPOL Convention (Annex VI) sets standards for SO_x, NO_x, and CO₂, while measures like the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) attempt to reduce emissions.²¹ However, enforcement remains inconsistent, especially among flag-of-convenience states, where lax regulations undermine global compliance.

(d) Economic Costs

Transitioning to sustainable shipping demands staggering financial resources. The Global Maritime Forum (2022) estimates that decarbonization will cost \$1.4 trillion by 2050²², including vessel retrofits, green port infrastructure, and fuel production facilities. Developing economies, where many ports are located, may struggle to mobilize these resources.

(e) Legal Complexities

International frameworks are fragmented. While UNCLOS (1982, Articles 192–196) obligates states to protect the marine environment, it does not explicitly address GHGs. The Paris Agreement (2015) leaves shipping outside its scope, relying instead on the IMO's complementary role. This creates uncertainty over enforcement and dispute settlement. The South China Sea Arbitration (Philippines v. China, PCA, 2016) demonstrated that UNCLOS provisions can be interpreted broadly to protect marine environments, suggesting potential extension to climate-related harms.

¹⁹ Fourth Greenhouse Gas Study 2020 - <https://share.google/wctEnstl8oNVyAFv7>

²⁰ Digitalization in the Shipping Industry: Maritime Digitalization Operations – <https://share.google/Ehcij4Ni7uxQVXCmp>

²¹ Key requirements in MARPOL Annex VI – <https://share.google/csSXau0HskvE9r1XL>

²² New Fuels: Total cost of operation |Global Maritime Forum – <https://share.google/L38MuD1cJbA86COUV>

Equity Challenges: -

(a) Disproportionate Burdens

Small Island Developing States (SIDS) and coastal nations face rising sea levels, port disruptions, and economic vulnerability. Yet, they possess limited financial and technological resources to adapt, despite contributing minimally to global emissions. A focus on a “just and equitable transition” for the shipping sector is crucial to ensure that the burdens of decarbonization and the benefits of modernization are shared fairly, according to UN Trade and Development (UNCTAD).²³

(b) Just Transition for Workers

Decarbonization and automation risk displacing seafarers, dock workers, and small-scale operators. A “just transition” requires training programs, reskilling, and safety nets to ensure livelihoods are not sacrificed for sustainability. A shift to greener shipping can lead to job losses in traditional roles, while the necessary new skills for green technologies may not be available, leaving workers without adequate training or support.²⁴

(c) Unequal Access to Technology

Advanced economies are pioneering AI integration and zero-carbon fuels, while developing states risk being excluded. This creates a “green divide” that mirrors broader North–South inequities in climate governance. Lack of resources and infrastructure prevents many from adopting digital tools, leading to manual processes that are prone to errors and inefficiencies.²⁵ Delaying digitalization exacerbates existing inequalities between nations, potentially increasing the economic isolation of poorer countries.

(d) Cost Pass-Through

Market-based measures (MBMs), such as carbon levies on bunker fuels, could increase freight costs. Such costs are often passed on to consumers, disproportionately impacting poorer nations reliant on imports. When ports are overwhelmed or there’s a lack of vessel space, carriers can charge higher rates due to increased demand and delayed turnaround times. Extended payment cycles in the logistics industry, combined with rising costs, can strain cash flow, especially for smaller businesses that may have tighter margins.²⁶

²³ <https://unctad.org>

²⁴ International Journal of Labour Research, “Climate Change and labour: the need for a ‘just transition’” (2010)

²⁵ Digital inequality in logistics: Causes, impact and solutions | Maersk – <https://share.google/KfBjYl3mdZqNiTGtX>

²⁶ <https://share.google/jsoyHa3yACEgcxuUv>

(e) Legal and Policy Equity

The principle of Common but Differentiated Responsibilities (CBDR) under international environmental law highlights the need for equitable treatment. Shipping decarbonization must align with this principle, ensuring that developing nations receive support in technology transfer, capacity building, and financing. Developing policies that consider the needs of diverse maritime stakeholders, including smaller operators and communities, can help foster greater equity. Efforts to democratize access to financing and investment can help level the playing field for smaller shipping companies and developing nations.²⁷

Pathways Forward

- AI-Enabled Efficiency: AI-driven route optimization, predictive maintenance, and digital twin technologies can reduce emissions without major capital investments, making sustainability accessible across regions.
- Green Corridors: Regional initiatives like the EU's "Fit for 55" package and IMO's promotion of "green shipping corridors" create scalable models for global adoption.
- Financing Mechanisms: Climate funds, concessional loans, and public-private partnerships must channel resources toward vulnerable states to bridge infrastructure gaps.
- Legal Reform: Stronger enforcement of MARPOL, integration of climate obligations into UNCLOS dispute settlement, and adoption of AI as a compliance tool are needed.
- Human-Centric Transition: Policies must prioritize training, seafarer welfare, and stakeholder consultation to ensure equity in decarbonization.

Sustainability in shipping extends beyond emission reduction to include equity, social justice, and environmental fairness. Financial barriers, technological gaps, and workforce transitions pose significant challenges for developing countries and small operators. Integrating principles like CBDR, promoting green shipping corridors, and linking actions to SDGs ensure that decarbonization efforts are inclusive and effective. A balanced approach combining technological innovation, regulatory enforcement, financial support, and workforce adaptation is necessary to meet the dual objectives of climate resilience and equity.

²⁷ Maritime Finance Insights: Trends, Investments & Opportunities – <https://share.google/7NbuJ63xbTJe3E299>

CONCLUSION

Climate change represents an existential challenge for the shipping industry, which both contributes to and is affected by environmental shifts. This paper has examined the interplay between climate change, shipping operations, AI innovations, sustainability imperatives, and legal frameworks, providing a comprehensive analysis of emerging challenges in maritime law. The shipping industry stands at a critical juncture where climate change, technological innovation, and evolving maritime law converge. As both a contributor to and a victim of environmental shifts, the sector must urgently embrace decarbonization while adapting to rising sea levels, extreme weather, and disrupted trade routes.

Artificial intelligence offers powerful tools to achieve sustainability—through efficient routing, predictive maintenance, and optimization of alternative fuels—while legal frameworks such as UNCLOS, MARPOL, and the Paris Agreement provide the foundation for accountability. Yet, these efforts must be reinforced by equity-focused measures. Developing nations and Small Island Developing States face high costs, technological barriers, and workforce transitions, making capacity-building and inclusive policies essential.

Looking ahead, maritime governance must evolve to address new realities, including liability for AI-driven vessels, climate-induced disputes, and transboundary environmental harm. A multi-layered approach—integrating AI, harmonized international laws, green shipping corridors, and equitable incentives—can create a pathway to resilience.

By aligning economic activity with ethical, environmental and ecological responsibility, the shipping industry has the opportunity not only to secure global trade but also to protect the marine environment for future generations.

“The tide of climate change is rising, but with law, technology, and fairness as its sails, shipping can lead the voyage towards a greener tomorrow.”

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