

IMO Net-Zero Framework: Pathways to Maritime Decarbonization

Jie Yao*, Ziming Hu

COSCO Shipping Technology Co., Ltd., Shanghai, China

Email: *yao.jie@coscoshipping.com

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Abstract

As a core pillar of global trade, the maritime industry transports approximately 90% of international cargo while contributing nearly 3% of global greenhouse gas (GHG) emissions. Without effective intervention, this proportion could rise to 10% - 13% by 2050. The International Maritime Organization (IMO) established a net-zero framework through its revised GHG Strategy in 2023. This framework aims to achieve the maritime sector's decarbonization transition via stringent emission reduction targets and technological innovation, including at least a 40% reduction by 2030, a 70% reduction by 2040, and net-zero emissions around 2050. This paper reviews core elements of the IMO net-zero framework, including the Global Fuel Intensity (GFI) standard, GHG emissions pricing mechanisms, and the establishment of a net-zero fund. It analyzes implementation progress by 2025, such as the draft amendments to MARPOL Annex VI approved at MEPC 83 and their formal adoption at the MEPC/ES.2 special session. Through literature analysis, this paper examines current maritime research trends, including technological innovations (e.g., green hydrogen and ammonia fuels), policy-economic impacts, regional equity, and modeling simulations. Looking ahead, the framework is projected to accelerate zero-carbon fuel commercialization but faces challenges from geopolitical divisions and technology lock-in. The study highlights opportunities, such as supporting developing nations' technology transfer through funds, and proposes policy recommendations including enhanced international coordination and dynamic evaluation mechanisms to advance global climate action. Findings provide insights for the sustainable maritime transition and call for further empirical research to validate the framework's effectiveness.

Keywords

Maritime Decarbonization, Greenhouse Gas Emissions Reduction,

1. Introduction

As a core pillar of global trade, the shipping industry transports approximately 90% of international cargo while contributing nearly 3% of global greenhouse gas (GHG) emissions [1]. Without effective intervention, this proportion could rise to 10% - 13% by 2050, exacerbating the impacts of climate change [2]. The International Maritime Organization (IMO) established a Net-Zero Framework through its revised GHG Strategy in 2023, aiming to achieve the shipping industry's decarbonization transition via stringent emission reduction targets and technological innovation [3]. This framework emphasizes reducing emissions by at least 40% by 2030, 70% by 2040, and achieving net-zero emissions around 2050, marking the industry's shift from carbon intensity management to full lifecycle emissions reduction [4].

In 2025, the framework entered a critical implementation phase. The IMO Marine Environment Protection Committee (MEPC) approved draft amendments to MARPOL Annex VI at its 83rd session in April, introducing the Global Fuel Intensity (GFI) standard and GHG emissions pricing mechanisms [5]. Subsequently, the MEPC/ES.2 Special Session from October 14 - 17 focused on formally adopting the framework, expected to take effect in 2027 despite geopolitical disagreements such as U.S. opposition to carbon taxation [6]. These developments not only respond to pressures from the EU's FuelEU Maritime regulation and Carbon Border Adjustment Mechanism (CBAM) but also accelerate the commercialization of zero-carbon fuels like green hydrogen and methanol [7].

Existing research has extensively explored the technical, economic, and policy dimensions of shipping decarbonization. Early work centered on alternative fuels and energy efficiency measures [8], while recent literature emphasizes just transition and infrastructure challenges under net-zero frameworks [9]. For instance, research simulations indicate that emissions pricing mechanisms could generate tens of billions of dollars to support technology transfer in developing countries [10]. However, existing reviews are often confined to specific technological pathways, lacking systematic integration of the framework's overall evolution, current research trends, and future prospects.

This paper reviews the core elements of the IMO's net-zero framework, progress toward 2025 targets, the current state of shipping research, future development prospects, and associated challenges and opportunities. By analyzing the latest literature and policy developments, this study aims to provide insights for the sustainable transformation of the shipping industry and propose policy recommendations to advance global climate action.

The literature review for this study was conducted using databases such as Scopus, Web of Science, and Google Scholar, searched between January 2023 and Oc-

tober 2025. Keyword strings included combinations like “IMO net-zero framework” AND “maritime decarbonization”, “shipping GHG emissions reduction” OR “alternative fuels”, and “emissions pricing mechanisms” AND “net-zero funds”. Selection criteria focused on peer-reviewed articles, reports from reputable organizations (e.g., IMO, EU), and studies published in English with relevance to the framework’s core elements, resulting in approximately 50 sources after excluding duplicates and non-empirical works for reproducibility.

2. Core Elements of the Net-Zero Framework and Progress by 2025

The core elements of the IMO Net Zero Framework aim to drive the shipping industry toward achieving net-zero GHG emissions by 2050 through regulatory and economic incentive mechanisms. This framework integrates mid-term measures, including a global GHG fuel intensity (GFI) standard, GHG emissions pricing mechanisms, and the establishment of the IMO Net Zero Fund. These elements are grounded in a well-to-wake emissions assessment methodology, ensuring comprehensive emissions reductions from fuel production to vessel operation [11]. The GFI standard targets vessels over 5000 gross tons (covering approximately 85% of international shipping GHG emissions), setting progressive reduction thresholds: at least 20% - 30% by 2030 and 70% - 80% by 2040. It introduces remedial units to flexibly address non-compliance [12], as shown in **Table 1**. This standard not only reinforces the application of existing Carbon Intensity Indicator (CII) and Energy Efficiency Operational Indicator (EEOI) metrics but also promotes the adoption of zero-carbon fuels like green ammonia and hydrogen [13].

Table 1. IMO Greenhouse Gas (GHG) strategy implementation timeline and emission reduction targets (relative to 2008 baseline).

Timeline	Key Events and Measures	Emission Reduction Target (vs. 2008 baseline)
Jul-23	Revised GHG Strategy adopted; initiation of mid-term measure development	-
Apr-25	MEPC 83 approves draft amendments to MARPOL Annex VI	-
Oct-25	MEPC/ES.2 extraordinary session formally adopts the framework	-
2027	Framework enters into force; initiation of GFI reporting and verification	-
2030	Implementation of baseline GFI threshold	20% - 30%
2040	Strengthened GFI threshold; introduction of direct compliance targets	70% - 80%
2050	Achieve net-zero emissions	Net-zero

The GHG emissions pricing mechanism forms the economic core of the framework, generating funds through contributions levied on non-compliant vessels to support R & D and infrastructure development for low-emission technologies [14]. The mechanism employs a dual-tier compliance structure: a baseline target requires vessels to meet annual GFI thresholds, with non-compliant vessels purchasing remedial units from the fund; a direct compliance target allows low-emission vessels to earn surplus units, creating market-based incentives [15]. Research indicates this mechanism could generate tens of billions of dollars annually for technology transfer and equitable transition in developing countries [16]. Additionally, the framework emphasizes alignment with the EU's FuelEU Maritime regulation to prevent global regulatory fragmentation [15]. Studies indicate this mechanism could generate tens of billions of dollars annually for technology transfer and equitable transition in developing countries [16]. Additionally, the framework emphasizes alignment with the EU's FuelEU Maritime regulation to prevent global regulatory fragmentation [17].

As the financial pillar, the IMO Net Zero Fund will allocate levied funds toward incentive mechanisms, infrastructure investment, and capacity building—particularly supporting Small Island Developing States (SIDS) and Least Developed Countries (LDCs) [18]. Fund operations include annual reporting and verification processes to ensure transparency and compliance [19]. These elements collectively form a closed-loop system bridging regulation and innovation, propelling the shipping industry toward sustainable transformation [20].

In 2025, the framework achieved a landmark breakthrough. The 83rd session of the Marine Environment Protection Committee (MEPC) convened in London from April 7-11, approving the draft new chapter to MARPOL Annex VI. This formally established the legal foundation for the GFI standards and pricing mechanism, operationalizing the 2030 target of 20% - 30% emission reductions by mandating initial fuel intensity thresholds and remedial units for non-compliant vessels, projected to cut emissions by incentivizing early adoption of low-carbon fuels [21]. His approval marked the transition from the 2023 GHG Strategy revision to substantive regulations, expected to take effect in 2027 [22]. Subsequently, the framework draft underwent member state review, with focus shifting to the MEPC/ES.2 Special Session on October 14-17, aimed at formally adopting the framework and linking it to the 2040 target of 70% - 80% reductions through strengthened GFI thresholds and fund allocations for technology scaling, expected to enable 15% - 25% cumulative cuts via economic incentives by 2035 [16] [23]. By October 16, 2025, on the third day of the session, majority member states expressed support—including the EU, China, and several African nations—advancing global harmonized carbon pricing [24]. However, opposition from countries like the United States and Saudi Arabia to the carbon tax mechanism, driven by concerns over trade costs and economic impacts, may lead to divisions [25]. The IMO Secretary-General emphasized that while the framework is imperfect, it provides a foundation for further work [26].

Additionally, refer to the following timeline info-graphic for a visual framework of development (Figure 1).

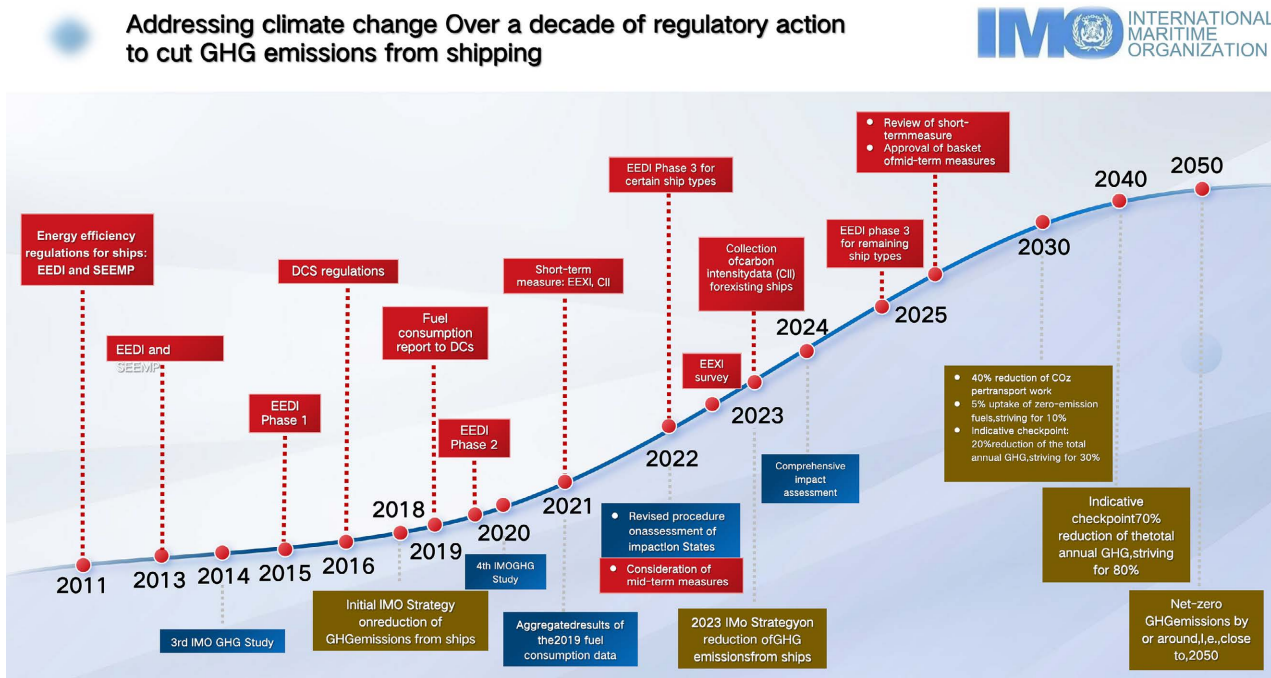


Figure 1. Timeline of key milestones and GHG reduction targets in the IMO net-zero framework.

The GHG emission reduction target chart can further illustrate the pathway (Figure 2).

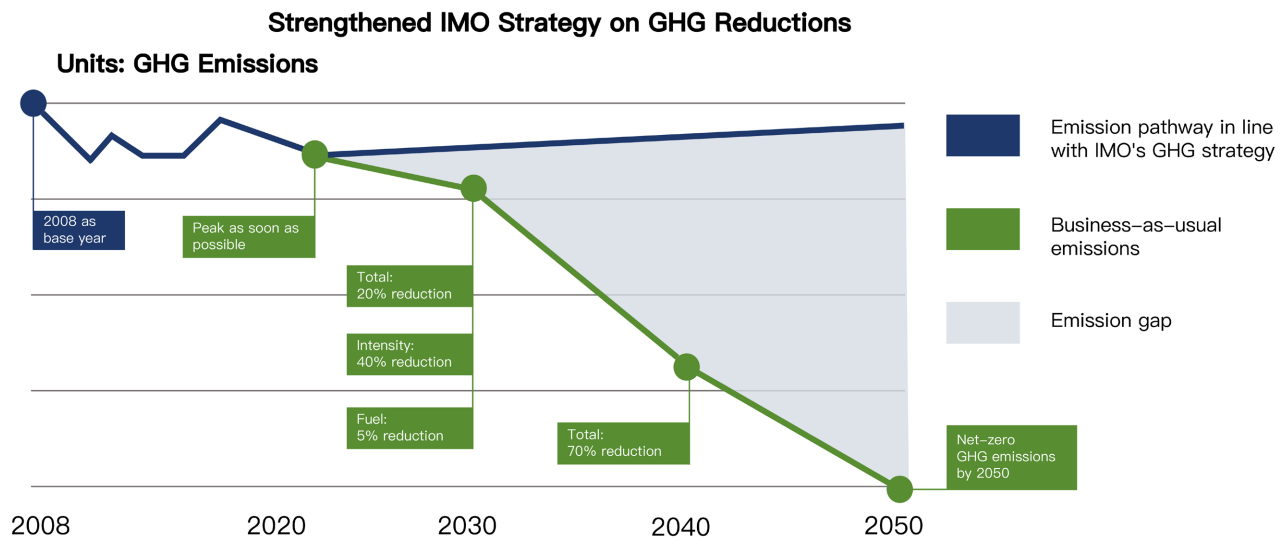


Figure 2. Overview of decarbonization measures and their emission reduction potentials in maritime shipping [27].

These developments reflect the interplay between international cooperation and geopolitical challenges, driving shipping research toward policy impact and equity assessments.

3. Current State of Shipping Research

Maritime research is currently undergoing rapid development, focusing on the implementation of the IMO Net Zero Framework and emphasizing an integrated approach spanning technological innovation to policy coordination. These studies not only assess the framework's feasibility but also explore its multidimensional impacts on global supply chains, economic equity, and environmental sustainability—including potential shifts in trade patterns and enhanced supply chain resilience [11]. Since the 2023 revision of the GHG Strategy, literature has surged in 2024–2025. Bibliometric analysis reveals key research hotspots, including zero-carbon fuel adoption, the impact of emissions pricing mechanisms, and transition challenges for developing nations [13]. For instance, a 2025 bibliometric study indicates a 300% increase in the frequency of keywords “maritime decarbonization” and “IMO net-zero” over the past two years, reflecting academic attention to the framework while revealing a shift in research focus from isolated technology assessments toward systemic pathway simulations [15]. This trend indicates that the net-zero framework has become a catalyst for research paradigms, driving scholars to shift from isolated technological perspectives toward holistic analyses integrating policy, economic, and technological factors to address the complexity of life-cycle emissions assessments within the framework.

3.1. Research on Technological Innovation

The core of the net-zero framework lies in scaling up zero-carbon technologies. Current research extensively explores the potential of alternative fuels and energy efficiency measures, emphasizing life-cycle cost-benefit analyses and technology maturity assessments for these technologies. Green hydrogen, ammonia, and methanol fuels are focal points, with literature evaluating their full life-cycle emissions and feasibility for vessel integration—including critical parameters such as fuel storage, safety, and engine compatibility [14]. A 2024 study simulated hydrogen fuel application on container ships, integrating the GFI standard from the action framework. It projected a 20% emissions reduction by 2030 but highlighted infrastructure investment requirements. Sensitivity analysis indicated fuel price volatility could extend the payback period to 8 - 10 years [12]. Similarly, wind-assisted propulsion and carbon capture and storage (CCS) technologies were integrated into the framework. Research indicated CCS could provide a transition pathway for existing fleets, reducing bulk carrier emissions by 15% - 25%, while also evaluating engineering challenges of onboard CO₂ storage, such as space requirements and increased energy consumption [18].

Digital tools like AI optimization and the Internet of Things (IoT) increasingly feature in research, enabling real-time monitoring of CII metrics to support framework reporting requirements and predicting emission patterns through machine learning algorithms [16]. A 2025 paper analyzed AI's role in energy management, demonstrating a 10% fuel efficiency improvement when combined with net-zero fund incentive mechanisms. Case studies (e.g., European route optimi-

zation) illustrated how AI could reduce voyage times by 5% - 8%, indirectly supporting the framework's 2040 emissions reduction targets [17]. These studies highlight synergies between technology and the framework, calling for accelerated R & D to achieve the 2040 70% reduction target. They also note that the absence of standardized protocols may hinder cross-fleet adoption and recommend that the IMO fund international technical standard development through dedicated funds [28]. Overall, technological innovation research reveals a gradient pathway from short-term efficiency gains to long-term fuel transition under the net-zero framework. However, it also warns of technology lock-in risks, such as early investment in transitional fuels potentially delaying the penetration of zero-carbon technologies.

To visualize the technology pathway, the following table summarizes key technical measures and their emission reduction potential within the net-zero framework (Table 2):

Table 2. Maritime decarbonization technologies: Descriptions, integration frameworks, and emission reduction potentials.

Technical Measure	Description and Integration Framework	Emission Reduction Potential (%)	Representative Studies
Green Hydrogen Fuel	Zero emissions across full lifecycle; suitable for long-haul routes; incentivized by GFI standards	80 - 100	[12] [14]
Ammonia Fuel	Compatible with dual-fuel engines; pricing mechanisms reduce cost barriers	70 - 90	[29] [30]
Wind-Assisted Propulsion	Supplements conventional fuels; retrofitting supported by dedicated funds	10 - 30	[17]
Carbon Capture and Storage (CCS)	Onboard CO ₂ capture; offers flexibility through offsetting units	15 - 50	[18] [31]
AI-Based Energy Management	Optimizes routing and combustion efficiency; supported by reporting and verification mechanisms	5 - 15	[16] [17]

3.2. Policy and Economic Impact Studies

Policy research focuses on the regulatory design and economic impacts of net-zero frameworks, analyzing the fairness and effectiveness of emissions pricing mechanisms, including the design of revenue generation models and redistribution schemes [32]. A 2025 study evaluated fund revenue distribution, recommending prioritized support for SIDS and LDCs to alleviate burdens on developing nations. It simulated global emission reduction efficiencies under different al-

location scenarios using game theory models, demonstrating that equitable distribution could increase overall compliance rates by 15% [19]. Economic models indicate the pricing mechanism could generate \$20 - 50 billion annually, but without global consensus, it may increase trade costs by 5% - 10%. A computable general equilibrium (CGE) model analyzed how these costs would be passed on to consumer prices and global GDP [33]. The literature also compares the framework with EU regulations, emphasizing the need to avoid fragmentation to optimize global emissions reductions, and assesses potential carbon leakage risks, such as shipping routes shifting to unregulated regions [34].

Fair transition remains a focal point, with studies exploring the application of CBDR-RC principles within the framework, including quantitative metrics for differentiated responsibilities [35]. A 2024 paper analyzes the vulnerability of island economies, projecting that carbon taxes could increase their import costs by 15%. It calls for technology transfer through dedicated funds and demonstrates, via case studies (e.g., Pacific Island nations), how integrating local renewable energy can mitigate impacts [36]. These studies underscore the need for policies balancing emissions reduction with economic equity, supporting the framework's 2027 implementation while highlighting weaknesses in enforcement mechanisms—such as the absence of international standards for data verification—which could create compliance loopholes. They recommend enhanced coordination between the IMO and WTO to prevent trade disputes [37]. Overall, policy and economic research reveals the potential of net-zero frameworks as market-driven instruments, while cautioning that geopolitical risks challenge economic model assumptions and necessitate more empirical data to validate theoretical projections. Fair transition remains a focal point, with studies exploring the application of CBDR-RC principles within the framework, including quantitative metrics for differentiated responsibilities [35]. Looking ahead, policy will emphasize dynamic adjustments, such as a 2028 comprehensive assessment to optimize pricing mechanisms and generate \$30 - 50 billion annually in fund revenues for developing countries [4]. Projections indicate carbon taxes rising to \$300/ton CO₂e by 2040, stimulating 15% green investment growth via CGE models, while integration with EU ETS could cover 90% of emissions by 2035 and yield 20% efficiency gains [15] [16]. These outlooks underscore the need for buffer mechanisms against economic shocks and enhanced IMO-WTO coordination to prevent trade disputes [37], sharpening the narrative toward equitable, market-driven decarbonization

3.3. Regional and Equity Studies

Regional studies highlight the role of developing countries in the net-zero transition, with frequent case studies of China and the EU, analyzing how these regions align domestic policies with the IMO framework [38]. A 2025 literature review assesses China's leadership in green hydrogen production, leveraging international cooperation under the framework to decarbonize Asian shipping routes. A

SWOT analysis explores the strengths (e.g., large-scale production) and challenges (e.g., technological export barriers) of China's supply chain [39]. Studies on Africa and Latin America emphasize infrastructure gaps, recommending fund investments in port facilities to ensure equity. They assess the feasibility of regional green corridors (e.g., East African coast), projecting a 20% reduction in local emissions but requiring international financing support [40].

Equity analyses encompass gender and labor impacts. A 2024 paper examines maritime workforce transitions, projecting that net-zero goals will create green jobs but require training to prevent inequality. It analyzes survey data on female seafarers' participation in technological transformation (currently under 10%) and recommends incorporating gender equality indicators into framework fund allocations [41]. These studies broaden the scope of equity from economic to social dimensions, emphasizing that net-zero frameworks must integrate with the SDGs framework to prevent exacerbating global inequalities. Cross-cultural comparisons reveal biases in research dominated by developed nations, highlighting the need for greater contributions from Global South perspectives.

3.4. Modeling and Simulation Research

The simulation study employed a scenario analysis evaluation framework to assess pathways, including comparisons of baseline, optimistic, and pessimistic scenarios [42]. A 2025 paper developed an Integrated Assessment Model (IAM) predicting that under a net-zero framework, shipping emissions would peak in 2025 and reach zero by 2050, contingent on fuel supply chain maturity. Monte Carlo simulations assessed the impact range of uncertainties such as fuel prices and policy implementation effectiveness (emission reduction deviation $\pm 10\%$) [4]. Uncertainty analysis incorporates geopolitical factors like U.S. opposition, with simulations indicating a potential 25% reduction in global emission reduction efficiency if the framework becomes fragmented [43].

These models integrate bottom-up and top-down approaches, supporting iterative refinement of the framework and emphasizing data quality importance, such as standardizing real-time vessel emission data [7]. Research also explores multi-objective optimization, such as simultaneously considering emissions reduction, cost, and safety, identifying optimal pathways through Pareto frontier analysis [20]. Overall, modeling studies provide quantitative support for net-zero frameworks but highlight limitations, such as neglecting extreme events (e.g., geopolitical conflicts), suggesting future integration of machine learning to enhance predictive accuracy [44].

Collectively, the current research landscape demonstrates that net-zero frameworks have entered the academic mainstream, driving interdisciplinary collaboration and evolving along a continuum from theory to application [20]. However, the literature highlights data gaps and model limitations, calling for more empirical research to validate framework effectiveness. It also emphasizes the need for long-term longitudinal studies to track the actual impacts of framework imple-

mentation, thereby guiding mid-term adjustments [44].

4. Future Development Prospects

Looking ahead, the IMO Net Zero Framework will serve as the core driver for decarbonizing the shipping industry. It is projected to achieve the goal of net-zero GHG emissions by 2050 through technological innovation, policy evolution, and international cooperation. This outlook is based on the framework's phased implementation, including enhanced GFI standards after 2027 and allocation of the Net Zero Fund. This is projected to accelerate zero-carbon fuel penetration from 5% - 10% in 2030 to 70% - 80% by 2040, based on integrated assessment models from the International Council on Clean Transportation (ICCT) and IMO projections, which estimate these rates under optimistic scenarios assuming global cooperation and subsidy support [12], thereby reshaping the carbon footprint of global shipping supply chains and enhancing industry resilience [1]. By 2035, the framework will drive 80% of global ship orders toward dual-fuel or zero-carbon designs. Combined with digital transformation, this will further reduce operational emissions while stimulating private sector investment through economic incentives, potentially generating a trillion-dollar green market [45]. However, this development hinges on geopolitical consensus and infrastructure investment. Successful adoption of the framework at the MEPC/ES.2 meeting would establish a foundation for future pathways; failure could instead trigger regionalized approaches, delaying global harmonization and increasing risks of trade friction [7]. This paper analyzes future prospects from technological, policy, regional, and modeling perspectives, emphasizing iterative optimization of the framework to address uncertainties such as fuel price volatility and the impacts of climate extremes. It also calls for interdisciplinary research to validate the feasibility of long-term pathways.

4.1. Prospects for Technological Innovation

Future technological development will focus on scaling up zero-carbon fuels and auxiliary systems to meet the framework's GFI thresholds, ensuring sustainability through life-cycle assessments. Green hydrogen and ammonia fuels are projected to become mainstream. Literature simulations indicate that by 2040, hydrogen fuel cell vessels could cover 30% of deep-sea routes, reducing lifecycle emissions by over 90%. However, challenges in storage density and safety must be addressed, including engineering optimization of high-pressure storage systems and management strategies for hydrogen leakage risks [11]. For instance, a 2025 study predicts that ammonia dual-fuel engines, combined with the framework's incentive mechanisms, will reduce NO_x emissions through technological iteration while lowering costs to 1.5 times that of conventional fuels, supporting the 2050 net-zero target. Case simulations (e.g., Pacific routes) demonstrate ammonia fuel's economic viability in long-haul vessels, emphasizing the need for global deployment of supporting infrastructure like refueling stations [39]. Wind-assisted pro-

pulsion and CCS technologies will serve as transitional tools, achieving 50% adoption by 2030 with annual emission reduction potentials of 15% - 30%. Integration with AI enables intelligent optimization, while compatibility assessments reveal hybrid systems like wind-wing and hydrogen-powered configurations can further boost efficiency by 10% - 15% [46].

Digitalization prospects include blockchain for emissions verification and IoT real-time monitoring, supporting framework reporting systems while reducing data latency through edge computing to enhance compliance efficiency [18]. A 2024 paper outlook projects that by 2050, autonomous vessels will reduce manpower requirements by 20% through framework fund financing and improved energy efficiency. It also explores the robustness of autonomous navigation algorithms in complex weather conditions, predicting a 5% reduction in accident rates [4]. These innovations transform the framework from a regulatory tool into a technological ecosystem, yet require overcoming supply chain bottlenecks—such as scaling green fuel production, with a projected 40% supply gap by 2035. Sensitivity analysis indicates policy subsidies could narrow this gap to 20% [43]. Overall, the technological innovation outlook reveals a gradient evolution from efficiency gains to disruptive transformation under the net-zero framework. However, it also highlights challenges related to the Technology Readiness Level (TRL) curve, necessitating sustained R & D investment to avoid locking into suboptimal pathways.

To visualize the technology pathways, the following table summarizes future adoption scenarios for key technologies within the framework (Table 3):

Table 3. Maritime decarbonization technologies: integration outlook, projected adoption by 2040, and emission reduction potentials.

Technical Measure	Integration Outlook	Projected Adoption by 2040	Emission Reduction Potential (%)	Representative Studies
Green Hydrogen Fuel	GFI standards driving large-scale production; infrastructure supported by subsidies	40%	90 - 100	[11] [19]
Ammonia Fuel	Dual-fuel compatibility; pricing mechanisms lowering transition costs	35%	80 - 95	[33] [39]
Wind-Assisted Propulsion	Complements zero-carbon fuels; reporting mechanisms optimize deployment	50%	20 - 40	[46]
Carbon Capture and Storage (CCS)	Onboard CO ₂ capture; flexibility through offsetting units	25%	50 - 70	[12] [34]
AI and Digitalization	Energy management optimization; automated verification systems	70%	10 - 25	[4] [18]

4.2. Regional and Equity Outlook

Regional development will exhibit diversification, with China projected to dominate green hydrogen supply chains by 2040. Framework cooperation will advance green shipping routes under the Belt and Road Initiative, contributing 30% of global emissions reductions. A SWOT analysis examines regional strengths (e.g., manufacturing scale) and challenges (e.g., intellectual property protection) [47]. The EU will expand ECAs through Fit for 55, achieve regional net-zero by 2030, influence global standards, and assess cross-border impacts like carbon adjustment mechanisms for Asian exports, projected to reduce EU import emissions by 15% [48]. Prospects for Africa and Latin America hinge on fund support for port infrastructure, aiming to increase coverage from the current 10% to 60% by 2050 to mitigate inequality. Field cases (e.g., Brazilian port upgrades) demonstrate local employment growth potential of up to 25% [49].

Equity outlooks encompass workforce transitions, projecting 5 million green jobs by 2040. However, frameworks must incorporate social indicators to prevent gender gaps. Research quantifies training needs, such as a 3 - 5 year return on investment for seafarer retraining in developing countries [50]. The literature emphasizes that the CBDR-RC principle will guide future resource allocation, ensuring developing countries are not left behind. This principle extends to environmental justice dimensions, such as reducing the impact of the dark fleet on vulnerable ecosystems [51]. These outlooks reveal the regional adaptability of net-zero frameworks but caution against risks of uneven development, necessitating monitoring indicators to adjust fund priorities.

4.3. Modeling and Simulation Outlook

Future modeling will employ advanced IAMs, projecting peak emissions in 2028 under the framework scenario with an 80% probability of net-zero by 2050. However, this outcome remains sensitive to fuel price fluctuations, with uncertainty ranges ($\pm 15\%$) quantified via Monte Carlo methods [52]. Uncertainty analysis incorporates climate feedbacks, integrates AI projections by 2040 to enhance accuracy by 20%, and examines feedback loops such as the impact of ice sheet melting on Arctic shipping routes [29]. Research outlooks indicate multi-objective optimization will balance emissions reductions with costs, support framework iteration, and employ Pareto analysis to identify trade-offs—such as the equilibrium between efficiency and equity [30].

These simulations will transition from static to dynamic, incorporating real-time data to guide policy adjustments, and emphasize cross-model comparisons to reduce bias. Overall, modeling prospects provide a quantitative blueprint for net-zero frameworks, though data-sharing platforms are needed to enhance global collaboration.

In summary, the future outlook for net-zero frameworks is optimistic, yet requires continuous monitoring and adjustment to achieve sustainable transformation, ensuring pathway robustness through cross-sectoral integration.

5. Challenges and Opportunities

Although the IMO Net Zero Framework provides a clear roadmap for decarbonizing the shipping industry, its implementation faces multiple challenges while also presenting significant opportunities. These challenges and opportunities are intertwined across technological, policy, economic, regional equity, and global cooperation domains, directly impacting the effectiveness of the framework's GFI standards, emissions pricing mechanisms, and Net Zero Fund. Through a systematic analysis of these factors, this paper aims to reveal how the net-zero framework can overcome obstacles while stimulating innovation and sustainable growth, thereby propelling the shipping industry toward a net-zero transition.

5.1. Technical Challenges and Opportunities

At the technical level, implementing the net-zero framework faces challenges from immature infrastructure and fuel supply chain bottlenecks. While zero-carbon fuels like green hydrogen and ammonia offer high potential for lifecycle emissions reductions, current production scales remain limited. Global supply is projected to meet only 20% - 30% of demand by 2030, increasing the difficulty of achieving GFI threshold compliance. Additionally, vessel retrofitting and new technology integration involve substantial upfront investments and technical risks. For instance, hydrogen fuel cells currently lack sufficient power density for large ocean-going vessels, while ammonia fuel poses toxicity management challenges. These issues may delay achieving the framework's 2040 target of 70% - 80% emissions reduction. These challenges are amplified in developing countries, where weak local R & D capabilities and inadequate technology transfer mechanisms could widen the technological divide.

However, these challenges also present opportunities. The framework's incentive mechanisms and fund support can spur technological innovation, such as accelerating the commercialization of hydrogen electrolysis and onboard CCS applications through subsidies. By 2050, economies of scale are projected to reduce fuel costs by over 50%, driving fleet modernization. Simultaneously, integrating digital tools like AI optimization and IoT monitoring will enhance energy efficiency by 15% - 20%, providing real-time data support for the framework's reporting and verification. Opportunities lie in the framework's potential to foster cross-sector collaboration—such as joint R & D between shipping and renewable energy sectors—spawning novel hybrid systems that enable a smooth transition from transitional technologies to zero-carbon pathways. Overall, technical challenges drive the framework's evolution into an innovation platform, potentially reshaping the shipping technology ecosystem.

5.2. Policy and Economic Challenges and Opportunities

Policy challenges primarily stem from regulatory complexity and the absence of international consensus. While the net-zero framework's emissions pricing mechanism is ingeniously designed, its implementation requires unified global stand-

ards to avoid fragmented conflicts between the EU's FuelEU Maritime regulation and the IMO framework, potentially increasing administrative burdens and compliance costs by 10% - 15%. Geopolitical divisions—such as U.S. opposition to carbon taxes and economic concerns among oil-exporting nations—could delay MEPC/ES.2 meetings or weaken the framework, jeopardizing the 2027 implementation timeline. Additionally, developing nations face policy execution challenges, including inadequate local regulatory frameworks and enforcement capabilities, while inequitable distribution of net-zero funds may exacerbate North-South divides.

Economic challenges include high transition costs, with global fleet renewal requiring trillions in investment—unaffordable for small shipowners and potentially driving industry consolidation. Simultaneously, carbon tax pass-through could raise trade costs by 5% - 10%, impacting global supply chain stability, particularly in island economies.

Opportunities lie in policies driving economic transformation. The framework's pricing mechanism is projected to generate hundreds of billions of dollars annually. Through fund redistribution, it supports infrastructure development and capacity building while expanding green finance markets. By 2040, this will stimulate job growth and economic expansion. The Net-Zero Fund can prioritize high-potential projects like green corridor development, achieving both emissions reductions and economic gains. Policy opportunities also include synergies with the Paris Agreement, elevating shipping's role in global climate governance. Adaptability to economic fluctuations through dynamic assessment mechanisms—such as five-year threshold reviews—ensures the framework's resilience. Economic opportunities highlight the rise of sustainable business models like carbon credit trading and green bonds, potentially positioning shipping as a leader in the low-carbon economy.

5.3. Regional and Equity Challenges and Opportunities

Regional challenges manifest in uneven development. While China and the EU lead in green technologies, Africa and Latin America lag in infrastructure, with port refueling station coverage below 10%, hindering the framework's global implementation. Equity concerns are prominent. While the CBDR-RC principle is embedded in the framework, Small Island Developing States (SIDS) and Least Developed Countries (LDCs) may receive only 10% - 20% of the fund allocation in practice, leading to delayed transition and social injustice. Additionally, labor transition challenges include reduced maritime employment and technical skill gaps, with low participation rates among women and minority groups potentially amplifying social inequality.

Opportunities lie in the framework's potential to foster regional cooperation and equitable growth. Fund-supported green corridor initiatives, such as the Rotterdam-Singapore route expansion, could cover 50% of global trade by 2035, enabling coordinated regional emissions reductions. Equity opportunities include

workforce retraining programs, creating millions of green jobs by 2040, while integrating social indicators ensures gender equality and inclusive development. Regional opportunities also manifest in local innovations, such as Africa's solar-powered green hydrogen production contributing to global supply chains. The framework can serve as a bridge to facilitate North-South technology transfer, enabling synergies toward the United Nations Sustainable Development Goals.

To visually illustrate challenges and opportunities, the table below summarizes key areas under the net-zero framework (**Table 4**):

Table 4. Key challenges and opportunities in maritime decarbonization across critical domains.

Domain	Key Challenges	Key Opportunities
Technological Innovation	Supply chain bottlenecks, technology risks, insufficient infrastructure	Economies of scale, hybrid system innovation, digitalization enhancements
Policy and Economics	Regulatory fragmentation, high costs, geopolitical divisions	Recycling of fund revenues, green finance markets, job creation
Regional Equity	Uneven development, social inequity, labor shortages	Regional cooperation, inclusive growth, technology transfer
Implementation & Geopolitics	Lack of consensus, implementation complexity, external uncertainties	International coordination, adaptive governance, global climate leadership

5.4. Implementation and Geopolitical Challenges and Opportunities

Implementation challenges include the complexity of data verification and monitoring systems. The framework requires full life-cycle assessments, but insufficient standardization of current vessel data may lead to compliance loopholes and enforcement difficulties. Geopolitical challenges such as US-China trade tensions and energy geopolitical conflicts could disrupt fuel supply chains, affecting the stability of the framework's net-zero pathway.

Opportunities lie in the framework's potential to strengthen global governance by fostering multilateral dialogue through the MEPC mechanism, establishing a unified carbon market by 2050, and enhancing shipping resilience. Implementation opportunities include pilot projects—such as green port demonstrations—to validate the framework's effectiveness and optimize pathways through big data analytics. Geopolitical opportunities manifest as the framework serving as a diplomatic tool to promote climate cooperation, potentially resolving disputes and achieving mutual benefits.

Overall, the net-zero framework presents both challenges and opportunities. Through strategic responses, these can be transformed into a driving force for sustainable development.

5.5. Limitation

This study relies primarily on secondary data from existing literature, policy documents, and projections, which may introduce biases or gaps in real-time empirical evidence. Additionally, forward-looking projections, such as emission reduction pathways and fuel adoption rates, are subject to uncertainties including geopolitical shifts, technological breakthroughs, and economic variables, potentially affecting the accuracy of long-term forecasts.

6. Conclusion

The IMO Net Zero Framework marks a pivotal shift toward full life-cycle GHG emissions reduction in shipping, targeting net-zero by 2050 through GFI standards, emissions pricing, and the Net Zero Fund. Key findings highlight accelerated adoption of zero-carbon fuels (e.g., green hydrogen), policy-economic incentives generating billions for equitable transitions, and modeling projections peaking emissions by 2028 under optimistic scenarios. Challenges include geopolitical divisions and infrastructure gaps, but opportunities lie in technological innovation and international cooperation. Implications call for enhanced coordination, dynamic evaluations, and empirical research to validate effectiveness, ensuring a sustainable maritime transition aligned with global climate goals.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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