A Study on Pathways for Shipping Energy Emission Reduction from the Perspective of International Maritime Environmental Law

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Abstract

At present, the shipping industry consumes a vast amount of fossil fuels each year, with carbon dioxide emissions accounting for about 3% of global total emissions. In addition, pollutants such as sulfur oxides and nitrogen oxides released during shipping pose severe threats to the environment of coastal areas and to human health. In response to this situation, the International Maritime Organization (IMO) has established a series of conventions and regulations, including the International Convention for th e Prevention of Pollution from Ships and the IMO Strategy on Reduction of GHG Emissions from Ships, setting explicit targets and standards for emission reductions in the shipping industry. Conducting an in-depth study of energy emission reduction pathways in shipping from the perspective of international maritime environmental law is of great significance for promoting the green transformation of the shipping industry, achieving global climate governance goals, protecting the marine ecological environment, and fostering the sustainable development of international trade. Taking this as a starting point, this paper analyzes the current status of energy consumption and emissions in shipping, reviews relevant IMO regulations, identifies technical challenges, economic cost pressures, and policy coordination dilemmas faced by shipping energy emission reduction, and explores multidimensional pathways. The aim is to provide theoretical support and practical reference for the industry's transition to low-carbon development and the achievement of global maritime environmental goals.

Keywords

Shipping energy, Emission reduction pathways, International Maritime Organization, International maritime environmental law.

1. Introduction

In the tide of globalization, the shipping industry, with its advantages of high capacity and low cost, has become a critical driver of global trade, handling over 90% of international freight transport and profoundly influencing the rhythm of the world economy. However, while propelling economic growth, the industry has also become a major consumer of energy and a significant source of pollution due to its heavy reliance on traditional fossil fuels. The large volume of greenhouse gases emitted during ship operations has continuously exacerbated global climate warming, while pollutants such as sulfur oxides and nitrogen oxides have caused multidimensional damage to marine ecosystems and the living environments of coastal populations [1-2].

To address this global challenge, the international community has steadily strengthened the regulation of the shipping industry's environmental responsibilities, and an international maritime environmental law system has gradually been established and improved. This provides both a legal framework and practical guidance for shipping energy emission reduction.

Against this backdrop, it is of particular importance to systematically explore effective emission reduction pathways for shipping from the unique perspective of international maritime environmental law. Such exploration can contribute to coordinated international efforts in maritime environmental protection and provide momentum for the sustainable development of the shipping industry worldwide.

2. Current Status of Energy Consumption and Emissions in Shipping

Table 1: Differences Among Various Types of Ships (Data source: IMO 2024 Global Shipping and Energy Consumption Emission Report)

Ship types	Operation mode	Power size range (megawatts)	Typical voyage distances	Energy consumption characteristics	Energy consumption per unit of freight (tons of oil per 10,000 ton-miles)	Carbon emissions per unit of freight (tons of CO2 per 10,000 ton-miles)
Container ship	Fixed routes, high-frequency round trips	30 - 100	Transoceanic long-distance (such as the Asia-Europe route, approximately 12,000 kilometers)	Under full-load conditions, energy consumption is stable and high-intensity. The energy consumption per unit cargo volume decreases as the ship type becomes larger (large ships are more efficient).	2.8-3.2	65-72
Oil tanker	Point-to-point transportation of crude oil / refined oil products	20 - 80	Intercontinental long-distance (such as from the Middle East to China, approximately 12,000 kilometers)	During empty return trips, energy consumption is 30% - 40% lower than when fully loaded. When large oil tankers sail at low speed, the energy consumption per tonnage is better.	2.1-2.5	48-55
Bulk carrier	Transportation of bulk goods such as ores and coal	15 - 60	Medium-long distance (such as from Australia to China, approximately 8,000 kilometers)	Energy consumption is greatly affected by the density of the cargo. When the cargo is heavy, the power demand is high, and the speed is generally lower than that of container ships.	1.9-2.3	43-50
Passenger ship	Coastal / ocean passenger transport, regular schedules	5 - 50	Mainly medium-short distance (such as the inland sea routes in Europe, approximately 500 - 2,000 kilometers)	In addition to the energy consumption during navigation, the energy consumption of on-board living facilities (air conditioning, lighting, etc.) accounts for 20% - 30%.	8.5-9.2	195-210

At present, the shipping industry relies predominantly on fossil fuels such as heavy fuel oil and diesel. According to data from the International Energy Agency (IEA), global shipping consumes a massive amount of fuel each year, with total energy consumption continuing to rise. In terms of emissions, the International Maritime Organization (IMO) estimates that the shipping industry emits approximately one billion tons of carbon dioxide annually, accounting for nearly

3% of global CO_2 emissions. Moreover, sulfur oxides, nitrogen oxides, and particulate matter emitted by ships pose significant threats to air quality in coastal regions and port cities.

In some busy port areas, ship emissions are among the primary sources of local air pollution, causing adverse impacts on residents' health and the ecological environment. Different categories of ships—such as container ships, oil tankers, and bulk carriers—display significant variations in energy consumption and emission levels depending on their operating models, engine power, and voyage distances (see Table 1). Large container ships, due to long-distance and high-load operations, generally demonstrate higher energy consumption and emission scales. Although individual small vessels emit less, their large numbers mean their cumulative emissions are also considerable.

3. Relevant Conventions and Regulations of the International Maritime Organization

3.1. International Convention for the Prevention of Pollution from Ships

With the rapid development of the global shipping industry, the diverse pollutants emitted by ships have caused increasingly severe damage to marine ecosystems and the atmospheric environment [3]. The international community urgently required a unified set of rules to regulate ship pollution, and it was under this background that the *International Convention for the Prevention of Pollution from Ships* (MARPOL) emerged as a major international maritime environmental convention.

MARPOL comprises several annexes, among which Annex VI (*Regulations for the Prevention of Air Pollution from Ships*) sets explicit limits on emissions of sulfur oxides, nitrogen oxides, particulate matter, and greenhouse gases from ships. It specifies the maximum allowable sulfur content in marine fuels in different regions. Since 2020, the global sulfur cap for marine fuels has been reduced to 0.5%, while more stringent requirements are applied in Emission Control Areas (ECAs). These measures aim to reduce sulfur oxide emissions by restricting fuel sulfur content.

MARPOL also establishes tiered standards for nitrogen oxide emissions from marine engines, categorized according to the engine's output power and construction date. New ships and existing vessels are required to progressively comply with stricter emission requirements. By formulating unified international standards, MARPOL provides a regulatory framework for ship emissions worldwide, making significant contributions to mitigating the shipping industry's pollution of the marine and atmospheric environment.

3.2. IMO Strategy on the Reduction of GHG Emissions from Ships

As the problem of global climate change becomes increasingly severe, the impact of greenhouse gas (GHG) emissions from the shipping industry on the global climate has become more evident, prompting more urgent emission reduction demands from the international community. The *IMO Strategy on the Reduction of GHG Emissions from Ships* was launched in response to this trend, providing systematic guidance for the global shipping industry in reducing GHG emissions.

This strategy establishes long-term goals and phased targets for the reduction of GHG emissions in global shipping. By 2030, the carbon intensity of international shipping must be reduced by 40% compared with 2008 levels, and the share of near-zero or zero-emission technologies, fuels, and energy sources must reach at least 5%, with a target of 10%. By 2050, the strategy aims to achieve net-zero GHG emissions (see Figure 1).

To achieve these targets, the strategy proposes a series of measures, including improving ship energy efficiency, promoting the use of low-carbon and zero-carbon fuels, and optimizing ship operational management [4]. Notably, in 2023 the IMO issued a supplementary revision to the strategy, which further clarified the required proportion of zero-carbon fuel applications after 2030, while simultaneously releasing the IMO Guidelines on the Safety of Ships Using Zero-Carbon Fuels. For the first time, these guidelines defined technical safety standards for the storage and bunkering of zero-carbon fuels such as hydrogen, ammonia, and methanol. For example, hydrogen-fuelled ships must have storage equipment that passes IMO-certified explosion-proof testing, while methanol bunkering systems are required to comply with anti-leakage and anti-corrosion specifications. This revision brings the IMO's decarbonization strategy into closer alignment with the technical requirements of the MARPOL Convention, thereby improving the regulatory framework for emission reduction under international maritime environmental law.

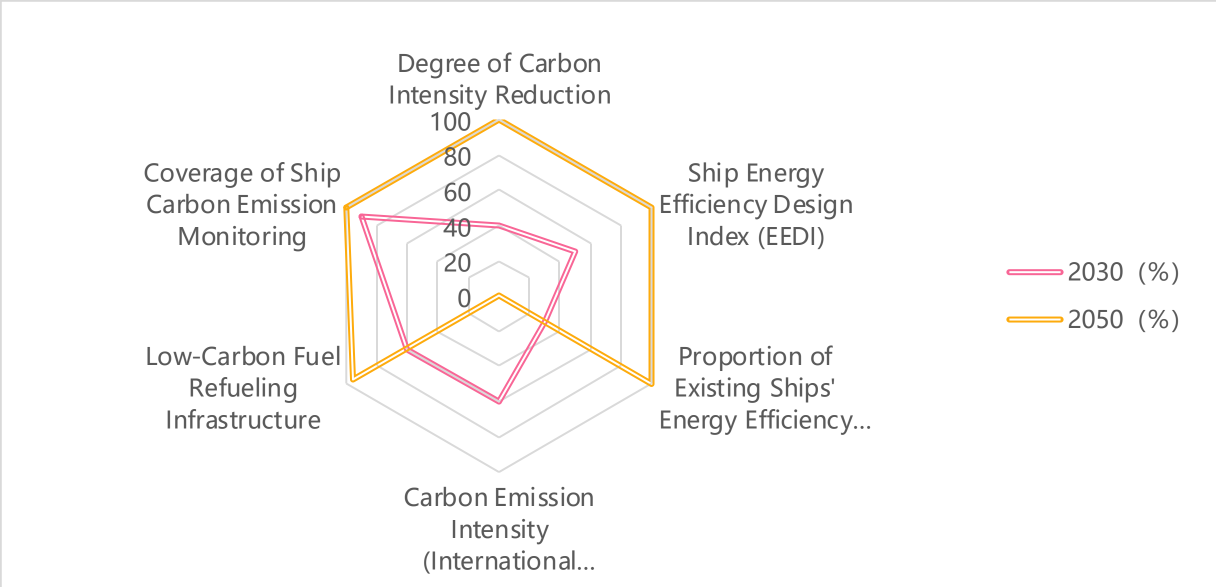

Figure 1: Targets of the IMO Strategy on the Reduction of GHG Emissions from Ships for 2030 and 2050 (The vertical axis "Carbon Intensity Reduction" represents the reduction in carbon intensity compared to 2008; data source: IMO Update Report on the 2024 Ship Greenhouse Gas Emission Reduction Strategy)

4. Challenges Facing Shipping Energy Emission Reduction

4.1. Technical Difficulties

Due to multiple factors, shipping energy emission reduction faces significant technical challenges. At present, marine engine technology cannot achieve major breakthroughs in the short term to meet increasingly stringent emission requirements. The development of efficient and low-emission new engines requires substantial financial investment and long-term technological accumulation. Key technical aspects such as improving combustion efficiency and pollutant control remain bottlenecks. For example, traditional internal combustion engines cannot completely prevent the formation of nitrogen oxides during combustion. Developing new engines often requires overcoming interdisciplinary barriers in materials science, thermodynamics, and related fields.

Technologies for applying low-carbon and zero-carbon fuels are still at an immature stage. The use of hydrogen fuel cells, methanol fuel, and other alternative energy sources faces challenges such as fuel storage, insufficient bunkering infrastructure, and safety assurance, making them difficult to meet the demands of regular ship operations. According to the IMO Guidelines on the Safety of Ships Using Zero-Carbon Fuels, ships powered by zero-carbon fuels must comply with both technical standards and regulatory certification requirements. For instance, the high-pressure storage technology of hydrogen-fuelled ships must conform to IMO explosion-proof specifications, while the bunkering systems of methanol-fuelled ships are required to obtain anti-leakage certification. These requirements further increase the difficulty of technological research, development, and implementation, as enterprises must simultaneously overcome technical bottlenecks and legal compliance barriers, thereby extending the commercialization cycle of such technologies [10].

4.2. Economic Cost Pressures

As a capital-intensive industry, shipping faces systemic and transmissive economic cost pressures during the energy transition. These pressures are reflected not only in the increased expenditures of individual links but also across the entire operational chain of enterprises.

The adoption of emission reduction technologies and equipment requires substantial upfront investment. For instance, the purchase and installation of a marine exhaust gas scrubber can cost several million USD. Energy-efficiency retrofitting of ships, covering hull optimization and propulsion system upgrades, can exceed tens of millions of USD per vessel. For small and medium-sized shipping companies, such expenses may surpass their financial capacity.

The cost disparity of low-carbon and zero-carbon fuels is even more pronounced. Green methanol, due to its complex production process and limited production capacity, is priced at more than three times that of conventional heavy fuel oil. For example, a single voyage of an 18,000-TEU container ship using green methanol could increase fuel costs by several hundred thousand USD, directly weakening the intrinsic motivation of enterprises to adopt emission reduction measures.

4.3. Policy Coordination Dilemmas

Policy coordination can consolidate strong momentum for global shipping energy emission reduction. Only when countries and regions reach consensus on emission reduction policies and act collaboratively can loopholes be avoided and the unified goals of international maritime environmental law be realized [5-6].

However, significant differences exist among countries and regions in terms of the development of the shipping industry, energy composition, and environmental policies, leading to divergent targets, policy approaches, and implementation schedules. For instance, the European Union has introduced the *Carbon Border Adjustment Mechanism* and integrated shipping into its carbon emission trading system, imposing strict requirements on ship carbon intensity. By contrast, some island nations and developing countries, where shipping is vital to their economies and emission reduction technologies are limited, prefer longer transitional periods with more lenient policies.

Such policy differences create “policy loopholes” in the international shipping market. Some companies, in order to reduce costs, may shift their business to regions with less stringent regulations, resulting in unfair competition and undermining the overall efficiency of global emission reduction efforts. From the perspective of international maritime environmental law, the core of this conflict lies in the dispute over the priority of effectiveness between regional law and global law. According to Article 192 of the United Nations Convention on the Law of the Sea (UNCLOS), which stipulates the “general obligation of States to protect and preserve the marine environment,” as well as the MARPOL principle of “primacy of international rules,” the EU CBAM should remain consistent with the IMO’s 2030 carbon intensity targets. In practice, this would mean granting CBAM tax reductions or exemptions to vessels that have already complied with IMO standards and paid the relevant fees, thereby avoiding double compliance costs for enterprises [10]. However, the absence of a clear legal coordination mechanism has resulted in the persistence of policy conflicts, undermining the overall efficiency of global emission reduction efforts.

5. Exploring Pathways for Shipping Energy Emission Reduction

5.1. Technological Innovation as a Driver of Emission Reduction

Expanding investment in marine engine research and development to create new engines capable of high-efficiency combustion and low emissions can significantly improve energy utilization efficiency and reduce pollutant discharges (see Figure 2). For instance, advanced turbocharging technologies can enhance air intake efficiency and promote more complete fuel combustion; intelligent fuel injection systems can precisely control fuel volume and timing according to operational conditions, thereby optimizing combustion processes to improve power output while reducing energy consumption.

Promoting the application of new and clean energy technologies, such as hydrogen fuel cells, solar energy, and wind power, also presents viable solutions. For example, solar photovoltaic panels can be installed on ship decks to supply electricity for auxiliary equipment such as navigation and communication systems, thereby reducing the load on the main engine. Similarly, wind-assisted propulsion systems using adjustable sail designs can harness wind power under favorable conditions to provide auxiliary thrust and reduce fuel consumption [7]. In line with the IMO Guidelines on the Safety of Ships Using Zero-Carbon Fuels, enterprises advancing the application of hydrogen and methanol fuel technologies must integrate legal compliance requirements into the R&D process. For instance, the bunkering systems of methanol-fuelled vessels must comply with anti-leakage and anti-corrosion standards, while hydrogen storage equipment must obtain IMO explosion-proof certification. A case in point is MAN Energy Solutions' newly developed ME-GI engine, which, through optimizing its combustion system, has achieved a 12% reduction in the EEXI value compared with existing models, thereby meeting in advance the Phase II assessment standards of the 2024 Amendments to MARPOL Annex VI [8].

Moreover, accelerating the digitalization and intelligentization of ship energy management systems is essential. By integrating big data analytics with AI algorithms, ships' operational states and load conditions can be monitored in real time to optimize energy consumption. For instance, engine power can be automatically adjusted according to route characteristics to prevent unnecessary energy waste, achieving precise emission reduction.

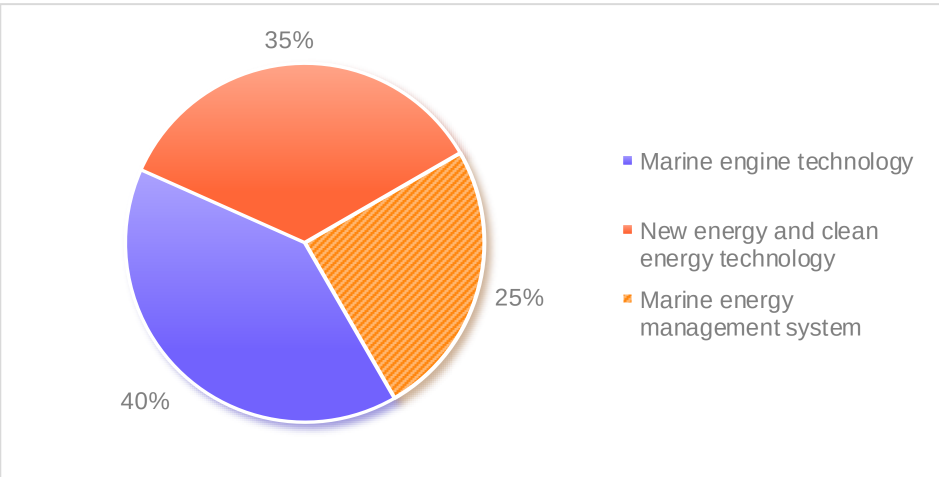

Figure 2: Proportion of Different Types of Technologies Driven by Technological Innovation for Emission Reduction (Data source: 2024 Global Top 20 Shipping Companies' Statistical Report on Technological Investment)

5.2. Optimizing Shipping Operation Management

With the increasingly stringent requirements of international maritime environmental law on shipping emissions, optimizing shipping operations and management has become an effective short-term approach to achieving energy conservation and emission reduction. By reasonably allocating resources and meticulously controlling procedures, it is possible to cut down on energy consumption and emissions without significantly increasing costs.

According to the IMO's Ship Emission MRV Regulation (newly added to MARPOL Annex VI), the establishment of a "voyage-wide emission ledger" is required—mandating ships to record in real time their fuel consumption, speed, route, and other data. These records must be integrated with satellite positioning systems and port-based onshore systems to ensure data authenticity and traceability, thereby preventing compliance loopholes caused by "data falsification." These MRV data provide a core basis for route optimization—by analyzing the correlation between historical energy consumption data and route parameters, it is possible to accurately identify high-energy-consuming segments, thereby offering data support for intelligent route planning. The restrictions on ship emissions stipulated in the International Convention for the Prevention of Pollution from Ships indirectly drive shipping companies to optimize operational management.

Rational route planning is essential. By comprehensively considering meteorological conditions, oceanic states, and port congestion, the most economical and fuel-efficient routes can be chosen. This minimizes unnecessary detours and waiting times, thereby reducing fuel consumption. Relying on ship navigation software and meteorological forecasting systems, routes can be adjusted in real time to avoid regions affected by severe weather. For instance, some Maersk container vessels on trans-Pacific routes have adopted intelligent route planning systems that integrate real-time weather data with port congestion warnings; in 2023, the average voyage distance per vessel was shortened by nearly 80 nautical miles, cutting fuel consumption by over 3%.

Improving the rationality of ship speed is also crucial. The IMO GHG Emission Reduction Strategy recommends speed optimization (e.g., reducing the speed of large container vessels from 24 knots to 20 knots can cut carbon emissions by about 30%). By taking into account vessel load and voyage distance, the "optimal economic speed" can be determined and enforced through the SEEMP system, thereby preventing unnecessary energy waste from "high-speed competition for schedules." In addition, adopting fleet sailing patterns, where multiple vessels maintain appropriate distances and speeds, allows them to benefit from the aerodynamic and hydrodynamic interactions between ships, thereby improving energy efficiency [8].

5.3. Policy Support and Guidance

Policy support and guidance serve as a guarantee for promoting energy conservation and emission reduction in the shipping industry. They provide clear direction and strong backing for the sector's green transition while coordinating various stakeholders to form a joint force for emission reduction.

Governments can introduce financial incentive measures, such as granting subsidies to enterprises that install exhaust gas scrubbers or use low-carbon fuels, and offering tax reductions to vessels adopting emission-reduction technologies. Article 4 of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL), "Equivalents and Technical Assistance," encourages member states to support ships in adopting compliant emission-reduction technologies through financial means. This also aligns with the IMO GHG Emission Reduction Strategy requirement for "funding and technical support." Subsidies and tax incentives can help address the high cost of emission-reduction technologies, thereby lowering the financial burden on enterprises and enhancing their willingness to participate in emission reduction [9].

At the same time, governments should establish strict regulations and standards for energy conservation and emission reduction in shipping, clearly defining the limits of energy consumption and emissions for vessels. Stronger regulatory enforcement and penalties for non-compliance will ensure the effective implementation of these standards.

Developing carbon emission trading markets and including the shipping industry in such mechanisms can also help enterprises manage carbon costs through market-based transactions, thereby encouraging proactive carbon-reduction actions.

In addition, strengthening port infrastructure, particularly shore power supply facilities, is essential. Article 18 of MARPOL Annex VI, "Mandatory Use of Shore Power," specifies the standards for building shore power systems in ports. Supportive policies should be introduced to encourage vessels to use shore power while at berth. This aligns with the IMO GHG Emission Reduction Strategy target that by 2030, "low-carbon infrastructure coverage" should reach 60%. The adoption of shore power reduces reliance on ship-generated electricity, thereby lowering emissions during port stays.

5.4. Strengthening International Cooperation

Given the global nature of the shipping industry, energy reduction efforts cannot be achieved without international collaboration. Strengthening international exchanges and cooperation can break down geographical barriers, integrate global resources, and achieve emission reduction goals while avoiding inefficiency and resource waste caused by fragmented national actions. Governments, international organizations, and shipping companies should intensify communication and cooperation, sharing technological expertise through international forums.

In addressing conflicts between the EU CBAM (Carbon Border Adjustment Mechanism) and IMO regulations, reference can be made to Article 192 of the United Nations Convention on the Law of the Sea (UNCLOS) and the IMO GHG Emission Reduction Strategy's principle of "global coordination." This would involve aligning CBAM carbon-intensity standards with the IMO's 2030 targets, and, based on the MARPOL principle of "international rules taking precedence", granting CBAM tax exemptions for vessels that have already paid IMO carbon levies. The International Maritime Organization (IMO) should play a leading role in coordinating policy divergences among countries. According to Article 11 of MARPOL on "Port State Control," a "Global Emission Reduction Policy Coordination Mechanism" could be established, requiring countries such as the United States to provide "equivalency statements" for additional port-level environmental standards to prevent regulatory gaps.

International forums and cooperative mechanisms should also be leveraged to share emission-reduction technologies, experiences, and policy tools, jointly addressing the challenges of global shipping decarbonization. The IMO must take a leadership role by actively coordinating cross-national differences in shipping energy reduction policies and regulations, facilitating the development of unified international standards and norms, and ensuring that global emission-reduction actions in the shipping sector are carried out under fair and consistent rules [10].

Furthermore, under the "technical assistance" provision of the IMO strategy, an Emission Reduction Assistance Fund should be established to provide low-interest loans for vessel retrofitting in developing countries. In line with the principle of "common but differentiated responsibilities" outlined in the United Nations Framework Convention on Climate Change (UNFCCC), this mechanism would alleviate financial burdens and support equitable participation.

Finally, cooperation should be enhanced in the production, transportation, and bunkering of low-carbon and zero-carbon fuels. By jointly establishing production bases, optimizing global transport networks, and creating a unified international fuel-supply framework, costs can be reduced and favorable conditions created for the large-scale adoption of new energy sources in the shipping industry.

6. Conclusion

In summary, as a cornerstone of global trade, the shipping industry's energy consumption and emissions have become focal points of international concern. Conventions and strategies formulated by the International Maritime Organization, such as MARPOL and the IMO Strategy on the Reduction of GHG Emissions from Ships, provide a vital legal framework for shipping energy emission reduction.

Although the industry faces challenges including technological limitations, economic cost pressures, and policy coordination difficulties, effective pathways exist. These include driving emission reduction through technological innovation, optimizing operational management, strengthening policy support and guidance, and deepening international cooperation.

Guided by international maritime environmental law, continuous exploration and refinement of emission reduction strategies will be of great importance for addressing global climate change, protecting marine ecosystems, and promoting the sustainable development of the shipping industry. Such efforts carry not only immediate practical significance but also far-reaching historical implications.

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