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Shipping decarbonization governance in Arctic waters: theoretic logic and implementation pathways

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Abstract The accelerated decline of Arctic sea ice since the 1980s has paradoxically amplified greenhouse gas (GHG) emissions through increased shipping activities in this ecologically vulnerable region. This study investigates how to reconcile the decarbonization of Arctic shipping with conflicting environmental, economic, and geopolitical interests. Through systematic literature review and interest-balancing analysis, our findings identify three systemic barriers: (1) inadequate adaptation of International Maritime Organization (IMO) regulations to Arctic-specific environmental risks, (2) fragmented enforcement mechanisms among Arctic and non-Arctic States, and (3) technological limitations in clean fuel adoption for ice-class vessels. To address these challenges, a tripartite governance framework is proposed. First, legally binding amendments to International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI introducing Arctic-specific Energy Efficiency eXisting ship Index (EEXI) standards and extending energy efficiency regulations to fishing vessels. Second, a phased fuel transition prioritizing liquefied natural gas (LNG) and methanol, followed by hydrogen-ammonia synthetics. Third, enhanced multilateral cooperation through an Arctic Climate Shipping Alliance to coordinate joint research and development in cold-adapted technologies and ice-route optimization. By integrating United Nations Convention on the Law of the Sea (UNCLOS) obligations with IMO Polar Code implementation, this study advances a dynamic interest-balancing framework for policymakers, offering actionable pathways to achieve Paris Agreement targets while safeguarding Arctic ecosystems.

Keywords **shipping**, **decarbonization**, **Arctic waters**, **GHG emission**, **IMO**

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1 Introduction

Since the 1980s, the volume of Arctic sea ice has shrunk by 72% due to the impacts of greenhouse gases (GHGs) and black carbon (Mandelbaum, 2017). This rapid decline in Arctic sea ice has led to an expansion of navigable waters in the Arctic and an extended navigable period, gradually improving the navigation conditions in Arctic waters. With the increasing number of ships crossing the Arctic, navigation activities in Arctic waters are becoming more frequent, carbon emissions in Arctic waters also increase correspondingly. Arctic shipping vessels lead to GHG emissions. The increase in GHG emissions in the atmosphere is a primary driver of climate change (Allen et al., 2022). The Arctic is experiencing the effects of climate change at an unprecedented pace and scale, including rising temperatures, melting ice caps, and thawing permafrost (Grigorieva, 2024). If carbon emissions from Arctic shipping are not addressed, the GHG emissions from Arctic shipping vessels will continue to rise, exacerbating environmental pressure. While Arctic shipping emissions represent a small fraction of global totals, their impact cannot be overlooked due to the region's unique environment. Therefore, to mitigate climate change in the Arctic and protect its fragile ecosystems and human well-being, it is essential to regulate GHG emissions from

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Arctic shipping vessels.

2 Materials and methods

2.1 Literature review

The environmental and climate issues arising from the increasing frequency of Arctic shipping activities have garnered widespread attention, making the decarbonization of shipping a critical issue for the sustainable development of the Arctic. Numerous studies have explored the decarbonization governance of Arctic shipping from various perspectives, which can be summarized into the following key areas.

2.1.1 Arctic route shipping conditions

In general, polar vessels have high navigation potential for most of the year. With the continuous melting of Arctic ice, it is expected that ships will gain easier access to Arctic routes (Mahmoud et al., 2024). Shipping activities in the Arctic region increased by 25% overall between 2013 and 2019, while the total distance traveled by ships in the Arctic grew by 75% (Kinsey, 2021). From 2013 to 2023, the number of ships entering Arctic waters, as defined by the International Maritime Organization (IMO), increased by 37% (Arctic Council, 2024a). The share of global shipping trade rerouted through the trans-Arctic routes would reach 4.7% by 2030 (Bekkers et al., 2018). Polar Class 6 ships could navigate unimpeded along the Northern Sea Route (NSR) and Northwest Passage (NWP) in November under a 2 ℃ warming scenario, while ordinary ships might be able to traverse the NSR under a 3 ℃ warming scenario (Chen et al., 2022). By the end of the 21st century, the NSR is expected to have an ice-free period of three to six months per year, and the NWP is projected to have an ice-free period of two to four months annually (Khon et al., 2010).

2.1.2 Fuels used by ships in Arctic waters

Maritime transportation in Arctic waters heavily relies on fossil fuels. Approximately half of the vessels operating in the Arctic use residual fuels, including those categorized as heavy fuel oil (HFO), while the other half use distillate fuels (Figure 1, Arctic Council, 2024b).

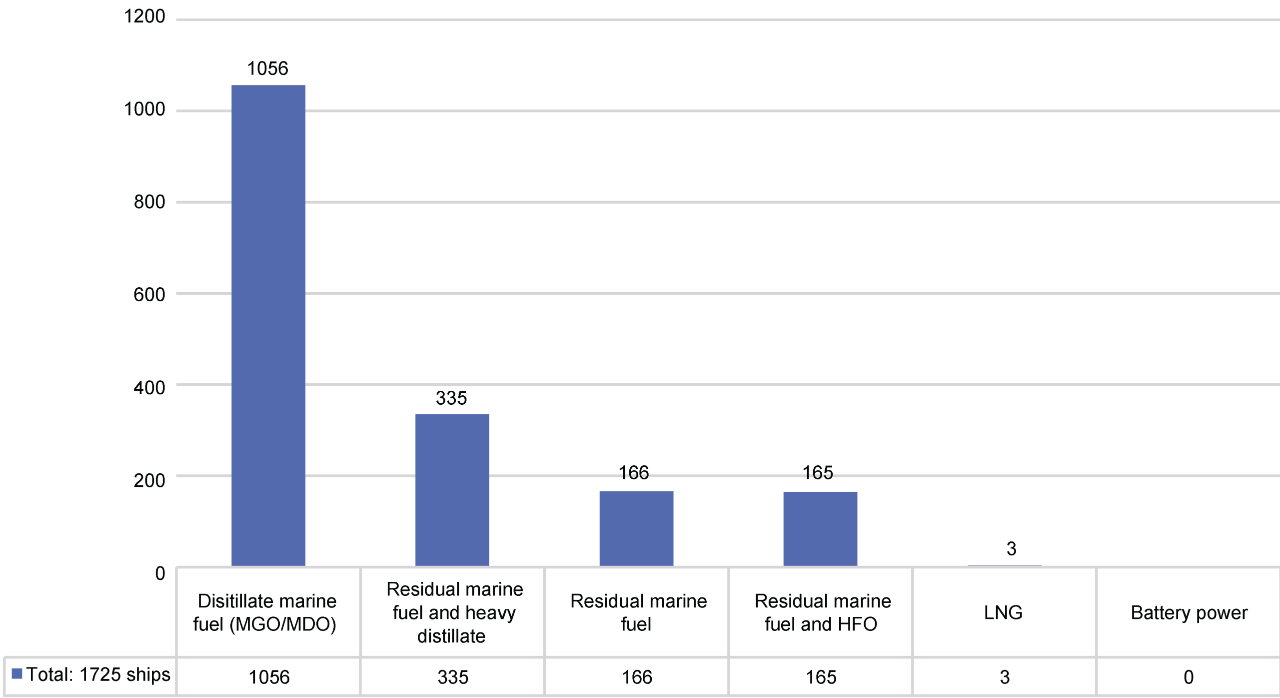

Figure 1 Number of ships using the six fuel types Arctic Polar Code area 2019.

The specific details of ship fuel usage are presented in Figure 1 (Arctic Council, 2020). Currently, HFO is the most widely used marine fuel in the Arctic (ICCT, 2017). While Figure 1 provides a snapshot of fuel usage in Arctic shipping (2019), a longitudinal analysis reveals critical trends. Between 2013 and 2023, the proportion of vessels using HFO in Arctic waters declined by 18%, coinciding with the phased implementation of IMO's strategy and national incentives for cleaner alternatives. This shift aligns with emission reduction targets: replacing HFO with distillates alone could reduce black carbon emissions by 44% (Clean Arctic Alliance, 2021).

However, the adoption of low-carbon fuels (e.g., liquefied natural gas (LNG), methanol) remains limited (<5% of Arctic fleets), hindered by infrastructure gaps and higher costs. Analysis by the International Council on Clean Transportation (ICCT) indicates that if the European Union were to mandate that ships navigating the Arctic cease using HFO and switch to cleaner distillate fuels, black carbon emissions in Arctic waters could be reduced by 50%–80%

(Osipova and Comer, 2022).

2.1.3 Impact of shipping carbon emissions on the Arctic environment

The intensification of shipping activities has caused greater harm to the fragile Arctic ecosystem. A research indicates that Arctic shipping activities have widespread impacts, primarily affecting water bodies, air emissions, and animal survival (Qi et al., 2024). In terms of climate impact, shipping emissions have the potential to warm the climate by darkening ice and snow surfaces (Stephenson et al., 2018). Studies have shown that the rate of temperature rise in the Arctic is already four times the global average (Voosen, 2021). Chen et al. (2022) simulated and estimated the emissions and global warming potential of Arctic shipping. Their results reveal that under conditions of the past 20 years, as well as global warming scenarios of 2 ℃ and 3 ℃, when the annual energy consumption of ships navigating Arctic routes reaches 109 kWh, CO_2 emissions peak at 10^6 t, making it the most significant factor influencing climate change. It is predicted that by 2050, under the Business As Usual (BAU) scenario, the total CO_2 emissions from ships in the Arctic routes will reach 5.5 teragrams (Tg) (approximately 6.1×10^6 t), 1.76 times the emission levels of 2020 (Jing et al., 2021).

2.1.4 Legal regulations on carbon emissions from Arctic navigation vessels by IMO and relevant States

2.1.4.1 IMO's legal regulations on carbon emissions from Arctic navigation vessels

As a specialized agency of the United Nations, the IMO is responsible for the safety, security, and environmental protection of the international shipping industry, including Arctic shipping. It plays a central leadership role in promoting carbon emission reductions in Arctic shipping. The IMO's Marine Environment Protection Committee (MEPC) has also been actively advancing related issues. In 2011, the IMO adopted Resolution MEPC.203(62), incorporating the Energy Efficiency Regulations for Ships into Annex VI of the MARPOL 73/78 Convention (IMO, 2011). This resolution mandates two key energy efficiency requirements: the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) for all vessels, which came into effect on January 1, 2013, to control carbon emissions from newly built ships. According to EEDI rules, new ships must reduce emissions by at least 10% starting in 2015, 20% by 2020, and 30% by 2025.

At the 73rd session of the MEPC held in October 2018, IMO agreed that the Sub-Committee on Pollution Prevention and Response (PPR) should develop a ban on the use and carriage of HFO as ship fuel in Arctic waters, based on an appropriate impact assessment (MEPC, 2018). This potential ban would undoubtedly contribute to reducing carbon emissions from Arctic shipping. During the MEPC 76 session held from 10 to 17 June 2021, amendments to Annex I of the International Convention for the Prevention of Pollution from Ships (MARPOL) were adopted (Regulation 43A), which prohibit the use and carriage of HFO in Arctic waters by ships from 1 July 2024, onwards (IMO, 2021a). Despite these provisions, the MARPOL Convention also stipulates three exemptions and deferral conditions:

(1) Ships engaged in ensuring safety, search and rescue operations, or oil spill response are exempt.

(2) For ships complying with the fuel tank protection requirements under MARPOL Regulation 12A, the effective date is deferred to 1 July 2029.

(3) For regions with Arctic coastlines, ships flying their flag and operating within waters under their sovereignty or jurisdiction are temporarily exempt until 1 July 2029.

The 2023 IMO Strategy on Reduction of GHG Emissions from Ships (hereinafter referred to as the GHG Reduction Strategy), adopted at IMO MEPC 80 on 7 July 2023, provides a clearer and more comprehensive framework (IMO, 2023a). This non-mandatory legal document establishes goals and targets for reducing GHG emissions in the international shipping industry, as well as targets for the adoption of zero or near-zero GHG emission technologies. The GHG Reduction Strategy adopts a phased implementation approach. That is, by 2030, total emissions should be reduced by at least 20%, striving for 30%, compared to 2008 levels; by 2040, emissions should be reduced by at least 70%, striving for 80%, compared to 2008 levels; by 2050, net-zero GHG emissions from international shipping should be achieved. Accordingly, the timeline for achieving net-zero GHG emissions has been advanced to around 2050. While the GHG Reduction Strategy is not specifically designed for the Arctic region, its universal applicability means that the governance of GHG emissions from Arctic shipping will also be advanced within this strategic framework.

The 82nd session of the IMO's MEPC (MEPC 82), held from 30 September to 4 October, 2024, addressed the issue of reducing GHG emissions from ships. The session discussed and advanced the development of the IMO Net-Zero Framework and established a working group dedicated to GHG emission reduction from ships (IMO, 2024a).

2.1.4.2 Legal and policy measures by relevant States on carbon emissions from Arctic navigation vessels

As the Arctic ice cover continues to shrink, the challenges of Arctic development are gradually diminishing, and the strategic value of the Arctic in terms of geopolitics, shipping routes, and energy resources has rapidly become prominent, positioning it as the next global focal point of competition (Wu, 2018). In light of this, States have placed unprecedented emphasis on addressing carbon emissions from Arctic navigation ships.

Norway is one of the early adopters of measures to control carbon emissions from shipping in Arctic waters. As an advocate for green transformation in the shipping sector, Norway aims to reduce carbon emissions from domestic shipping and fishing vessels by 50% by 2030. Norway is actively promoting low-carbon emission reduction efforts across various types of vessels through legislative planning, financial support, public-private partnerships, quota systems, green public procurement, and registration incentive mechanisms, thereby accelerating the green development of the shipping industry (Koasidis et al., 2020).

Canada signed the Declaration on Zero Emission Shipping by 2050 in April 2022, with a focus on establishing the Canadian Green Shipping Corridor framework to support the maritime industry in achieving net-zero emissions (UN, 2021). In terms of domestic legislation, the Canadian Net-Zero Emissions Accountability Act, passed in 2020, commits Canada to reducing GHG emissions by 40% to 45% below 2005 levels by 2030 and achieving net-zero GHG emissions by 2050 (Government of Canada, 2022). Regarding the jurisdictional issues of Arctic shipping routes, Canada maintains a sovereignty-first principle in Arctic governance, particularly asserting its legal claim over the NWP as historic/internal waters (Chang and Khan, 2021). The Sino-Canadian scholarly dialogue highlighted that such unilateral legal construction creates normative tensions with the freedom of navigation principle enshrined in United Nations Convention on the Law of the Sea (UNCLOS) Article 87, presenting a governance challenge in the multilateralization process of Arctic shipping (Chang, 2019a)

The United States is one of the member States of the Clean Arctic Alliance advocating for the IMO to strengthen control over carbon emissions from shipping in the Arctic region. The Implementation Plan for the NSAR (NSARIP), serving as the detailed implementation plan for the National Strategy for the Arctic Region (NSAR) released in 2022, proposes reducing GHG emissions in the Arctic through existing bilateral and multilateral initiatives (White House, 2023a). Specific measures include evaluating further options for reducing local emissions, such as establishing a North American Arctic multilateral emission control area and creating Arctic-specific green shipping corridors, including the availability of near-zero or zero-emission marine fuels and related infrastructure from local sources; collaborating with Arctic Council member States to update the Enhanced Black Carbon and Methane Emission Reduction Framework; and partnering with Arctic States to conduct scientific research on the Arctic to deepen understanding of permafrost thawing and GHG emissions from Arctic shipping (White House, 2023b).

The European Union (EU) and its member States have been proactive in controlling carbon emissions from shipping in the Arctic region. The EU's Arctic Policy for 2021 proposes that the EU will take action against major sources of marine pollution affecting the Arctic, such as black carbon, chemicals, and transport emissions, and promote zero-emission and zero-pollution shipping in the Arctic (Le Service Diplomatique de l'Union européenne, 2024).

Japan is committed to introducing ultra-low or zero-emission vessels by 2030, viewing the development of LNG fuels and the increased use of clean alternative fuels such as hydrogen and ammonia as effective pathways to promote green shipping, aiming to achieve a 90% or greater reduction in GHG emissions compared to 2008 levels (Zheng et al., 2020).

Given the fragile ecosystem of the Arctic region, China is committed to developing Arctic shipping in a sustainable manner (Zhang et al., 2020). China's Arctic Policy, released by the State Council Information Office of the People's Republic of China (2018) in January 2018, identifies protecting the Arctic ecological environment and addressing climate change as one of China's primary policy positions in Arctic affairs. China's Arctic Policy proposes that China advocates for strengthening international maritime technical cooperation, vigorously promoting energy conservation, emission reduction, and green low-carbon development, and seeking globally coordinated solutions for reducing GHG emissions from shipping within the framework of the IMO. Research indicates that establishing normative synergy between domestic maritime legislation and the IMO Polar Code, particularly through alignment with Article 4 (national obligations) of the United Nations Framework Convention on Climate Change (UNFCCC), can effectively elevate the legal hierarchy of environmental standards for Arctic shipping (Chang, 2019b). This dynamic adaptation of international-domestic legal systems will enhance the implementation effectiveness of polar vessel Energy Efficiency eXisting ship Index (EEXI) and Carbon Intensity Indicators (CII).

Research on the decarbonization governance of Arctic shipping has achieved significant progress, encompassing a wide range of aspects. Scholars generally emphasize the balance between economic development and environmental protection, with in-depth discussions spanning technology, law, policy, and international cooperation. Current research highlights the importance of formulating and implementing strategic plans to reduce ship emissions, enhancing ship energy efficiency measures, advancing the development of alternative marine fuels, and strengthening international legal regulations. These findings have laid a theoretical foundation and implementation pathways for the decarbonization governance of Arctic shipping. However, they also reveal that numerous obstacles remain within the international governance system, requiring further efforts to overcome. Future research must continue to focus on these critical issues to promote the sustainable development of Arctic shipping.

2.2 Method

Decarbonization governance in shipping involves multiple interests, including economic development, environmental protection, energy security, and pollution prevention. This paper adopts the interest balancing analysis method, which emphasizes considering these diverse interests in the decision-making process. By identifying the various stakeholders involved in shipping decarbonization governance (such as Arctic States, non-Arctic coastal states, shipping companies, international organizations, and non-governmental organizations (NGOs)) and analyzing their interests and influences, the aim is to achieve a balance between economic and environmental interests, as well as between energy security and pollution prevention, when exploring pathways for shipping decarbonization governance.

This study is grounded in global environmental governance theory and the Common but Differentiated Responsibilities (CBDR) principle. Global environmental governance theory emphasizes multilateral cooperation and institutional frameworks to address transboundary environmental challenges. The CBDR principle, rooted in intergenerational equity, mandates differentiated obligations for developed and developing nations in climate action. These frameworks guide the analysis of systemic barriers and the proposed tripartite governance model integrating legal, technological, and cooperative measures.

3 Results

3.1 A stricter target for shipping GHG emissions control is necessary in Arctic waters

Although IMO bears the core responsibility for leading the process of carbon emission reduction in Arctic shipping and has formulated and implemented a series of policies and regulations aimed at reducing GHG emissions from shipping, these efforts have not yet fully addressed the severe GHG emission challenges faced by Arctic waters.

Firstly, compared to shipping in ordinary waters, the Arctic region highlights the urgency of GHG emission governance due to its critical role in the global climate system. Arctic sea ice and terrestrial snow cover, which originally reflect a significant amount of solar radiation to maintain Earth's energy balance, are increasingly threatened by the large amounts of carbon dioxide, methane, and other GHGs released from ships burning fossil fuels. Additionally, black carbon emissions from engines burning HFO have a non-negligible impact on the climate. As Arctic shipping becomes more frequent, increased GHG emissions exacerbate global warming, leading to sea ice melt and rising sea levels. These impacts are not confined to the Arctic region but affect coastal ecosystems and human societies worldwide.

Secondly, Arctic shipping operates in a highly sensitive region with more complex navigation conditions, making the harm caused by GHG emissions more severe and challenging to manage. The risks associated with Arctic maritime navigation are significant, as the low temperatures in the Arctic slow down the decomposition of oil-based substances. Fossil fuel spills can persist for extended periods, disrupting the balance of aquatic ecosystems. The risk of HFO spills is particularly catastrophic, as its high viscosity makes it nearly impossible to clean up in the cold, icy, and inaccessible waters of the Arctic.

Furthermore, as Arctic ice continues to melt, access to Arctic shipping routes will become increasingly easier. With the growing frequency of shipping activities in the Arctic, the pressure from emissions associated with increased Arctic shipping will rise significantly. This means that without stringent controls, GHG emissions from Arctic shipping will escalate sharply. Despite the constraints of existing measures, current IMO emission reduction strategies, such as improving energy efficiency, remain insufficient to address the impact of GHG emissions in Arctic waters, and total emissions continue to show an upward trend.

In summary, the increase in shipping activities in the polar regions poses significant challenges to the unique environment and ecosystems of Arctic waters. The existing emission reduction measures by the IMO are notably inadequate in addressing the actual needs for controlling GHG emissions in Arctic waters. Relying solely on current mitigation strategies makes it difficult to effectively curb the melting of Arctic glaciers or prevent the further intensification of global warming in the Arctic. To protect the fragile ecological environment of the Arctic, IMO member States must take action to establish stricter GHG emission control targets for shipping in Arctic waters, further strengthen practical controls over GHG emission from Arctic shipping, and ultimately reduce and halt these emissions.

3.2 Insufficient cooperation among the international community on GHG shipping emissions in Arctic waters

As for GHG emissions from Arctic shipping, there is a notable lack of international cooperation, and a unified and robust international legal framework to comprehensively regulate GHG emissions from Arctic shipping is still absent. States often formulate strategies based on their own interests, primarily focusing on national-level responses, with limited impact on international coordination. The universality and transboundary nature of environmental issues, coupled with the limitations of one State's inadequate governmental capacities, have driven the international community to address environmental problems as an integrated whole for governance, thereby achieving global environmental governance (CGG, 1995). According to global environmental governance theory, addressing the decarbonization of Arctic shipping requires establishing a new and more effective set of international mechanisms and institutions at the global level to manage and resolve transboundary environmental challenges. However, the widespread and in-depth cooperative mechanisms among States have yet to be established at the international level.

While there has been some progress in soft law cooperation under international law, the lack of binding enforcement makes it difficult to ensure effective implementation by all countries. The differing positions and actions of various nations in addressing GHG emissions from Arctic shipping have not been effectively integrated, failing to create a synergistic effect.

There are significant gaps in establishing unified standards, sharing technology, and implementing joint oversight, resulting in low overall governance efficiency. The CBDR principle, a cornerstone of international environmental law, is designed to address the collective action dilemma in confronting the climate system crisis as a common concern of humankind. The CBDR principle embodies a synthesis of procedural justice and substantive equity. The common responsibilities component articulates universal participation and cooperative engagement, whereas the differentiated responsibilities dimension necessitates tailored implementation frameworks, accounting for material asymmetries in national circumstances through differentiated scopes, modalities, and timelines of obligation fulfillment (Liu and Peng, 2016). The CBDR principle serves as both a pivotal norm within the international climate governance framework and the operational embodiment of the equity principle in practical implementation. Rooted in intergenerational equity under international environmental law, the CBDR principle institutionalizes differential obligation thresholds by mandating developed countries to undertake leadership in mitigation financing, while recognizing developing countries' capability constraints shaped by historical emission inequities. As a result, the issue of GHG emissions from Arctic shipping has not been effectively curbed. The international community urgently needs to strengthen cooperation as required by the CBDR principle to address the severe challenges posed by GHG emissions from Arctic shipping.

4 Discussion

4.1 IMO formulating special rules for the control of shipping GHG emissions in Arctic waters

4.1.1 Requiring the use of alternative fuels for ships navigating the Arctic

Environmental organizations have expressed concerns over the five-year exemption granted under the ban on the use and carriage of HFO in Arctic waters (MARPOL Annex I, Regulation 43A). This exemption allows certain vessels to continue using HFO until 2029, restricting only 16% of HFO used as fuel and 30% of HFO carried as fuel, while HFO transported as cargo remains entirely unrestricted (Wang, 2024). As a result, the risk of HFO spills in the Arctic marine ecosystem remains high. At the MEPC (MEPC 77) meeting, Canada, Finland, France, Germany, Iceland, the Netherlands, Norway, the Solomon Islands, Sweden, the United Kingdom, and the United States jointly called for Member States and ship operators to voluntarily use distillate of low aromaticity or other cleaner alternative fuels or methods of propulsion (IMO, 2021b).

Tomos et al. (2024) conducted a lifecycle assessment comparing hydrogen, ammonia, methanol, and waste-derived biofuels as shipping fuels, concluding that green hydrogen, waste-derived biodiesel, and biomethanol have the best decarbonization potential. Compared to HFO, these fuels can potentially reduce emissions by 74%–81%, 87%, and 85%–94%, respectively. As the industry transitions to cleaner, carbon-neutral fuel sources, the environmental impact of shipping will decrease (Chen et al., 2022). A complete shift by ships navigating Arctic waters to cleaner alternative fuels, replacing HFO and distillate fuels, will help vessels achieve emission reduction targets, thereby significantly advancing efforts to protect the Arctic marine environment.

4.1.2 Extending ship energy efficiency regulations to fishing vessels in the Arctic

The MEPC.278(70) resolution, adopted in 2016, mandates that international vessels over 5000 gross tons (GT) collect and report their fuel consumption on a calendar year basis starting 1 January 2019 (IMO, 2016). In June 2021, IMO amended MARPOL Annex VI during the 62nd meeting of the MEPC. This amendment sets an achievable target of reducing ship carbon intensity by 11% compared to 2019 levels by 2026 and introduces short-term GHG reduction measures, namely the EEXI and the Annual Operational CII along with its rating system (IMO, 2021c). The EEXI extends the EEDI applicable to new ships to existing vessels, addressing the carbon emissions from a significant number of current ships, with most procedures mirroring those of the EEDI. The CII measures the CO_2 emissions per ton of cargo transported per nautical mile. Based on the CII calculations, ships are classified into five categories: A, B, C, D and E, where A represents the best performance and E the worst (IMO, 2023b).

The IMO Data Collection System (DCS) and CII apply to international ships of 5000 GT and above, while the EEXI and SEEMP apply to all ships above 400 GT. Arctic shipping exhibits unique characteristics, with fishing vessels constituting the largest fleet in the region. In the 2015 Arctic fleet composition, fishing vessels accounted for 36.2% of the IMO Arctic fleet, far exceeding general cargo ships (11.6%), service vessels (9.5%), and bulk carriers (8.7%) (Comer et al., 2017). Within the fishing vessel category, there is a wide range of vessel sizes. While there are large ocean-going fishing vessels and those used for large-scale Arctic fishing operations, the majority are small fishing vessels with well below 5000 GT, and many even below 400 GT. As a result, these vessels fall outside the scope of the IMO's energy efficiency regulations. This means that fishing vessels are not subject to mandatory requirements to improve fuel efficiency when newly built or undergoing major modifications.

Extending the ship energy efficiency regulations to fishing vessels in the Arctic is essential. Although fishing fleets primarily use distillate fuels, they remain the largest contributors to black carbon emissions in the Arctic, accounting for 29.7% of total black carbon emissions (Mjelde et al., 2014). Compared to other vessel types, the fuel consumption of fishing vessels is not only influenced by navigation operations but also largely depends on fishing methods and gear (Suuronen et al., 2012). Most fishing methods heavily rely on fossil fuels. For example, active fishing gear such as bottom trawling consumes significantly more fuel than passive gear like pots, traps, longlines, and gillnets (Suuronen et al., 2012). The excessive use of any type of fishing gear, even low-energy gear, can lead to significant emissions due to over-exploitation and the corresponding high level of fishing vessel activity (Zhang et al., 2019).

In light of this, to more effectively promote emission reductions in Arctic shipping and mitigate the negative environmental impacts of fishing vessels, it is necessary to extend the ship energy efficiency regulations to fishing vessels in the Arctic. This will facilitate comprehensive improvements in energy efficiency and emission reductions across the entire Arctic shipping industry, contributing to its sustainable development.

4.1.3 Introducing mandatory regulations for the Arctic in MARPOL

Arctic shipping will exacerbate both Arctic and global warming, highlighting the urgency of controlling GHG emissions from Arctic shipping. However, in the face of the growing trend of Arctic shipping, the industry lags behind in achieving net-zero emission controls (Liu et al., 2024). In November 2021, IMO adopted a resolution at the MEPC 77 meeting urging ship operators to switch to cleaner fuels in the Arctic (IMO, 2021d). However, this remains a voluntary measure. In fact, banning the use and carriage of HFO in the Arctic is of great significance, as it would not only significantly reduce the risk of HFO spills but also effectively cut emissions, including black carbon. Given that ships registered in Arctic States, particularly Russia, account for a substantial proportion of HFO use, carriage, and black carbon emissions in the Arctic, it is more efficient to develop region-specific carbon reduction policies for the Arctic. Therefore, one of the key measures to address GHG emissions from Arctic shipping is to actively promote the development of internationally binding regulations for GHG emission reductions. Consequently, it is necessary to introduce new mandatory regulations specifically for the Arctic in Annex VI of the MARPOL Convention, setting clear emission reduction targets and promoting the use of net-zero fuel technologies to reduce carbon emissions.

Specifically, the carbon emission reduction targets for Arctic shipping should align with and strive to exceed the goals of the Paris Agreement, which aim to reduce emissions by 45% by 2030 and achieve net-zero emissions by 2050 (UN, 2024). The implementation of these reduction targets can follow the phased approach outlined in the IMO's GHG Reduction Strategy. Without stronger climate policies, oil and gas production in the Arctic is expected to continue rising, with fossil fuel production projected to peak by 2040. By 2050, the gap between Arctic fossil fuel production and the Paris Agreement's reduction targets could reach 700% (Tracy, 2023). Considering these factors, the ideal target for Arctic shipping carbon emission reduction would be to achieve at least a 50% reduction by 2030 and to reach net-zero emissions by around 2040. By enacting regulations that limit ship carbon emissions, the adoption of cleaner fuels and technologies can be strongly incentivized, significantly reducing the carbon impact of shipping activities on the polar environment. Specifically, it is necessary to establish clear GHG reduction targets and timelines for Arctic shipping, covering detailed aspects such as ship fuel quality standards, emission reduction targets, emission quota allocation, and penalties for non-compliance. This will ensure effective control of carbon emissions from Arctic shipping, contributing positively to the protection of the Arctic ecosystem and global climate stability.

4.2 Enhancing international cooperation on shipping decarbonization governance in Arctic waters

4.2.1 The necessity of international cooperation

Faced with the rapid growth of trans-Arctic shipping, the lack of unified technical standards and imperfect mechanisms for interest distribution make international cooperation an unavoidable necessity. An increasing number of non-Arctic States' vessels are entering the Arctic shipping domain, and numerous stakeholders are becoming deeply involved in Arctic affairs. This has led to a growing diversification of interest groups and increasingly complex relationships in Arctic route governance. In this context, no single country, regardless of its influence in the Arctic, can comprehensively and effectively manage and govern Arctic shipping on its own. International cooperation on carbon emission reduction in Arctic shipping can leverage complementary strengths, enhancing the overall level and effectiveness of decarbonization governance in Arctic shipping.

From the perspective of international law, the difficulty in policy coordination among States is a prominent issue in the decarbonization governance of Arctic shipping. The regulations related to carbon-emission rights clarify the interdependent relationships between nations, where each country enjoys certain environmental rights while also bearing the obligation not to hinder the rights of others (Shao, 2024). This obligation cannot be fulfilled by a single country alone. International cooperation can effectively address the dilemma of shared interests in Arctic governance, encouraging Arctic governance actors to make compromises and concessions in their national actions, thereby establishing stable rights and obligations (Bai, 2017).

4.2.2 Models of international cooperation

The model of international cooperation presents a diversified landscape. Multiple States have made sovereignty claims over the Arctic, and the differing interests of these nations in the region may lead to challenges in reaching consensus on issues such as route planning, resource development, and environmental protection (Boylan, 2021). This creates a complex geopolitical situation when determining the responsible entities and management authority for Arctic route governance. Strengthening cooperation and coordination among States in the field of Arctic shipping decarbonization governance has become an urgent priority. While scientific research and climate issues in the Arctic are public in nature and require global participation and response, the Arctic also involves sensitive issues such as sovereignty and security (Wang and Sun, 2019). This necessitates that countries, while respecting each other’s sovereignty and interests, jointly explore and develop a series of practical cooperation strategies and action plans.

Intergovernmental cooperation among nations serves as the foundation and core, particularly among Arctic States. Coastal Arctic nations play a pivotal role in shipping carbon reduction cooperation due to their sovereignty and jurisdiction in the region. States like Norway and Russia implement stringent domestic legislation and policy frameworks to rigorously control emissions from their vessels and foreign vessels operating within their territorial waters. For instance, Russia implements an independent approval mechanism through the Northern Sea Route Administration, establishing environmental protection standards for Arctic waters that are stricter than those outlined in the Polar Code (Kseniia et al., 2021). Concurrently, these nations actively engage in bilateral and multilateral collaborations, such as establishing joint monitoring mechanisms to share vessel emission data; conducting collaborative research projects to explore emission reduction technologies and management models suitable for the Arctic environment; and cooperating in Arctic route management to develop unified navigation rules and environmental standards.

Non-Arctic States such as China, Japan, and Republic of Korea, with their increasing involvement in Arctic shipping activities, are also actively participating in international cooperation. By establishing various forms of cooperative relationships with Arctic coastal states, such as signing bilateral agreements and participating in multilateral initiatives, they play a positive role in areas such as financial investment, technological research and development, and shipping market regulation. For example, Republic of Korea leads the world in the construction of polar shipping vessels, particularly in the LNG vessel sector, accounting for over 90% of the global LNG vessel market (Liu et al., 2024). Leveraging the commercial development of shipping routes, Republic of Korea has made significant strides in the Arctic icebreaker market. Daewoo Shipbuilding & Marine Engineering has constructed 15 icebreaking LNG carriers for the Yamal project (Yamal LNG, 2012). Technological expertise in shipbuilding, information systems, and port infrastructure from non-Arctic states like China, Japan, and Republic of Korea can support the transition to cleaner Arctic shipping through innovations such as smart ports and green vessels (Yang and Shi, 2022).

In addition to intergovernmental cooperation, industry organizations and NGOs are indispensable driving forces in international cooperation. Industry organizations such as the International Chamber of Shipping (ICS) and the Baltic and International Maritime Council (BIMCO) represent the interests of shipping companies. By developing industry self-regulation standards and technical guidelines, they encourage shipping companies to adopt environmentally friendly ship designs, clean fuels, and advanced emission reduction technologies, thereby improving the environmental performance of the entire industry. For example, “Reducing Greenhouse Gas Emissions: A Guide to International Regulatory”, published by ICS, provides shipping companies with a comprehensive and actionable set of technical recommendations and operational procedures, covering key areas such as ship energy management, power system optimization, and emission monitoring and reporting (ICS, 2024). These guidelines have become an important reference for many shipping companies in their emission reduction efforts. NGOs like the Clean Arctic Alliance, through advocacy, policy recommendations, and independent monitoring and evaluation of shipping activities, provide decision-making references and social oversight for governments and shipping companies. They also organize international conferences, seminars, and other events to offer platforms for dialogue, promote communication and cooperation among different stakeholders, and advance the development of decarbonization governance concepts and practices in Arctic shipping.

Additionally, the Arctic Council, composed of the eight Arctic States—Canada, the Kingdom of Denmark, Finland, Iceland, Norway, Sweden, the United States, and the Russian Federation—serves as the primary intergovernmental forum addressing issues related to the Arctic environment and sustainable development. Given the significant impact of shipping carbon emissions on the Arctic ecosystem and global climate stability, the Arctic Council should further strengthen its functions and role in Arctic affairs. In the field of shipping carbon emission control, the Arctic Council’s Protection of the Arctic Marine Environment (PAME) working group should focus on deepening measures to regulate shipping emissions. This includes enhancing the monitoring and evaluation system for ship emissions, utilizing advanced technologies to accurately and comprehensively collect ship emission data, and conducting in-depth analysis of emission trends and impacts. These efforts will provide a solid foundation for developing scientific and effective emission reduction strategies.

4.2.3 Specific aspects of international cooperation

Under the prevailing climate governance architecture, capacity-building initiatives and international aid regimes have emerged as the practical linchpin operationalizing the CBDR principle (Zhou, 2023). According to this, joint technological research, collaborative establishment of monitoring networks, sharing of Arctic shipping emissions data, policy coordination, and the formulation of reasonable funding and resource allocation plans are specific aspects of international cooperation for the decarbonization of Arctic shipping.

Firstly, in terms of technological research and innovation, joint efforts should be made in the development of technologies for managing Arctic shipping emissions. The development and application of clean fuels and emission reduction technologies for ships require research on the suitability of LNG, hydrogen fuel cells, biofuels, and other clean fuels in the Arctic environment. This includes addressing technical challenges such as fuel storage, construction of supply infrastructure, and engine modifications. By establishing international cooperation platforms, the widespread adoption of technologies and the sharing of expertise can be promoted, ultimately ensuring effective advancements in carbon emission reduction technologies for Arctic shipping.

Secondly, the construction of a monitoring and evaluation system is also a crucial aspect of international cooperation. The Arctic Monitoring and Assessment Programme (AMAP) working group under the Arctic Council regularly conducts scientific assessment reports on the Arctic climate and environment. These reports aim to provide new insights and progress on climate and environmental changes in the Arctic region based on the latest scientific data. Building on this foundation, a shared platform for Arctic shipping emissions data should be established to facilitate the analysis of emission trends and governance effectiveness, thereby providing a basis for policy adjustments and technological improvements.

Lastly, in terms of funding and resource allocation, international cooperation requires the establishment of a fair and reasonable mechanism. Generally, marine insurance serves as the primary means for shipping companies to address operational pressures. However, the high risk of damage and costly nature of Arctic waters will lead to significant pressure on insurance payouts (Novikova et al., 2022). According to CBDR principle, solidarity-based assistance mechanisms targeting technological and financial capacities are fundamentally designed to offset the incremental costs incurred by states in reconciling economic and environmental interests (Zhou, 2023). Considering this issue, developed countries, in line with their responsibilities and commitments in global climate change governance, should increase their financial contributions to the decarbonization of Arctic shipping (Ari and Sari, 2017). For instance, special funds could be established to support green shipping technology research and development, environmental infrastructure construction in the Arctic region, and compensation and development assistance for local communities affected by ship emissions. Developing countries, on the other hand, can participate in shipping carbon emission governance projects by contributing human and material resources, as well as sharing their experience and data in operating within the Arctic shipping market.

In summary, the severity and uniqueness of ship emissions in the Arctic region necessitate international cooperation. Diversified cooperation models and multifaceted collaborative efforts will provide a solid foundation for effectively addressing this issue, driving Arctic shipping toward a green and sustainable future.

4.3 Using alternative fuels in Arctic waters

4.3.1 Alternative fuels for consideration in Arctic waters

To restrict the use and transportation of HFO in the Arctic and reduce the risk of HFO spills, the adoption of alternative fuels can be considered to mitigate the dual risks of air pollution and fuel leakage from ships in the Arctic region. As fossil fuels are progressively phased out, Arctic shipping is expected to transition towards vessels powered by ammonia, methanol, or hydrogen (Frederiksen, 2024). For instance, ships could switch to distillate fuels, LNG or other alternative fuels. Existing research has identified several alternative marine fuels with the potential to significantly reduce GHG emissions, including LNG, methanol, hydrogen, ammonia, fuel cells, and nuclear power (Li and Hu, 2024). However, the use of different clean fuels in Arctic shipping is subject to various limitations, such as storage, transportation, safety, and toxicity (Liu et al., 2024). Therefore, it is necessary to compare these fuels in terms of technological maturity, safety, and emission reduction effectiveness to select the optimal alternative fuel. This approach would help reduce GHG emissions from Arctic shipping vessels at the source.

4.3.2 Barriers and facilitators to the uptake of alternative fuels in Arctic waters

4.3.2.1 Nuclear energy

Utilizing nuclear energy as a maritime power source in Arctic waters offers a distinct advantage: nuclear power generation does not emit GHGs, except for emissions associated with the handling of nuclear materials. While nuclear energy could serve as a decarbonization option, its application in the unique Arctic environment involves balancing energy security and marine pollution prevention (Wang et al., 2024). Nuclear-powered vessels could be a cost-effective choice for reducing carbon dioxide emissions from shipping (Eide et al., 2013). However, the limited availability of nuclear resources means it is not considered a truly sustainable alternative energy source. Unless the lifecycle costs and corresponding infrastructure of commercial nuclear-powered vessels improve compared to traditional vessels, it is unlikely that more commercial nuclear-powered ships will be built for maritime cargo transportation (Schøyen and Steger-Jensen, 2017). Particularly, public concern in most States about the potential consequences of nuclear fuel accidents remains a significant barrier. Therefore, the feasibility of adopting nuclear energy as a maritime power source in the Arctic will depend on technological advancements and societal acceptance. At least in the short term, the application of nuclear propulsion technology in ships remains highly unlikely.

4.3.2.2 Fuel cells

Fuel cells convert the chemical energy of fuel into electricity through electrochemical reactions, offering high power generation efficiency (approximately 40%–65%), superior system reliability, and lower maintenance costs (Pan et al., 2021). However, the cost of installing battery systems on ships is significantly higher compared to traditional diesel engines. Therefore, the use of shore power in Arctic waters requires addressing the capacity of onshore power grids and the availability of battery charging facilities, including investments in infrastructure to provide electricity. Another issue with battery use is that battery fuels are only suitable for short-distance voyages, such as ferries. As for shore power facilities, progress has been made in regions like the European Union. By implementing Shore Side Electricity (SSE) in Europe, the potential for reducing carbon emissions could reach 8.0×10^5 t of CO_2, equivalent to a 39% reduction in annual CO_2 emissions from all maritime shipping (Winkel, 2016).

4.3.2.3 Ammonia

For long-distance voyages, liquid fuels can provide the extended range required. Ammonia, which can be stored in liquid form at approximately −33 ℃, requires relatively short cooling times, and its transportation methods are already well-established (Lloyd's Register, 2024). In March 2024, the Norwegian Directorate for Civil Protection (DSB) approved plans to construct an ammonia fuel bunkering facility at the Fjord Base in Florø, Norway. This facility aims to support the adoption of ammonia as a common fuel for shipping (Europawire, 2024). However, ammonia is highly toxic, flammable, and corrosive, posing significant risks to humans and aquatic life in the event of accidents or leaks (Global Maritime Forum, 2022). Additionally, the widespread adoption of ammonia-fueled ships faces challenges related to storage and bunkering infrastructure. Safely and efficiently handling ammonia requires specialized equipment and facilities.

4.3.2.4 Hydrogen

Hydrogen can be utilized most effectively in fuel cells, but it also has the potential to be used in modified internal combustion engines. In Norway, there is an ongoing development where DNV GL is supporting the national road authorities in introducing new hydrogen-fueled ferries by 2021 (Norwegian Maritime Authority, 2017). However, the use of hydrogen fuel faces challenges such as high costs, the current lack of production infrastructure to meet future anticipated demand for green hydrogen, and the transportation of hydrogen (Incer-Valverde, 2023). Finding volumetrically efficient methods to store hydrogen is a significant challenge, and the storage and refueling of hydrogen for ships will require specially designed tanks and refueling systems.

4.3.2.5 Methanol

Its high energy density and clean combustion characteristics make methanol a promising green marine fuel (Chang, 2020). Methanol is comprehensively judged as the best current choice for green marine fuel in the shipping industry due to its technological maturity, difficulty of infrastructure modification, safety, convenience in refueling, and low cost (Longspur Research, 2023). There are almost no technical barriers to using renewable methanol as a shipping fuel, and the investment costs for ship operators are considered reasonable. From a supply chain perspective, there are no significant technical obstacles to commercialization (Svanberg et al., 2018). In fact, methanol is rapidly emerging as one of the most viable, lower-emission, and cost-effective alternative fuels for maritime use.

4.3.2.6 LNG

For the Arctic region, recent studies indicate that LNG is also an attractive ship fuel (Klimentyev et al., 2017). However, the lack of bunkering infrastructure in the Arctic and the relatively limited operational range of current designs of LNG-powered vessels pose significant barriers to the widespread adoption of LNG as a marine fuel (IMO, 2024b). Without the necessary infrastructure, shipowners are unlikely to adopt new fuels, and energy suppliers will not fund expensive infrastructure without first securing customers. To break this deadlock, it is essential to strengthen international cooperation in the construction and operation of Arctic shipping route infrastructure, including regional and intergovernmental collaboration, and to coordinate the political will to invest in new infrastructure. In this context, China and Republic of Korea, as emerging economies with strong technological capabilities and economic strength, can play a pivotal role in advancing Arctic infrastructure development through joint efforts. The 2017 Norwegian Arctic Policy: Between Geopolitics and Social Development also emphasizes focusing on economic development and infrastructure construction in the Arctic (Norwegian Ministries, 2017). Meanwhile, Russia is seeking international cooperation to attract investment and technology for infrastructure development and the NSR (Wei and Zhu, 2021). Therefore, overcoming the challenges of insufficient LNG bunkering infrastructure and limited vessel operational range requires coordinated industry efforts and political will to invest, paving the way for the green transition and sustainable development of the Arctic region.

4.3.2.7 Prospects and challenges of alternative marine fuels in Arctic waters

Through the above analysis of alternative marine fuels in terms of technological maturity, safety, economic viability, and supply chain robustness, the following conclusions can be drawn.

First, the green transition of shipping necessitates the adoption of alternative marine fuels, which vary in their effectiveness in reducing air pollution caused by GHG emissions. Technologically, the production, land-based transportation, bunkering, onboard storage, and utilization of these fuels require innovations in modern energy systems, ship energy storage technologies, and propulsion systems. Currently, such innovations are largely limited to the use of LNG and methanol during the primary stage of decarbonization transformation in Arctic shipping.

Second, existing energy storage and propulsion technologies have not yet met the requirements for widespread adoption of cleaner fuels such as liquid hydrogen or ammonia. Liquid hydrogen must be stored and transported at temperatures below −262 ℃, while liquid ammonia is highly toxic; leaks could lead to poisoning of crew members, air pollution, and aquatic contamination. Both fuels also pose explosion risks. Moreover, the widespread adoption of alternative marine fuels depends on establishing secure, cost-effective, and stable industrial supply chains. This involves coordinating all stages, from raw material sourcing and fuel production to land transportation, storage, and bunkering, which entails substantial investments and collaboration among numerous stakeholders, creating significant uncertainties. Therefore, liquid hydrogen and liquid ammonia may be utilized in the mid-term to achieve decarbonization of Arctic shipping, although these fuels demonstrate clear benefits in reducing GHG emissions from vessels.

Finally, commercially viable alternative fuels today are predominantly gray fuels derived from fossil-based feedstocks, which only partially reduce carbon emissions. Achieving net-zero GHG emissions in Arctic and global shipping hinges on the adoption of zero-carbon clean fuels. However, uncertainties regarding the availability and affordability of such fuels indicate that substantial challenges remain.

4.4 Feasibility analysis and implementation pathways for decarbonizing in Arctic waters

4.4.1 Legal-economic-technical synergy challenges

Implementing mandatory decarbonization regulations under the MARPOL may face resistance from sovereign states due to economic costs, technological limitations, or geopolitical interests.

First, economic barriers dominate short-term challenges. Zero-carbon fuels such as ammonia and hydrogen cost 2–3 times more than traditional HFO in Arctic applications (IRENA, 2022). For developing countries, the cost of technological upgrades accounts for 30%–50% of annual profits for shipping companies (Jing et al., 2023), underscoring the necessity of the CBDR principle—developed countries must alleviate this burden through green financing and technology transfers.

Second, legal conflicts arise from diverging national security and interests. A comparative analysis of Russia's principal Arctic strategy documents in the existing literature reveals that Russia's Arctic policy is incremental, focusing primarily on security issues in the Arctic region and the sustainable social and economic development, seeking a balance between international cooperation and national security needs (Lagutina, 2021).

Third, technological constraints further exacerbate challenges. Low temperatures may cause the electrolyte membrane of fuel cells to freeze, thereby reducing their efficiency. This impact may be more pronounced in the extremely cold Arctic region (Fu et al., 2023). Addressing these issues requires international collaboration, such as establishing a Tripartite Arctic Energy Laboratory to enhance hydrogen fuel efficiency in icy conditions.

4.4.2 Policy synergy mechanisms and implementation pathways

To address the aforementioned challenges, a governance framework integrating legal, economic, and technical tools must be developed under the guidance of global environmental governance theory, the CBDR principle, and multilateral cooperation mechanisms. This framework must balance equity and operational feasibility.

Economically, phased carbon taxation and financial incentives can drive market transformation. Drawing on net-zero framework stipulated in MARPOL Annex VI, an Arctic Green Transition Fund is advised to be established to levy compliance fees on Arctic shipping routes. The fund would direct investments toward research and development for alternative fuels, infrastructure development, and financial rewards for ships meeting emission standards.

Legally, MARPOL Annex VI is advised to be amended to create an Arctic-Specific Carbon Market (ETS-Arctic), allocating emission quotas based on historical emissions and energy efficiency improvements. Revenue from carbon auctions would prioritize investments in developing countries' alternative fuel technologies and infrastructure, aligning with the CBDR principle's mandate for differentiated responsibilities.

Simultaneously, blockchain-based emission data sharing, such as the China-Russia co-developed Arctic Monitoring Chain, is helpful for enhancing its transparency. This mechanism transforms technical tools into buffers against geopolitical risks, ensuring coordinated progress toward decarbonization, offering a robust pathway to reconcile competing interests in Arctic shipping governance.

4.4.3 Roadmap for Arctic shipping decarbonization

Building on the preceding analysis, Arctic shipping decarbonization must be initiated through legal mandates and economic incentives, adopting a multi-level governance framework to phase in emission reduction targets. The implementation can be structured into three stages:

Short-Term (2025–2030): Revise the Polar Code to incorporate safety standards for alternative fuels and establish green corridor pilot projects. These pilots will test the feasibility of Arctic emission monitoring technologies and market mechanisms under updated MARPOL regulations.

Mid-Term (2031–2040): Strengthen policy coordination and technological scale-up. Tighten emission thresholds for Arctic vessels, phase out 50% of HFO-powered ships on Arctic routes, and expand LNG/ammonia bunkering infrastructure to cover key ports along the NSR.

Long-Term (2041–2050): Achieve full synergy among legal, economic, and technical frameworks. Enforce a complete ban on fossil fuel vessels in Arctic shipping lanes, targeting an 80% share of net-zero emission fuel vessels (e.g., hydrogen-powered ships). Simultaneously, implement comprehensive monitoring of shipping emissions to ensure accountability and transparency.

This roadmap balances regulatory enforcement with market-driven innovation, ensuring the Arctic transitions toward sustainable shipping while addressing geopolitical and economic complexities.

5 Conclusion

The decarbonization governance of Arctic shipping is a critical issue in addressing global climate change and protecting the fragile Arctic ecosystem. This study identifies three systemic barriers to current decarbonization efforts: inadequate adaptation of IMO regulations to Arctic-specific environmental risks, fragmented enforcement mechanisms between Arctic and non-Arctic States, and technological limitations in adopting clean fuels for Arctic shipping. To address these challenges, the study proposes a tripartite governance framework integrating legal, technological, and international cooperative measures.

First, legally binding amendments to MARPOL Annex VI should be introduced to establish EEXI standards and extend energy efficiency regulations to fishing vessels, thereby closing regulatory gaps. Second, a phased fuel transition should prioritize LNG and methanol as interim solutions, gradually shifting to hydrogen-ammonia synthetic fuels to reduce GHG and black carbon emissions at the source. Third, multilateral cooperation mechanisms must be strengthened to coordinate joint research and development in cold-adapted technologies and optimize shipping routes. This approach integrates obligations under the United Nations Convention on the Law of the Sea with the implementation of the Polar Code, balancing environmental, economic, and geopolitical interests.

Arctic shipping decarbonization is not merely a technical challenge but a microcosm of global climate governance. The study emphasizes the need to address the economic burdens faced by developing nations in technological upgrades through differentiated policy design and international financial support under the principle of CBDR. Simultaneously, platforms like the Arctic Council should enhance their roles in facilitating emissions data sharing and joint monitoring to ensure transparency and accountability. The synergistic integration of legal mandates, market incentives, and technological innovation will contribute to achieving the green transition and sustainable development of Arctic shipping.

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