# ALTERNATIVE MARINE FUELS: A GREEN APPROACH TOWARDS ACHIEVINGCARBON NEUTRALITY

**Abstract**

The fisheries sector is experiencing rapid growth to meet the escalating global demand for seafood. One critical factor contributing to the environmental impact of this sector is fuel consumption, which varies significantly based on the fishing methods employed. This paper reviews the findings of numerous studies that have assessed the environmental implications of capture fisheries using the life cycle assessment (LCA) method. It is reported that the annual fuel consumption in the fisheries industry amounts to approximately 50 million cubic meters, equivalent to 1.2% of global oil consumption. With global marine fish and invertebrate landings reaching 80.4 million tonnes, the average fuel-use intensity stands at 620 liters (527 kg) per live weight tonne or approximately 1.9 tonnes of catch per tonne of fuel. Fishing vessels collectively release 134 million kilograms of carbon dioxide ($CO_2$) into the atmosphere, averaging 1.7 kg of $CO_2$ emissions per tonne of live-weight landings. Specifically in India, mechanized and motorized fishing boats emit 1.18 tonnes of $CO_2$ per tonne of fish caught. Among these mechanized vessels, trawlers exhibit higher CO2 emissions (1.43 t $CO_2$/t of fish) compared to gillnetters, baguettes, seiners, liners, and do letters (ranging from 0.56 to 1.07 t $CO_2$/t of fish). To address the pressing need for reducing carbon emissions from the maritime industry, alternative fuels and energy sources have gained significant attention, aligning with the goal of achieving carbon neutrality. Various countries, including Japan, Europe, Australia, China, Poland, and Norway,

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have been at the forefront of exploring alternative marine fuels. This paper delves into ten potential alternative fuels that hold promise for powering future marine vessels in the quest for sustainability and carbon neutrality. As the shipping sector increasingly commits to achieving carbon neutrality, transitioning to alternative fuels and energy sources emerges as a practical and necessary choice. This transition not only mitigates the environmental impact of the fisheries sector but also contributes to the global effort to combat climate change.

**Keywords:** Alternate Fuel, Green Technology, Carbon Neutrality, Environmental Sustainability

## I. INTRODUCTION

The fisheries sector is a vital source of affordable protein and a key player in addressing global malnutrition and food scarcity. India ranks fourth in global capture fisheries production, contributing 5.49% of the total in 2018 (FAO, 2020). Marine fish production in India reached 3.69 million tonnes in 2017-18, comprising approximately 29.35% of the country's total fish production and supporting nearly 3.79 million fishermen (CMFRI, 2018; HBFS, 2019). The northwest coast of India alone, with 28.57% of the country's coastline, contributed 32.14% of the total landings in 2017-18, solidifying its position as a significant contributor to the global fisheries landscape.

However, the global fisheries industry faces sustainability challenges, escalating fuel consumption, and associated environmental concerns, particularly in the prevalent trawling sector. In India, where fisheries play a pivotal role in employment and food security, the energy cost associated with seafood production is a matter of concern for consumers, traders, and fishing communities.

Mechanized fishing, constituting 82% of India's marine landing (Handbook on Fisheries Statistics 2022), is notably energy-intensive and relies exclusively on finite and non-renewable fossil fuels. Fossil fuel usage has far-reaching environmental implications, contributing to greenhouse gas emissions, climate change, sea-level rise, and air pollution (TERI, 1999; Pelletier et al., 2007; Avadi & Freon, 2013; Parker & Tyedmers, 2015). Therefore, fuel consumption plays a pivotal role in assessing the environmental sustainability of fisheries, with the type of fishing method employed being a prominent factor (Boopendranath, 2008; Thrane, 2004; Tyedmers et al., 2005; FAO, 2007; Schau et al., 2009; Cheilari et al., 2013; Parker & Tyedmers, 2015). Trawling, one of the most common methods, is notably energy-intensive, surpassing other fishing methods by a significant margin (Wiviott & Mathews, 1975; Leach, 1976; Edwardson, 1976; Lorentzen, 1978; Rawitscher, 1978; Nomura, 1980; Hopper, 1982; Watanabe & Okubo, 1989; Tyedmers, 2001). Moreover, factors such as vessel size, design, engine capacity, weather conditions, fishing gear type and size, location, crew expertise, and vessel size further influence fuel consumption (Wiviott & Mathews, 1975; Rochereau, 1976; Edwardson, 1976; Lorentzen, 1978; Watanabe & Okubo, 1989).

It's worth noting that fuel consumption within a fishery can fluctuate due to changes in resource abundance, fleet expansion, vessel size growth, longer travel distances, and technological advancements (Thrane, 2006). Rising fuel prices, coupled with concerns over the future availability of fossil fuels and heightened environmental risks, have spurred increased awareness of fuel efficiency within the fisheries sector.

## II. ENERGY INPUTS TO FISHERIES

Several studies in the Indian context have conducted energy analyses of fishing systems and operations, shedding light on the significant increase in fuel consumption and its environmental implications. Notably, the intensified fishing efforts and enhanced efficiency in Indian marine fisheries over the past five decades have led to a substantial rise in fuel consumption, equating to a rise in $CO_2$ emissions from 0.30 million tons (mt) in 1961 to 3.60 million metric tons (MMT) in 2010. This increase translated to a rise in $CO_2$ emissions from

0.50 to 1.02 tons for every ton of fish caught during the same period. Furthermore, variations in CO2 emissions were observed based on craft types and age, with larger mechanized boats emitting 1.18 tons of CO2 per ton of fish caught in 2010, while smaller motorized boats emitted 0.59 tons of CO2 per ton of fish caught. Within the mechanized craft category, trawlers were found to have higher CO2 emissions, emitting 1.43 tons of CO2 per ton of fish, compared to gillnetters, baguettes, seiners, liners, and do letters, which emitted between 0.56 and 1.07 tons of CO2 per ton of fish (Vivekanandan, 2013). Additionally, numerous studies employing the life cycle assessment method have explored the environmental impact of capture fisheries, including research by Tyedmers (2001), Ziegler et al. (2003), Thrane (2004, 2006), Ellingsen & Aanondsen (2006), Ziegler & Valentinsson (2008), Vázquez-Rowe et al. (2010a and 2010b), Ramos et al. (2011), and Svanes et al. (2011). These studies have revealed insights into the technical efficiency of different ring seine types, particularly those employing lower horsepower engines, in terms of catch per adjusted horsepower (Edwin & Hridayanathan, 1997). Evaluating food production systems based on energy input and carbon footprint has been a longstanding practice spanning over a century (Edwin & Hridayanathan, 1997; Boopendranath, 2000; Boopendranath & Hameed, 2009; Boopendranath & Hameed, 2010; Vivekanandan, 2013; Ghosh et al., 2014).

## III. CURRENT ESTIMATES OF FUEL USE AND COST

Tyedmers et al. (2005) provided insights into global fuel consumption in the fisheries sector, indicating an annual usage of approximately 50 million cubic meters, equivalent to 1.2% of the world's total oil consumption. This level of consumption was associated with marine fish and invertebrate landings totalling 80.4 million tonnes, resulting in a global average fuel-use intensity of 620 liters (527 kg) per live weight tonne or roughly 1.9 tonnes of catch per tonne of fuel. The emissions impact was substantial, with fishing vessels releasing 134 million kilograms of carbon dioxide (CO2) into the atmosphere, averaging 1.7 kg of CO2 per tonne of live-weight landings. It's important to note that these estimates are likely conservative, as they did not encompass freshwater fisheries or significant illegal, unreported, and unregulated (IUU) catches. In the context of Indian marine capture fisheries, substantial growth in fossil fuel consumption was observed over the past five decades, resulting in CO2 emissions escalating from 0.30 million tonnes (mt) in 1961 to 3.60 mt in 2010. During this period, CO2 emissions per tonne of fish caught rose from 0.50 to 1.02 tons. Notably, variations in CO2 emissions were observed among different types of craft, with mechanized and motorized boats emitting 1.18 and 0.59 tons of CO2 per tonne of fish caught, respectively, in 2010. Among mechanized craft, trawlers exhibited higher CO2 emissions at 1.43 tons of CO2 per tonne of fish compared to gillnetters, baguettes, seiners, liners, and do letters, which emitted between 0.56 and 1.07 tons of CO2 per tonne of fish (Vivekanandan, 2013).

## IV. GREEN TECHNOLOGY

Technology typically refers to the application of various techniques, skills, methods, and processes to achieve specific objectives, such as scientific research or practical purposes. When a technology is designed to be environmentally friendly throughout its production, supply chain, or usage, it is referred to as Green Technology or Green Tech.

 

Green tech serves as an encompassing term that encompasses the development of products, systems, or equipment with reduced environmental impact, aiming to mitigate and minimize the negative consequences of human activities on the natural environment and its resources.

Our world possesses finite natural resources, often referred to as non-renewable resources, some of which have already been depleted due to human actions. According to estimates from the Global Footprint Network in 2018, humans are consuming natural resources at a rate 1.7% faster than the Earth can replenish them. Consequently, the urgent need of our time is to prioritize investments in Green Tech for several reasons:

- Green Tech is less detrimental to the natural environment, thereby reducing the depletion of valuable resources.
- It significantly reduces or eliminates the emission of greenhouse gases (GHGs) like carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), which are major contributors to climate change.
- Green Tech encourages the utilization of renewable resources, such as wind and solar power, which are sustainable and do not deplete over time. By embracing Green Tech, we can work towards a more sustainable and environmentally responsible future.

1. **Understanding Green Tech:** The primary objective behind the development of Green Tech is to combat climate change, safeguard the natural environment, reduce our reliance on non-renewable resources like fossil fuels, and address environmental degradation. Although the market for Green Tech is still in its nascent stages, investment capital in this sector is flourishing. While Green Tech has gained increasing prominence in recent times, elements of environmentally conscious business practices have been in use since the 18th and 19th centuries during the height of the Industrial Revolution. During the early 19th century, manufacturers began adapting their production methods to minimize negative environmental impacts, such as reducing soot and waste by-products. However, the formal recognition of Green Tech as a distinct business sector only began to emerge in the 1990s.

   According to a United Nations study published in 2018, the global cumulative investment in renewable energy sources and green technology processes exceeded $200 billion in 2017. Furthermore, an astonishing $2.9 trillion has been invested in areas like solar and wind power since 2004. The report from the U.N. also highlighted China as the world's leading investor in this field, with approximately $126 billion invested in 2017 (United Nations, 2018).

2. **Advantages of Green Technology and Challenges to Overcome**

   **Green technology, or Green Tech, offers several notable advantages:**

   - **Waste Management:** Green Tech plays a crucial role in recycling and efficiently managing waste materials.
   - **Environmental Friendliness:** It is inherently environmentally friendly, emitting little to no harmful substances into the environment.

- **Cost Efficiency:** Maintaining Green Tech is cost-efficient, offering economic benefits.
- **Energy Conservation:** It contributes to energy conservation, helping reduce overall energy consumption.
- **Ecosystem Health:** Green Tech can aid in rejuvenating and preserving the health of ecosystems.

**However, the Adoption of Green Tech Faces Significant Challenges:**

- **Fossil Fuel Dependency:** The world has historically depended on fossil fuels for about 90% of its energy needs, making the transition to eco-friendly Green Tech a major hurdle.
- **Intermittency of Renewable Energy:** While renewable sources like wind and solar energy hold promise, their intermittency poses challenges as the sun doesn't always shine, and the wind doesn't always blow. This intermittency can be mitigated through energy storage solutions.
- **Location Dependency:** Certain green technologies, like tidal energy and geothermal energy, are location-specific, limiting their widespread applicability.
- **Infrastructure Development:** To fully harness the potential of Green Tech, new transmission lines are needed to transport renewable energy from remote areas to urban centers.

Despite these challenges, the long-term benefits of Green Technology make the effort worthwhile.

## V. MARITIME EMISSIONS AND ALTERNATIVE FUELS:

Maritime transport continues to be a significant contributor to air pollution (IMO, 2021). Addressing this issue requires the adoption of alternative marine fuels, a key strategy for decarbonizing the maritime sector. These alternative fuels encompass liquefied natural gas (LNG), liquefied biogas (LBG), hydrogen, ammonia, methanol, ethanol, hydrotreated vegetable oil (HVO), and even nuclear power and electricity, as indicated in various studies (ITF, 2018; Wang and Wright, 2021; Al-Enazi et al., 2021; Santos et al., 2022). The transition to these cleaner energy sources has become a necessity for shipping companies following the International Maritime Organization's (IMO) greenhouse gas reduction strategy (IMO, 2018). Clean and reliable alternative fuels and energy sources are now a top priority for the maritime industry (Al Enazi et al., 2021), playing a pivotal role in achieving carbon neutrality in international shipping (Wang and Wright, 2021). Several countries, including the USA, Japan, Europe, Australia, China, Poland, and Norway, have directed their attention toward developing and utilizing alternative marine fuels (Bicer et al., 2016; Tanaka, 2013; Prussi et al., 2021; Paul et al., 2018; Yang et al., 2019; Miętkiewicz, 2021; Laribi and Guy, 2020). This article explores ten potential alternative fuels suitable for future marine vessels powered by eco-friendly technology (Author's data, Year).

1. **Liquefied Natural Gas (LNG):** Liquefied Natural Gas, abbreviated as LNG, is the result of cooling natural gas to an extremely low temperature of approximately -256$^{o}$F (161$^{o}$C) at atmospheric pressure, causing it to transform into a liquid state. This liquefaction process reduces the volume of natural gas by a factor of about 600, making it

economically viable for transportation across long distances using specialized marine vessels. In contrast, conventional pipeline transportation may not be as economically attractive and could face technical or political challenges, thus highlighting the significance of LNG technology in facilitating global natural gas accessibility. To make LNG accessible for consumption in countries such as the United States, energy companies must undertake a series of interconnected operations. The primary stages of the LNG value chain, excluding pipeline operations connecting these stages, include:

- **Exploration and Production:** The process of discovering natural gas reserves within the Earth's crust and extracting it for eventual distribution to end-users. Often, natural gas discoveries occur during oil exploration.
- **Liquefaction:** Converting natural gas into its liquid form to enable efficient transportation via specialized ships.
- **Shipping:** Transporting LNG using dedicated vessels designed for this purpose.
- **Storage and Regasification:** Transforming the stored LNG, kept in specially designed tanks, from its liquid state back into a gaseous form. This regasified gas is then ready for distribution through the natural gas pipeline network to its final destination.

Liquefaction not only facilitates the transportation of natural gas but also offers the opportunity to store it for later use, particularly during high-demand periods in regions lacking suitable geological conditions for underground storage facilities. In areas like the northeastern United States, where underground storage is limited, LNG plays a crucial role in ensuring a stable gas supply, especially during severe cold spells. Additionally, in regions where pipeline capacity from production areas can be prohibitively expensive and usage is seasonal, LNG liquefaction and storage take place during low-demand periods, effectively reducing the costly commitments associated with peak-period pipeline capacity.

2. **Ammonia:** Ammonia as a Zero-Carbon Fuel: Ammonia stands out as a potential zero-carbon fuel alternative, much like hydrogen. Presently, a significant portion of ammonia production relies on natural gas. Ammonia can serve as an energy source for fuel cells or be integrated into the fuel mix for internal combustion engines. It's worth noting that "green" ammonia presents a unique opportunity for achieving emissions-free shipping throughout the entire energy production and utilization chain, encompassing both the production phase ("well-to-wake") and its utilization onboard ships ("tank-to-wake"). Nevertheless, there are several challenges that need to be addressed, including the scalability of production, ensuring an adequate supply, developing innovative engine technologies, addressing safety concerns, and establishing robust supply chain systems. Additionally, regulatory and technical hurdles related to the use of potentially hazardous fuels must be navigated.

In a recent report, "Maritime Forecast to 2050 Energy Transition Outlook 2021" by DNV, ammonia emerges as one of the most promising options for achieving carbon-neutral shipping. However, a crucial requirement for ammonia to become a viable future fuel is its production through low-carbon processes.

3. **Biofuels:** Biofuels primarily biodiesel, are commonly derived from sources like soybean oil, rapeseed oil, sunflower oil, corn oil, olive oil, and certain waste materials like used frying oils. These materials are attractive options for biodiesel production. Biodiesel is a renewable fuel that is compatible with existing engines, offering the potential to reduce our reliance on fossil fuels and mitigate air pollution, thereby addressing associated public health risks. However, biodiesel has its drawbacks, including challenges with cold weather starting, some storage stability issues, and a slight increase in NOx emissions (approximately 2% to 5%). This increase is attributed to the higher oxygen content of biodiesel. Nonetheless, adjustments in engine operation, such as retarding ignition timing and moderating fuel burn rates within the combustion chamber, can help mitigate NOx emissions. Despite its promise as an environmentally friendly fuel source, biodiesel availability remains limited.

4. **Nuclear:** The inception of nuclear and marine propulsion dates back to the 1940s, with the USA witnessing the establishment of its first test reactor in 1953. A significant milestone occurred in 1955 with the deployment of the USS Nautilus, the world's first nuclear-powered submarine. This event marked a pivotal shift in submarine technology, transforming them from slow underwater vessels into formidable warships capable of maintaining speeds between 20 and 25 knots, even while submerged for extended durations. The success of the Nautilus spurred the concurrent development of additional Skate-class submarines, all powered by single pressurized water reactors (PWRs). In 1960, the USS Enterprise, an aircraft carrier, was introduced, featuring a power plant comprising eight PWR units. Shortly thereafter, in 1961, the cruiser USS Long Beach was commissioned propelled by two of these early reactor units. Remarkably, the USS Enterprise continues to serve actively, highlighting the enduring potential of nuclear-powered vessels. Nuclear propulsion finds particular relevance in vessels that operate at sea for prolonged periods without the need for refueling, especially in the realm of powerful submarine propulsion.

   However, the deployment of nuclear-powered ships and offshore platforms introduces the potential for marine radioactive contamination in the absence of stringent nuclear safety protocols. This risk is particularly pronounced during extraordinary circumstances, including severe weather conditions, collisions, external threats, or operational errors, which may result in the release of radioactive materials, leading to substantial incidents of marine pollution. In cases of reactor meltdowns accompanied by breaches in the primary containment structure, nuclear fuel may escape from the core into the surrounding environment, giving rise to extensive marine pollution. It is crucial to recognize that "radioactive wastes are not biodegradable, nor is there any possibility of removing them from the sea once they have entered it. These substances vary in effect, but in general, they are absorbed by marine organisms, often becoming concentrated as they move up the food chain, affecting the growth, reproduction, and mortality of marine life" (Churchill et al., 2022).

5. **Hydrogen:** Hydrogen has long been regarded as a renewable energy source and has been hailed as the future's primary fuel for several decades. The exploration of hydrogen's application in transportation gained traction in the aftermath of the initial oil crisis, with numerous automobile manufacturers embarking on development initiatives aimed at creating hydrogen-powered vehicles featuring internal combustion engines. This

movement commenced in Germany and Japan, subsequently drawing participation from the United States. Presently, the United States has established national initiatives dedicated to advancing hydrogen systems, particularly in the realm of fuel cell applications, to address challenges related to combustion-related issues. Notably, the greenhouse gas (GHG) emissions associated with hydrogen fuel predominantly hinge on its energy source, with steam methane reforming and liquefaction processes constituting major emission sources (Hwang et al., 2020). Regrettably, the primary method for hydrogen energy production involves fossil fuels, including coal gasification and steam methane reforming, resulting in substantial GHG emissions during the otherwise environmentally benign hydrogen production process (Hwang et al., 2020; Van Hoecke et al., 2021). Safety is of paramount concern during hydrogen bunkering, storage, and usage onboard vessels due to hydrogen's explosive and diffusive nature, posing risks to hull integrity and crew safety. Despite its non-toxic nature, hydrogen can form flammable concentrations (4% to 75% in air) and ignite at low temperatures, potentially leading to combustion or oxygen displacement in confined environments (Hydrogen Tools, 2022). Even minor sparks, such as those from a crew member's cigarette, can ignite hydrogen, and in the event of a ship collision, pressurized hydrogen storage systems may leak, potentially resulting in hydrogen explosions and fires that can cause extensive damage to various onboard elements (Hydrogen Tools, 2022).

6. **Electricity:** Electric ships are often perceived as environmentally benign during their operational phases. However, it is crucial to recognize that they can have adverse environmental impacts during the generation and disposal of electric energy. These impacts manifest in the form of acidification, eutrophication of water bodies, and potential harm to human health. Notably, one significant contributor to these environmental concerns is the disposal of waste generated from lignite mining in surface landfills (Bicer and Dincer, 2018). Eutrophication, a particularly concerning process, disrupts the ecological balance of aquatic ecosystems when substantial amounts of nitrogen- and phosphorus-containing compounds are discharged into water bodies. This influx triggers the overgrowth of algae and other aquatic organisms, leading to excessive oxygen consumption and subsequent depletion in the water. As a consequence, the mortality of fish plankton ensues due to oxygen deprivation, with the decomposition of their remains further exacerbating water pollution.

7. **Methanol:** The extent of greenhouse gas (GHG) emissions associated with methanol primarily hinges on the raw materials used in its production and the specific conversion processes employed (Martin, 2021). Methanol derived from natural gas exhibits a global warming potential equivalent to that of heavy diesel fuels, whereas methanol and bioethanol tend to have a lower global warming potential. Nevertheless, it's important to note that bioethanol fuels used in marine engines carry the risk of methane slips. Methanol is biodegradable but can be toxic at higher concentrations, potentially leading to localized environmental impacts in marine ecosystems in the event of a collision, grounding, or other ship accidents resulting in methanol leakage (Brynolf et al., 2014). Moreover, methanol and methanol-based fuels possess an eutrophication potential roughly twice that of liquefied natural gas (LNG), which could disrupt marine water ecosystems. Additionally, the low flash point of methanol poses a fire risk on ships.

## VI. FISCHER–TROPSCH (F-T) DIESEL PRODUCTION PROCESS

The Fischer–Tropsch (F-T) diesel production process, whether from natural gas (gas to liquid or GTL) or coal (coal to liquid or CTL), involves the conversion of these resources into diesel fuel using methods such as steam reforming, auto-thermal reforming, or gasification. The availability and suitability of this process depend on the primary fuel source, whether it's natural gas or coal. F-T diesel fuel is characterized by its lack of sulfur, minimal aromatic compounds, and high cetane rating. However, it's essential to note that the F-T process is highly energy-intensive and requires substantial capital investment, making the resulting fuel relatively expensive.

## VII. NATURAL GAS

Natural gas is a mixture of paraffinic hydrocarbons, including methane, ethane, propane, and butane. It stands out as a fuel with low density and minimal sulfur content compared to petroleum products, and it is virtually free from carbon monoxide emissions. The transformation of natural gas into liquefied natural gas (LNG) involves cooling it to approximately -162 degrees Celsius, causing it to transition into a liquid state and significantly reducing its volume by over 600 times. Consequently, natural gas has become the fevered fuel choice due to its intrinsic environmental friendliness, higher efficiency, and cost-effectiveness.

## VIII. ALCOHOL

Alcohols, specifically ethanol ($C_2H_5OH$) and methanol ($CH_3OH$), can be derived from renewable sources like sugarcane waste and various agricultural products. These alcohols have a history dating back to their use in motor vehicles since 1954. Their attractiveness as alternatives lies in their ready availability from local sources, ease of handling, low emissions, and the high thermal efficiency achievable when utilized. This makes them a plausible choice for the future, particularly as an alternative to hydrogen generation for fuel cells. Recent research has indicated the feasibility of methanol as an alternative fuel, particularly in dual-fuel engines. However, challenges associated with the use of methanol or its blends include emissions of aldehydes, phase separation, vapor lock, cold starting issues, and cost-effectiveness concerns.

## IX. CONCLUSION

In conclusion, with the increasing global commitment to achieving carbon neutrality, the maritime industry is actively transitioning towards alternative fuels and energy sources to reduce carbon emissions. While these environmentally friendly alternatives hold promise, it's crucial to acknowledge that they may introduce new environmental risks to the marine ecosystem.

Effectively addressing these challenges necessitates interdisciplinary research efforts and the strengthening of international regulatory bodies responsible for overseeing vessels powered by alternative fuels. This includes regulating fuelling facilities, ensuring unhindered navigation, establishing global environmental standards specific to alternative fuels, rectifying shortcomings in liability and compensation systems for pollution incidents, and enhancing international collaboration in pollution prevention and response efforts.

It's worth noting that international law plays a pivotal role in shaping regulations for vessels utilizing alternative fuels. However, relying solely on international law may not fully address the distinct environmental challenges posed by these new technologies. Developing a more robust international response mechanism requires a multifaceted approach, considering aspects such as scientific and technological advancements, economic factors, and the dynamics of international relations.

The existing framework of international laws and agreements demonstrates limitations in dealing with these emerging challenges. Consequently, there is a clear imperative for further enhancements to ensure effective prevention of marine pollution and the provision of swift and adequate compensation for environmental harm. This progress is indispensable in upholding ecological integrity in maritime transport amid the pursuit of carbon neutrality.

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