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Comparative Study of Different Alternative Fuel Options for Shipowners Based on Carbon Intensity Index Model Under the Background of Green Shipping Development

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Abstract: The International Maritime Organization (IMO)'s annual operational carbon intensity index (CII) rating requires that from 1 January 2023, all applicable ships meet both technical and operational energy efficiency requirements. In this paper, we conduct a comparative study of different alternative fuel options based on a CII model from the perspective of shipowners. The advantages and disadvantages of alternative fuel options, such as liquefied natural gas (LNG), methanol, ammonia, and hydrogen, are presented. A numerical example using data from three China Ocean Shipping (Group) shipping lines is analyzed. It was found that the overall attained CII of different ship types showed a decreasing trend with the increase of the ship's deadweight tonnage. A larger ship size choice can obtain better carbon emission reduction for the carbon emission reduction investment program using alternative fuels. The recommended options of using LNG fuel and zero-carbon fuel (ammonia and hydrogen) on Route 1 and Route 3 during the study period were analyzed for the shipowners. Carbon reduction scenarios using low-carbon fuels (LNG and methanol) and zero-carbon fuels (ammonia and hydrogen) on Route 2 are in line with IMO requirements for CII.



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1. Introduction

In 1992, the United Nations Framework Convention on Climate Change became the first international convention with the main objective of limiting greenhouse gas (GHG) emissions, and it was also the basic framework for GHG emission reduction and international cooperation [1]. In 1997, the International Maritime Organization (IMO) initiated the discussion of GHG emission reduction in international maritime transportation and subsequently introduced relevant control measures and technical standards. It was responsible for regulating air pollution and GHG emissions from international shipping and adopted a number of technical and operational measures aimed at reducing local emissions of air pollutants (SO_x, NO_x, PM) or GHGs into its MARPOL convention [2,3].

Industrialized countries have committed themselves under the Kyoto Protocol to reduce GHG emissions, particularly CO₂. The Kyoto Protocol entered into force in February 2005 (see United Nations Framework Convention on Climate Change, <http://unfccc.int/2003.php> (accessed on 1 April 2023)) [4]. However, no decision has been made on how to allocate international GHG emissions from ships to individual countries.

These mandatory policy instruments incorporate a number of different regulations. For instance, the Energy Efficiency Design Index (EEDI), which required a minimum level of energy efficiency per capacity mile for ships built after 2012. The Ship Energy Efficiency Management Program (SEEMP) established a mechanism for improving the energy efficiency of ship operations and a system for collecting data on ship fuel consumption.

The IMO has also discussed the development of a number of market-based tools. The EU regulation 2014/94 required shipowners and operators to monitor, report, and

verify annually in any EU and EFTA. In 2016, the 70th Marine Environment Protection Committee (MEPC) adopted a strategic roadmap for the reduction of GHG emissions from ships, with a preliminary timetable for the implementation of a “three-step” strategy for GHG reduction. In 2018, after the adoption of the initial strategy, the IMO has taken an important step toward planning a low-carbon future for the global shipping industry [5].

The IMO’s decision to implement new regulations for short-term measures for GHG emissions reductions globally on 1 January 2023 has created a strong incentive in the shipping industry to use alternative fuels. Shipowners are considering alternative marine fuels to meet the requirements of the new measures. In order to meet the global carbon reduction requirements set by the IMO, the main replacement fuels on the market today fall into two categories: the first is the low-carbon fuels (liquefied natural gas [LNG] and methanol); the second is the zero-carbon fuels (ammonia and hydrogen).

Switching to alternative fuels can significantly affect a ship’s emission profile and its attained CII values. Typically, LNG can reduce CO₂ emissions by about 20–30% compared to heavy fuel oil (HFO). Methanol can reduce CO₂ emissions by up to 15–25% compared to HFO when produced from fossil sources. When produced from renewable sources (green methanol), it can be carbon-neutral. When produced from renewable energy sources, ammonia combustion releases no CO₂, offering a path to zero-carbon shipping. Hydrogen, when produced via electrolysis using renewable energy, results in zero CO₂ emissions at the point of use.

The heating value of a fuel represents the amount of energy released during combustion and is typically measured in megajoules per kilogram (MJ/kg). The heating value provides a measure of the energy density of a fuel. Higher energy density means more energy can be released from a given mass of fuel, which directly impacts fuel efficiency and the amount of fuel required for a specific operation. The heating values are used to calculate CO₂ emissions, as they determine how much energy can be obtained from burning one unit of fuel. In this paper, the heating values of HFO, MGO, LNG, methanol, ammonia, and hydrogen are 40.5 MJ/kg, 42.5 MJ/kg, 55 MJ/kg, 19.9 MJ/kg, 18.6 MJ/kg, and 120 MJ/kg, respectively.

The transition to replacement fuels often requires modifications to existing engines or adoption of new engine technologies, particularly when switching from conventional marine fuels like HFO to alternative fuels such as LNG, methanol, ammonia, or hydrogen. These changes can significantly impact the attained CII values of ships.

Existing HFO engines can be retrofitted to use LNG, but this typically involves significant changes, including the installation of gas injection systems, cryogenic fuel tanks, and safety systems to handle the low temperatures of LNG. The use of LNG can lead to a substantial decrease in CO₂ emissions (up to 25%), thus potentially improving the attained CII values significantly.

Methanol can be used in modified diesel engines. These modifications include changes to the fuel injection system, seals, and materials to be compatible with methanol’s corrosive nature. Methanol, especially when sourced from renewable feedstocks, can significantly reduce CO₂ emissions, positively impacting the attained CII values.

Ammonia requires extensive engine modifications or entirely new engine designs due to its high ignition temperature and toxicity. Safety systems must also be enhanced to address the risks of ammonia exposure. As a zero-carbon fuel when sourced renewably, ammonia can dramatically improve attained CII values, assuming efficient combustion and handling.

Hydrogen can be used in fuel cells or modified internal combustion engines (ICEs). Significant modifications are needed to handle hydrogen’s low energy density per volume, its propensity to embrittle metals, and its flammability. Hydrogen, particularly green hydrogen, can eliminate CO₂ emissions from the combustion process, leading to excellent attained CII ratings.

2. Literature Review

In order to better sort out the relevant policies of IMO for GHG, we summarized the IMO's main GHG policies in Table 1. At the 62nd meeting of the Marine Environment Protection Committee (2011), the IMO adopted proposed amendments to add a new EEDI for ships and a SEEMP for all ships to Chapter 6 of the MARPOL Annex. This is ultimately aimed at reducing GHG emissions from ships in international shipping and is effective for ships weighing 400 GT from year 2013 [6]. At the 70th MEPC, a plan to develop a road map for a comprehensive IMO strategy to reduce GHG emissions from ships was approved, and the 78th MEPC finalized the preparation of guidelines on EEDI, CII, and SEEMP, which, when adopted, will enable IMO to prepare for the implementation of energy efficiency-related regulations [7]. The 79th MEPC has completed the discussion of the proposal for a harmonized interpretation of MARPOL Annex VI, incorporating the relevant elements of the route-based actions to reduce GHG emissions from ships and clarifying the more stringent GHG reduction strategy planned for the revised MEPC 80 in 2023.

Table 1. Main international carbon reduction policies and regulations for IMO.

Year	IMO Timetable for Action to Reduce GHG from Ships
1997	Ship CO ₂ emissions resolution established, authorizing IMO to control GHG emissions
2003	IMO resolution on policies and implementation to reduce GHG emissions from ships
2013	New regulatory efforts to improve the energy efficiency of international ships: Mandatory design requirements for new ships (EEDI), with stringent carbon-intensity standards and mandatory ship energy efficiency management program (SEEMP) for all ships to improve energy efficiency of ships
2015	EEDI Phase I: 10% reduction in ship carbon intensity
2016	Mandatory IMO data collection system: from 1 January 2019, ships of 5000 GT and above, which account for more than 85% of emissions from international shipping, will be required to clerk fuel consumption data and report annually to IMO
2018	IMO resolution on preliminary strategies for reducing GHG emissions from ships
2020	EEDI Phase II: 20% reduction in ship carbon intensity
2023	Completion of short-term measures and revision of initial strategy
2025	EEDI Phase III: 30% reduction in ship carbon intensity
2023–2030	Medium-term measures: reduce carbon intensity of the fleet by at least 40%
2030–2050	Long-term measures: reduce the carbon intensity of the fleet by at least 70%

Data sources: IMO and Clarkson.

There is a very large amount of existing shipping emissions reduction literature. Without loss of generality, this paper focuses on a literature review from the following three perspectives: emissions reduction policies and regulations, shipping emissions reduction response programs, and carbon emissions reduction response programs.

2.1. Emissions Reduction Policies and Regulations

Many carbon emission control policies have been adopted by governments around the world [8]. Especially, as many governments such as those of China, France, and Germany have declared targets for achieving carbon neutrality by the mid-twenty-first century [9], the emission reduction policies within various economic sectors are bound to become more rigorous.

Studies of carbon emission reduction policies fall into three categories: (1) those aimed at assessing the effects of emission reduction policies once they are in place. Studies on the impact of emission reduction policies tend to focus on the impact of the policies on pollutant emissions from ships. For example, Chen et al. [10] used a bottom-up approach based on automatic identification system (AIS) data to assess the effect of emission reduction on ships after the implementation of the emission reduction policy. Song and Xu [11] proposed a business activity-based method to estimate CO₂ emissions. Chung et al. [12] research explored GHG emissions analysis in the Korean shipbuilding industry through a bottom-up approach, using detailed industry-specific data like energy demands and conversion factors.

Tian et al. [13] examined the trajectories and characteristics of GHG emissions from China's freight transport modes in order to assist Chinese policymakers in developing standardized measures for assessing GHG emissions in order to achieve energy savings and pollution reduction. (2) To study the impact of emission reduction policies on port throughput. For example, Wu et al. [14] developed three innovative data envelopment analysis (DEA) models to assess the environmental efficiency of port operations under different scenarios, including environmental and non-environmental controls and inter-port cooperation on particulate matter (PM) emissions. (3) Studying the impact of emission reduction policies on shipping. For example, Chang studied that in order to comply with emission reduction policies and regulations, ships need to be retrofitted to comply with IMO regulations, which increased the investment expenditure of shipowners [15]. Vierth studied the impact of the implementation of the Emission Control Area (ECA) policy on shipowners and analyzed that with more stringent emission policies, shipowners need more additional costs in the technical transformation of ship emission reduction [16]. Cariou and Cheaitou compared the impact of regional speed limit areas and international fuel taxes on shipping business and the resulting CO₂ emissions [17].

Existing studies on carbon emission policies fall into two main categories:

(1) In the impact assessment of emission-related regulations, the existing literature tends to cover broader economic impacts in a specific region [18], the effectiveness of the measures [19,20], and the impacts at the ship or fleet level [21]. For instance, Hoang and Pham [22] examined the environmental impact assessment and emission reduction strategies in the maritime transportation field. Halim et al. [23] concentrated on the broader economic impacts of decarbonizing shipping.

(2) Scholars deployed modeling at the macro level to assess the impacts of carbon emission reduction on transportation costs, modal shifts, and international trade. For example, Han et al. [24] examined the impacts of policies and strategies related to emission reduction in shipping on impacts on ship sailing speeds, as well as assessing the impacts of several emission regulations on air quality along the coasts of the United States. Gössling et al. examined a review of global policies on marine air pollution and their scope as well as effectiveness and concluded that if global low pollution and net zero carbon goals are to be achieved, low carbon fuels need to be introduced in [8]. Comer et al. proposed a model-based approach for examining the effectiveness of low carbon fuels, speed reductions of existing ships, and improvements in the efficiency of new shipbuilding technologies [25]. W.P.C controlled port shipping emissions by analyzing the GHG emissions from ships docked at ports in order to calculate the carbon footprint of the port and control the carbon emissions from container terminals [26,27].

2.2. Shipping Emissions Reduction Response Programs

The essence of carbon reduction in shipping is how to minimize tonne-kilometre carbon emissions while ensuring operational requirements during the voyage [28]. The main approaches are divided into three categories:

(1) Reducing tonne-kilometre carbon emissions by operational means. The ship scheduling optimization offered the possibility to save fuel, and the relevant authorities have increased their investment in this area. Operational solutions were usually implemented under the SEEMP for ships larger than 400 GT on international voyages [29]. Operational solutions were usually associated with the shipping company's energy management strategy, including slow steaming. In the case of cargo ships, fuel savings can be realized through proper fleet routing [30], scheduling [31], and hull cleaning and engine maintenance.

Since GHG emissions were positively correlated with fuel consumption, emissions and negative environmental impacts were also effectively reduced by reducing the speed of navigation [32]. For instance, Fagerholt et al. proposed a speed optimization problem on a fixed route with the objective of finding the optimal speed for each section to minimize fuel consumption and reduce carbon emissions [33]. The design of the shipping network in

terms of the number of ships, ship size, and ports of call had an important impact on CO₂ emissions [34,35]. Rational planning of fleet deployment had a significant impact on carbon emission reduction [36,37]. The design of intermodal transportation networks (e.g., by shifting or integrating transportation between ships and railroads) should be implemented to achieve overall carbon emission reductions [38].

(2) Reducing ship resistance and improving energy efficiency from hull design and engine drive efficiency. The right choice of main dimensions and ship type provided an interesting mechanism to improve fuel efficiency. Slim designs and spherical bows had been widely used to reduce ship drag [20,39]. Bouman et al. summarized the extensive literature on the potential emission reductions related to energy efficiency, ship design, and fuel changes. They concluded that a combination of technologies would lead to significant reductions in carbon emissions [40]. Yuan et al. investigated cost savings through the selection of energy efficiency measures [41] and the potential for global fleet fuel emission reductions under uncertainty. Quantitative analyses and calculations of energy efficiency or ship design-related emission reduction measures yielded that most new buildings would only need to improve their energy efficiency over a period of 0 to 10 years (the actual amount depended on the ship type and size), but that the index would be progressively tightened every 5 years. However, there were loopholes in the index [42,43].

(3) Using alternative fuels. The use of alternative fuels for ships had the advantage of being characterized by lower carbon emissions and quick results, for example, the use of LNG alternative fuels [44]. In particular, many studies have also analyzed policy mechanisms that may achieve the decarbonization of shipping, such as market-based mechanisms (MBMs) and further efficiency improvement legislation [30,45,46]. Nabi and Hustad investigated the emission reduction effect of marine gas oil (MGO) and concluded that the use of MGO fuel reduced sulfide emissions, but fine PM emissions increase [47]. In order to achieve the ambitious goals of the IMO, new alternative fuels had become a hot research topic for experts and scholars. For example, the use of ammonia fuel was evaluated for the feasibility of ammonia SOFC on container ships, and it was concluded that the ammonia fuel system was feasible for future marine applications by analyzing the capital expenditures, carbon taxes, and carbon emissions of the different scenarios [48]. Xing et al. analyzed and compared some key considerations of replacement fuels (hydrogen, ammonia, and methanol), including emissions, supply, safety, and storage, while computing the cost and feasibility of four different potential alternative fuel solutions, and concluded that the emission reduction option using hydrogen was more achievable [49].

2.3. Carbon Emissions Reduction Response Programs

At the stage of sulfur emission control area, the shipowners' response to sulfur limitation is mainly realized through speed reduction and bypassing of ships. In the stage of global sulfur restriction implementation, shipowners mainly use low-sulfur oil, retrofit exhaust gas cleaning system, and switch to LNG-powered ships.

In terms of changing sailing speed and detouring, since GHG emissions are positively associated with fuel consumption, emissions and negative environmental impacts are also effectively reduced by reducing sailing speed [32]. Fagerholt et al. proposed a speed optimization problem on a fixed route, aiming to determine the optimal speed that minimizes fuel consumption and reduces carbon emissions [33]. The design of the shipping network in terms of the number of ships, ship size, and ports of call has a significant impact on CO₂ emissions [34,35]. Rational planning of fleet deployment has a significant impact on reducing carbon emission [36,37]. The design of intermodal transportation networks (e.g., by shifting or integrating transportation between ships and railroads) should be implemented to achieve overall carbon emission reductions [38].

Regarding improving energy efficiency in terms of hull design and engine drive efficiency, the correct choice of primary main dimensions and vessel type provided an interesting mechanism for improving fuel efficiency. Slim designs and spherical bows had been widely used to reduce ship drag [20,39]. Bouman et al. summarized the extensive

literature on potential emission reductions associated with energy efficiency, ship design, and fuel changes. They concluded that a combination of these technologies could lead to significant reductions in carbon emissions [40]. Yuan et al. explored cost savings achieved by selecting energy efficiency measures under conditions of uncertainty [41] and the potential for global fleet fuel reductions. Quantitative analyses and calculations of energy efficiency or ship design-related emission reduction measures yielded that most new buildings will only need to improve their energy efficiency over a period of 0 to 10 years (the actual amount depended on the ship type and size), but the index will be progressively tightened every 5 years [42,43].

The use of alternative fuel options has the advantage of producing lower carbon emissions, for example, the use of LNG as an alternative fuel [44]. In particular, many studies have also analyzed policy mechanisms that may lead to the decarbonization of shipping, such as MBMs and further efficiency improvement legislation [30,45,46]. Nabi and Hustad investigated the emission reduction effects of MGO and concluded that the use of MGO fuel reduced sulfide emissions but increased fine PM emissions [47]. In order to achieve the ambitious goals of the IMO, new replacement fuels had become a hot research topic for experts and scholars. The feasibility of ammonia SOFC on container ships was assessed, and it was concluded that ammonia fuel systems were feasible for future marine applications by analyzing the capital expenditures, carbon taxes, and carbon emissions of different scenarios [48].

In summary, the previous studies on shipping carbon emission reduction mainly explore the use of HFO and LNG fuels, and the fuels of methanol, ammonia, and hydrogen are very rarely taken into account. Their fuels and freight price data does not comply with the shipping and energy market in the era of the post-epidemic, Russian–Ukrainian war, and the Houthi Red Sea crisis; thus, their conclusions may have less reference value. In their case studies, most of them take a single ship and a single route as the research object, and fewer consider the comparative analysis of different ship types and different routes.

Given this context and the critiques of existing studies on shipping carbon emission reduction, it's clear that there are some research gaps that need to be addressed to provide more relevant and current insights:

(1) Fuels focus: Previous studies have heavily focused on HFO and LNG as marine fuels. Research on alternative fuels such as methanol, ammonia, and hydrogen is limited, despite their potential to contribute significantly to decarbonization efforts in the shipping industry.

(2) Outdated economic data: The economic analyses in these studies often relied on fuel and freight price data that did not reflect the current market dynamics influenced by recent global events like the COVID-19 pandemic, the Russian–Ukrainian war, and geopolitical tensions affecting key maritime routes such as the Red Sea. These events had led to fluctuations in fuel prices and shipping costs, impacting the economic feasibility of different fuels, especially LNG.

(3) Research scope: Most existing studies focused on emissions from a single ship on a single route. There was a lack of comparative analysis across different types of ships and routes, which could provide a more comprehensive understanding of emissions across the sector.

In summary, this literature review synthesizes current research and policy developments concerning the use of alternative fuels, such as LNG, methanol, ammonia, and hydrogen, in maritime transportation. It highlights their potential to reduce GHG emissions and the economic challenges associated with their adoption under current market conditions. This paper provides a detailed analysis using the CII to measure the full life cycle emissions of these fuels, contributing novel insights into the decarbonization of the maritime sector. By incorporating up-to-date data on fuel prices and freight charges that reflect current market conditions, we assess the economic feasibility of transitioning to these alternative fuels. This approach allows for a comprehensive evaluation across various operational routes, including major global shipping lanes. By integrating both environmen-

tal impacts and economic implications, our study enhances understanding of sustainable maritime practices amidst ongoing technological advancements and market dynamics.

3. Comparison of Alternative Fuel Programs

We will analyze the advantages and disadvantages of these various replacement fuel options in this part.

3.1. LNG Fuel System Program

LNG is a mixture composed primarily of methane. It is non-toxic and non-corrosive, with a lower carbon content than diesel. Natural gas is competitive in the energy market and can be used as an alternative transportation fuel [50]. LNG has been used as a fuel for LNG carriers since the 1970s. The total fleet of ships that can use LNG as of 2022 is 58.55 million deadweight tons. Considering its environmental and economic advantages, LNG is an ideal alternative fuel for ships [51].

The LNG fuel propulsion system is composed of fuel (LNG) storage system, i.e., fuel tanks (tanks); fuel (LNG) filling system pipelines, valves, and components; gas supply system-related equipment, piping, and valves; auxiliary systems, equipment, piping, valves, and fittings for gas supply systems; and gas-using equipment, i.e., dual-fuel main engines, auxiliary engines, boilers and other main engines, auxiliary engines, fuel tanks, and storage systems.

There are currently four types of engines available on the market for gas-fueled ships: thin-burning spark ignition; low-pressure dual-fuel four-stroke (LPDF four-stroke); high-pressure dual-fuel two-stroke; and low-pressure dual-fuel two-stroke (LPDF two-stroke). The use of an LNG fueling solution depends greatly on the size of the ship, the price of the LNG fuel, and the ship's operation.

Compared to conventional marine fuels, liquid emissions are decreased by about 80–85% as a result of the lean combustion process used in dual-fuel ICEs. The absence of sulfur in LNG leads to nearly complete elimination of emissions, and the production of PM is significantly low. CO emissions are reduced by 20–30% because LNG has a higher hydrogen content than HFO/MDO. Natural gas generates comparatively low levels of sulfur oxides, nitrogen oxides, and carbon dioxide [52].

Advantages of LNG fuel mainly include:

- Safe and reliable: LNG is lighter than air. Even if there is a slight leakage, it will be quickly volatilized and diffused, not to spontaneous combustion and explosion or formation of the limit concentration of fire explosion.
- Clean and environmentally friendly: According to the sample analysis and comparison, LNG as a fuel, NO_x reduction of 30% to 40%, CO₂ reduction of 90%, particulate emissions reduced by 40%, and no lead, benzene, and other carcinogens basically does not contain sulfide.
- Economic and efficient: LNG liquefied volume is reduced to 1/625 of gaseous natural gas, and its storage cost is only 1/70 to 1/6 of gaseous natural gas, which saves investment, occupies less land, and has high storage efficiency.
- Flexible and convenient: LNG can transport large amount of natural gas to any user that is hard to reach by pipeline through specialized tankers or ships, which not only saves investment compared with underground gas pipeline but also is convenient, reliable, less risky, and adaptable.

Disadvantages of LNG fuel mainly include:

- Storage issues: LNG has a boiling point of $-162\text{ }^{\circ}\text{C}$, making tank insulation a critical concern. For instance, a spill can lead to high gas expansion ratios, posing risks of frostbite to personnel and structural brittleness. In addition, the wide flammability range and low flash point of methane are potential hazards associated with gas release.
- The availability of LNG refueling facilities is limited, and ships can only serve specific markets and routes.

- The use of LNG fuel also faces issues related to effective management and operation. Additional design adjustments to accommodate LNG storage tanks and power stations may increase ship operating costs.

3.2. Methanol Fuel System Program

Methanol is a sulfur-free, toxic, corrosive, and liquid normal fuel. It requires twice the space of marine diesel oil (MDO). Methanol is an alcohol-based liquid fuel with the lowest carbon content and the highest hydrogen content, with an oxygen content of more than 50%, full combustion, and less pollution, which reduces emissions of pollutants and harmful gases and protects the environment. Therefore, methanol has the potential to improve air quality and GHG emissions from ships at low cost. Methanol is prepared from two main types of fossil-sourced methanol fuels and renewable methanol fuels. Methanol can also be synthesized by catalytic synthesis of CO₂ and hydrogen generated by electrolysis, a process known as power-to-liquid (PtL). Holmgren et al. demonstrated another method of using hydrogen by adding gasified syngas, which permits the replacement of water-to-gas shift reactors [53]. Ammar found that due to the similarity of methanol to conventional marine fuels, methanol can be used in current marine infrastructure with only minor modifications [54].

According to MAN Engines, corrosive levels of methanol fuel and formaldehyde production can be easily addressed in currently operating two- and four-stroke marine diesel engines. A marine engine is now available that can run on methanol as a dual fuel. *MS Stena Germanica* is the world's first large ship to run on methanol fuel since its refit in 2015. As of 2018, there are seven methanol-fueled vessels in operation, with another four scheduled to enter service in 2019 [55].

With the development of engine technology and the improvement of methanol fuel supply, methanol-powered ships are becoming more and more recognized in the market, which is no longer limited to passenger ferries and methanol carriers, but developed to oceangoing container ships and tankers. The investment cost of converting a ship to methanol is estimated to be lower than that of converting to LNG [56]. Bengtsson's study found that the investment cost for a methanol propulsion system is lower than that of an LNG propulsion system when constructing a new ship [57]. As experience with this new fuel increases, it is expected that the investment cost will decrease. Since methanol is a liquid at ambient temperature, its use necessitates some modifications to tanks, piping, and safety systems, although to a lesser extent than LNG [58].

Advantages of methanol fuel mainly include:

- Huge potential: With the expansion of global fuel production from renewable sources, there is a huge potential for the use of bio-methanol in the shipping industry.
- Potential positive environmental impacts: Methanol, especially bio-methanol, is considered a cleaner shipping replacement fuel for the shipping industry due to its very low carbon emissions. The combustion of methanol as the primary fuel used to power ships has lower emissions of CO₂ and other common air pollutants [44].
- Low investment cost and economic feasibility: New dual-fuel engines [6] have been produced with good results. Alcohol-based fuels are adaptable and can be mixed with gasoline, diesel, biodiesel, and so forth in different proportions without any modification to the equipment. Methanol fuels have been extensively tested and used in spark-ignited engines that require little or no tuning.

Disadvantages of methanol fuel mainly include:

- Methanol has a lower energy density than fossil fuels and therefore requires greater storage space.
- The application of methanol on ships still faces considerable barriers due to the lack of adequate safety instructions, operating experience, and infrastructure to meet refueling needs [59].
- During combustion, the alcohol-based fuel starts to turn into gas when the temperature reaches about 64.7 °C, but when the temperature reaches about 250 °C, it starts to

form carbon, which clogs up the gas pipe and burner, thus hopelessly deforming and prolonging its use in gaseous conditions.

- Low flame temperature, low firepower, and slow heating rate.
- Since the flash point of methanol is lower than the flash point of marine fuels specified in the IMO Safety of Life at Sea Convention, the United Nations defines methanol as a Class III hazardous chemical, which needs to be carried out.

3.3. Ammonia Fuel System Program

Ammonia, with the molecular formula NH_3 , is a compound of hydrogen and nitrogen, with a boiling point of -33.5°C and a calorific value of 18.6 kJ/kg , and can be liquefied into liquid ammonia at atmospheric pressure and a temperature of -33.5°C , or at a pressure of $8.6 \times 10^5\text{ Pa}$ and a temperature of 20°C [60]. Ammonia is a non-carbon fuel and can be utilized on its own or in combination with another fuel in an internal combustion engine.

When employed in direct ICEs, ammonia combustion can reach system efficiency of up to 44%. Hyundai Mipo Shipbuilding recently received a request from Lloyd's Register to develop an ammonia-fueled ship and plans to commercialize an ammonia-propelled ship within the next five years. Samsung Heavy Industries develops ships equipped with ammonia engines with a view to commercialize them in 2030. In January 2022, Professor Long Wuqiang's team at Dalian University of Technology successfully developed China's first principal prototype of a compound/diesel dual direct-injection, two-stroke internal combustion engine, achieving a new breakthrough in the core autonomous technology of zero-carbon-fueled ICEs.

The Viking Energy, which was built in 2003 and is currently being refitted in Norway, will be the first ammonia-powered vessel. Singapore's Pacific International Lines has confirmed a shipbuilding agreement with China's Jiangnan Shipyard for four 14,000 TEU ammonia-powered container ships. The ships will initially be powered by LNG or low-sulfur fuel oil, but will also be equipped with an ammonia intermediate preparation fuel tank, which will allow the ships to be retrofitted to run on ammonia when the technology becomes commercially available.

The use of ammonia fuel in ICEs can be categorized into two forms: port fuel injection (PFI) and direct injection (DI). Compared with DI, PFI is more mature in application technology and easier to manufacture, specifically in its injection system not needing to withstand the huge pressure in the cylinder like DI. The injection pump and nozzle design technology are relatively simple and mature, but there is fuel that cannot be fully combusted, resulting in a waste of fuel and a relatively large amount of hazardous gas emissions. In other words, the advantages of the DI engine are a low amount of fuel consumption and a large lift power rate.

The advantages of ammonia fuel systems are mainly summarized as follows:

- Ammonia production offers several key advantages over hydrogen fuel, including lower cost per unit of stored energy and higher volumetric energy density. Ammonia is also simpler to produce, handle, and distribute due to its well-developed infrastructure. These properties make ammonia an attractive energy carrier and a competitive candidate relative to other alternative fuels, such as hydrogen [61]. Ammonia can be produced from renewable electricity by using electrolysis to extract hydrogen from water and then combining it with nitrogen sourced from the air.
- The potential for explosions is low.
- The ease of storage and transportation, high energy density, and well-established industrial base offer ammonia fuels a relatively significant advantage.

The disadvantages of ammonia fuel systems are summarized as follows:

- High toxicity, low safety factor, and the ammonia fuel is highly toxic to humans. The ammonia fuel systems must be designed, manufactured, operated, and maintained in a manner that ensures the safety of the crew, harbor staff, and fuel suppliers. Ammonia is not currently used as a fuel in commercial applications because of its high toxicity

and laminar flame speed that is approximately five times lower than methane [62]. This makes it difficult to burn in engines.

- The use of ammonia-fueled ships involves large layout changes and high investment costs. Existing ship engines and fuel systems are usually located in confined spaces on the lower deck. Different requirements for ammonia may change the ship layout and may even lead to a complete redesign.

3.4. Hydrogen Fuel System Program

Hydrogen is considered a clean fuel. Hydrogen is divided into three categories:

- (1) Gray hydrogen: produced from hydrocarbon-based fuels, which means that CO emissions are associated with its production.
- (2) Blue hydrogen: in which gray hydrogen is accompanied by carbon capture technology.
- (3) Green hydrogen: in which hydrogen is produced from renewable energy sources with zero emissions.

Hydrogen thus has the potential to replace traditional fossil fuels as a cleaner alternative fuel.

Most ships use combustion methods in the form of ICEs. Hydrogen can be used to power ICEs [63]. So far, only a few ships at sea have used hydrogen as fuel. The first ship to run on hydrogen was *Hydra* in 2000, followed by *Zemships* in 2008 [64]. Both ships run on compressed hydrogen (CH₂). Another well-known demonstration project with CH₂ is the Ship Energy Observer, which has been in operation since 2017. In 2021 or 2022, a ship was planned to be built in Western Norway using liquefied hydrogen in combination with fuel cells and batteries. If the project proceeds as planned, it was likely to be the first maritime application of hydrogen fuel suitable for compression ignition engines and spark ignition engines, as well as gas turbines and boilers [65]. Of these types of engines, spark ignition engines can better accommodate hydrogen fuel because of its very high self-ignition temperature (~585 °C) [66].

Given the development of hydrogen fuel technology, it is more common to find hydrogen-fueled engines operating in dual-fuel mode, in which hydrogen is added as a complementary component to the combustion process of another hydrocarbon fuel (diesel, liquefied natural gas, biodiesel, etc.) [67]. In the shipping industry, hydrogen has been the subject of research into suitable ship engine models to utilize the fuel for higher power density and lower emissions. Considering life cycle assessment, hydrogen fuel used in maritime transportation, even as a fuel in a dual-fuel engine combining another fossil fuel, has the potential to reduce CO₂ emissions per unit of transport work by up to 40% [68].

The advantages of hydrogen fuel systems are summarized as follows:

- It is a renewable energy source with an abundant supply. Hydrogen is an abundant source of energy for a number of reasons. Hydrogen can be used on-site or produced centrally and then redistributed.
- It is virtually a clean energy source. When hydrogen is burned to produce fuel, the byproducts are completely safe.
- Hydrogen energy is non-toxic. It is a non-toxic substance and is rarely used for fuel. This means it is environmentally friendly and does not cause any harm or damage to human health.
- Compared to diesel or gasoline, hydrogen is a more efficient type of energy because it delivers a lot of energy per pound of fuel. Essentially, this means that a ship utilizing hydrogen fuel will travel more miles, compared to using an equivalent amount of fuel.

The disadvantages of hydrogen fuel are summarized as follows:

- Difficulty in storage and high unit costs in bulk transportation and storage, low volumetric energy density compared to conventional fossil fuels, and lack of adequate storage infrastructure: Even the storage tank capacity of liquefied hydrogen is twice as high as that of LNG [69].

- High initial cost for marine use: Hydrogen-fueled marine engines have little applicability to reality. Wärtsilä Engines dual-fuel marine engines can only be used with mixtures of up to 25% hydrogen, and for proportions of hydrogen above 25%, engine modifications must be made, increasing investment and operating costs [70].
- Hydrogen fuel is expensive. Electrolysis and steam reforming, the two main processes for hydrogen extraction, are very expensive. This is the real reason why it is not widely used worldwide.

4. Model Formulation

The CII applies to ships of more than 5000 GT on international voyages (12 ship types are listed in MARPOL Annex VI, Sections 2.2.5, 2.2.7, 2.2.9, 2.2.11, 2.2.14–2.2.16, 2.2.22, and 2.2.26–2.2.29), which are required by the IMO to determine an annual operational CII. The CII is a new method of measuring CO₂ emissions from ship operations that characterizes the actual level of energy efficiency of a ship's operations.

After the mandatory entry into force of the rules on 1 January 2023, the actual annual operational CII of all ships of 5000 GT and above (limited to the types of ships to which the EEDI applies) will be measured each calendar year based on the data collected in the previous calendar year and will be rated from the best to the worst, with a total of five grades from A to E (with A being the best and E being the worst).

A ship's attained CII must meet a certain standard or be operated in accordance with certain rules. Ships with an annual carbon intensity rating of E or three consecutive years of D are required to develop a corrective action plan in the SEEMP.

Shipowners can obtain higher CII ratings by using alternative fuels on their ships. The carbon emission model is used to find out the economic feasibility of the existing alternative fuel program for carbon emission reduction of ships. In order to verify the carbon emission reduction effect of the replacement fuel in the actual operation of the ship, based on the IMO operational carbon emission index rating mechanism, the operational CII is calculated and rated, and then the impact of the use of the replacement fuel on the rating results and the carbon emission reduction effect is analyzed for the reference of the relevant parties.

4.1. Assumptions

A1: The guidelines for the calculation and rating methodology of CII for ship operations refer to MEPC 76 adopted:

- Resolution MEPC.336(76) Guidelines for Operational Carbon Intensity Indicators and Calculation Methods for 2021 ("CII Guidelines", G1).
- Resolution MEPC.337(76) Guidelines for Reference Baselines for Use in Conjunction with Operational Carbon Intensity Indicators for 2021 ("CII Guidelines", G2).
- Resolution MEPC.338(76) Guidelines on the Operating Carbon Intensity Discounting System Associated with the Reference Baseline for 202 ("CII Discounting System Guidelines", G3).
- Resolution MEPC.339(76) Guidelines for the Rating of Vessels for their Operational Carbon Intensity for 2021 ("CII Rating Guidelines", G4).

A2: Ship's data are available at Clarkson Intelligence Network. Vessel operation data is obtained from the official website of China COSCO Shipping.

A3: Annual carbon emissions are obtained by multiplying the annual fuel consumption and carbon emission factor of the fuel.

4.2. The CII Model

The calculation and rating of a ship's operational CII can be divided into four steps. The first step is to calculate the ratio of the total mass emitted by the ship in the calendar year (M) and the total transportation work done by the ship in the calendar year (W) based on the guideline 1 and the basic information of the ship and the reported operation data for the calendar year, i.e.:

:

$$\text{Attained } CII = M/W \quad (1)$$

where $M = FC \times CF$, according to MEPC.336(76). It is noted that FC depends on the data reported by the ship in the IMO Data Collection System (DCS); Carbon Conversion Factor (CF) depends on the fuel type, as specified in the Guidelines on EEDI Calculation Methods (2018) (Resolution MEPC.308(73)).

The work done in transportation (W) is the product of the transportation capacity C and the distance traveled in one calendar year for a refueled ship D_i , i.e.:

$$W = C \times D_i \quad (2)$$

where i denotes the route i .

In the second step, the operational CII reference baseline for a ship type is calculated according to the CII Reference Baseline Guidelines. This is defined here as the total mass of fuel consumed by the replacement-fueled ship in a calendar year multiplied by the conversion factor of the fuel.

$$CII_{ref} = aCapacity^c \quad (3)$$

where CII_{ref} is the baseline value of the CII for 2019 and parameters of a , $Capacity$, and c are defined by the guidelines, as shown in Table 2, where DWT is the abbreviation for deadweight tonnage.

Table 2. Parameters for determining the 2019 ship type specific baseline values.

Ship Type		Capacity	a	c
Bulk carrier	$\geq 279,000$ DWT	279,000	4745	0.622
	$< 279,000$ DWT	DWT	4745	0.622
Gas carrier	$\geq 65,000$	DWT	$14,405 \times 10^7$	2.071
	$< 65,000$ DWT	DWT	8104	0.639
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489

Step 3: Calculate the required annual operating CII for the calendar year y of a ship type in accordance with the CII Discount Factor Guidelines:

$$\text{Required } CII = \left(1 - Z/100\right) CII_{ref} \quad (4)$$

where Z represents the annual reduction factor for the required annual operational CII from year 2023 to 2030, given by the following Table 3. It is noted that Z factors for the years from 2027 to 2030 are not given yet but will be determined later, taking into account the review of the short-term measure of IMO.

Table 3. Reduction factor ($Z\%$) for the CII relative to the 2019 baseline.

Year	Reduction Factor Relative to 2019
2023	5%
2024	7%
2025	9%
2026	11%
2027	-
2028	-
2029	-
2030	-

Data source: IMP MEPC.338(76).

Step 4: Calculate the four rating boundary values for a ship type vessel for calendar year y in accordance with the CII Rating Guidelines and compare the attained annual

operating CII for calendar year y of the vessel with the four rating boundary values to determine the vessel's rating results, as shown in Figure 1.

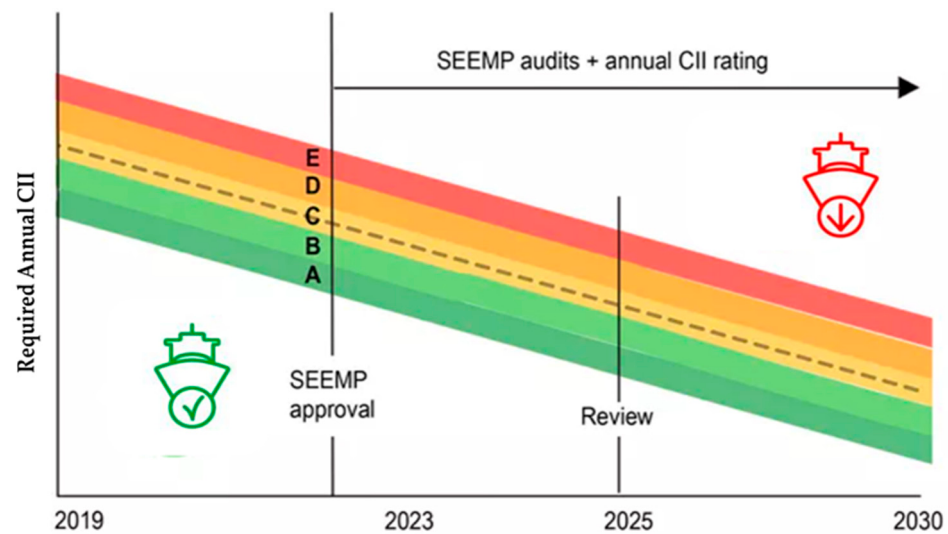


Figure 1. Decreasing CII annually to 2030.

The CII is a measure used by IMO to assess the efficiency of a ship in transporting goods or passengers in relation to its carbon emissions. The CII calculation results in a rating from A to E, with A being the most efficient and E being the least efficient in terms of carbon intensity. Each rating reflects how well a ship performs compared to a set standard, and the boundaries between these categories are determined by specific percentage deviations from this standard.

The CII categories are based on the ship's annual operational carbon intensity compared to the required annual operational CII for that ship type and size category. The boundaries for the CII categories are typically expressed as percentages relative to this required CII:

- A (Major Superior Performance): More than 20% better than the required CII.
- B (Minor Superior Performance): Between 10% and 20% better than the required CII.
- C (Moderate Performance): Within 10% above or below the required CII.
- D (Minor Inferior Performance): Between 10% and 20% worse than the required CII.
- E (Major Inferior Performance): More than 20% worse than the required CII.

For example, for a bulk carrier, with the deadweight tonnage (DWT) 50,000 tonnes, the required CII is 6 g of CO₂ per tonne-mile, if

- Ship 1: Annual CII = 4.8 g CO₂/tonne-mile (20% better than required)
- Ship 2: Annual CII = 5.4 g CO₂/tonne-mile (10% better than required)
- Ship 3: Annual CII = 6.6 g CO₂/tonne-mile (10% worse than required)
- Ship 4: Annual CII = 7.2 g CO₂/tonne-mile (20% worse than required)
- Ship 5: Annual CII = 5.9 g CO₂/tonne-mile (within 10% of required)

then

- Ship 1: Rated as A (Major Superior Performance)
- Ship 2: Rated as B (Minor Superior Performance)
- Ship 3: Rated as D (Minor Inferior Performance)
- Ship 4: Rated as E (Major Inferior Performance)
- Ship 5: Rated as C (Moderate Performance).

This categorization provides a framework for regulators and operators to evaluate and incentivize improvements in ship efficiency. Ships rated D and E might face restrictions or penalties, such as being unable to operate in certain areas or during certain times, to

encourage improvements or retrofitting. Conversely, ships rated A or B might receive incentives like reduced port fees or preferred berthing options. This rating system encourages the shipping industry to adopt more fuel-efficient technologies and operations, ultimately contributing to global efforts to reduce maritime emissions.

4.3. Calculation of CO₂ Emission for LNG and Methanol

To calculate the total mass of emissions from a container ship using fuels like LNG and methanol, a detailed methodology was given as follows.

Firstly, we need to calculate the fuel consumption. To conduct the fuel consumption calculation, we need to gather several vessel specifications and optional data, like the ship's engine type, efficiency, power rating, and operational hours. Then, calculate the rate of fuel consumption based on the ship's operational parameters (speed, engine power usage, and efficiency). This can be estimated from the specific fuel oil consumption (SFOC) given by the engine manufacturer, usually in grams per kWh.

Secondly, determine the emission factors. Obtain emission factors for each pollutant for LNG and methanol. These factors are usually in grams of pollutant per kilogram of fuel burned and can vary based on engine technology and operating conditions.

Finally, calculate emissions. To obtain the total fuel consumption, multiply the total operational hours by the fuel consumption rate to get the total fuel used over a given period. To calculate the total mass of emissions, multiply the total amount of fuel consumed by the emission factor for each pollutant.

For example, for a hypothetical CO₂ calculation of LNG fuel, suppose:

An LNG-powered ship consumes 150 g of LNG per kWh. The ship operates for 1000 h at an average load factor using 10,000 kWh per hour. LNG has an emission factor of 2.75 kg CO₂ per kg of LNG burned.

Total Fuel Consumption = 150 g/kWh × 10,000 kWh/h × 1000 h = 1,500,000 kg of LNG

Total CO₂ Emissions = 1,500,000 kg × 2.75 kg CO₂/kg = 4,125,000 kg CO₂

To calculate the total mass of CO₂ emissions from a container ship fueled by methanol, suppose:

Vessel Specifications: Assume a medium-sized container ship with an engine rated at 20,000 kW.

Operational Data: Assume the ship operates 300 days a year at 24 h per day.

Fuel Properties: Methanol has a lower energy content compared to LNG. For methanol, the energy content is approximately 20 MJ/kg.

Fuel Consumption Rate: If the SFOC for methanol is about 185 g/kWh (this can vary based on engine type and efficiency).

Emission Factors for Methanol: Assume an emission factor for CO₂ for methanol of about 1.375 kg CO₂ per kg of methanol burned (since methanol combustion releases CO₂ and water).

Daily Fuel Consumption: Calculate the daily fuel consumption based on the engine's power usage and SFOC:

Daily Fuel Consumption = Power × SFOC × Operational Hours

= 20,000 kW × 185 g/kWh × 24 h

= 88,800,000 g/day

= 88,800 kg/day

Annual Fuel Consumption: Calculate the total annual fuel consumption:

Annual Fuel Consumption = 88,800 kg/day × 300 days

= 26,640,000 kg

Total CO₂ Emissions: Multiply the total fuel consumed by the CO₂ emission factor:

Total CO₂ Emissions = 26,640,000 kg × 1.375 kg CO₂/kg methanol

= 36,630,000 kg CO₂.

Route 2 is a direct service from Xiamen Port, which is the fastest container shipping liner service from South China to Australia in the shipping market. Shipping vessels depart from Xiamen Port and call at Xiamen Port, Hong Kong Port, Sydney Port, Melbourne Port, and Brisbane Port, in turn, and finally return to Xiamen Port. The port mileage chart for Route 2 is given in Table 5.

Table 5. Port mileage chart for Route 2 of Company Z.

Route 2	Shekou	Hong Kong	Sydney	Melbourne	Brisbane	Xiamen
Xiamen	322	-	-	-	-	-
Shekou	-	21	-	-	-	-
Hong Kong	-	-	4480	-	-	-
Sydney	-	-	-	583	-	-
Melbourne	-	-	-	-	1024	-
Brisbane	-	-	-	-	-	3984

Route 3 is a direct service covering Sohar/Hamad in the Middle East from Qingdao Port. Sohar Port is currently planning to take advantage of the unique geographical location and the high-speed trade development between the Persian Gulf region and Singapore, the United States, and other high-speed service to create an important gateway port in the Persian Gulf region for the world. Container ships depart from Qingdao Port; call at Ningbo Port, Shekou Port, Jebel Ali Port, Bahrain Port, Dammam Port, Sohar Port, and Singapore Port; and finally return to Qingdao Port. The port mileage chart for Route 3 is given in Table 6.

Table 6. Port mileage chart for Route 3 of Company Z.

Route 3	Ningbo	Shekou	Singapore	Jebel Ali	Bahrain	Dammam	Sohar	Singapore	Qingdao
Qingdao	440	-	-	-	-	-	-	-	-
Ningbo	-	734	-	-	-	-	-	-	-
Shekou	-	-	1451	-	-	-	-	-	-
Singapore	-	-	-	3511	-	-	-	-	-
Jebel Ali	-	-	-	-	301	-	-	-	-
Bahrain	-	-	-	-	-	57	-	-	-
Dammam	-	-	-	-	-	-	493	-	-
Sohar	-	-	-	-	-	-	-	3302	-
Singapore	-	-	-	-	-	-	-	-	2468

The IMO's 76th MEPC meeting has determined the CII and the effective date of its rating, i.e., from 1 January 2023. Ships that fail to meet the CII rating may be forced to take corrective measures, which will affect the normal operation of the current ships and their valuation on the secondhand market.

In order to avoid the unreasonable impact of CII rating on ship operation, this paper discusses the calculation of carbon intensity of container ships using replacement fuels. In order to comply with IMO regulations, selecting the typical ship types operating on the three main routes of Company Z, as shown in Table 7, calculates the carbon intensity of their operation and analyzes the ratings of different ship types according to the calculation results. We compare different alternative fuel options to inform ship operators in their choice of alternative fuel options in this paper.

Combining Equations (1)–(3) and the ship data in Table 4, we calculate and analyze the CII of the different types of ships that use replacement fuels.

According to Table 8, the overall attained CII of different ship types shows a decreasing trend with the increase of the ship's deadweight tonnage. Under the same operating condition, the fuel consumption of the ship will not increase in the same proportion, and the ship's larger size will reduce its attained CII.

Table 7. Basic ship information on Routes 1, 2, and 3 of Company Z.

	Route 1	Route 2	Route 3
Ship type	S1	S2	S3
Cost of new-building ships (Million \$)	180	87	145
Salvage value of ships (Million \$)	38	17.25	27.25
Ship capacity (TEU)	19,150	5250	13,386
Ship age (Years)	5	21	9
Main engine	MAN B. & W. 11S90ME-C10.5	MAN B. & W. 10L90MC Mk4	MAN B. & W. 12K98ME7.2
Auxiliary engine	Hyundai Electric HSJ7 915-10P	-	Yanmar Electric 6N330L-GW
Power of main engine (KW)	95,072	42,950	72,240
Power of auxiliary engine (KW)	8200	4700	7944
Forward displacement (tonnes)	157,344	39,318.6	122,932.8
Reverse displacement (tonnes)	118,008	52,424.8	92,199.6
Loan ratio of initial investment amount	80%	80%	80%
Loan interest rate	6%	6%	6%
Forward freight (\$)	722	190	879
Reverse freight (\$)	433	114	527
Depreciation rate	8%	8%	8%
CII rating	D	C	E

Table 8. Evaluation of the CII on different routes with replacement fuels.

	Route 1 (19105TEU)		Route 2 (5250TEU)		Route 3 (13386TEU)	
Fuel Type	LNG	Methanol	LNG	Methanol	LNG	Methanol
Carbon emissions (tons)	66,482	86,431	29,845	34,006	60,086	66,636
Dead weight tonnage	194,381	194,381	35,453	35,453	154,131	154,131
Total annual voyage miles (nile)	95,272.8	95,272.8	83,392	83,392	89,299	89,299
Total transportation workload	18,519,222,137	18,519,222,137	2.956×10^9	2.96×10^9	1.3764×10^{10}	1.38×10^{10}
attained CII	3.58989×10^{-6}	4.6671×10^{-6}	10.094718	11.50213	4.36552723	4.841415
CII rating for 2025	A	C	B	C	B	B
CII rating for 2030	B	D	C	E	B	C

In conclusion, the carbon emission reduction investment program using alternative fuels can obtain better carbon emission reduction by choosing a larger ship size, which is in line with the IMO's stipulation on CII.

Since the annual attained CII of a ship is affected by many factors, we consider the baseline conditions (such as different ship performance and operation mode) and calculate the CII value of ships using alternative fuels in the coming years with a 2% decay value per year. The latest amendments to MARPOL Annex VI require that a declaration of operational carbon intensity compliance shall not be issued to a ship that has been rated D or E for three consecutive years, unless corrective actions have been appropriately developed and reflected in a SEEMP. Corrective actions have been appropriately developed and reflected in the SEEMP and verified by the competent authority or any organization duly authorized by the competent authority, i.e., a ship's CII rating of C and above is the only way to withhold improvement under the current mechanism.

The carbon intensity for each year of the existing CII program for ships using replacement fuels was calculated and analyzed. From Table 3, it can be seen that the carbon intensity of the ships using replacement fuels under the baseline conditions by 2025 can meet the IMO regulations on CII. Among the ships using replacement fuels under the baseline conditions by 2030, the ships using methanol fuels on Route 1 and Route 2 do not meet the IMO regulations on CII at the end of the study period.

In summary, the options of using LNG fuel on Route 1 and Route 2 are recommended for investment of the vessels during the study period. The carbon reduction scenarios using LNG and methanol on Route 3 are in compliance with the IMO regulations on CII.

The zero-carbon fuel (ammonia and hydrogen) option meets IMO CII requirements for Routes 1, 2, and 3, if economically feasible.

Validating calculated values, especially those relating to emissions from marine fuels and their impact on the CII, is crucial for ensuring that these calculations accurately reflect

real-world conditions. Validation involves comparing the calculated results with actual measurements and observations, as well as using established models that have been peer-reviewed and are widely accepted in the industry.

Validation can be conducted based on empirical data. This involves measuring emissions directly from ship exhausts using sensors and other monitoring equipment during operation. This data can provide a real-time, accurate assessment of emission types and quantities. Ships maintain detailed logs of fuel consumption, which can be used to calculate emissions based on known emission factors for each fuel type.

While calculations of emissions and their impact on CII provide valuable insights, they must be continually validated and adjusted based on actual operational data and through comparisons with empirical measurements. This iterative process helps ensure that the models and calculations remain relevant and accurate, providing ship operators and regulators with reliable data to make informed decisions.

Fuel costs typically represent 50–60% of total operating costs. The current price differential between different replacement fuels is likely to increase as many operators will have to use replacement fuels when stringent GHG reduction policies are implemented by IMO globally. However, as replacement fuel suppliers, which are subject to high market demand, high prices, and scientific and technological advances, may expand their production capacity and may reduce their fuel prices as economies of scale take hold. In this case, alternative fuels will become more viable, despite their high initial investment costs on engine modifications or replacements [37,71].

6. Conclusions

IMO's annual operational CII rating requires that from January 1, 2023, all applicable ships meet both technical and operational energy efficiency requirements. In this paper, from the perspective of shipowners, we take container liner shipping vessels as an example to study the response options for shipowners under the short-term measures for carbon emission reduction. Our analysis primarily focused on LNG and methanol as currently viable alternative fuel options for reducing CO₂ emissions. While acknowledging the potential of ammonia and hydrogen, we note these options require significant technological developments and are not yet widely implementable with existing engine technologies.

The analysis using carbon intensity modeling yielded that the recommended options of using LNG fuel and zero-carbon fuel on Route 1 and Route 3 during the study period were analyzed for investment feasibility decisions for the ships. The carbon reduction scenarios using low-carbon fuels (LNG and methanol fuels) and zero-carbon fuels (ammonia and hydrogen fuels) on Route 2 are both in line with IMO regulations for CII. Our focus was on the feasible application of LNG and methanol fuels. Ammonia and hydrogen, as zero-carbon options, were mentioned to acknowledge their potential but highlighted the need for future research due to their current technological and regulatory challenges.

As regulations evolve and technology advances, the shipping industry's emission profiles, particularly for container ships using alternative fuels like LNG and methanol, are expected to undergo significant changes. These changes will be influenced by the need to meet increasingly stringent environmental standards and the shipping industry's response to these regulations through technological innovations.

Some regions may offer incentives for adopting cleaner fuels or impose penalties for higher emissions, affecting fuel choice. For example, the EU's inclusion of maritime emissions in its Emissions Trading System can make lower-emission fuels like methanol and LNG more economically attractive.

Technological advancements in LNG-fueled engines, such as improved efficiency and reduced methane slip, can enhance LNG's environmental profile. Technologies like high-pressure direct injection can significantly reduce methane emissions from LNG engines.

Developments in methanol technology, including more efficient combustion processes and the introduction of renewable methanol, can further reduce CO₂ emissions. Renewable

methanol, also known as green methanol, is made from sustainable sources like biomass or synthesized from captured CO₂ and hydrogen produced from renewable energy.

The interplay between evolving regulations and technological advancements will significantly shape the future emission profiles of container ships. As the industry moves toward a decarbonized future, the adoption of LNG and methanol, supported by continuous technological innovations, offers a pathway to comply with both current and future environmental standards. This transition not only helps shipping companies mitigate regulatory risks but also positions them as leaders in sustainability practices.

This paper does not quantify other potential alternative fuel options (fuel cells, all-electric propulsion, etc.), which are currently successful in the laboratory with low utilization rates, but have a promising future as a cleaner and investment-value carbon emission reduction option that deserves further research.

In the maritime industry, particularly when assessing the environmental impact of different fuels, it is crucial to consider emissions of other GHGs and pollutants beyond just CO₂. These include nitrogen oxides (NO_x), sulfur oxides (SO_x), PM, and, in the case of some fuels like LNG, methane slip, which is the release of unburned methane into the atmosphere. Each of these has different environmental and health impacts, and their regulation is increasingly stringent under international maritime law, particularly under the IMO regulations.

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