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Decarbonizing in Maritime Transportation: Challenges and Opportunities

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Abstract

As global warming caused by greenhouse gases grows (GHGs) into a global environmental threat, carbon dioxide emissions are drawing increasing attention in these years. Among all emission sources, transportation is a major contributor to climate change because of its high dependence on fossil fuels. The International Maritime Organization (IMO) has therefore been promoting the reduction of fuel usage and carbon emissions for container ships by such measures as improving shipping route selection, shipping speed optimization, and constructing clean energy propulsion systems. In this paper, a review of the impact of carbon dioxide emissions on climate change is presented; the current situations of carbon dioxide emissions, decarbonizing methods, IMO regulations, and possible future directions of decarbonizing in the maritime transportation industry are also discussed. Based on the result, it is found that in the case that non intelligent ships still occupy the vast majority of operating ships, the use of new energy as the main propulsion fuel has the defects of high renewal cost and long effective period. It is more likely to achieve energy conservation and emission reduction in the shipping industry in a short period of time by using intelligent means and artificial intelligence to assist ship operation.

Keywords

Carbon Neutrality, Alternative Fuel, Shipping and Environment, Greenhouse Gases, International Maritime Organization (IMO) Regulations, Energy Efficiency, Marine Technology

1. Introduction

Global climate has witnessed tremendous changes since the industrial revolution. Emissions of greenhouse gases (GHGs) turn out to be the major culprit for the fast-growing temperature. The consequences of climate change caused by GHGs include global temperature rise, extreme weather events, warmer oceans, sea level rise, etc. [1]. Among different sources leading to the buildup of GHG emissions, the transportation sector is one of the major contributors to GHG emissions due to its heavy dependence on fossil fuels (**Figure 1**) [2]. Historically, high and volatile freight rates, congestion, closed ports and new demands for shipping following COVID-19 and the war in Ukraine have all had measurable impacts on people's lives. With ships carrying over 80% of the volume of global trade, higher shipping costs and lower maritime connectivity lead to higher inflation, shortages of food, and interruptions of supply chains—all of which are among the features of the current global crisis. Concretely, the review estimates that higher grain prices and dry bulk freight rates in early 2022 contributed to a 1.2 percent increase in consumer food prices. Container ships spent 13.7 percent longer in port in 2021 compared to 2020, exacerbating delays and shortages. And during the last year, total green-house-gas emissions from the world fleet increased by 4.7 percent [1] [2]. Although international shipping contributes about 2.2% to global CO_2 emissions [3], maritime transportation is still considered to be the most efficient mode of transportation and the smallest contributor to CO_2 emissions.

Jimenez *et al.* [4] analyzed the research on energy efficiency and decarbonization in the maritime industry published between 2006 and 2021. Publications on energy efficiency and emission reduction in the maritime domain have seen an exponential growth since 2016. The number of publications from 2006 to 2015 was 76, while the number of publications in the past six years (2016 to 2021) was 260, indicating a substantial interest in energy efficiency and decarbonization in the maritime industry. Reducing emissions in the marine field can be achieved

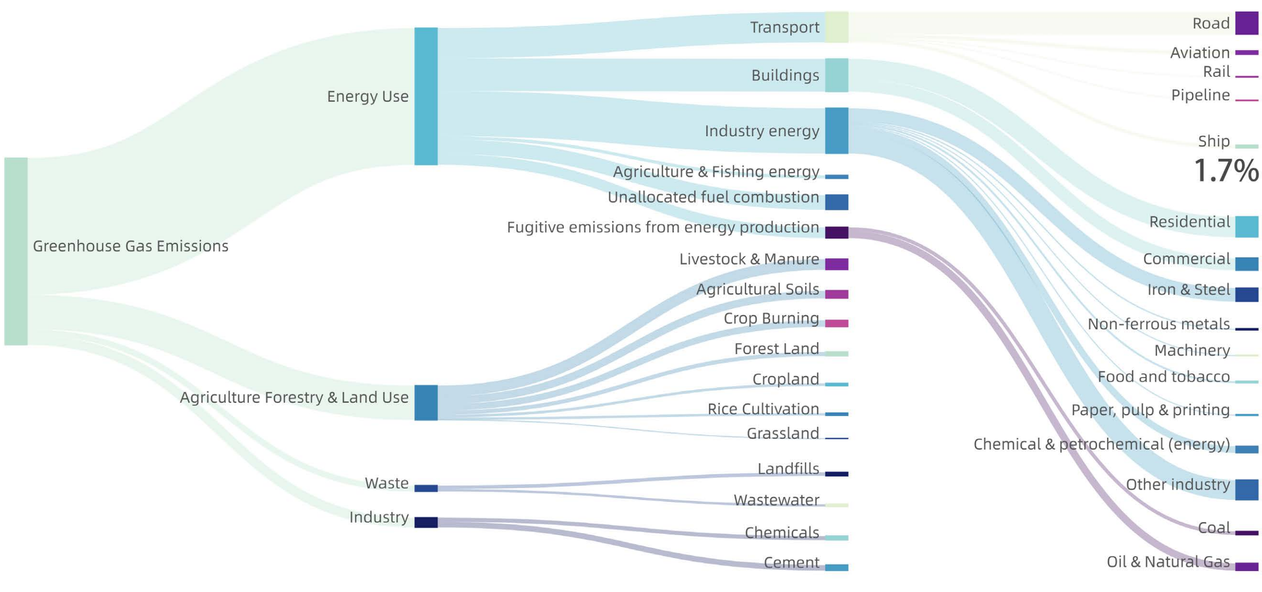

Figure 1. Global GHG emissions by sector [2] [6].

in many ways. There are several comprehensive studies on emission reduction, Alenazi *et al.* [5] focused on the use of alternative energy, and Xing *et al.* [1] focused on various decarbonization measures. In addition, Xing *et al.* [1] focused on reviewing various technologies and operational measures for decarbonization in the shipping industry.

Given the weight of CO_2 emissions in maritime transportation, this paper reviews the history of CO_2 emissions control in the shipping industry, and discusses existing measures, including international policies and research methods, for emissions control, with a vision to provide some inspirations for CO_2 emissions control in the future. Thus, the second section reviews the existing carbon emission reduction regulations, which contains about international organizations regulations, government/region regulations, and industries regulations and technology. The third section describes decarbonizing methods in the shipping industry, including alternative fuels and shipping optimization methods. The final section is a conclusion.

2. Carbon Emission Reduction Regulations Review

To minimize CO_2 emissions, different nation's government and organizations has made effort for decarbonization in maritime transportations.

2.1. International Organizations Regulations [7]

2.1.1. United Nations

Staring on May 2009, the international community started to make decarbonation target for maritime transportation on 15th UNFCCC (COP15) and the IMO will be in charge of internal organizing and the low-carbon transformation of shipping is gradually brought into the supervision.

2.1.2. International Maritime Organizations (IMO)

As a specialized agency of the United Nations, IMO exercises its power and assumes responsibility for greenhouse gas emissions from shipping, and relevant mandatory regulatory regulations are mainly implemented through the MARPOL Convention. Until Now, IMO has proposed a series of energy efficiency indicators for ships, such as the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operating Index (EEOI), four Emission Control Areas (ECAs) in major areas of maritime transport, and rules to reduce emissions of sulfur dioxide, nitrogen oxide and carbon dioxide. Through these initiatives, IMO targeted at a 14% cut in CO_2 emissions by 2020 [8]. The IMO has also addressed greenhouse gas (GHG) emission from international shipping for decades (MEPC 2018). Assembly resolution A.963(23) adopted on 5 December 2003 requested the Maritime Environment Protection Committee (MEPC) to prepare consolidated statements to limit or reduce GHG emissions from international shipping (Resolution A 2003). In response to this request, MEPC adopted MEPC.203(62) that introduced mandatory requirements for energy efficiency of ships (MEPC 2011) in 2011, MEPC.229(65) that urged IMO to promote the transfer of energy-efficient technologies (MEPC 2013) in 2013, and MEPC.278(70) that required to collect record and report fuel oil consumption data (MEPC 2016) in 2016. As the continuation of these efforts, IMO published Initial IMO strategy on reduction of GHG emission from ships (Initial Strategy) in 2018 (MEPC 2018) [9]. In the 20 years from 2000 to 2020, IMO has conducted four studies on GHG emissions. Each study estimated the multi-year annual total GHG emissions from all kinds of shipping actions. The latest study (IMO GHG Study 2020) provided the updated international shipping GHG emissions between 2012 and 2018, with an estimation of future shipping emissions from 2018 to 2050. The GHG emissions of total shipping (international, domestic and fishing) have increased from 977 million tonnes in 2012 to 1076 million tonnes in 2018, a 9.6% change [10]. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 [11]. Based on the above work, IMO passed the amendment to Annex VI of MARPOL Convention in June 2021. From January 1, 2023, EEXI calculation and CII rating will become mandatory requirements (MEPC 2021). By the end of 2022, IMO has formed all-round regulatory requirements from technology to operation for carbon intensity level of new/existing ships. **Figure 2** shows the progress of GHG emission reduction plan for IMO from 2008 to 2100. And **Table 1** shows the total shipping and voyage/vessel-based International Shipping CO_2 Emissions by years.

The major highlights of IMO's CO_2 reduction plan are as follows (**Table 2**):

1) Reduce the level of carbon intensity of international shipping by 40% by 2030 and 70% by 2050 compared to 2008;

2) Reducing GHG emissions by 50% in 2050;

3) Achieving zero GHG emissions from international shipping by the end of 2100.

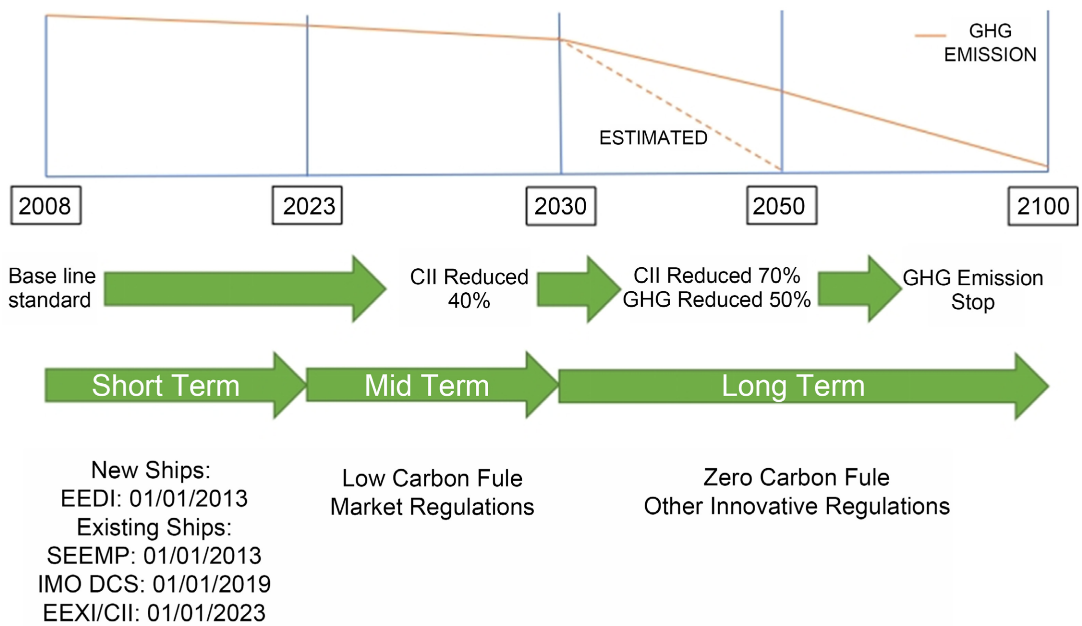

Figure 2. IMO ship greenhouse gas reduction roadmap.

Table 1. Total shipping and voyage-based and vessel-based international shipping CO_2 emissions (million tonnes) and the corresponding percentage of global anthropogenic CO_2 emissions [11] [12].

Year	Global Anthropogenic CO_2 Emissions	Total Shipping CO_2 Emissions	Total Shipping as a Percentage of Global	Voyage-based International Shipping CO_2 Emissions	Voyage-based International Shipping as a Percentage of Global	Vessel-based International shipping CO_2 Emissions	Vessel-based International Shipping as a Percentage of Global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1062	2.90%	727	2.05%	894	2.53%
2017	35,810	1064	2.97%	746	2.08%	929	2.59%
2018	36,573	1056	2.89%	740	2.02%	919	2.51%

Table 2. Major highlights of IMO's CO_2 reduction plan [13].

Year	Plan	Description
2018	IMO adopts initial strategy to reduce GHG emissions	Sets a series of GHG emissions reduction milestones through 2050
2020	Low-sulfur fuel mandate	Reduces the limit for sulfur content of fuel oil used in ships to 0.5 percent from 3.5 percent, effective Jan 1, 2020
2023	Short-term decarbonization deadline	Requires finalized short-term measures to reduce CO_2 emissions by 2030
2030	Mid-term decarbonization deadline	Mandates an average 40 percent reduction in CO_2 emissions per transport work by 2030 compared with 2008 levels
2050	Long-term annual GHG reduction deadline	Required a 50 percent reduction in total annual GHG emissions by 2050 and encourages efforts to phase out GHG emissions completely

Up to now, different schemes and indicators have been proposed by IMO for the evaluation of ship fuel efficiency.

The Ship Energy Efficiency Management Plan (SEEMP) measures ship's energy efficiency. SEEMP provides a tool for ship owners to manage the energy efficiency of their ships and it is a mandatory requirement for ships of at least 400 GT (gross tons) [14]. SEEMP is a custom-built plan that takes many factors into account including the ship type, nature of goods, and shipping routes. Applicable ships need to hold energy efficiency management plans approved by competent authorities or organizations. The SEEMP Guidelines are intended to help the maritime industry achieve the carbon intensity target in Annex VI of MARPOL Convention, one of which is to encourage companies to take measures to improve ship energy efficiency and carbon intensity in ship management. SEEMP achieves the maximum energy utilization efficiency from three aspects: management measures, technical measures and operational measures. By taking and continuously improving effective energy conservation and consumption reduction measures, it can improve ship energy efficiency and reduce carbon emissions.

Till now, several measures are needed for ship's carbon emission performance. Energy Efficiency Operational Indicator (EEOI): EEOI is a voluntary rating scheme developed by the International Maritime Organization (IMO) to measure and report the carbon emissions of ships during their operation. It is a ratio of the amount of CO_2 emitted by a ship to the amount of cargo it carries over a certain distance. The EEOI provides a standardized framework for assessing the carbon emissions of existing ships and provides guidelines for improving energy efficiency. The EEOI rating is given in grams of CO_2 per tonne-kilometer (gCO_2/tkm). Energy Efficiency Design Index (EEDI): EEDI is a mandatory regulation adopted by the IMO that requires new ships to meet a minimum energy efficiency standard. It is a measure of the amount of CO_2 emitted by a ship per unit of transportation work. The EEDI sets a minimum energy efficiency requirement for each ship type and size, based on its carrying capacity and speed. The EEDI is calculated by dividing the amount of CO_2 emissions by the amount of cargo transported over a certain distance. Energy Efficiency Existing Ship Index (EEXI): EEXI is a new regulation adopted by the IMO that requires existing ships to meet a minimum energy efficiency standard. Similar to the EEDI, the EEXI is a measure of the amount of CO_2 emitted by a ship per unit of transportation work. However, unlike the EEDI, the EEXI applies to existing ships and sets a minimum energy efficiency requirement based on the ship's technical characteristics and age. The EEXI is calculated by dividing the amount of CO_2 emissions by the amount of cargo transported over a certain distance, with adjustments made for factors such as the ship's engine power and fuel consumption.

The Energy Efficiency Design Index (EEDI) was incorporated into MARPOL in 2001 [15] and is only applicable to new-produced ships. EEDI is an index that estimates grams of CO_2 per transport work, which is considered as the 1st global policy for regulate CO_2 emission standard. It can be expressed as the ratio of "environmental cost" to "benefit of society":

$$\text{EEDI} = \frac{\text{CO}_2\ \text{Emission}}{\text{Transport Work}} \tag{1.1}$$

The Energy Efficiency Operational Indicator (EEOI), improved by the IMO, is used to evaluate the shipping activities' carbon emissions. EEOI is the total carbon emissions for per unit revenue ton-miles each time. Variations in the index are mainly caused by three factors: the shipping speed, the amount of cargo transported per unit time, the ship's technical efficiency. However, since the EEOI is an aggregate number, it is difficult to determine the impact of these factors. The EEOI can be expressed as:

$$\text{EEOI} = \frac{\sum_i FC_j \times C_{F,j}}{m_{\text{cargo}} \times D} \tag{1.2}$$

where is the mass of fuel consumed, is the fuel type, is the fuel mass to conversion, is the cargo unit depending on ship type, and is the sailing distance in nautical miles.

The Energy Efficiency Existing Ship Index (EEXI) is a measure proposed by IMO to reduce ships' GHG emissions. It is first approved by IMO as amendments to MARPOL Annex VI. The EEXI is a measure related to the technical design of a ship and will be enforced in 2023 to "all vessels above 400 GT falling under MARPOL Annex VI [16]". Since EEXI is only a index rather than an operational index, it does not have measurements from previous years, nor does it have on-board measurements. Therefore, EEXI only measures the ship's design index [17]. The existing ships in operation have higher main engine power (higher speed), lower maintenance cost, lower energy efficiency and more greenhouse gas emissions. By adopting energy efficiency improvement measures, EEXI can be reduced from the technical aspect, and then GHG emissions can be reduced. The measurements that can be taken include Engine Power Limitation (EPL), fuel change and/or the use of Energy-Saving Devices (ESD), EPL + ESD, elimination of old ships and replacement of new ships, and other verifiable options.

The other metrics indicating the average CO_2 emissions per transport work of a ship are generally referred to as operational Carbon Intensity Indicator (CII). It is also first approved as amendments to MARPOL Annex VI. CII is mainly the division of carbon dioxide emitted per nautical mile of cargo carried in a given calendar year. It includes two calculation metrics: attained CII and required CII. The calculation of attained CII is based on the actual CO_2 emissions of each ship. Required CII of each ship is a reduced value of a reference line defined as a function of capacity. Comparing attained and required CII, each ship can be assigned a ranking label from A to E per year. Considering that the given reduction factors increase year by year, required CII will then get smaller and as a result, the rating for each ship will be downgraded as time past. CII will include cargo ships, RoPax ferries and cruise ships over 5000 GT. For ships that achieve a D rating for three consecutive years or an E rating for one year, a corrective action plan is required and approved as part of the SEEMP [16]. **Figure 3** shows the development of CII by IMO's Marine Environment Protection Committee (MEPC).

2.1.3. European Union (EU)

Another important international organization which has made effort on the reduction of carbon emissions is the European Union (EU). The EU has implemented the EU Carbon Emission Trading System (EU ETS) since 2005, and proposed to include the maritime industry in EU ETS since 2013. In April 2015, the EU passed the Regulation on Monitoring, Reporting and Certification of Carbon Dioxide Emissions from Maritime Transport (EU MRV). On December 11, 2019, the new European Commission issued the European Green Deal, which became the general outline of its policy guidance. On June 28, 2021, the European Union passed the European Climate Law, which aims to reduce greenhouse

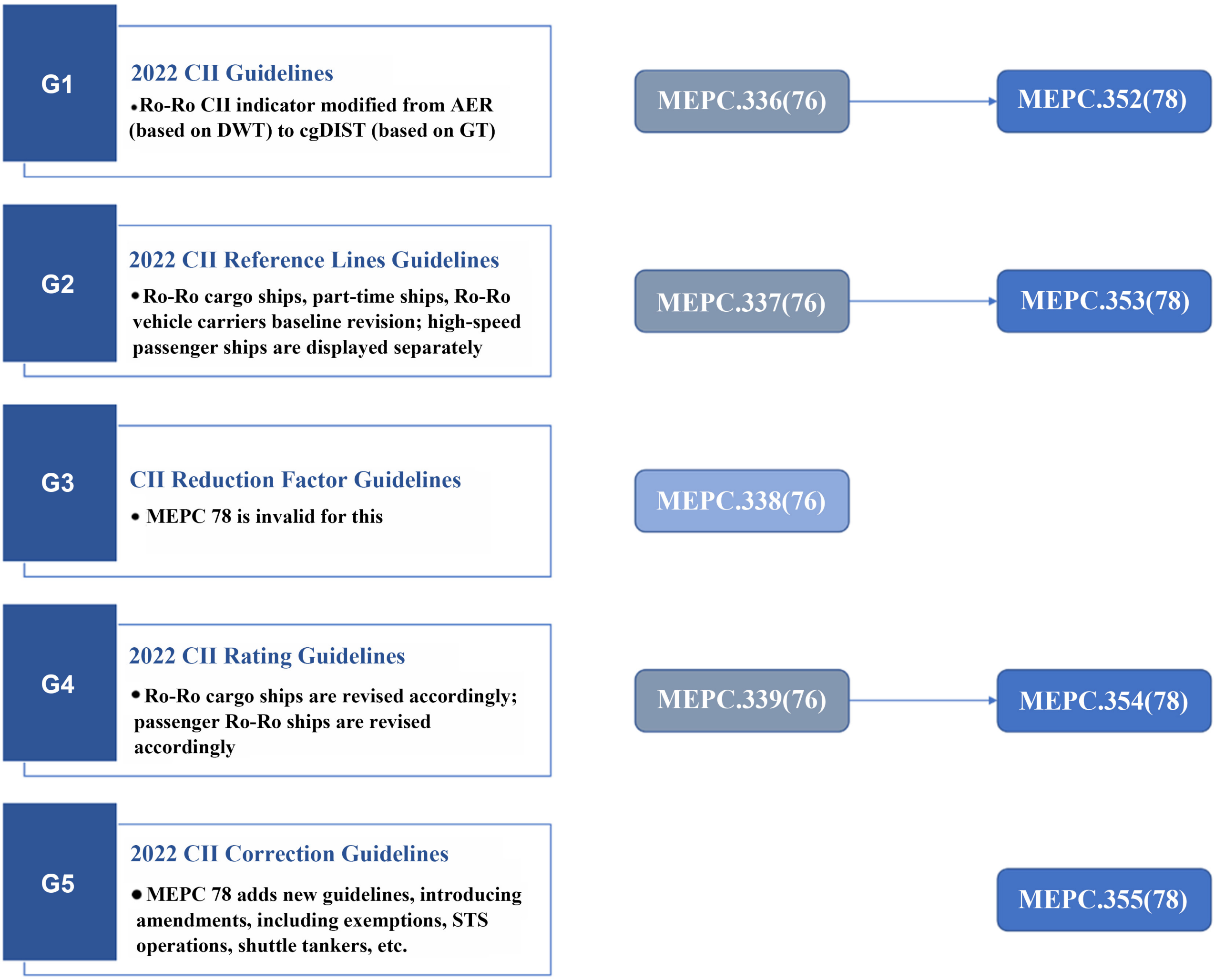

Figure 3. CII guidelines.

gas emissions by at least 55% in 2030 compared with 1990 (the original target was 40%), and achieve carbon neutrality by 2050. On July 14, 2021, the European Commission proposed a "Fitfor55" package of legislation, which involves the shipping industry, including bringing the shipping industry into EUETS; Increase the demand for renewable and low-carbon fuels for ships, set a maximum limit on the greenhouse gas content of the energy used by ships calling at European ports, and encourage the use of zero emission technology for ships at berth; Promote alternative fuel infrastructure, etc. Fuel EU Maritime and the new EU ETS will become the regulatory framework for EU shipping carbon emission regulation, and the latter is expected to be fully implemented in the shipping industry in 2026.

2.1.4. Global Maritime Forum (GMF)

The Global Maritime Forum (GMF) is committed to making it commercially feasible for zero emission fuel powered ships to be put into far-reaching shipping operations by 2030, and achieving shipping decarbonization by 2050. In September 2021, the Alliance launched the "Call to Action for Shipping Decarbonization" to promote the shipping industry to meet the temperature control objectives of the Paris Agreement and fully use net zero energy before 2050.

2.2. Government/Region Regulations [7]

2.2.1. United Kingdom (UK)

On March 10, 2022, the British government announced that it would invest 4 billion pounds in shipbuilding in the next 30 years to ensure the future development of the shipbuilding industry. One of the specific measures is to invest £206 million in the shipping bureau for research and development of zero emission ships and infrastructure. On January 24, 2019, the UK released Maritime 2050: navigating the future), in which considerable space was devoted to the development of maritime environmental protection policies and regulations, new technologies and energy and fuel. Its goal is to make the UK an important role in the formulation and improvement of environmental protection rules in Europe and IMO, and become the authority of low/zero emission marine transport. On July 11 of the same year, the UK launched the Clean Maritime Plan: Maritime 2050 environment route map, which described in more detail the road map of the UK government's transition to zero emission shipping in the future.

2.2.2. Singapore

In 2011, the Maritime and Port Authority of Singapore (MPA) launched the Singapore Maritime Green Initiative (MSGI), promising to invest up to $100 million in the project within five years to reduce the impact of shipping related activities on the environment and promote the development of clean and green shipping in Singapore. In 2019, MSGI was further extended to December 31, 2024, and promote shipping decarbonization. The initiative mainly includes four projects: Green Ship Plan; Green Port Plan; Green energy and technology plan; Green Awareness Program. On August 1, 2021, Singapore Global Marine Decarbonization Center (GCMD) was officially established, funded by Singapore MPA and six founding partners (BHP, BW, DNV Foundation, Eastern Pacific Shipping, Ocean Network Express and Sembcorp Marine), 1 and became the backbone of Singapore's efforts to promote decarbonization and emission reduction in shipping. In order to formulate a long-term strategy for the sustainable development of the maritime industry, in March 2022, MPA released the Singapore Maritime Decarbonization Blueprint: Towards 2050. On October 26, 2022, the Ministry of Trade and Industry (MTI) of Singapore released the Singapore's National Hydrogen Strategy, proposing the vision of developing new technologies, establishing a low hydrocarbon energy supply chain, and achieving net zero GHG by 2050.

2.2.3. United States of America (USA)

In November 2021, at the COP26 meeting held in Glasgow, the United Kingdom, the United States used its diplomatic influence to promote several important agendas for decarbonizing the shipping industry, which are expected to have far-reaching effects. Specifically, the United States and 12 other countries signed a statement sponsored by Denmark to achieve zero emissions from shipping by 2050; The United States announced the launch of the "First Movers Coalition" plan to promote the decarbonization of the private sector. Maersk and 34 other shipping related companies (organizations), such as logistics, trade and cargo owners, became the founding members of this alliance; During the meeting, 22 countries, including the United States, signed the Clydebank Declaration initiated by the United Kingdom, promising to establish at least six "green shipping corridors" in the world by 2025 and decarbonize the shipping industry by 2050. In January 2022, C40 Cities Climate Leadership Group, Los Angeles Port and Shanghai Port jointly launched the initiative to establish the "Shanghai Los Angeles Green Shipping Corridor", so as to realize the clean and low-carbon port to port cargo transportation between Shanghai Port and Los Angeles Port; In June of the same year, Long Beach Port also announced to join the corridor. On April 12, 2022, the State Department of the United States issued a document on green shipping corridors, expressing its determination to promote the construction of green shipping corridors at home and abroad. In addition, according to the Infrastructure Investment and Employment Act passed in November 2021 and the Inflation Reduction Act passed in August 2022, the United States will add tens of billions of dollars in investment in green ports and waterway infrastructure in the next five years. Three local governments, including Los Angeles, Long Beach and Minneapolis, have introduced local regulations related to "zero emission ships" through the Ship It Zero Alliance resolution.

2.2.4. Japan

In October 2020, Japan announced the goal of carbon neutrality by 2050. In May 2021, the Senate of the National Assembly of Japan formally passed the amendment to the Global Warming Strategy Promotion Act, which clarifies the goal of achieving carbon neutrality by 2050 proposed by the Japanese government in the form of legislation. In June 2021, the Ministry of Economy, Industry and Technology (METI) of Japan released the latest version (GGS), focusing on the development of green and low-carbon industries in 14 fields, including offshore wind and solar energy, hydrogen and ammonia fuel, next generation heat energy, nuclear energy, automobiles and energy storage batteries, semiconductors and communications, shipping, transportation and logistics, food/agriculture, forestry and aquatic products, aviation, carbon cycle and materials, next generation housing and construction, resource cycle, and lifestyle. In order to achieve the goal of carbon neutrality in 2050, METI set up the Green Innovation Fund of 2 trillion yen (about 19.2 billion US dollars) in March 2021 as a part of Japan's New Energy Industry Technology Comprehensive Development Organization (NEDO). In the next ten years, it will be used in areas that need long-term and continuous support, including the 14 key areas mentioned by GGS. In March 2020, the Ministry of Land, Infrastructure, Transport and Tourism of Japan, together with the Japan Ship Technology Research Association and The Nippon Foundation, released the Road Map for Zero Emission from International Shipping to promote Japan's relevant research, policies and regulations to achieve zero emission from international shipping. On October 26, 2021, the Japanese Shipowner's Association officially released the Japanese Shipping Industry; The mature LNG fuel infrastructure should be used to expand the use of renewable methane, as well as the use of hydrogen and ammonia, so that the three fuels can become concentrated fuels in the future. The report of the Japan Shipowners Association basically reflects the attitude and choice of the Japanese shipping industry towards low-carbon transformation at this stage. The three major shipowners, NYKLine, MOL and K Line, are all strong supporters of LNG fuel at present, but they are also actively promoting the transition to renewable methane, hydrogen and ammonia zero carbon fuels before 2050.

2.2.5. China

On September 22, 2020, at the general debate of the 75th United Nations General Assembly, the Chinese President solemnly declared that China will increase its national independent contribution, adopt more effective policies and measures, strive to reach the peak of carbon dioxide emissions by 2030, and strive to achieve carbon neutrality by 2060. China is taking action to achieve this goal. The relevant policies and measures are as follows: The State Council of China issued the Opinions on the Complete, Accurate and Comprehensive Implementation of the New Development Concept to Do a Good Job of Carbon Peak and Carbon Neutralization, the Notice on the Action Plan for Carbon Peak by 2030, and the Implementation Plan for the Implementation of the Carbon Peak and Carbon Neutralization Target to Promote the Green and High Quality Development of Data Centers and 5G and Other New Infrastructures, Nine departments including the Ministry of Science and Technology issued the Implementation Plan for Science and Technology to Support Carbon Peak and Carbon Neutralization (2022-2030), and the Work Plan for Strengthening the Construction of Higher Education Talent Training System for Carbon Peak and Carbon Neutralization issued by the Ministry of Education. Build a green and low-carbon transportation system, adjust the transportation structure, reduce the highway transportation of bulk goods, increase the railway and waterway transportation, and encourage the use of shore power during the docking of ships. Improved green transport systems and standards, issued 221 standards in energy conservation and carbon reduction, and actively promoted green travel. Accelerate the replacement and optimization of transportation fuels, promote the upgrading of transportation emission standards and oil product standards, and improve transportation efficiency through information technology. **Figure 4** shows the Timeline of Main Efforts on GHG Emissions.

2.3. Industries Regulations and Technology

Under the leading of IMO and many nations, major companies in maritime

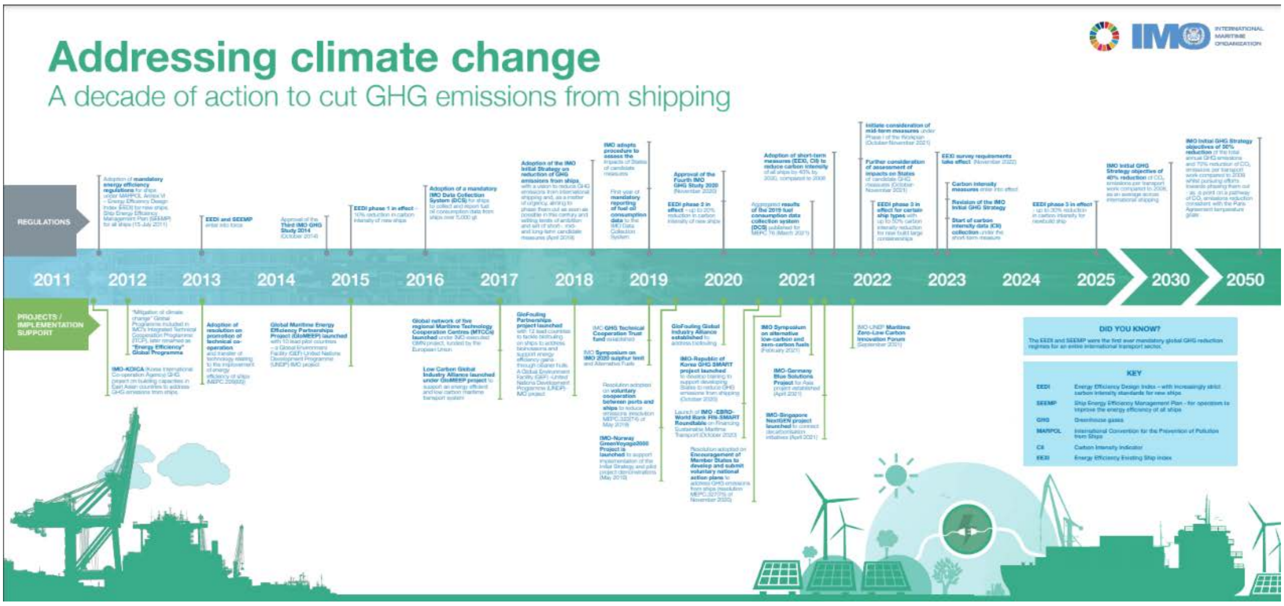

Figure 4. Timeline of main efforts on GHG emissions [18].

transportations are also putting great effort on low-carbon fuels and technologies. According to the DET NORSKE VERITAS Alternate Fuel Insight (DNV AFI) statics [19], there are 338 LNG fueled ships with 518 orders; 28 LPG fueled ships with 93 orders; 20 methanol fueled ships with 60 orders; 6 hydrogen fueled ships with 19 orders; battery electric operation 555 ships, 194 orders. Low carbonization of ships has also become a trend in enterprises.

2.3.1. A. P. Moller-Maersk

As the leading company in maritime transportation, as early in the year of 2018, Maersk has made its promise to reach zero carbon in maritime operation before 2050. In 2021, Maersk has accelerated this process to 2040 as shown in **Figure 5**. Maersk's effort on cutting off the carbon emission is mainly from the use of low carbon fuel such as methane. At the same time, Maersk is also actively deploying a methanol fuel network, seeking port cooperation to ensure fuel supply, and signing agreements with a number of methanol suppliers. In addition to green methanol fuel, Maersk will also give priority to exploring biodiesel and green ammonia.

For cargo owners, Maersk has specially launched the Maersk ECO Delivery service. Shippers are able to obtain an Eco-Transport Carbon Reduction Certificate stating how many tonnes of CO_2 emissions have been saved in a given period. These savings are based on the average emissions accumulated during the transport of goods if fossil fuels are used. Includes the amount of environmentally friendly fuel used, FFE for transport, and details on CO_2 reductions from energy to fuel and fuel to power. Maersk also stated that the choice of environmentally friendly transportation only needs to be added to the contract, and there is no need to sign another agreement with the cargo owner, which reduces the long-term investment of the cargo owner.

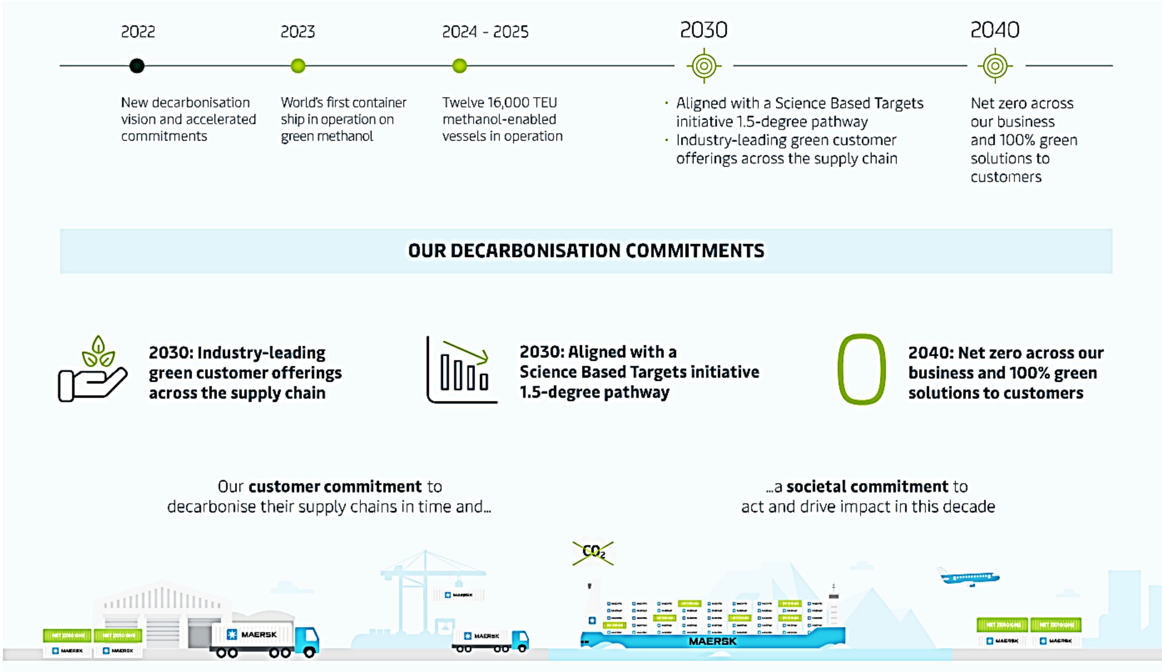

Figure 5. Maersk roadmap to deliver net zero by 2040 [20].

2.3.2. China COSCO Shipping Group

China COSCO Shipping Corporation Limited (COSCO Shipping) is a Chinese state-owned multinational company headquartered in Shanghai. The group is focused on marine transportation services. As of March 2020, the company's fleet was among the largest in the world—1310 vessels with a capacity of 105.92 million DWT.

As the world's largest maritime fleet in capacity, COSCO is aiming to achieve carbon neutrality by 2060 by using alternative fuels and renewable energy. The state-owned organization is also looking to reduce the greenhouse gas emission intensity of its container shipping business by 12 percent (compared with 2019) and its holding terminals by 20 percent (compared with 2020) by 2030. COSCO is looking to achieve these aims through the use of clean fuel, renewable energy, and ships with green passports shown in **Figure 6**.

Besides the use of alternative fuels, based on advanced technologies such as cloud computing, Internet of Things, artificial intelligence and big data algorithms, "Vessel Value Visulization" collects 8 million historical route data from 30 billion AIS records of 120,000 merchant ships and 50,000 records from more than 4100 ports around the world. Multiple berth data can intelligently identify the behavior of ships in their entire life cycle, so as to provide analysis, prediction and early warning capabilities for ships, ports and routes. Relying on the identification of the entire life cycle of ships formed by the dynamic identification of ships, the analysis of port congestion, and the forecast data of ship arrivals, through the "business scenario + digital" technology, around the market environment, green ecology and other factors, using cutting-edge big data mining and machine learning modeling technology to establish corresponding big data

Figure 6. COSCO Shipping environmental protection objectives [21].

models for ship driving and fleet operation in different scenarios based on indicators such as speed optimization curve, navigation plan accuracy, and effective operation efficiency, and provide ship operation efficiency reminders and assistance The decision-making function is to improve the efficiency of ship navigation, increase the efficiency of shipping scheduling, and further optimize the cost of ship operation including energy consumption to assist the green and low-carbon operation of shipping companies. Figure 7 shows an example of CII simulator development by COSCO Technology company for optimization of CII plans of ships.

2.3.3. Others

CMA CGM, which has always chosen to invest in liquefied natural gas (LNG)-powered ships, made its first attempt to invest in methanol-powered container ships, becoming the second container shipping giant to build methanol-powered ships after Maersk Line. In addition to the enthusiasm of Japanese and Singaporean companies in the field of marine ammonia fuel supply chain, companies in energy, chemical, shipbuilding, shipping and other related industries such as Norway and South Korea are also quite active in the development of ammonia fuel ships and the construction of ammonia fuel supply chain. In July 2021, Norwegian bulk carrier Viridis signed a memorandum of understanding with five shippers, Elkem, Vestkorn, BioMar, Franzefoss Minerals and Saltimport, to build a Nordic zero-emission shipping network based on its new ammonia-powered ships.

3. Decarbonizing Methods in the Shipping Industry

3.1. Alternative Fuels

There are over 80,000 merchant vessels across the world which can consume

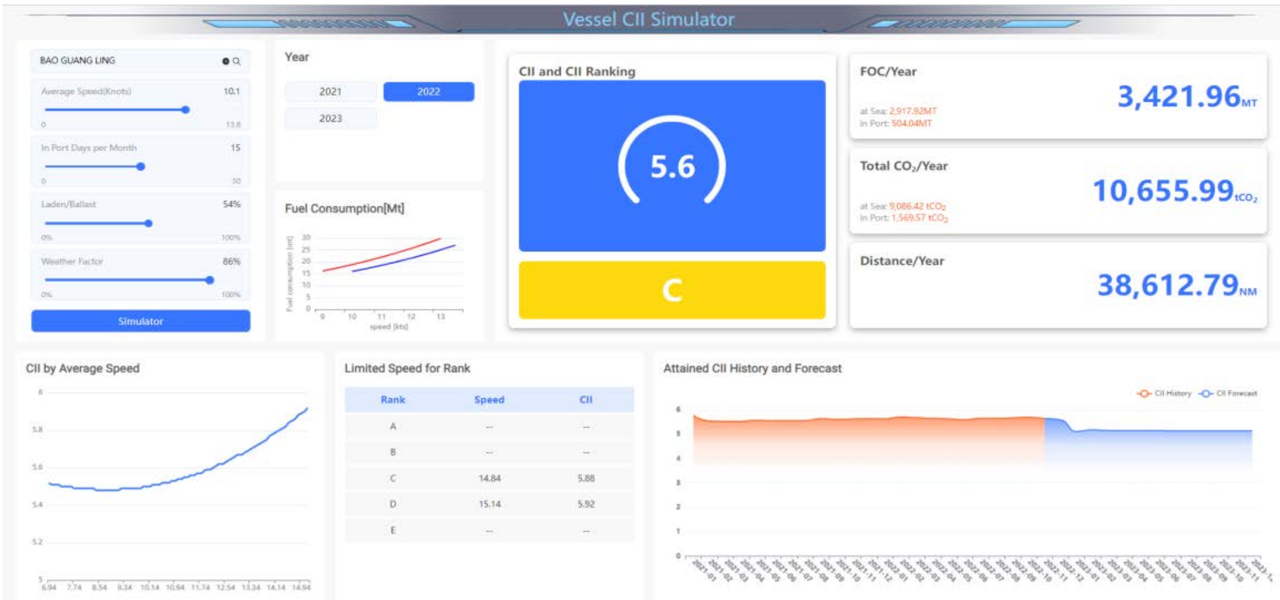

Figure 7. Low-carbon platform (Carbon Index Simulator) in "Vessel Value Platform".

over 400 million tons of marine fuel annually. However, despite regulations on the sulphur content in fuels, 80% - 85% of ships are using fuels with a high sulphur content [22]. More than 50% of the ship operational cost is due to fuels [23]. Thus, to reduce GHG emissions and achieve cost efficiency, replacing fossil fuels by greener alternatives is necessary.

The traditional marine fuel is mainly fossil fuel. In the context of green and low-carbon development of shipping, fossil-based LNG, LPG and methanol are also considered as low-carbon fuel. Considering only the emissions at the combustion end, LNG and methanol rank the top two in terms of carbon reduction potential, which can theoretically achieve 25% and 10% carbon reduction compared with fuel oil; However, if methane escape and upstream emissions are considered, the carbon reduction potential will be significantly reduced. Therefore, for carbon-neutral shipping, while considering the whole life cycle emissions, zero-carbon or carbon-neutral synthetic fuels and biofuels are an inevitable trend. Renewable hydrogen, ammonia, methanol, and biomass fuels have entered the public view.

Liquefied natural gas (LNG) is mostly cooled to be condensed into liquid, which is the most widely-used alternative fuel to comply with the current SOx and NOx limits while reducing CO_2 emissions. One advantage of LNG as an alternative fuel is its low sulphur content (<0.004%). Compared to conventional marine fuels, LNG can reduce a ship's CO_2 emissions by approximately 25% while providing the same amount of propulsion; in addition, it is cheaper than marine gas oil (MGO) and heavy fuel oil (HFO). Over the years, the bunkering infrastructure has grown far beyond the few key bunkering ports. There are now 96 ports that can supply LNG to ships, with another 55 LNG bunkering ports under development [24]. However, the methane from LNG which can be extracted from biomass has a very high cost during the purification process. This cost is considered as the major barrier for wide adoption of biomethane as fuel [25].

Hydrogen produced during the use of renewable energy is the cleanest marine fuel with zero carbon emissions. Though the lightest of all gas molecules which can offer a higher energy-to-weight storage ratio than any other fuels, hydrogen still seems to be a marginal concept when it comes to marine applications. Because hydrogen usually exists in the form of compounds, it means that the extraction of hydrogen will consume energy. Moreover, the transportation, storage and distribution of hydrogen are significantly affected by its bulk energy density, so liquid hydrogen is expensive and difficult to produce, transport and store. Electrolysis utilizing renewable energy sources can provide clean hydrogen production capacity, but currently accounts for only 3.9% of total global hydrogen production capacity [26]. Therefore, novel production methods, including green technologies, currently have cost-related drawbacks due to their limited implementation [27]. The defects of hydrogen fuel in storage, transportation and terminal use have limited its direct application in ocean-going merchant ships, while renewable ammonia and methanol with hydrogen as the energy carrier are highly expected.

Ammonia's global production amounted to nearly 180 million tons in 2016. Ammonia mainly produced by the electricity demanding Haber Bosch process and the nitrogen used is produced from air via the reforming step or by a separate air separation process [2]. Ammonia has been demonstrated as a fuel in compression ignition engines, spark ignition engineers, and fuel cells. But there are issues with ignition, specific fuel consumption, material and emissions. Liquid ammonia has high explosion risk and toxicity, and the safety of storage and transportation is particularly important. In terms of terminal use, higher self-ignition temperature, lower flame propagation speed, narrower flammability limit and higher NOx emission are all challenges faced by the development of ammonia fuel engines. Besides ammonia slip, there are potential emissions of nitrogen oxides, carbon oxides, hydrocarbons. At present, ammonia fuel engines and ammonia-powered ships have not been commercially available, but the world's major marine engine manufacturers are actively promoting the research and development of ammonia fuel engines; At the same time, many ship design companies, shipyards, shipping enterprises and shipowners are also developing ammonia-powered ships.

Compared with traditional fuels, renewable methanol can reduce CO_2 emissions by up to 95% and NOx emissions by 80%, and has no SOx and PM emissions at all. Although methanol has certain toxicity, it is lower than ammonia, and because of its strong volatility and biodegradability, its threat to human health, marine and atmospheric environment is lower than that of fuel oil and ammonia. Compared with other gaseous fuels, methanol is easy to transport, store and distribute. A complete supply chain can be established by slightly modifying the existing marine fuel storage and transportation facilities. For end use, methanol is suitable for internal combustion engines and fuel cells. At present, the efficiency of direct methanol fuel cell (DMFC) is still relatively low, which needs to be further developed and improved; The methanol-fueled internal combustion engine technology is relatively mature. Good storage, transportation, combustion and emission performance make methanol one of the most promising alternative marine fuels.

Biofuels are fuels produced from organic material, such as plant materials and animal waste. Advanced biofuels are produced by extracting biofuels from materials such as wood, crops and waste material. Biofuels can be solid, gas or liquid. Advanced biofuels have high potential in reducing CO_2 emissions. According to the quality, type and the way the bio feedstock is processed, biofuels are estimated to reduce CO_2 emissions between 25% and 100% for very good biofuels. In addition, biofuels also lead to very low sulphur emissions. However, the supply of biofuels may not be sufficient to power the whole shipping fleet. The current biofuels supply, which consists of both biodiesel and bioethanol, can only cover about 15% of the total demand (IEA, 2017). As proposed by Smith *et al.* (2016), it means that biofuels can only provide power for a limited part of the global ship fleet. By mixing mandates and fuel standards, the government has the ability to create stable demand, thus ensuring the absorption of biofuels and affecting the availability of biofuels.

Shore power (SP) is a method of reducing emissions that involves switching from fossil fuel used on board to energy brought in from the land. Smaller ships can now use battery-powered propulsion systems thanks to advancements in battery technology like lithium-ion. High initial investment, lack of infrastructure and potential fire risk are all key obstacles to the development of electric ships. Due to the high weight and low power density of battery, the application of battery power system in deep sea and large ships is limited. When the power demand increases, it is an inevitable choice to use diesel engines, fuel cells, wind auxiliary systems, solar photovoltaic systems and other energy storage batteries to form hybrid power systems. Co-benefits of shore power facilities include the reduction of other air emissions from ships and the reduction of ship noise. Batteries can be combined with other renewable energy sources like solar and wind, but they cannot be used as a solo solution given technical limitations, whereas solar energy is not suitable and unreliable for deep-sea transportation and operations because of weather constraints.

Among the alternatives suggested by shipping experts as a superior ship retrofit are LNG, hydrogen, sails, and batteries. These recommended alternatives are excellent, but the vessel owners may have difficulty in making a decision. Thus, the options should be narrowed down to help ship owners identify the optimal choice and build a greener shipping sector. There are three keys to determine the transformation and development speed of low-carbon shipping: renewable fuels; Production, storage, transportation and filling infrastructure; Equipment and systems related to renewable fuels. The green shipping supply chain depends on the cross regional, cross industry and cross value chain collaboration of global and regional industry organizations, flag countries, port countries, ship owners, port operators, equipment suppliers, fuel suppliers, financial and insurance institutions and other multi stakeholders. The conclusion of partial scientific literature was shown in Table 3.

3.2. Shipping Optimization Methods

Instead of using alternative fuels or replacing ship power systems, the shipping industry can turn to voyage optimization (VO), which can provide key theoretical and technical insights for efficient shipping operations. VO of fuel consumption and GHG emissions involves routing problems, *i.e.*, configuring ship trajectories and engine power for different weather conditions. Here, VO is considered as a multi-objective function that needs to be minimized, while ship motion and expected time of arrival (ETA) are set as constraint variables [28]. Ship motion can usually be represented by shipping latitude, longitude, time, speed, and direction. The parameters of ship motion, combined with environmental conditions, including wind, waves, currents, seawater temperature and air temperature, can affect ship navigation and may make some navigation routes unusable during unfavorable periods [29] [30].

Due to the strong relationship between weather condition and GHG emissions, many voyage optimization algorithms have been proposed with respect to GHG emissions and weather routing to solve the ship's voyage problem with carbon emission minimization as the objective. In those algorithms, such as the isochrone method [31], dynamic programming method [32], a reasonable speed is set to let the ship find a two-dimensional route composed of a series of waypoints between the starting port and the destination. Later, long-distance transoceanic

Table 3. Conclusion of partial scientific literature.

Author	Herdzik [19]	K. Andersson [20]	J. Hansson [21]	Hyungju Kim	M. Mollaoğlu [22]	Zhong Shuo Chen [23]	Francielle Carvalho [24]
Year of Publication	2021	2020	2020	2020	2022	2022	2019
Method	Fuel Parameter Comparison	Sustainability Assessments	multi-criteria decision analysis	Integrated evaluation	TOPSIS	Life cycle assessment	Life cycle assessment
Research Range	Global	Global	Global	Global	Global	tugboats	Brazil
Alternative Fuel	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Biofuel	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Alcohols	Yes	Yes	Yes	No	Yes	Yes	Yes
Ammonia	Yes	Yes	Yes	Yes	Yes	No	No
Hydrogen	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electricity	Yes	Yes	Yes	Yes	Yes	Yes	No
LNG	Yes	Yes	Yes	No	No	No	No
Dual fuel	Yes	No	No	No	Yes	Yes	No

ships have different sailing speeds and engine settings (*i.e.*, engine power) in each sailing period, and a constant speed may lead to a local optimal solution rather than a global optimal solution [33]. Thus, three-dimensional routing models are developed: The 3D VO model describes a forward dynamic planning approach where the power settings and heading of the ship are considered to minimize fuel consumption [34]. When a ship is moving forward under the 3D VO mode, the seeking space in the time dimension is dynamically created. Almost all the sub-routes leading to the node (indicated by the best outcomes e.g., by longitude and latitude) can endure each stage of the optimization process, with additional side routes ignored or eliminated. When applying the optimization methods, the nodes which are being eliminated may contribute to the route that is the global optimal solution of some ETA.

Thanks to the rapid development of computational power, Internet of Things (IoTs) and widely-equipped ship automatic identification systems (AISs), the wide adoption of advanced machine learning (ML) and deep learning (DL) algorithms become possible. Deep learning offers a new solution to prediction tasks. Instead of relying on explicit physical laws, deep learning models predict weather patterns directly from observed data and can generate prediction outcomes faster than physics-based techniques. DL approaches can also increase the frequency, scope, and accuracy of the predicted forecasts. For example, Gkerekos *et al.* [35] used a shallow artificial neural network (ANN) and a multiple regression (MR) model to predict ship fuel consumption under varying weather conditions. Through a case study on the optimal route selection of 160,000 DWT crude oil tanker sailing between the Gulf of Guinea and Marseille anchorage, an R2 of 89.4% was obtained while predicting the vessel's FOC and five optimal routes were identified and ranked for two sailing speeds corresponding to different operating profiles, *i.e.* ballast and fully loaded. Wang *et al.* [36] used the wavelet transform neural network to predict the operating state of the ship for short distances ahead and established a real-time energy efficiency optimization model to determine the optimal speed under different weather conditions. Experimental studies showed that the proposed optimization model was effective in energy saving and emission reduction, which could provide theoretical guidance for optimal sailing of the ship in service and have more practical significance to the improvement of ship energy efficiency. Mao *et al.* [37] established three different statistical models (auto-regression, least squared estimation, and maximum likelihood method) for ship speed prediction based on weather information (wave height, wave period, wind speed). Finally, the data from improvement of photovoltaic (PV) plants in northeast China are used for validation. The results show that the annual average day-ahead prediction AR of the composite prediction framework (DC (DWT-DAE)-CNN) model can reach 90.17%, which is better than other competing models. Coraddu *et al.* [38] investigated the problems of predicting the fuel consumption and of providing the best value for the trim of a vessel in real operations based on data measured by the onboard automation

Table 4. Selected studies for research with methods used and carbon/fuel reduction results.

No.	Document	Methods	Results
1	Gkerekos *et al.* [35]	ANN	R^2 of 89.4%
2	Wang *et al.* [36]	Wavelet transform neural network	CO_2 Reduction by 5%
3	Mao *et al.* [37]	statistical models	90.17% prediction accuracy
4	Zis *et al.* [39]	Speed reduction by ports	CO_2 max reduction by 20%

systems, and proposed online selection of leveling using historical data of ships to reduce fuel consumption and ultimately CO_2 emissions. Zis *et al.* [39] investigated the reduction of speeds in various ports through policy interventions. They describe methods for estimating greenhouse gas emissions from ships near ports, and the potential to reduce emissions through various port policies. The findings suggest that each port play an important role in policy implementation. Full compliance of ships with the deceleration framework could result in reductions of 20%, 40% and 17% in CO_2, SOx and NOx, respectively. Jia *et al.* [40] empirically assessed the possible reductions in fuel consumption and emissions by implementing a global virtual arrival (VA) policy using ship position data based on AIS data. VA is defined as "an agreement to reduce the speed of a ship in order to meet the required arrival time when there is a known delay at the port of discharge" (INTER-TANKO, 2011) [41]. The study assessed 5066 voyages by 483 VLCCs between 44 countries between 2013 and 2015, and calculated the ability to save fuel if idle time at destination ports was instead reduced. The results show that by reducing the estimated waiting time in port by only 50%, and thus reducing the speed of sailing, about 430 tons of CO_2 and 7 tons of SOx emissions per voyage can be saved; moreover, the fuel savings rate is between 7% and 19%. A summarized of studies with carbon/fuel reduction methods being used and results in shown in **Table 4**.

Recent studies also try to combine other advanced algorithms such as the genetic algorithm [42], simulated annealing algorithm [42], and slime mould algorithm [43] with traditional path searching models like Dijkstra's algorithm uses fuel consumption predictions at different points to plan optimal routes [44] [45].

4. Conclusions

GHG emissions from the maritime transport sector have been a hot research topic for more than two decades. IMO states that to achieve the goal of zero carbon emissions by 2100, the development of alternative fuels, such as biofuels from waste biomass and hydrogen from water using renewable energy sources, must be accelerated. Therefore, it is necessary for the major global manufacturers of marine engines to continue to actively promote the research and development or production of biofuel engines, as well as for several ship design companies, shipyards, shipping enterprises and ship owners to continue to develop relevant power ships; While renewable energy sources such as solar and wind are increasingly being used offshore, it is unclear whether they are a viable solution for deep-sea navigation due to the geographical latitude, season, climate, day and night, and the limited available surface area of the ship. The energy sector needs to find alternative solutions to reduce emissions while meeting the growing demand for energy.

Besides, based on the current number of merchant vessels, regulations made by different nations and technical restrictions, replacement of power systems and usage of alternative fuels will take time. Therefore, indicators are released by authorities to quantify the vessel's "energy efficiency" such as EEDI, EEXI and CII. Nonetheless, those measurements are mainly built upon an accurate estimation of fuel consumption and CO_2 emissions. Thus, it is important to find a cost-efficient data-driven solution to monitoring and prediction of ship carbon emissions based on public ship information and environmental conditions.

Current methods for optimal shipping route prediction are transforming from physics law-based mathematical models to big data-based models. Efforts for future decarbonizing in maritime transport can be made in the following aspects:

1) It is necessary to find a statistical algorithm model that combines traditional shipping dynamics and environmental science, to determine a more accurate real-time energy efficiency optimization model and optimal shipping route prediction model based on weather information (wave height, wave period, wind speed), so as to more accurately monitor GHG emissions and achieve the goal of energy conservation and emission reduction. One way of doing that is the use of physical informed Neural Network model (PINN) which will combine traditional shipping dynamics and environmental science into the constrained function in deep learning model in order for the network to be able to understand environmental science and other expert knowledge.

2) With the increasing environmental pressure imposed on the shipping industry by international regulatory agencies, data sharing has become increasingly important for optimizing shipping routes and reducing carbon emissions. Model transformation based on big data requires more massive data in the world to obtain accurate prediction results, the issue of data sharing confidentiality in the shipping industry should be addressed by shipyards, design institutes, shipowners, and inspection institutions to help the progress of the entire marine ecosystem.

3) As the digitalized methods for carbon emission reduction becoming more efficient, the carbon itself is becoming a valuable "currency" in maritime transportation. Thus, the carbon trade exchange (CTX) should be formalized: the regulations on the trading of carbon should be formalized to motivate shipping industry carbon reduction intentions.

Author Contributions

Conceptualization, Data curation, Methodology, Writing, Validation, Shaohan

Wang; Conceptualization, Methodology, Project Administration, Xinbo Wang; Writing, Validation, Feiyang Re; Formal analysis, Project administration, review & editing, Yi Han; review & editing, Validation, Xiangyu Wang; Validation, Data curation, He Jiang; Data curation, Data Cleaning, Junli Duan; Validation, Rui Hua.

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Conflicts of Interest

The authors declare no conflict of interest.

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