frontiers | Frontiers in Marine Science

TYPE Review
PUBLISHED 22 November 2022
DOI 10.3389/fmars.2022.1076352

OPEN ACCESS

EDITED BY
Jihong Chen,
Shenzhen University, China

REVIEWED BY
Liupeng Jiang,
Hohai University, China
Liehui Wang,
East China Normal University, China
Shidong Liang,
University of Shanghai for Science and Technology, China
Mengli Xiao,
East China University of Science and Technology, China

*CORRESPONDENCE
Yanbin Yang
yanbinyang321@163.com

SPECIALTY SECTION
This article was submitted to Marine Affairs and Policy, a section of the journal Frontiers in Marine Science

RECEIVED 21 October 2022
ACCEPTED 08 November 2022
PUBLISHED 22 November 2022

CITATION
Dong J, Zeng J, Yang Y and Wang H (2022) A review of law and policy on decarbonization of shipping. *Front. Mar. Sci.* 9:1076352. doi: 10.3389/fmars.2022.1076352

A review of law and policy on decarbonization of shipping

Junjie Dong[1], Jia Zeng[1], Yanbin Yang[2*] and Hua Wang[3,4]

[1]School of Law, Shanghai Maritime University, Shanghai, China, [2]College of Transport and Communications, Shanghai Maritime University, Shanghai, China, [3]School of Foreign Studies, Xi'an Jiaotong University, Xi'an, China, [4]Center for Asia-Europe Studies, Xi'an Jiaotong University, Xi'an, China

The carbon emission of shipping industry accounts for about 3% of the global total. With the continuous growth of international trade, the decarbonization and carbon neutralization of shipping industry has become an important direction for future development. New technologies, fuels and operational measures can help reduce the industry's greenhouse gas emissions, but without appropriate laws and policies, it will be difficult to achieve the targets set by the industry. Therefore, this paper reviews the decarbonization laws and policies introduced by International Maritime Organization, the European Union and the national levels. Then, this paper reviews the literature from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies. On this basis, we summarize the challenges of shipping in formulating laws and policies and suggestions for improving them. Among them, the most important problem is the coordination between unilateral regulation and uniform regulation. Finally, this paper proposes the development principles based on shipping decarbonization laws and policies, that is, to comply with the principle of "common but differentiated responsibilities", to coordinate the relationship between international trade and international environmental protection, and to guarantee technical assistance to developing countries.

KEYWORDS

shipping, decarbonization, law and policy, emissions, review

1 Introduction

Economic and population growth has become important factors driving global energy demand. They have led to the significant development of international maritime trade and the increase in the number of global shipping ships (Elgohary et al., 2014). In terms of total volume, more than 80% of goods are transported by sea, which accounts for 70% of the total international trade (Yang and Liu, 2022). In the process of consuming fuel oil, the main engine, auxiliary engine and boiler of a ship will produce carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SO_x), carbon monoxide (CO), Unburned coals (HC), and particulate matter (PM2.5, PM10). These gases are major sources of air pollution and greenhouse gases(GHG) that contribute to climate change (Richter et al., 2004; Traut et al., 2018). It has been found that the air pollution near the port is particularly serious (Saxe and Larsen, 2004). Among them, NO_x, SO_2 and inhalable particulates (PM2.5) will harm human health (Pandolfi et al., 2011; Anderson and Bows, 2012; Marelle et al., 2016). CO_2 is the main GHG, which has promoted global warming to a certain extent.

The International Maritime Organization (IMO) Fourth GHG Study estimated the current carbon footprint of the shipping industry and projected GHG emissions from shipping. The study calculated total GHG emissions (including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions, in terms of carbon dioxide equivalents) of the entire ocean sector. GHG emissions from marine sector totaled 977 Mt in 2012 and 1,076 Mt in 2018, an increase of 9.6% compared to 2012. Carbon dioxide accounts for the largest share of GHG emitted. In 2012, 962 Mt of GHG were carbon dioxide, while in 2018, this figure increased by 9.3% to 1056 Mt. Compared with other industries, the share of CO_2 emissions from shipping is still relatively low, accounting for 2.89% of the total anthropogenic CO_2 emissions in 2018. The expected growth rate of the industry shows that decarburization and carbon neutralization of the shipping industry are urgent.

IMO developed a series of scenarios of socioeconomic (GDP and population) and energy-related input variables to estimate the impact on transportation and finally predict the CO_2 emissions from shipping under Business As Usual (BAU). BAU refers to how emissions from shipping develop when other industries follow a certain economic and climate path but shipping does not. Different scenarios were referred to in the forecast. SSP2 and SSP4 refer to the framework of Shared Socioeconomic Pathways, where SSP2 represents A middle-of-the-road scenario (Fricko et al., 2017), SSP4 stands for Inequality - A Road Divided (Calvin et al., 2017). The scenario 'RCP2.6' refers to the framework of Representative Concentration Pathways (Moss et al., 2010; Van Vuuren et al., 2011). The letters 'L' and 'G' refer to the method of estimation used for establishing the relationship between transport work and the socioeconomic input variables, where letter 'L' represents the method used for logistics regression and letter 'G' represents the method used for gravity model.

Figure 1 shows the forecast of CO_2 emissions from shipping under BAU. With the continuous growth of maritime transport demand, this will eventually lead to the CO_2 emissions from 10 million tons in 2018 to 10 - 15 million tons in 2050, an increase of 0 - 50% over the level in 2018, equivalent to 90 - 130% of the level in 2008. The difference of the forecast of CO_2 emissions is due to the fact that the predicted values of traffic work and GDP are not identical under various scenarios. In addition to the impact of scenario setting, the methods of logistics regression and gravity model make differences in the predicted values of traffic work.

IMO's emission reduction target is to reduce the total GHG emissions of the international shipping industry by at least 50% by 2050 compared with 2008 (IMO, 2020a). At present, it is in the initial stage of strategy implementation and adjustment. At the beginning of 2023, EEXI, CII and other environmental new policies will be implemented. Numerous studies have shown that new corporate, technical and regulatory measures are needed to decarbonize the shipping industry (Bouman et al., 2017; Traut et al., 2018; Psaraftis, 2019a; Balcombe et al., 2019). Researchers have proposed several alternative fuels, including biofuels (Bengtsson et al., 2012), batteries (Lindstad et al., 2017), wind propulsion (Rehmatulla et al., 2017; Gilbert et al., 2018), and nuclear power (Schøyen and Steger-Jensen, 2017), and they have begun to investigate the drivers of energy conversion in the shipping environment (Geels, 2012; Mander, 2017). The new regulatory measures have also been intensively discussed by the maritime research community. These measures include market-based measures, such as the global fuel tax and emissions trading plan (Van Leeuwen and van Koppen, 2016; Kosmas and Acciaro, 2017), and command and control measures, such as the mandatory ship energy efficiency management plan (Poulsen and Johnson, 2016), more stringent energy efficiency design index (Devanney, 2011) and speed limit (Psaraftis, 2019b). In terms of environmental governance, the new mechanism of combining the public and private sectors in international shipping in a novel way to promote decarbonization has also begun to attract people's attention (Wuisan et al., 2012; Poulsen et al., 2018). These measures will contribute to decarbonization.

Figure 2 illustrates the overall GHG reduction pathway to achieve IMO's ambitious goals, i.e. the absolute level of GHG emission reduction identified in the IMO GHG Strategy (at least 50% reduction by 2050 expressed in the illustrative chart in solid colors and green stripes). The progress of shipping carbon emissions is affected by the unknown "innovative measures, fuels and technologies". At present, the known design, technical and operational measures are reducing the emissions of the industry at the level suggested by IMO, but it is still unclear how unknown innovations, legislation, policies can contribute to decarbonization, especially when the degree of emission reduction is increasing year by year.

The shipping industry will certainly continue to increase its carbon intensity, but energy-saving technologies and reduced speed will not be enough to meet the targets set for the industry. To facilitate this, appropriate laws and policies are needed to regulate. IMO is an international regulatory authority for the shipping industry. In 1997, it revised the International Convention for the Prevention of Pollution From Ships 73/78 (MARPOL for short). The important result of this revision is the birth of supplementary VI Regulations for the Prevention of Air Pollution from Ships, MARPOL Annex VI for short). However, MARPOL Annex VI initially only covered emission control of

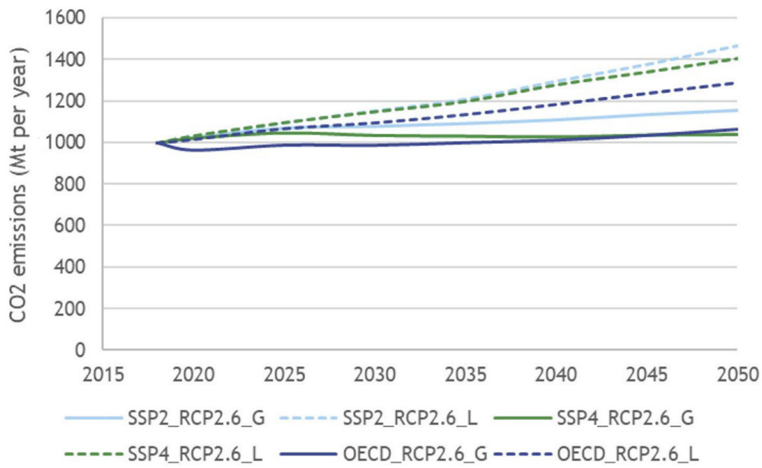

FIGURE 1
BAU forecasts of CO_2 emissions from ships under different scenarios. Source: IMO Fourth GHG Study (IMO, 2020).

air pollutants such as ozone-depleting substances, nitrogen oxides, sulfur oxides and volatile organic compounds, as well as standards and procedures for designating nitrogen oxides and sulfur oxides emission control areas, etc. It was not until 2011 that the IMO included marine GHG emission reduction in its regulatory framework. The GHG emitted by ship engines are regulated through the Ship Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). However, due to the high dispersion of ships in the shipping industry and the different sizes and types of ships, ships can be owned by a company in one country, and the owner of the company is a citizen of another country; It can be registered in another country (its flag country) and operated by a company in another country, which makes it difficult to reach consensus on decarbonization laws and policies (Shaffer and Bodansky, 2012). Appropriate laws and policies are conducive to the regulation of shipping decarbonization. However, there are some obstacles in the implementation of these laws and policies. For example, under the shipping decarbonization laws and policies, the cost of international maritime transport may increase. However, this will have an unequal impact on developing countries, which is also a major obstacle to the promotion of carbon reduction.

Therefore, this paper firstly introduces the legal and policy process of shipping decarbonization from IMO, EU level and national level. Then, based on the research of academic literature

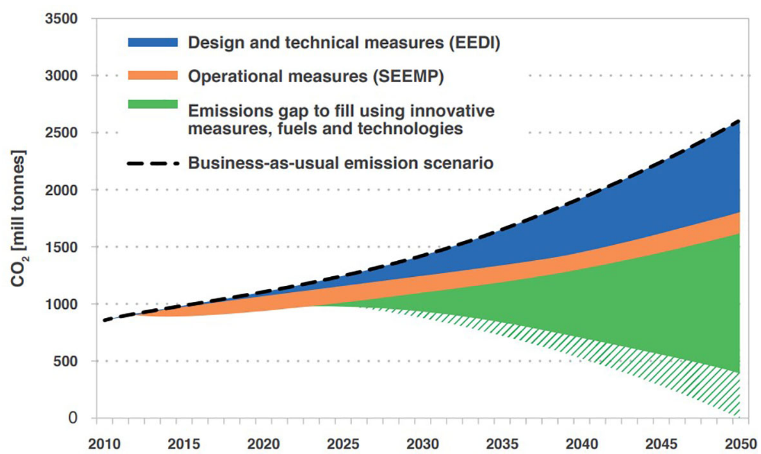

FIGURE 2
IMO GHG reduction pathway. Source: IMO (2020a).

on shipping decarbonization laws and policies, this paper reviews the literature from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies. Next, this paper summarizes the challenges of shipping in formulating laws and policies and suggestions for improving them. Finally, the paper puts forward some suggestions for future development.

2 Development history of laws and policies on shipping decarbonization

2.1 IMO level

In the 1970s, the IMO discussed the problem of controlling air pollution from ships, especially toxic gases from ship exhausts. Air pollution received more attention in 1988 when the Marine Environment Protection Committee (MEPC) agreed to include the issue in its work programme. In 1991, the IMO adopted resolution A.719(17) on the International Convention for the Prevention of Pollution from Ships (MARPOL) Convention. The resolution calls on MEPC to prepare a new draft of the Annex to the MARPOL Convention on reducing air pollution from ships.

In 1995, the United Nations Framework Convention on Climate Change began to address GHG emissions from international shipping, recognizing that such emissions are increasing in volume and have an impact on climate change and the marine environment. The Kyoto Protocol, adopted in December 1997, is an important step in addressing climate change. Article 2 (2) states that the IMO is entrusted with the management of GHG emissions from international shipping. In the same year, the conference of MARPOL adopted Resolution 8 on "Carbon Dioxide Emissions from Ships", which asked the IMO to conduct study on GHG emissions and consider strategies to reduce carbon dioxide.

At the meetings held from 1998 to 2003, IMO mainly discussed the possibility of developing an IMO Strategy for Greenhouse Gas Emissions from Ships through MEPC. It was not until 2003 that the IMO adopted a resolution on "IMO Policies and Practices for Reducing Greenhouse gas Emissions from Ships", urging the IMO to develop mechanisms to address the issue.

Subsequently, IMO continued to actively work on designing regulatory tools to reduce GHG emissions from ships. On July 15, 2011, the IMO made a breakthrough in regulation. Since then, GHG emissions from international shipping will be regulated by revising Annex VI of MARPOL 73/78. The regulatory phases of MARPOL 73/78 are as follows. Step 1: According to MARPOL 73/78, from July 1, 2010, new building regulations on NOx will be applied to ships equipped with 130 kW or above diesel engines. Step 2: Secondary regulation, starting in 2011, aims to reduce NOx emissions by a further 15% to 20%. Step 3: The three-level regulation, which was implemented in 2016, aims to reduce current emissions in the ECA region by 80%. MARPOL 73/78 also added a new Chapter 4 in Appendix VI, introducing the mandatory Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships.

EEDI is a measure of the inherent CO_2 emission level of a ship in the design and construction stages, representing the CO_2 emissions per ton/mile of the ship. EEDI aims to establish a minimum energy efficiency standard for ships in the future (Ren et al., 2019). The emission baseline is established through statistical analysis of existing ships of various types and tonnage, and the energy efficiency of new shipbuilding is controlled on the basis of the baseline. After the implementation of EEDI, the energy efficiency design index of newly built commercial ships of various ship types and different tonnage must be less than the specified baseline ship energy efficiency design index. The smaller the EEDI, the more energy-efficient the design of ships (Attah and Bucknall, 2015).

EEDI reference levels for specific ship type/size combinations are gradually tightened every five years, which is expected to promote technological innovation early in the design process to improve fuel efficiency (Lindstad and Bo, 2018; Ancic et al., 2018). The ship's EEDI has been implemented in three stages since 2015. The first stage is 2015-2020. The ship's EEDI needs to be 10% lower than the baseline, which is calculated based on the reference line of the average efficiency of ships built between 2000 and 2010. The second stage of ship's EEDI is 2020-2024, and the ship's EEDI needs to be 20% lower than the baseline. The third stage of ship's EEDI will start in 2025, and the required reduction of ship's EEDI is set as 30%. At MEPC 74, the implementation of the third stage of EEDI for 12 ship types, including container ships, general cargo ships, LNG carriers, non-traditional cruise ships and 15000 DWT and above gas carriers, has been advanced to 2022, where the EEDI reduction rate of container ships has been improved on the original basis according to different tonnage.

The core of SEEMP is to formulate and effectively implement energy efficiency measures applicable to specific ships, which is divided into four steps: planning, implementation, monitoring, self-evaluation and improvement. Measures include improving voyage plan, weather navigation, speed optimization, optimal trim, optimal ballast, hull maintenance, propulsion system maintenance, etc. (Perera and Mo, 2016a; Hansen et al., 2020). The SEEMP incorporates best practice guidelines for energy efficient operation of ships and promotes the management of efficiency performance of individual ships and fleets over time. This is mainly achieved by the energy efficiency operation index (EEOI), which is a tool for monitoring the ship operation status, enabling the ship operator to measure the fuel efficiency in the ship operation and measure the impact of any change in the operation (Perera and Mo, 2016b).

In 2016, IMO Maritime Environment Protection Committee Resolution 278(70) adopted Amendment VI to MARPOL 73/78, requiring ships subject to the Convention to prepare and implement the Ship Fuel Consumption Data Collection Plan (DCS) (which is part II of SEEMP). It is used to collect and report fuel consumption data of ships over 5000 gross tons. The first calendaryear data collection was completed in 2019.

In April 2018, IMO adopted a preliminary strategy for reducing GHG emissions from ships. This policy framework sets key goals to reduce the carbon intensity of a single ship by implementing the further stage of EEDI for new ships. It is also proposed that by 2050, the annual GHG emissions of ships engaged in international navigation will be reduced by at least half compared with the level in 2008. In addition, in the 21st century, efforts should be made to gradually achieve zero GHG emissions from ships as soon as possible. By 2030, the carbon emission intensity of ships engaged in international navigation should be reduced by at least 40% on average, and efforts should be made to reduce the carbon emission intensity by 70% compared with the level in 2008. The strategy will be revised in 2023 and assess the impact of all proposed measures on countries.

In June 2021, IMO adopted key short-term measures aimed at reducing the carbon intensity of all ships by at least 40% by 2030, which is in line with the IMO's initial strategic objectives. These measures combine technical methods with operational methods to improve ship's energy efficiency. All ships must calculate their EEXI, and ships with more than 5000 gross tons will establish their annual operational carbon intensity index (CII) and carbon intensity rating mechanism. According to the regulations, CII is applicable to ship types above 5000GT (international voyage). According to the CII reached, a ship will be rated from A to E every year, where A is the best and C is the lowest rating requirement (Reusser and Perez, 2020; Daniel et al., 2022). This is the first time that IMO has established a formal rating mechanism for ships. It also sends a strong signal to the market that government departments, port authorities and other stakeholders are encouraged to provide incentives for ships rated A or B. For ships rated as Class D or Class E for three consecutive years, an improvement plan shall be submitted to clarify how to reach the required level (Class C or above).

2.2 EU level

In order to reduce GHG emissions, EU has been promoting the most active laws and policies. In March 2011, the European Commission issued a white paper on transportation as a guiding document of EU, which proposed that the carbon emissions in the field of transportation in 2050 would be reduced by 60% compared with 2008, of which the carbon emissions in maritime transport would be reduced by 40% - 50% compared with 2008. In June 2013, the European Commission proposed a draft regulation on "Monitoring, Reporting, Verification" of GHG emissions from shipping, referred to as "MRV Regulation" (Christodoulou et al., 2021). According to the draft regulation, ships will monitor and calculate fuel consumption, carbon dioxide emissions and related information during their own operations, and the submitted data will be verified by a certified third-party institution and reported within a specified period.

In July 2021, the EU released a package of reform plans called "Fit for 55", which is intended to fully integrate the shipping industry into the existing carbon market by 2026, so as to ensure that the EU's GHG emissions in 2030 will be reduced by at least 55% compared with the 1990 level. The proposal requires that the carbon market covers all emissions from shipping within the European Economic Area, all emissions from ships berthing at European ports, 50% of the carbon emissions from ships sailing from European ports to European ports and 50% of the carbon emissions from ships sailing from European ports to European ports (Council of the European Union, 2021; Sikora, 2021).

CO_2 emissions from shipping account for about a quarter of all transport related emissions in the EU. The EU's "Fit for 55" package proposes to adopt various regulatory policies, including EU Emission Trading System (EU ETS), FuelEU Maritime Initiative, Energy Taxation Directive and Renewable Energy Directive.

2.2.1 EU Emission Trading System (EU ETS)

The EU ETS has been in operation since 2005 and is the earliest carbon market in the world. In 2020, the EU Green Agreement promised to include shipping in the EU ETS. In July 2021, the EU's "fit for 55" package (European Commission, 2021) reaffirmed this point.

In this proposal, the EU emissions trading plan is applicable to ships with 5000 gross tons and above that strictly navigate within the EU will pay for all carbon dioxide emissions, while ships entering and leaving the EU will pay for 50% of their carbon dioxide emissions (no matter how much of the voyage is located inside or outside the EU) (Shi, 2016; Christodoulou et al., 2021).

Shipping enterprises need to purchase emission quotas, and one quota can emit one ton of carbon dioxide. According to the requirements of ETS, each shipping enterprise will be assigned a specific EU member state agency to supervise its compliance. If the quota exceeds the needs of the shipping enterprise, it can be sold to other companies in need, or it can be reserved for use in the next year.

Historically, the new industries that joined ETS were gradually included in the first few years through some free quotas. Unfortunately, free quotas have proved counterproductive, so the European Commission has decided that shipping should not benefit from them. However, the

European Commission proposed a phased approach requiring shipping companies to submit quotas corresponding to their percentage emissions. This phase means that shipping companies will be required to submit quotas according to the following schedule (Cullinane and Yang, 2022).

20% of verified emissions reported in 2023;

45% of verified emissions reported in 2024;

70% of verified emissions reported in 2025;

100% of verified emissions reported in 2026 and every year thereafter.

The phased implementation means that by 2026, the carbon price of each ton of carbon dioxide used for shipping will gradually rise.

On 22 June 2022, the European Parliament passed its version of legislation. In the text, the assembly made significant changes to the Commission's proposal. The most noteworthy is shipping, which proposes to change the number of voyages between EU's and non EU's ports and increase the percentage to 100%. This significantly expanded the influence of the EU ETS outside Europe. Its purpose is to seek to reduce more GHG emissions, but with the increase of compliance costs, this will certainly have a financial impact on shipping. In addition, the version of the European Parliament cancels the phased implementation period, but applies ETS to 100% emissions from 2024.

On 29 June 2022, the Council of EU adopted its version of ETS legislation. In its text, the Council recommended that the Commission retain the quota requirements implemented progressively by the Commission, thereby gradually increasing the number of allowances required and thereby increasing the carbon price.

Both the European Parliament and the Council have taken positions on the ETS proposal, but there are some issues on which the two bodies and the Commission need to agree before the proposal becomes law in the subsequent legislative process.

2.2.2 FuelEU Maritime Initiative

The FuelEU Maritime Initiative will set a maximum limit on the GHG content of the fuel used by ships to stimulate ships calling at European ports to adopt sustainable marine fuel and zero emission technology. Starting from 2025, the EU will impose more and more strict restrictions on the GHG intensity used in marine fuels, and set specific targets for GHG emission reduction, namely, 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, and 75% by 2050 (Cullinane and Yang, 2022).

The reference value for calculating the onboard energy intensity corresponds to the fleet's average onboard energy GHG intensity in 2020, which is determined in 2015/757 according to the data monitored and reported within the framework of EU MRV regulations. This regulation is a necessary precursor to reduce CO_2 emissions at sea in Europe, because it has established the EU MRV database, which provides valuable information about ship energy efficiency, fuel consumption and CO_2 emissions once a year.

From the perspective of impact, the FuelEU Maritime Initiative will stimulate the development of sustainable marine fuels and zero emission technologies, including liquid biofuels, electronic liquids, decarbonized gases (including biological LNG and electronic gases), dehydrocarbon and dehydrocarbon derived fuels.

2.2.3 Energy Taxation Directive

In terms of the scope of energy tax collection, the EU's fossil fuel tax exemption policy in the shipping industry will be phased out, and the fossil fuel used in shipping will be retaxed, and the minimum tax rate will be set. According to the previous provisions of the Directive, marine fuels are tax exempt within the EU. All marine fuels sold in and used within the EU will be taxed from January 2023. In this way, marine fuels with serious pollution will be taxed the most. For example, when traditional fossil fuels are used as fuels, they will be taxed at a higher rate (i.e. 10.75 euro/GJ). When advanced sustainable biomass fuels and non-biomass renewable fuels (e.g. green hydrogen) are used, they can be taxed at the lowest rate (i.e. 0.15 euro/GJ) (Duscha and del Rio, 2017; Voulis et al., 2019).

2.2.4 Renewable Energy Directive

Renewable Energy Directive has set a higher target of 40% renewable energy in 2030. Among them, the intensity of GHG emissions in the transport sector is required to be reduced by 13%. These new goals will strengthen the demand for green hydrogen in the transport sector (Kohl et al., 2021). The plan also aims to promote renewable fuels to achieve the maximum emission reduction of GHG, and sets a target of 13% to reduce the carbon emission intensity in the transport sector, including international aviation and marine fuels. The target level of advanced biofuels has been raised to 2.2% of energy consumption in the transportation sector, and the target of 2.6% has been set for hydrogen and hydrogen based synthetic fuels in this industry. The Directive only sets targets, and more specific and directly related measures such as the EU ETS, FuelEU Maritime Initiative and Energy Taxation Directive are intended to help achieve them.

2.3 National level

As a global leader in the green transformation of shipping, Norwegian government aims to reduce the carbon emissions of domestic shipping and fishing vessels by 50% by 2030, and continue to promote the green development of the shipping industry through legislation, planning, financial support and other means. The Norwegian government also plays an important role in shipping carbon emission reduction. It has formulated a long-term subsidy and tax preference plan for the purchase of environment-friendly ships. In 2019, Norway's national budget set up a special fund to support the introduction of low emission and zero emission schemes for high-speed passenger ships, and used it as a subsidy for local governments to purchase environment-friendly high-speed ships. In July 2020, the Norwegian government required that all ships sailing in the Norwegian fjord area, which is listed as a world heritage site, must achieve zero emissions before 2026, becoming the first zero emissions area for ships in the world. In November 2020, IMO and the Norwegian government launched the GreenVoyage-2050 project, and the Norwegian government donated an additional 4.3 million dollars to IMO for this project. The project aims to support the decarbonization of the shipping industry according to IMO's initial strategy on reducing GHG emissions from shipping.

On April 20, 2021, the sixth carbon budget released by the UK government announced its latest emission reduction target, that is, by 2035, the carbon dioxide emissions will be reduced by 78% compared with the 1990 level. The UK became the first country in the world to include international shipping and aviation in its national carbon budget. In addition, the UK government has committed to provide 206 million pounds for research, which will be provided by the UK Ministry of Transport to the UK Shipping Office for Reducing Emissions. The purpose is to fund British companies to research and develop shipping emission reduction technologies, and support innovative enterprises.

In January 2022, the Danish Shipping Association introduced a strategy, which aims to accelerate the green transformation of global shipping by overcoming the regulatory, financial and political barriers that hinder the shipping neutralization. The strategy proposes to make good use of the potential of Denmark's shipping industry in offshore wind power and carbon capture and storage (CCS), and sets the goal of Denmark's shipping industry to achieve climate neutrality by 2050 without compensation, and to enable at least 5% of Denmark's operating fleet to use clean zero emission fuels such as green hydrogen, green ammonia, green methanol and advanced biofuels by 2030. All new ships ordered by Danish shipowners from 2030 will use net zero emission fuel or other zero emission propulsion methods.

Singapore Maritime and Port Authority (MPA) is the main body promoting the decarbonizing reform of Singapore's shipping industry. In 2011, MPA launched the Singapore Maritime Green Initiative (MSGI), aiming to reduce the environmental impact of shipping and related activities, and committed to investing up to 100 million Singapore dollars in MSGI within five years. The MSGI was updated in 2016, and the initiative was further extended to December 31, 2024 in 2019. In order to formulate a long-term strategy for the sustainable development of the marine industry, in March 2022, MPA released the Singapore Maritime Decarbonization Blueprint 2050, which will focus on supporting seven key areas of the maritime industry's decarbonization, and will add more than 300 million dollars to guarantee the implementation of the blueprint.

California of the United States promotes the use of shore power by legislation. In 2010, California formally raised the "Control of Toxic Air Pollutants Emission from Auxiliary Diesel Engines of Ocean going Ships at Ports" to California law, mandating container ships, mail ships and refrigerated cargo carriers attached to California ports to improve the utilization of shore power as required during docking. According to the law, the number of times the shipping company uses shore power when it is affiliated to a California port accounts for 50% of the total number of times it is affiliated to the port from 2014 to 2016; 70% from 2017 to 2019; After 2020, it will reach 80%. If it fails to meet the requirements, it will be fined. With the promotion of this law, the utilization rate of shore power in California ports has significantly increased, exceeding 80% in 2020.

China actively integrates with international shipping emission reduction rules to promote green development of domestic shipping industry. Drawing on IMO's practice of improving the design level of ship energy conservation and emission reduction through EEDI, China issued the Limits and Verification Methods for Fuel Consumption of Operating Ships and the Limits and Verification Methods for CO2 Emission of Operating Ships in 2012. Drawing on the policy of "Ship Emission Control Area" (ECA) in MARPOL Convention, China began to set up ECA in coastal waters in 2015 in accordance with the Air Pollution Prevention Law. In 2016, China issued the Limits and Measurement Methods for Exhaust Pollutants from Ship Engines (China's first and second stages) to control the emission of atmospheric pollutants from ships with stricter standards. Since 2017, the scope of water areas for controlling sulfur content in fuel oil used by ships has been continuously increased. In 2018, the Maritime Safety Administration of the People's Republic of China issued the Measures for the Collection and Management of Energy Consumption Data of Ships, which requires ships with a gross tonnage of 400 tons or more or a main propulsion power unit of 750 kilowatts or more to collect data on fuel consumption, sailing time, mileage, cargo turnover and other data according to the prescribed methods and procedures, laying a foundation for building a monitoring, reporting and verification (MRV) system for ship carbon emissions.

As a major player in the global shipping and shipbuilding industry, Japan is investing capital and research efforts in the introduction of ultra-low emission or zero emission ships, from shipbuilding to fuel development. In August 2019, Japan established the "Ship Carbon Recovery Working Group" to discuss the feasibility of using methane technology for zero emission ship fuel. In March 2020, the Japanese government released the "Zero Emission Roadmap for International

Shipping", which aims to build a "Zero Emission Ecological Ship" by 2028.

The Ministry of Ocean and Fisheries and the Ministry of Trade, Industry and Energy of the Republic of Korea jointly announced the "2030 Green Ship-K Initiative" to seek to develop an environment-friendly and sound image of Korean ships. The initiative aims to reduce GHG by 40% in the next 25 years and by 70% in the next 30 years. Various departments announced that they would provide 960 billion Korean won to develop the application of liquefied natural gas (LNG), battery power and hybrid power systems in shipping.

3 Literature review on laws and policies of shipping decarbonization

With the proposal of laws and policies on shipping decarbonization, scholars have also carried out some research to promote the development of laws and policies on shipping decarbonization. Romano and Yang (2021) proposed that the research was also carried out according to some regulations issued at that time. In their analysis, it was found that only one paper studied the impact of shipping emissions on port areas in 2005-08. From 2009 to 2012, there were 5 papers in this field. This increase may be due to the regulation formulated in 2008, namely the ECA amendment formulated by IMO to limit SO_x and NO_x emissions, which came into effect in July 2010. This paper sorts out the existing literature and reviews it from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies.

3.1 Applicability and evaluation of laws and policies

The concept of "common but differentiated responsibilities" means different treatment between developed countries and developing countries (Rajamani, 2000), which is the basis of climate change discussion in the United Nations Framework Convention on Climate Change (UNFCCC). The position of the IMO is that shipping industry regulation needs to be implemented at the global level, so it should be applied equally to all flag countries. Because of the international climate mitigation policy, the cost of international maritime transport may increase, and even if the cost increases slightly, it may also have a disproportionate impact on developing countries, especially small island countries and landlocked countries. The conflict between the two has always been a major obstacle to progress (Cullinane and Cullinane, 2013). Miola et al. (2011) proposed that if the sector is listed as a separate party to the post Kyoto Protocol, a fund should be set up to help developing countries cope with climate change. In this way, the global ceiling of marine fuel is in line with the principle of "equal treatment" of IMO, regardless of flag countries, while financial support is in line with the concept of "common but differentiated responsibilities" of international climate change negotiations.

Since the IMO Marine Environment Protection Committee reached an agreement on further considering the new work plan and guidelines for market-based measures (MBMs) in emission control, it has conducted some research on shipping carbon tax, and scholars have studied the feasibility and impact of this policy. Tseng and Pilcher (2016) proposed the port ship emission tax scheme, which they believe is feasible at the policy level. Han and Notteboom (2017) simulated the impact of the port emission tax plan on port competition, and believed that the collection of emission taxes would generally lead to the reduction of port cargo volume (due to the increase of related costs), which would damage the profitability of port operators and shipping companies. Zhu et al. (2018) proposed that the uncertainty of carbon tax policy would affect the fleet planning of shipping companies and increase costs. Under the uncertainty of policies, enterprises will lease more ships and invest more in fleet operation when facing the risk of high carbon tax. Ding et al. (2020) proposed two carbon tax schemes based on international reality: fixed tax rate scheme and progressive tax rate scheme. The study found that the unit cost under the progressive carbon tax is lower than that under the fixed carbon tax within a given route, so the company may be willing to comply with the progressive tax plan.

Niese et al. (2015) simulated the uncertainty of goods trade economy in the face of growing environmental problems and emission regulations. Results inform decisions about when, where, and how to incorporate the changeability that maximizes expected life cycle rewards. Balcombe et al. (2019) divided the shipping carbon reduction policies into three categories: Emissions price controls, Emissions quality controls, and Subsidies, and studied their main strengths and weaknesses. Emissions price controls, such as carbon taxes, represent high economic and environmental efficiency, but may lead to restrictions on development, and may lead to the transition from maritime transport to high carbon transport routes (air and road). Another disadvantage is the risk of carbon leakage. A quantity control mechanism like ETS has two main benefits. First, its flexible nature allows the upper limit to change, but can determine the emission reductions achieved. As the industry is highly cyclical, changes in demand for emissions will affect emission prices, so it is necessary to set an appropriate upper limit. Direct financial support through subsidies is very effective in other sectors, and can be acted upon quickly, and can be targeted at technology or interventions. Subsidies must be carefully implemented and monitored and revised when conditions change.

In addition, for some laws and policies that have been implemented, scholars have also studied the applicability of these policies and judged them. For example, Hansen et al.

(2020) discussed how to translate SEEMP legislation into practice, and how crew members can accept and use it in daily operations. It is found that many goals or requirements conflict with energy-saving operation. The implementation of SEEMP legislation is challenging to a certain extent, because multiple participants affecting ship operations need to cooperate and have the same priority in energy efficiency. Nikopolou et al. (2013) evaluated the increased cost of adopting different methods to comply with the strict emission requirements of the Nordic SECA. These cost increases are likely to directly translate into higher tax rates. This will have a significant impact on the field of competition, especially in arenas such as Northern Europe, where a large proportion of goods flow is relatively short (i.e. within Europe). However, the implementation of MBMs may bring benefits to the shipping industry, as these measures may help to partially reduce the additional cost burden of complying with atmospheric emission regulations. Xiao et al. (2022) evaluated the control effect of the ECA policies on pollutant emissions and found that the control effect of various ECA policies on pollutant emissions is not the same, that is, the impact of ECA policies on SO_2 and particulate matter is the largest, and that on NO_x is minimal. Touratier-Muller et al. (2019) studied the policy effectiveness of the French government on SMEs since the implementation of the two freight plans. Regarding the mandatory initiative to force all French carriers to use four computing technologies to calculate and transmit CO_2 information (Decree 2011-1336), they concluded that the government initiative was not successful. At Fedi's research (Fedi, 2017), he found that the EU MRV regulations are facing severe criticism from the European shipping industry, especially from the European Community Shipowners Association and the International Chamber of Shipping. The shipowner hopes to persuade the EU to align its unilateral MRV regulations with the DCS of the IMO, because the shipping industry is a global industry that needs global rules.

3.2 Improvement of laws and policies

The decarbonization of shipping needs the support of various laws or policies, including stricter energy efficiency targets, speed limits and low-carbon fuel standards. Halim et al. (2018) believed that these policies could be implemented by member states of IMO. Governments and ports can provide the necessary infrastructure, such as shore power facilities, charging systems and alternative fuel fuelling facilities. Governments can also encourage domestic green shipping, promote research and development of zero carbon technologies, and develop programs to improve the commercial feasibility of these technologies. Financial institutions can develop green financial programs to stimulate sustainable shipping. Kontovas and Psaraftis (2011) compared the emission standards and technical solutions of EU and IMO on climate change. It is found that from a political perspective, it is easier to require technical and operational measures through legislation, which may indeed have great potential to reduce emissions. Chircop (2019) proposed the need for new international standards, tools and best practices to supplement the existing energy efficiency management rules in the 1973/78 International Convention for the Prevention of Pollution from Ships. Miola et al. (2011) proposed that the international shipping sector should meet the following four points when formulating carbon reduction laws and policies: (1) policymakers should set binding and ambitious long-term emission reduction targets, (2) economic incentives to encourage flexible action, (3) knowledge and technology sharing of innovative mitigation practices, and (4) transparency, administrative feasibility and easy to implement monitoring and implementation mechanisms.

However, since major international strategies often do not produce immediate results, this means that IMO should take stronger measures and lay the foundation for stronger goals before 2023. IMO should seize the imminent opportunity to bring a set of revised objectives for COP26 and MEPC77 (Bullock et al., 2022). Shi and Gullett (2018) proposed The challenges of regulating GHG emissions from international shipping, including how to allocate emissions to individual states, how to determine the appropriate regulatory roles for the UNFCCC and the IMO, how to choose among different regulatory tools to achieve a unable reduction in shipping GHG emissions, and how to balance the interests of developed and developing states. The interest disputes between developed and developing states mainly lie in the "common but differentiated responsibilities" (CBDR) principle and "no more favorable treatment" (NMFT) principle. The CBDR principle requires both developed and developing countries to make contributions to solving environmental problems. However, because developed states have made great historical contributions to environmental problems and developing states have weak capabilities, developed states should bear the main responsibility. The NMFT principle refers to "the port country implements applicable standards for all ships in its ports in a unified way, regardless of the flag it flies". The NMFT principle seeks equal treatment for all countries, while the CBDR principle seeks to reduce the responsibilities of developing countries on the premise of fairness. This makes it difficult for shipping carbon emission reduction to form a global unified policy. Heitmann and Khalilian (2011) proposed the best way to allocate international shipping emissions within the UNFCCC system is to allocate them to all parties according to the nationality of the transport company, or the country where the ship is registered or the operator is located.

Regional or unilateral regulations such as emission control areas (ECAs) and regional speed limits were opposed by governments and regulators (Chang and Wang, 2012; Panagakos et al., 2014; Sys et al., 2016). Homsombat et al.

(2013) compared the unilateral and coordinated pollution tax policies of a region, and provided differentiated but alternative services for shipping companies in competing ports in the region. They found that ports that unilaterally levy local pollution taxes will not only push the shipping business to their competitors' ports, but also suffer more spill pollution. Sheng et al. (2017) developed a comprehensive model to investigate the economic and environmental impacts of the uniform marine emission regulation and uniform marine emission regulation. The results show that unilateral regulation may actually lead to an increase in total emissions, while unified regulation will always reduce total emissions. Under any kind of regulation, it may have an asymmetric impact on shipping companies and ports. Finally, it is recommended not to adopt unilateral regulations, and the importance of considering the impact of alternative emission policies on shipping companies and port operations is emphasized. Primorac's research (Primorac, 2018) has the same results. He studied Legal challenges of implementing the system of monitoring carbon dioxide emissions from maritime transport within ports of call under the jurisdiction of EU member states The European legal sources related to this issue were reviewed, and the impact of the application of relevant provisions on the reduction of CO_2 and emissions from ports was analyzed. Finally, it was considered that it was necessary to achieve international harmonization in laws and policies to reduce CO_2 emissions from global maritime transport.

Although unilateral laws and regulations have some shortcomings, there are different views in academic research and practice. Gilbert and Bows (2012) proposed that although the industry still prefers global emission reduction policies, the urgency of requiring emission reduction requires exploring complementary sub global measures. Wan et al. (2018) proposed that IMO should not only rely on universal or majority consensus (top-down approach) to regulate marine pollution, but should recognize and encourage constructive regional action (patchwork approach) to solve the problem of GHG emission reduction. Regional action should not be equated with illegitimate unilateralism; On the contrary, they can play an important catalytic role in promoting global policy action (Shaffer and Bodansky, 2012).

The concept of multi center climate governance proposed by Nobel Prize winner Elinor Ostrom believes that although no country can solve the problem of global climate change, it does not mean that only one global unified solution can solve it. Maritime supervision and governance scholars adopt the concept of multi center and emphasize the fragmented, multi-level and overlapping structure of shipping governance (Bloor et al., 2014; Van Leeuwen, 2015). The case of shipping sulfur and nitrogen emission reduction provides an example for policy experiment and learning how to occur in a multi center sequence. Since the early 2000s, some national or regional policies, such as Norway's voluntary agreement, different port taxes in Sweden, emission standard restrictions set by the EU and the introduction of the EU's emission control area (ECA), have not distorted the fair competition environment. Gritsenko (2017) put forward four principles that take into account the specificity of shipping to support polycentric marine government in his research, which are respectively promote institutional diversity, target shipping sectors, use subsidiarity as a criterion for policy implementation, demonization of information design

Yang et al. (2017) proposed that the establishment of China's MRV regulations is the basis for the introduction of carbon reduction regulations or policies. After quantifying CO_2 emissions, it is suggested that Chinese policymakers consider taking mitigation measures, such as a cap and trade program and carbon taxes. Policy formulation requires decision makers to conduct various deliberations and discussions to ensure that practices comply with international regulations. Walsh et al. (2017) proposed that it is necessary for the UK to adopt new strict policies, such as regulatory or financial incentives, to reduce the basic complexity of the shipping industry.

4 Conclusions

With the accelerated economic recovery and the increasing demand of the shipping market, more GHG emissions have also been caused. In order to promote the sustainable development of shipping and accelerate the process of carbon neutralization of shipping, IMO has also proposed the goal of reducing the total GHG emissions of the international shipping industry by at least 50% compared with 2008 by 2050. New technologies, fuels and operational measures will help reduce GHG emissions in the industry, but without appropriate laws and policies, it will be difficult to achieve the goals set by this industry.

IMO has been committed to promoting the emission reduction of GHG in the shipping industry, and listed reducing carbon emissions from ships as a key management measure. In order to promote the international shipping industry to achieve the emission reduction goal as soon as possible, the mandatory EEDI has been introduced for new ships, and the SEEMP has been introduced for all ships. It is required that ships to which the Convention applies should prepare and implement the Ship Fuel Consumption Data Collection Plan (DCS). In the latest regulations, all ships must calculate their existing EEXI. Ships with a gross tonnage of more than 5000 tons will establish their annual operational CII and carbon intensity rating mechanism. In the future, IMO will continue to strive to achieve the goals set in its "Preliminary Strategy". To this end, it has developed a work plan and timetable to consider candidate short-term and medium-term measures. In order to reduce GHG emissions, EU has been promoting the most active laws and policies, including the guidance document of the white paper on transportation, MRV regulations and the package reform plan of “Fit for 55”. The shipping related items in “Fit for 55” are EU ETS, FuelEU Maritime Initiative, Energy Tax Directive and Renewable Energy Directive. In addition, the national level is also actively promoting shipping carbon reduction legislation and policies.

In view of the academic literature on the research of shipping decarbonization laws and policies, this paper reviews the literature from two aspects: applicability and evaluation of laws and policies, improvement of laws and policies. The existing literature has analyzed the applicability of existing laws and policies in different countries and different subjects from multiple perspectives, proposed obstacles to policy implementation, and put forward some countermeasures and suggestions from the IMO and national levels. Under the laws and policies of shipping decarbonization, the cost of international maritime transport may increase, but this will have an unequal impact on developing countries, which is also a major obstacle to the promotion of carbon reduction. In addition, more research has been done on the coordination between unilateral regulations and unified regulations. The study found that ports that unilaterally levy local pollution taxes will not only push the shipping business to their competitors’ ports, but also suffer more spillover pollution. Unilateral regulations may lead to an increase in total emissions, while unified regulations will always reduce total emissions. But only global unified regulations cannot completely solve the problem of GHG emissions from shipping. Therefore, we should also recognize and encourage constructive unilateral or regional regulations to solve the problem of GHG emission reduction. It is worth noting that regional action should not be equated with illegitimate unilateralism. How to link unilateral laws and regulations with those of IMO is a problem worth studying in the future, and it is also a problem that each country or region must consider when formulating laws and regulations.

Now, facing the huge pressure of carbon emission targets and taking strict actions, IMO urgently needs more perfect laws and policies. This paper gives the following countermeasures and future research directions. First, it is suggested that CBDR principle in line with environmental justice should be placed in an overall position as the source of law in this field. Second, constructive regional laws and policies should be recognized and encouraged to solve the problem of GHG emission reduction, and regional laws and regulations should also be properly connected with the regulations of IMO. Third, it is very important to coordinate the relationship between international trade and international environmental protection. Fourth, it is necessary to introduce regulations on technology development and transfer under the WTO framework as soon as possible, so as to promote technical assistance from developed countries to developing countries at the legal level. Finally, it should be made clear that simply talking about principles cannot effectively promote decarbonization of shipping. In order to promote the construction of the carbon emission reduction mechanism of the maritime industry under the guidance of the principles, we should consider how to effectively implement it and how to avoid unilateralism and hegemonism in the implementation.

Author contributions

JD, JZ, YY, and HW conceived the manuscript. JD and YY wrote the manuscript and synthesized the data. JZ and HW helped write the manuscript and provided constructive feedback. All authors contributed to the article and approved the submitted version.

Funding

This research was funded by the National Key R&D Program of China, grant number 2022YFF0903401.

Acknowledgments

The authors are thankful to the referee for the useful suggestions and comments.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Ancic, I., Theotokatos, G., and Vladimir, N. (2018). Towards improving energy efficiency regulations of bulk carriers. *Ocean Engineering* 148, 193–201. doi: 10.1016/j.trd.2018.06.001

Anderson, K., and Bows, A. (2012). Executing a scharnow turn: reconciling shipping emissions with international commitments on climate change. *Carbon Management.* 3 (6), 615–628. doi: 10.4155/CMT.12.63

Attah, E. E., and Bucknall, R. (2015). An analysis of the energy efficiency of LNG ships powering options using the EEDI. *Ocean Engineering.* 110, 62–74. doi: 10.1016/j.oceaneng.2015.09.040

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., et al. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion Management.* 182, 72–88. doi: 10.1016/j.enconman.2018.12.080

Bengtsson, S., Fridell, E., and Andersson, K. (2012). Environmental assessment of two pathways towards the use of biofuels in shipping. *Energy Policy* 44, 451–463. doi: 10.1016/j.enpol.2012.02.030

Bloor, M., Sampson, H., and Gekara, V. (2014). Global governance of training standards in an outsourced labor force: The training double bind in seafarer license and certification assessments. *Regul. Governance.* 8 (4), 455–471. doi: 10.1111/rego.12042

Bouman, E. A., Lindstad, E., Rialland, A. I., and Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–a review. *Transportation Res. Part D: Transport Environment.* 52, 408–421. doi: 10.1016/j.trd.2017.03.022

Bullock, S., Mason, J., and Larkin, A. (2022). The urgent case for stronger climate targets for international shipping. *Climate Policy.* 22 (3), 301–309. doi: 10.1080/14693062.2021.1991876

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., et al. (2017). The SSP4: A world of deepening inequality. *Global Environ. Change-Human Policy Dimensions.* 42, 284–296. doi: 10.1016/j.gloenvcha.2016.06.010

Chang, C. C., and Wang, C. M. (2012). Evaluating the effects of green port policy: Case study of kaohsiung harbor in Taiwan. *Transportation Res. Part D: Transport Environment.* 17 (3), 185–189. doi: 10.1016/j.trd.2011.11.006

Chircop, A. (2019). The IMO initial strategy for the reduction of GHGs from international shipping: a commentary. *Int. J. Mar. Coast. Law.* 34 (3), 482–512. doi: 10.1163/15718085-13431093

Christodoulou, A., Dalaklis, D., Olcer, A. I., and Masodzadeh, P. G. (2021). Inclusion of shipping in the EU-ETS: Assessing the direct costs for the maritime sector using the MRV data. *Energies* 14 (13), 3915. doi: 10.3390/en14133915

Council of the European Union (2021) *Fit for 55.* Available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

Cullinane, K., and Cullinane, S. (2013). Atmospheric emissions from shipping: the need for regulation and approaches to compliance. *Transport Rev.* 33 (4), 377–401. doi: 10.1080/01441647.2013.806604

Cullinane, K., and Yang, J. (2022). Evaluating the costs of decarbonizing the shipping industry: A review of the literature. *J. Mar. Sci. Engineering.* 10 (7), 946. doi: 10.3390/jmse10070946

Daniel, H., Trovao, J. P. F., and Williams, D. (2022). Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo Carrier. *eTransportation* 11, 100150. doi: 10.1016/j.etran.2021.100150

Devanney, J. (2011). The impact of the energy efficiency design index on very large crude carrier design and CO2 emissions. *Ships Offshore Structures.* 6 (4), 355–368. doi: 10.1080/17445302.2010.546651

Ding, W., Wang, Y., Lei, D., and Hu, H. (2020). Does a carbon tax affect the feasibility of Arctic shipping? *Transportation Res. Part D: Transport Environment.* 80, 102257. doi: 10.1016/j.trd.2020.102257

Duscha, V., and del Rio, P. (2017). An economic analysis of the interactions between renewable support and other climate and energy policies. *Energy Environ.* 28 (1-2), 11–33. doi: 10.1177/0958305X16685456

Elgohary, M. M., Seddiek, I. S., and Salem, A. M. (2014). Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel. *Proc. Institution Mechanical Engineers Part M: J. Eng. Maritime Environment.* 229 (4), 365–375. doi: 10.1177/1475090214522778

European Commission (2021) *Regulation of the European parliament and of the council on the use of renewable and low-carbon fuels in maritime transport and amending directive.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021AE3630 2009.

Fedi, L. (2017). The monitoring, reporting and verification of ships' carbon dioxide emissions: a European substantial policy measure towards accurate and transparent carbon dioxide quantification. *Ocean Yearbook.* 31 (1), 381–417. doi: 10.1111/1467-9388.00243

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., et al. (2017). The marker quantification of the shared socioeconomic pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environ. Change-Human Policy Dimensions.* 42, 251–267. doi: 10.1016/j.gloenvcha.2016.06.004

Geels, F. W. (2012). A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *J. Transport Geogr.* 24, 471–482. doi: 10.1016/j.jtrangeo.2012.01.021

Gilbert, P., and Bows, A. (2012). Exploring the scope for complementary sub-global policy to mitigate CO2 from shipping. *Energy Policy.* 50, 613–622. doi: 10.1016/j.enpol.2012.08.002

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., and Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *J. Cleaner Production.* 172, 855–866. doi: 10.1016/j.jclepro.2017.10.165

Gritsenko, D. (2017). Regulating GHG emissions from shipping: Local, global, or polycentric approach? *Mar. Policy.* 84, 130–133. doi: 10.1016/j.marpol.2017.07.010

Halim, R. A., Kirstein, L., Merk, O., and Martinez, L. M. (2018). Decarbonization pathways for international maritime transport: A model-based policy impact assessment. *Sustainability* 10 (7), 2243. doi: 10.3390/su10072243

Han, C., and Notteboom, T. (2017). Modelling emission control taxes in port areas and port privatization levels in port competition and co-operation sub-games. *Transportation Res. Part D: Transport Environment.* 56, 110–128. doi: 10.1016/j.trd.2017.07.030

Hansen, E. K., Rasmussen, H. B., and Lützen, M. (2020). Making shipping more carbon-friendly? exploring ship energy efficiency management plans in legislation and practice. *Energy Res. Soc. Science.* 65, 101459. doi: 10.1016/j.erss.2020.101459

Heitmann, N., and Khalilian, S. (2011). Accounting for carbon dioxide emissions from international shipping: Burden sharing under different UNFCCC allocation options and regime scenarios. *Mar. Policy.* 35 (5), 682–691. doi: 10.1016/j.marpol.2011.02.009

Homsombat, W., Yip, T. L., Yang, H., and Fu, X. (2013). Regional cooperation and management of port pollution. *Maritime Policy Management.* 40 (5), 451–466. doi: 10.1080/03088839.2013.797118

IMO (2020) *Fourth GHG study*. Available at: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf.

IMO (2020a) *IMO Action to reduce greenhouse gas emissions from international shipping.* Available at: https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/IMO%20ACTION%20TO%20REDUCE%20GHG%20EMISSIONS%20FROM%20INTERNATIONAL%20SHIPPING.pdf.

Kohl, M., Linser, S., Prins, K., and Talarczyk, A. (2021). The EU climate package "Fit for 55" - a double-edged sword for europeans and their forests and timber industry. *For. Policy Economics.* 132, 102596. doi: 10.1016/j.forpol.2021.102596

Kontovas, C. A., and Psaraftis, H. N. (2011). Climate change policy IN shipping focusing ON emission standards and technology measures. *Environ. Eng. Manage. J.* 10 (10), 1589–1596. doi: 10.30638/eemj.2011.220

Kosmas, V., and Acciaro, M. (2017). Bunker levy schemes for greenhouse gas (GHG) emission reduction in international shipping. *Transportation Res. Part D: Transport Environment.* 57, 195–206. doi: 10.1016/j.trd.2017.09.010

Lindstad, E., and Bo, T. I. (2018). Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements. *Transportation Res. Part D: Transport Environment.* 63, 276–290. doi: 10.1016/j.trd.2018.06.001

Lindstad, H. E., Eskeland, G. S., and Rialland, A. (2017). Batteries in offshore support vessels – pollution, climate impact and economics. *Transportation Res. Part D: Transport Environment.* 50, 409–417. doi: 10.1016/j.trd.2016.11.023

Mander, S. (2017). Slow steaming and a new dawn for wind propulsion: A multi-level analysis of two low carbon shipping transitions. *Mar. Policy.* 75, 210–216. doi: 10.1016/j.marpol.2016.03.018

Marelle, L., Thomas, J. L., Raut, J. C., Law, K. S., Jalkanen, J. P., Johansson, L., et al. (2016). Air quality and radiative impacts of arctic shipping emissions in the summertime in northern Norway: from the local to the regional scale. *Atmospheric Chem. Physics.* 16 (4), 2359–2379. doi: 10.5194/acp-16-2359-2016

Miola, A., Marra, M., and Ciuffo, B. (2011). Designing a climate change policy for the international maritime transport sector: market-based measures and technological options for global and regional policy actions. *Energy Policy.* 39 (9), 5490–5498. doi: 10.1016/j.enpol.2011.05.013

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463 (7282), 747–756. doi: 10.1038/nature08823

Niese, N. D., Kana, A. A., and Singer, D. J. (2015). Ship design evaluation subject to carbon emission policymaking using a Markov decision process framework. *Ocean Engineering.* 106, 371–385. doi: 10.1016/j.oceaneng.2015.06.042

Nikopolou, Z., Cullinane, K., and Jensen, A. (2013). The role of a cap-and-trade market in reducing NOx and SOx emissions: Prospects and benefits for ships within the northern European ECA. *Proc. Institution Mechanical Engineers Part M-Journal Eng. Maritime Environment.* 227 (M2), 136–154. doi: 10.1177/1475090212459130

Panagakos, G. P., Stamatopoulou, E. V., and Psaraftis, H. N. (2014). The possible designation of the Mediterranean Sea as a SECA: A case study. *Transportation Res. Part D: Transport Environment.* 28 (5), 74–90. doi: 10.1016/j.trd.2013.12.010

Pandolfi, M., Gonzalez-Castanedo, Y., Alastuey, A., Jesus, D., Mantilla, E., de la Campa, A. S., et al. (2011). Source apportionment of PM10 and PM2.5 at multiple sites in the strait of Gibraltar by PMF: impact of shipping emissions. *Environ. Sci. pollut. Res.* 18 (2), 260–269. doi: 10.1007/s11356-010-0373-4

Perera, L. P., and Mo, B. (2016a). Data analysis on marine engine operating regions in relation to ship navigation. *Ocean Engineering.* 128, 163–172. doi: 10.1016/j.oceaneng.2016.10.029

Perera, L. P., and Mo, B. (2016b). Emission control based energy efficiency measures in ship operations. *Appl. Ocean Res.* 60, 29–46. doi: 10.1016/j.apor.2016.08.006

Poulsen, R. T., and Johnson, H. (2016). The logic of business vs. the logic of energy management practice: understanding the choices and effects of energy consumption monitoring systems in shipping companies. *J. Cleaner Production.* 112, 3785–3797. doi: 10.1016/j.jclepro.2015.08.032

Poulsen, R. T., Ponte, S., and Sornn-Friese, H. (2018). Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. *Geoforum* 89, 83–95. doi: 10.1016/j.geoforum.2018.01.011

Primorac, Z. (2018). Legal challenges of implementing the system of monitoring carbon dioxide emissions from maritime transport within ports of call under the jurisdiction of EU member states. *Pomorstvo* 32 (1), 3–9. doi: 10.31217/p.32.1.1

Psaraftis, H. N. (2019a). Decarbonization of maritime transport: to be or not to be? *Maritime Economics Logistics.* 21, 353–371. doi: 10.1057/s41278-018-0098-8

Psaraftis, H. N. (2019b). Speed optimization vs speed reduction: the choice between speed limits and a bunker levy. *Sustainability* 11 (8), 2249. doi: 10.3390/su11082249

Rajamani, L. (2000). The principle of common but differentiated responsibility and the balance of commitments under the climate regime. *Rev. Eur. Community Int. Environ. Law.* 9 (2), 120–131. doi: 10.1111/1467-9388.00243

Rehmatulla, N., Parker, S., Smith, T., and Stulgis, V. (2017). Wind technologies: Opportunities and barriers to a low carbon shipping industry. *Mar. Policy.* 75, 217–226. doi: 10.1016/j.marpol.2015.12.021

Ren, H., Ding, Y., and Sui, C. (2019). Influence of EEDI (Energy efficiency design index) on ship–Engine–Propeller matching. *J. Mar. Sci. Engineering.* 7 (12), 425. doi: 10.3390/jmse7120425

Reusser, C. A., and Perez, J. R. (2020). Evaluation of the emission impact of cold-ironing power systems, using a bi-directional power flow control strategy. *Sustainability* 13 (1), 334. doi: 10.3390/su13010334

Richter, A., Eyring, V., Burrows, J. P., Bovensmann, H., Lauer, A., Sierk, B., et al. (2004). Satellite measurements of NO_2 from international shipping emissions. *Geophysical Res. Letters.* 31 (23), L23110. doi: 10.1029/2004GL020822

Romano, A., and Yang, Z. (2021). Decarbonisation of shipping: A state of the art survey for 2000–2020. *Ocean Coast. Management.* 214, 105936. doi: 10.1016/j.ocecoaman.2021.105936

Saxe, H., and Larsen, T. (2004). Air pollution from ships in three Danish ports. atmospheric environment. *Atmospheric Environment* 38 (24), 4057–4067. doi: 10.1016/j.atmosenv.2004.03.055

Schøyen, H., and Steger-Jensen, K. (2017). Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications. *J. Cleaner Production.* 169, 152–160. doi: 10.1016/j.jclepro.2017.05.163

Shaffer, G. C., and Bodansky, D. (2012). Transnationalism, unilateralism and international law. *Transnational Environ. Law.* 1 (1), 31–41. doi: 10.1017/S2047102511000033

Sheng, D., Li, Z. C., Fu, X., and Gillen, D. (2017). Modeling the effects of unilateral and uniform emission regulations under shipping company and port competition. *Transportation Res. Part E: Logistics Transportation Review.* 101, 99–114. doi: 10.1016/j.tre.2017.03.004

Shi, Y. (2016). Reducing greenhouse gas emissions from international shipping: Is it time to consider market-based measures? *Mar. Policy.* 64, 123–134. doi: 10.1016/j.marpol.2015.11.013

Shi, Y., and Gullett, W. (2018). International regulation on low-carbon shipping for climate change mitigation: Development, challenges, and prospects. *Ocean Dev. Int. Law.* 49 (2), 134–156. doi: 10.1080/00908320.2018.1442178

Sikora, A. (2021). European Green deal – legal and financial challenges of the climate change. *ERA Forum.* 21, 681–697. doi: 10.1007/s12027-020-00637-3

Sys, C., Vanelslander, T., Adriaenssens, M., and Rillaer, I. V. (2016). International emission regulation in sea transport: Economic feasibility and impact. *Transportation Res. Part D: Transport Environment.* 45, 139–151. doi: 10.1016/j.trd.2015.06.009

Touratier-Muller, N., Machat, K., and Jaussaud, J. (2019). Impact of French governmental policies to reduce freight transportation CO2 emissions on small- and medium-sized companies. *J. Cleaner Production.* 215, 721–729. doi: 10.1016/j.jclepro.2019.01.052

Traut, M., Larkin, A., Anderson, K., McGlade, C., Sharmina, M., and Smith, T. (2018). CO2 abatement goals for international shipping. *Climate Policy.* 18 (8), 1066–1075. doi: 10.1080/14693062.2018.1461059

Tseng, P. H., and Pilcher, N. (2016). Exploring the viability of an emission tax policy for ships at berth in Taiwanese ports. *Int. J. Shipping Transport Logistics.* 8 (6), 705–722. doi: 10.1504/IJSTL.2016.079289

Van Leeuwen, J. (2015). The regionalization of maritime governance: Towards a polycentric governance system for sustainable shipping in the European union. *Ocean Coast. Management.* 117, 23–31. doi: 10.1016/j.ocecoaman.2015.05.013

Van Leeuwen, J., and van Koppen, C. S. A. (2016). Moving sustainable shipping forward: The potential of market-based mechanisms to reduce CO2 emissions from shipping. *J. Sustain. Mobility.* 3 (2), 42–66. doi: 10.9774/GLEAF.2350.2016.de.00004

Van Vuuren, D. P., Edmonds, J. A., Kainuma, M., Riahi, K., and Weyant, J. (2011). A special issue on the RCPs. *Climatic Change* 109 (1), 1–4. doi: 10.1007/s10584-011-0157-y

Voulis, N., Etten, M., Chappin, M. J. L., Warnier, M., and Brazier, F. M. T. (2019). Rethinking European energy taxation to incentivise consumer demand response participation. *Energy Policy.* 124, 156–168. doi: 10.1016/j.enpol.2018.09.018

Walsh, C., Mander, S., and Larkin, A. (2017). Charting a low carbon future for shipping: A UK perspective. *Mar. Policy.* 82, 32–40. doi: 10.1016/j.marpol.2017.04.019

Wan, Z., Chen, Y., and Tang, J. Y. (2018). Decarbonizing the international shipping industry: solutions and policy recommendations. *Mar. pollut. Bulletin.* 126, 428–435. doi: 10.1016/j.marpolbul.2017.11.064

Wuisan, L., van Leeuwen, J., and van Koppen, C. K. (2012). Greening international shipping through private governance: A case study of the clean shipping project. *Mar. Policy.* 36 (1), 165–173. doi: 10.1016/j.marpol.2011.04.009

Xiao, G., Wang, T., Chen, X., and Zhou, L. (2022). Evaluation of ship pollutant emissions in the ports of Los Angeles and long beach. *J. Mar. Sci. Engineering.* 10, 1206. doi: 10.3390/jmse10091206

Yang, Y., and Liu, W. (2022). Resilience analysis of maritime silk road shipping network structure under disruption simulation. *J. Mar. Sci. Engineering.* 10, 617. doi: 10.3390/jmse10050617

Yang, H., Ma, X., and Xing, Y. (2017). Trends in CO2 emissions from China-oriented international marine transportation activities and policy implications. *Energies* 10 (7), 980. doi: 10.3390/en10070980

Zhu, M., Chen, M., and Kristal, M. (2018). Modelling the impacts of uncertain carbon tax policy on maritime fleet mix strategy and carbon mitigation. *Transport* 33 (3), 707–717. doi: 10.3846/transport.2018.1579