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Research on China Ship CO2 Emission Reduction Path：Under IMO Stage Targets

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Research on Chinese Ship CO_2 Emission Reduction Path: Under IMO Stage Targets

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A dissertation submitted to the World Maritime University in partial fulfillment
of the requirements for the award of the degree of Master of Science
in Maritime Affairs

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

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ABSTRACT

Title of Dissertation: Research on Chinese Ship CO_2 Emission Reduction Path:
Under IMO Stage Targets

Degree: Master of Science

This paper focuses on the emission reduction path under the IMO emission reduction target and the important considerations that must be made while putting this path into practice, using Chinese international ships as the object.

To combat climate change problem, the IMO adopted an initial strategy which aims to reduce total GHG emissions from international shipping by at least 50% compared to 2008 levels. China must make clear the CO_2 emissions of its international shipping fleet and develop CO_2 emission reduction strategies that can fulfill IMO targets as a major shipping nation.

This paper calculates and forecasts the CO_2 emissions of Chinese international ships from the perspective of China's maritime authority, compares them to the IMO targets, suggests feasible strategies to meet emission reduction targets, and assesses the costs associated with emission reduction.

Additionally, based on the findings of the empirical research, qualitative analysis is done to determine the actions that the relevant authorities can do and the areas that need to be prioritized when developing the strategies.

According to this study, reducing ship speeds and utilizing zero-carbon energy sources are the two most crucial steps in achieving emission reduction goals. However, the ratio between these two methods is closely correlated with the ratio of ship capacity supplement and the cost of conventional fuels vs zero-carbon fuels, which will lead to a change in the trajectory of emission reduction.

Key words: Chinese international Ships; CO_2 emission; CO_2 emission prediction; Emission reduction path; Reduction cost; Emission reduction policies;

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LIST OF ABBREVIATIONS

AER	Annual efficiency ratio in gram
AIS	Automatic identification system
BAU	Business as usual
CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
COSCO	China Ocean Shipping Company
DCS	Data collection system
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EU-MRV	European Union Monitoring, Reporting and Verification
GDP	Gross Domestic Product
GHG	Greenhouse gas
HFO	Heavy Fuel Oil
IEA	International Energy Agency
III	IMO Instruments Implementation
IMO	International Maritime Organization
IMarEST	Institute of Marine Engineering, Science & Technology
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
MAC	Marginal abatement cost
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Maritime Environment Protection Committee
NASA	National Aeronauticsand Space Administration
OECD	Organisation for Economic Co-operation and Development

SEEMP	Ship Energy Efficiency Management Plan
SENEM	Ship's Energy Effificiency Model
SRES	Special Report on Emissions Scenarios
STEAM	Ship Transportation Emission Assessment Model
STEEM	Ship Traffific, Energy and Environmental Model
TEU	Twenty-feet Equivalent Unit
UMAS	Universal Miniature Avionics System

CHAPTER 1 INTRODUCTION

1.1 Research background and significance

The volume of trade has significantly increased as a result of globalization, with shipping serving as the industry's linchpin. However, this expansion of maritime transportation has led to a worrying rise in greenhouse gas emissions, especially CO_2. According to the IMO, international shipping contributed to approximately 2.89% of the world's CO_2 emissions in 2018 (IMO, 2020). If nothing is done, emissions are expected to rise from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050. Globally, there is increasing concern about the CO_2 emissions from ships and their effects on the environment.

In the Paris Agreement, signatories committed to limiting the temperature increase to 1.5°C above pre-industrial levels and to reducing the global average temperature increase to 2°C below pre-industrial levels. The IMO adopted an initial strategy in 2018 to reduce GHG emissions from ships in response to this initiative. With a focus on lowering CO_2 emissions, this policy seeks to reduce all GHG emissions from international shipping by at least 50% when compared to 2008 levels.

China, a significant exporter of goods, depends significantly on shipping to deliver its goods to markets all over the world. Container ships, bulk carriers, tankers, and other types of ships are all operated by Chinese maritime corporations. As can be seen in Figure 1, China's imports and exports have been steadily increasing their seaborne trade, and as can be observed in Figure 2, their proportion of the global seaborne trade has increased to about 28%, making Chinese shipping an increasingly significant factor in the reduction of CO_2 emissions.

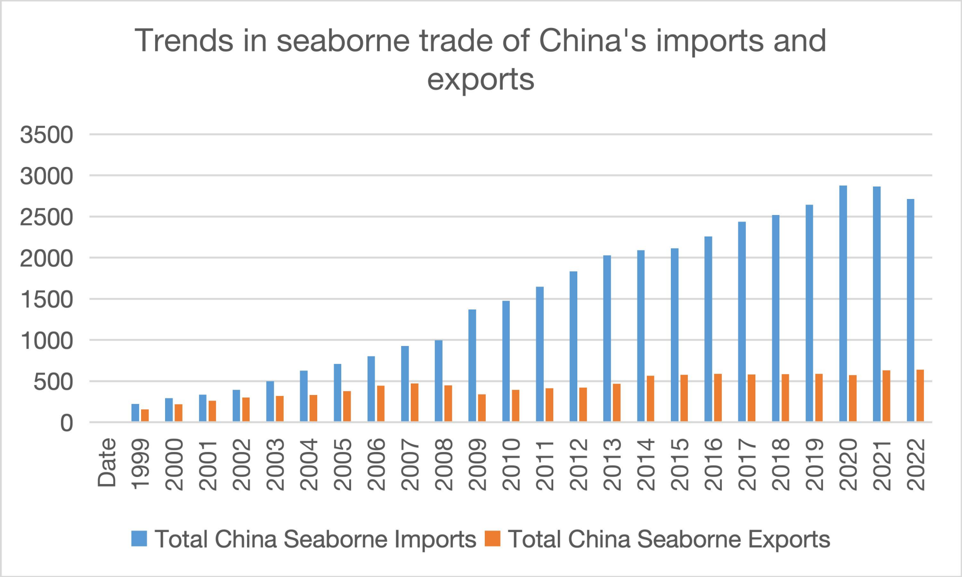


Figure 1- Trends in seaborne trade of China's imports and exports

source：Clarkson shipping intelligence network

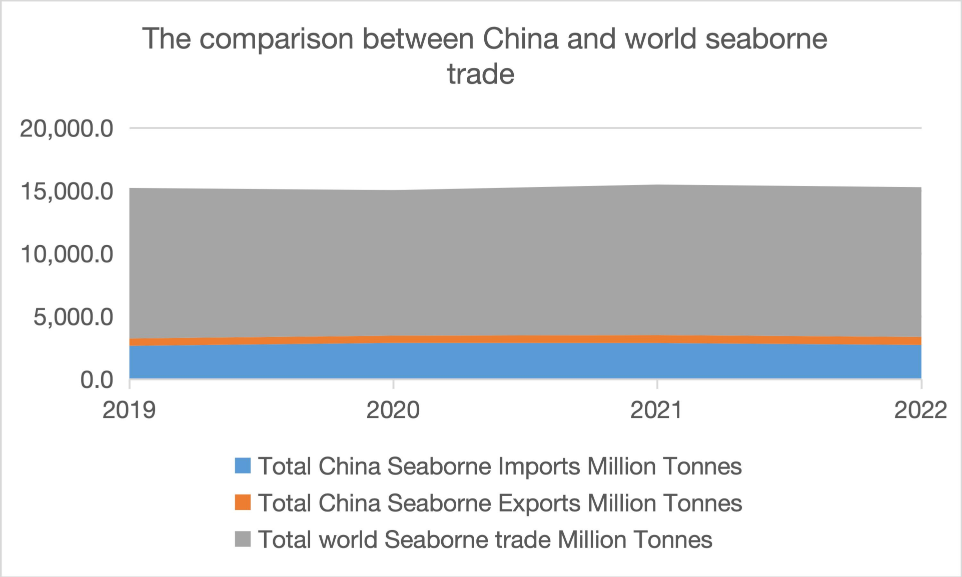


Figure 2- The comparison between China and world seaborne trade, 2019-2022

source：Clarkson shipping intelligence network

China became the 23rd nation to ratify the Paris Agreement on Climate Change on September 3, 2016, when the Standing Committee of the National People's Congress authorized its admission. The Chinese government has the duty and obligation to address climate change brought on by greenhouse gas emissions as a result of joining the pact.

Due to its borderless, mobile character, ship CO_2 emissions have been less examined. To meet its worldwide GHG reduction targets and achieve low-carbon marine transport and sustainable international trade, China must immediately reduce ship CO2 emissions.

1.2 Literature Review

Scholars have focused on maritime transport CO_2 emissions due to the international community's growing concern about them and the demand for sustainable maritime industry development. This section compares and summarises the relevant literature on CO_2 emission measurement studies, prediction studies, emission reduction path studies, and emission reduction scheme cost studies and identifies their shortcomings to illuminate and inform this paper's research theories, methods, and analytical approaches.

1.2.1 Progress in CO_2 emission measurement research

All in-depth research on CO_2 emissions is based on measurement, and reliable measurement of CO_2 emissions is a prerequisite for research and policy development.

The IMO GHG study report introduces two approaches to measuring CO_2 emissions: "top-down" and "bottom-up." “Top-down” approaches primarily assemble data on fuel consumption and fuel emission factors from reputable energy agencies for calculations, while "bottom-up" approaches primarily use AIS data to estimate regular fuel consumption and CO_2 emissions (IMO, 2020). These two methods are in accord with how the IPCC suggests quantifying CO_2 emissions. The "bottom-up" strategy is more frequently utilized in the shipping sector despite the "top-down" approach being more direct and accurate because of the challenge in acquiring data (Moreno-Gutiérrez et al. 2019, Endresen et al., 2007). For instance, Budiyanto, Habibie, and Shinoda, T. (2022) used a bottom-up approach to estimate CO_2 emissions and emission intensity of container ships. Chen et al. (2016) used the "bottom-up" approach to calculate the carbon emissions of coastal container ports in China using the STEAM model based on the AIS data of ships. According to Goldsworthy and Goldsworthy (2015), AIS data collected along the Australian coastline was used to estimate CO_2 emissions for Australian jurisdictions. After calculating the fuel consumption of each subsystem under various operating situations, Ren, L. et al. used the fuel consumption approach to calculate the carbon emissions of ocean-going fishing vessels. Additionally, Moreno-Gutiérrez and Durán-Grados (2021) developed the SENEM to compute CO_2 emissions using the STEAM and STEEM as a foundation. The SENEM's basic assumptions are the same as those of the two IPCC-recommended methods.

Numerous researchers have conducted reasonably advanced CO_2 emission measuring studies, particularly for single ships, specific geographic regions, and certain ship types. However, no studies have been found to quantify the entire ship carbon emission based on the present Chinese international ships. Additionally, the "top-down" approach is not commonly employed due to data limitations. A mix of "top-down" and "bottom-up" methods can be employed to measure CO_2 if pertinent data are available.

1.2.2 Progress in CO_2 Emission Trends Research

In order to create a trend projection model for CO_2 emissions, CO_2 projections are mostly based on many scenarios with various factors (Wang, W. J. et al., 2022). Due to varying data sources, researchers created various scenarios and variables. Some researchers used the IPCC SRES scenario as the base scenario and the future international shipping cargo turnover rate that corresponded to the GDP growth rate as the variable (Gu, W.H., & Xu, R.H., 2013; IMO, 2020; Zhou, et al., 2012; Gong, et al., 2018; Reis, et al., 2020). Some forecast the CO_2 emission trends of shipping to 2050 under various scenarios using the underlying economic growth rate as the base scenario and variables such as cargo turnover demand, energy technology, and fuel type (Ma, Xue-Fei, 2020; Ammar, 2019; Milakovi, et al., 2018). This paper selects to utilize the projection model of Ma Xue-fei as a reference since the scenarios defined by IPCC are mostly based on different warming targets and radiative forcing, which are different from the estimates of CO_2 emissions for specific regions and industries (Pedersen, et al., 2022).

The Chinese government has a varied role for Chinese and foreign international ships (as flag government and coastal government, respectively), and it can implement different actions in accordance with the III Code (IMO, 2013). This study focuses on carbon emission forecasts for Chinese international shipping in order to offer policy recommendations to the Chinese maritime authorities.

1.2.3 Progress on CO_2 Emission Reduction Options

The overall CO_2 emissions from international shipping must drop by 50% by 2050 compared to 2008, under the IMO's initial policy to reduce greenhouse gas emissions from ships (IMO, 2018). Evert A. Bouman and colleagues examined more than 150 studies on reducing ship emissions and came to the conclusion that there are primarily two ways to do so: by reducing technology and by reducing operation (Bouman, et al., 2017; Zhang, Zhang, & Li, 2010). Operational emission reduction mainly includes slow steaming, ship type optimization, use of energy saving devices, ship route design, speed optimization, small angle maneuvering optimization, ship energy efficiency management, and hull maintenance (Beşikçi, et al., 2016; Perera, & Mo, B., 2016; Wang, Ma, & Gu, 2017; Weng, Z.Y., & Yang, C.H., 2021; Cheng, Liu, & Feng, 2014; Pelić, et al., 2023). Improvements in ship design, the availability of shore power, the expansion of alternative energy sources, and the use of alternative fuels are the main technological emission reduction strategies (Huang, Zhang, and Wang in 2021; Guo in 2021; Shuai et al. in 2014; Christodoulou and Cullinane in 2022).

In order to meet the IMO's stage target for carbon emission reduction, the viability of emission reduction solutions must be assessed specifically, taking into account the various scenarios of existing and future shipbuilding in China.

1.2.4 Study on feasible CO_2 emission reduction path cost calculation

The amount of technological advancement and the availability of resources determine the viability of various carbon reduction pathways to reach the IMO's phased reduction targets, which unavoidably results in variances in the reduction costs of various pathways. Current cost analyses have focused on cost comparisons of existing abatement approaches, such as comparing the costs of different route plans (Wei, & Song, 2021; Guo, 2019; Xu, & Yang, D., 2020), costs of different deceleration schemes (Marques, et al., 2023; Chang, & Wang, 2014; Zhang, et al., 2013; Corbett, Wang, & Winebrake, 2009), or the cost of using energy efficient facilities (Aspelund, Molnvik, & De Koeijer, 2006; Wang, & Wei, 2021; Schinas, & Bergmann, 2021). The MAC per unit of clean energy has also been studied (Feng, Zhu, & Dong, 2022; Rennert, et al., 2022; IMO, 2017&2018).

In light of the IMO's abatement targets, it is necessary to increase the practicality of choosing an abatement path by calculating and comparing the economic costs of various abatement paths. The analysis above is primarily based on the comparison of existing approaches without clear target constraints.

1.3 Research ideas and contents

China's economic growth has increased maritime energy consumption and CO_2 emissions. International ship CO_2 emissions management has always been difficult due to their mobility, but after IMO set CO_2 reduction targets and adopted mandatory requirements like EEDI and EEXI, it has become urgent. In this paper, from the perspective of Chinese maritime authorities, we focus on Chinese international ships, starting from CO_2 emission estimation and trend prediction, to clarify the gap between the future CO_2 emission of Chinese international ships and the IMO reduction target in several scenarios, and then explore the CO_2 emission reduction path according to this gap. The cost of new technology and energy retrofit will be combined to compare CO_2 emission reduction paths and propose viable energy saving and emission reduction programs for competent authorities.

1. Calculating Chinese international ship CO_2 emissions.
2. To forecast key ship types' CO_2 emissions growth in multivariable scenarios.
3. To investigate IMO's 2050 emission reduction target-based emission reduction paths.
4. Calculate the economic expenses of possible emission reduction choices using CO_2 reduction paths.

1.4 Research methods and technical routes

1.4.1 research methods

This study uses the following approaches for quantitative and qualitative research.

Literature reserch method: The research results of CO_2 emission theory in domestic international shipping field are sorted out, and their characteristics and deficiencies are summarized to produce this paper's research perspective.

Logical deduction: Based on literature review, the research framework of "CO_2 emission estimation- CO_2 emission trend prediction- CO_2 emission reduction path study- CO_2 emission reduction path cost comparison" is proposed for Chinese international shipping.

Quantitative analysis method: Based on statistical data, a multiple linear regression model is used to calculate and anticipate ship CO_2 emissions and predict future trends.

Model construction: Building a model to estimate current and future CO_2 emissions involves gathering data on import and export trade as well as ship activity.

Reverse extrapolation method: Using the IMO CO_2 emission reduction target as a hard constraints, we examine and calculate potential emission reduction approaches to meet the target.

Qualitative research: Prioritize and start policy formulation based on quantitative analysis.

1.4. 2 Technical route

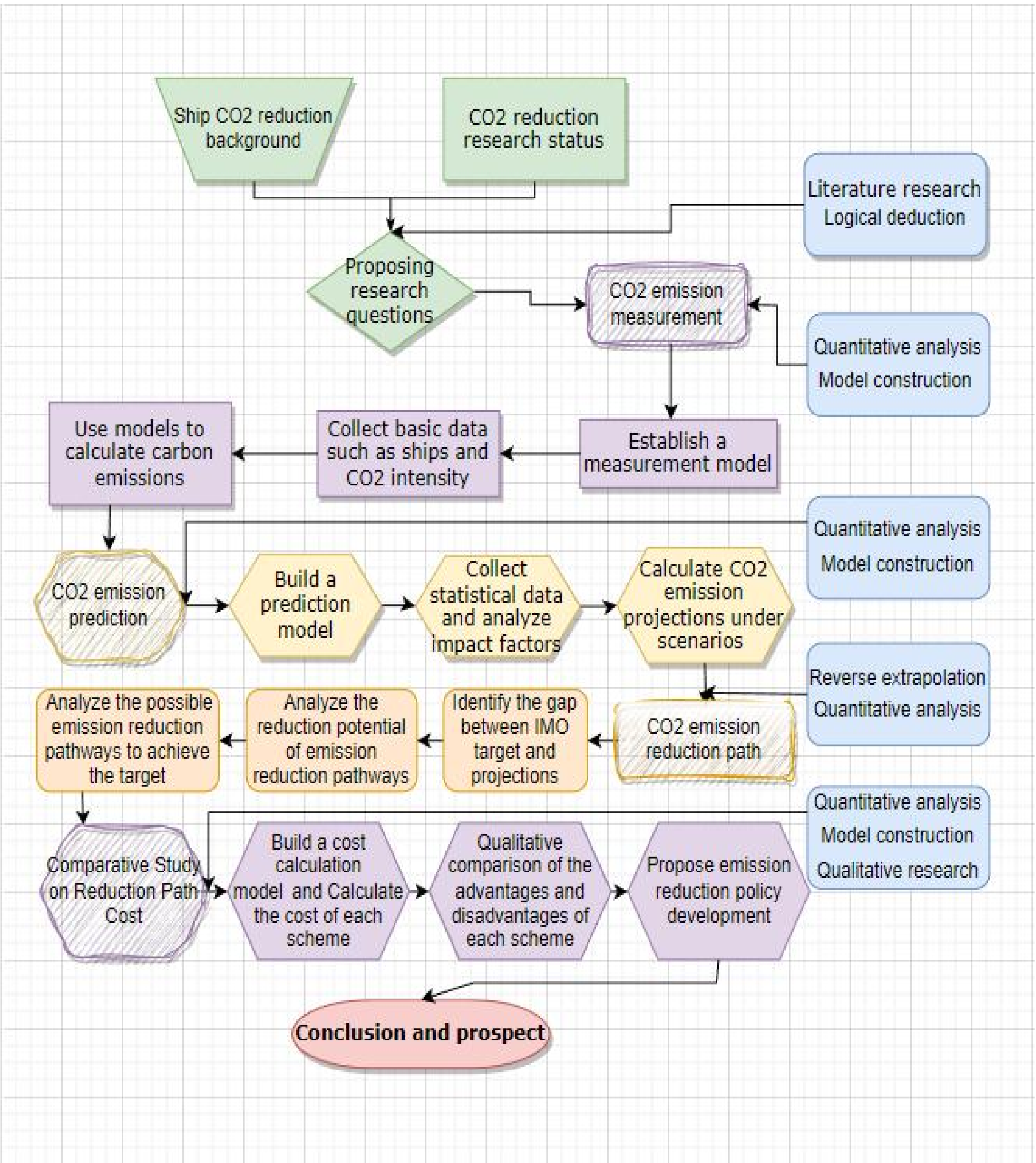


Figure 3- Technical route

1.4.3 Overview of the data sources used in the study

This study uses the second/third/fourth IMO GHG Study's CO_2 measurement formula and cargo ship carbon intensity data. China Statistical Yearbook and Clarkson shipping intelligence provide economic, population, and import/export data. The majority of ship data is derived from Clarkson's shipping intelligence work and annual report data of China's listed shipping firms. IMO and IMarEST provide ship CO_2 abatement cost statistics, whereas the IEA/OECD Renewable Energy for Industry report provides clean energy pricing trends. The article also references Transportation Research and Science Direct.

CHAPTER 2 CALCULATION OF CO_2 EMISSIONS

This study analyzes Chinese international ship CO_2 emissions from a government perspective to develop a viable CO_2 emission reduction policy for China. We all know that proper quantitative analysis supports successful policy making. The logic of CO_2 emission variations from Chinese international ships and the study of CO_2 emission reduction concerns require accurate measurement and analysis of CO_2 emissions from each ship type.

2.1 Construction of ship CO_2 emission calculation model

2.1.1Definition of basic concepts

2.1.1.1 CO_2 emissions

The IPCC says CO_2 is the biggest GHG emitted by humans. CO_2 accounts for 76% of long-lived GHG radiative forcing (IPCC, 2018). The energy that the Earth gets from the sun and the energy that it emits back into space differ, and this discrepancy is what causes radiative forcing. The Earth's temperature has increased overall as a result of CO_2 and other GHG emissions trapping part of the emitted radiation. Greenhouse impact. Thus, climate change mitigation requires CO_2 reduction.

Since 1950, CO_2 emissions have exceeded historical highs, and with the burning of fossil fuels, the amount of CO_2 retained in the atmosphere has skyrocketed. From 1970 to 2010, cumulative CO_2 emissions reached 1,300±110 Gt, three times the amount emitted in the last two centuries (Birch, 2014).

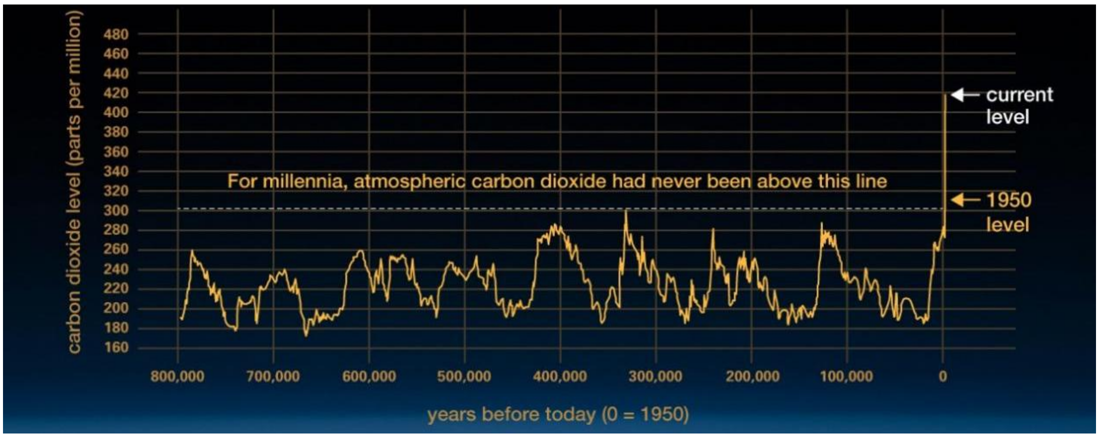


Figure 4- Atmospheric CO_2 has increased since the Industrial Revolution

Source: NASA

Since CO_2 emissions have a significantly bigger influence on the greenhouse effect than other greenhouse gases, this research only looks at CO_2 emissions instead of other greenhouse gases.

2.1.1.2 CO_2 emissions from ships

Marine CO_2 emissions come from the ship's diesel engine's fuel burning, cargo vapourization, and equipment leaks like refrigeration leaks. Maritime CO_2 emissions are borderless and challenging to locate because ships transit through various places while transporting cargo.

The IPCC and IMO define international maritime transport as bunker fuel emissions from ships travelling globally, independent of flag state. International shipping can take place along the shore and on the high seas (Ma, Yang, & Xing. 2018). The paper addresses China's international marine cargo CO_2 emissions, but it also advises the Chinese maritime authorities, which cannot supervise ships flying other flags. The research object of this paper is restricted to international sailing ships flying the Chinese flag because if a country's international shipping trade is used as the basis for calculation, there will be a significant task deviation from the national responsibility target due to the involvement of a large number of foreign ships.

2.1.2 Explanation of the methodology used to construct the ship CO_2 emission calculation model

The "bottom-up" and "top-down" methodologies are the two main methods for measuring GHG emissions, according to the Third IMO GHG Study 2014. The characteristics of particular activities and processes are combined in the bottom-up method to create a model that accurately represents reality. Regarding the range of its application, the bottom-up method is mostly used in the accounting of carbon emissions for particular projects, goods, or businesses. Since it is broken down from top to bottom, the top-down approach is utilized worldwide to account for the total CO2 emissions produced by a nation, area, or industry.

The bottom-up strategy begins by gathering activity data, such as the distance traveled, and vessel parameters (such as size, engine type), as was done in earlier IMO GHG Studies. The fuel usage is calculated using these data. Ship CO_2 emissions are calculated using the following formula:

$$\mathrm{EM}_{i_{IMO3}} = FC_i \cdot EF_f = AER_{i,j} \cdot T_{i,j} \cdot S_{i,j} \cdot DWT_{i,j} \cdot CF_i = (SFC_{base} \cdot CF_L \cdot \dot{W}_l) \cdot \left(\frac{EF_e}{CF_L \cdot SFC}\right) \qquad (1)$$

$\mathrm{EM}_{i_{IMO3}}$: the emission of GHG;

FC_i: the fuel consumption;

EF_f: the fuel-based emission factor;

EF_e: the energy-based emission factor;

SFC: the special fuel consumption;

SFC_{base}: the baseline of SFCs;

CF_L: the engine load correction factor;

W_l: the engine power;

$AER_{i,j}$: the annual efficiency ratio in gram of type *j* ships using type *i* fuel;

$T_{i,j}$: the average sailing time of type *j* ships using type *i* fuel;

$S_{i,j}$: the average speed of type *j* ships using type*i* fuel;

$DWT_{i,j}$: the total deadweight of type *j* ships using type *i* fuel;

The top-down method involves multiplying ship fuel consumption by the fuel's CO2 emission factor to determine shipping's contribution to global warming. Assumptions and other types of data processing are minimized because the underlying data is derived from ship fuel consumption records, leading to more precise predictions of CO_2 emissions. It uses the following calculation formula:

$$\mathrm{E}_i = \sum_j E_{i,j} = FC_{i,j} \cdot CF_i \qquad (2)$$

E_i: total CO_2 emissions from all ship types usingtype*i* fuel;

$E_{i,j}$: total CO_2 emissions from fuel consumption of type *j* ships using type *i* fuel;

$FC_{i,j}$: fuel consumption of type *j* ships using type *i* fuel;

CF_i: CO_2 emission factors for type *i* fuels;

The current data on Chinese ships in Clarkson is mostly classified by flag country and contains just basic ship statistics. AIS historical data depicting ship activity is not included. The cargo turnover data of different ship types is mostly based on Chinese customs' cargo import and export data, however it contains a lot of foreign flag ship data, making it hard to discern. Thus, this study cannot use the algorithm of computing products turnover by import and export data and multiplying energy consumption. This paper uses Clarkson's ship statistics due to data availability. It uses data-specific calculating methods instead of "top-down" or "bottom-up" methods. The "top-down" strategy is more accurate if listed firms disclose container ship, oil carrier, and general cargo ship fuel consumption data in their annual reports. Due to a lack of fuel consumption data, the "bottom-up" technique works better for dry bulk and chemical carriers. AER, average sailing days, speed, and other information from the fourth IMO GHG Study 2020 were integrated with Chinese ship deadweight tonnage data to calculate.

In conclusion, the two approaches are merged to reduce the discrepancy between the estimated value and the real value.

2.1.3 Description of the model's input parameters and data sources

The top six fuel-consuming ship types account for 85.4% of international shipping fuel consumption in 2018, according to the *fourth IMO GHG Study 2020*. The six categories are general cargo ship, oil tankers, liquefied gas tankers, chemical tankers, bulk carriers, and containers.

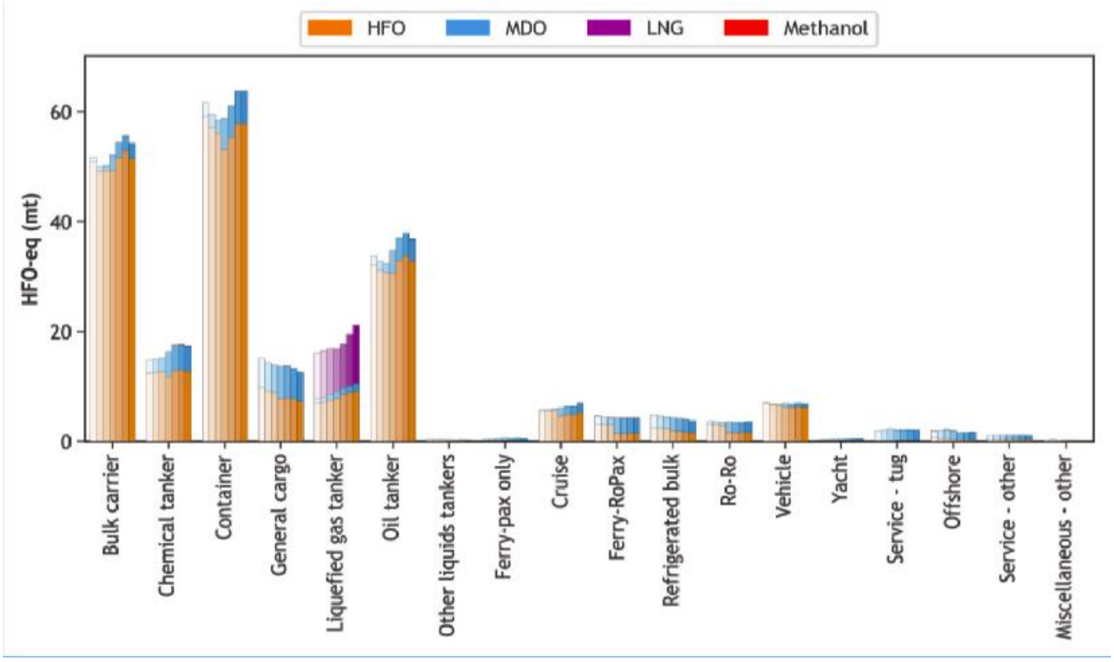
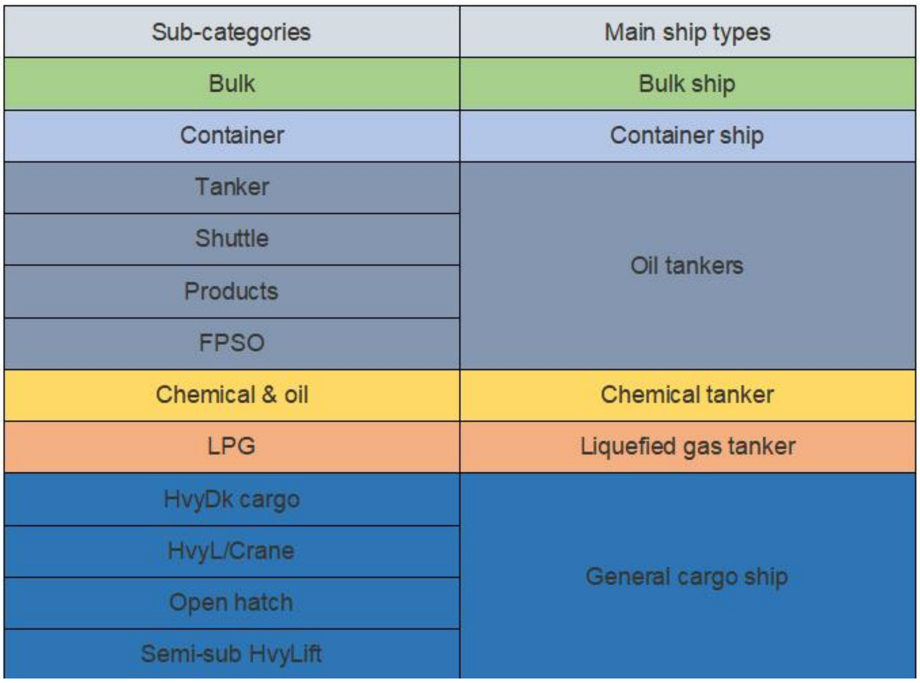


Figure 5-Total annual HFO-equivalent fuel consumption per ship type

Source：UMAS

Since it is difficult to calculate the specific CO_2 emissions of each ship type, this paper selects the six ship types that account for the largest proportion for preliminary calculation and then estimates the CO_2 emissions of all ship types using proportionality. Clarkson classified ship types into 12 subcategories. This paper will match these 12 sub-categories to the 6 main ship classes based on similarities for calculation. Products may contain oil or chemical tankers. Products are included in oil tanker for computation since oil tanker accounts for a big part. The specific correspondence is provided in the following table:

Table 1- Correspondence table of ship types



Sub-categories	Main ship types
Bulk	Bulk ship
Container	Container ship
Tanker	Oil tankers
Shuttle	
Products	
FPSO	
Chemical & oil	Chemical tanker
LPG	Liquefied gas tanker
HvyDk cargo	General cargo ship
HvyL/Crane	
Open hatch	
Semi-sub HvyLift	

Source：Clarkson shipping intelligence network

This article calculates CO_2 emissions using Clarkson shipping intelligence network data on China-flagged international vessels in 2022, as indicated in the figure. This research computed the deadweight tons of all Chinese-flagged international ships using the aforesaid classification technique. The legend places restrictions on the container data. Although it is displayed here as deadweight, the real calculation will utilize TEUs as the calculating unit; 6413283DWT equates to 485268TEUs.

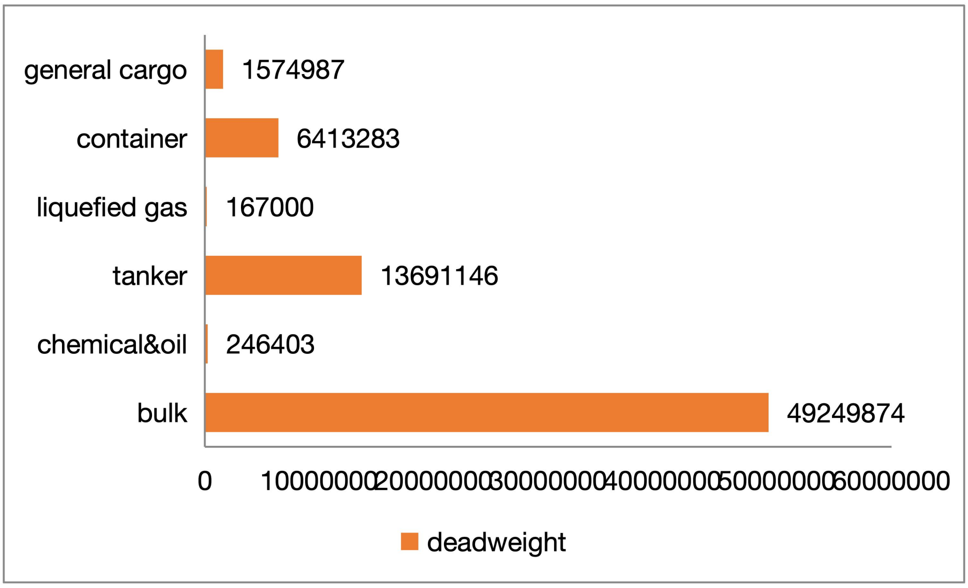
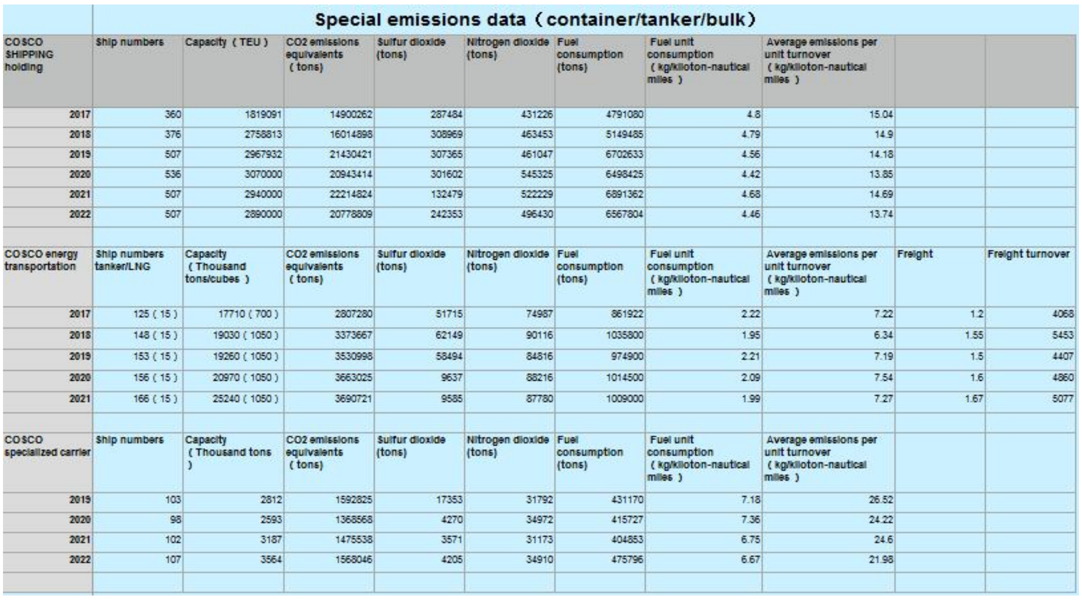


Figure 6-Statistics of deadweight tons of various types of ships

Source：Clarkson shipping intelligence network

According to the calculation method described in 2.1.2, for tankers, general cargo ships, container ships, this paper selects the emission data published in the annual reports of three typical listed companies in China as the basic data source, they are COSCO shipping holding (container ship), COSCO shipping energy transportation (oil tanker) and COSCO shipping specialized carriers (general cargo), and the specific data are listed in the following table:

Table 2- COSCO CO_2 emission data of container/tanker/bulk



	Special emissions data（container/tanker/bulk）									
COSCO SHIPPING holding	Ship numbers	Capacity（TEU）	CO2 emissions equivalents（tons)	Sulfur dioxide (tons)	Nitrogen dioxide (tons)	Fuel consumption (tons)	Fuel unit consumption（kg/kiloton-nautical miles）	Average emissions per unit turnover（kg/kiloton-nautical miles）		
2017	360	1819091	14900262	287484	431226	4791080	4.8	15.04		
2018	376	2758813	16014898	308969	463453	5149485	4.79	14.9		
2019	507	2967932	21430421	307365	461047	6702633	4.56	14.18		
2020	536	3070000	20943414	301602	545325	6498425	4.42	13.85		
2021	507	2940000	22214824	132479	522229	6891362	4.68	14.69		
2022	507	2890000	20778809	242353	496430	6567804	4.46	13.74		
COSCO energy transportation	Ship numbers tanker/LNG	Capacity（Thousand tons/cubes）	CO2 emissions equivalents（tons)	Sulfur dioxide (tons)	Nitrogen dioxide (tons)	Fuel consumption (tons)	Fuel unit consumption（kg/kiloton-nautical miles）	Average emissions per unit turnover（kg/kiloton-nautical miles）	Freight	Freight turnover
2017	125（15）	17710（700）	2807280	51715	74987	861922	2.22	7.22	1.2	4068
2018	148（15）	19030（1050）	3373667	62149	90116	1035800	1.95	6.34	1.55	5453
2019	153（15）	19260（1050）	3530998	58494	84816	974900	2.21	7.19	1.5	4407
2020	156（15）	20970（1050）	3663025	9637	88216	1014500	2.09	7.54	1.6	4860
2021	166（15）	25240（1050）	3690721	9585	87780	1009000	1.99	7.27	1.67	5077
COSCO specialized carrier	Ship numbers	Capacity（Thousand tons）	CO2 emissions equivalents（tons)	Sulfur dioxide (tons)	Nitrogen dioxide (tons)	Fuel consumption (tons)	Fuel unit consumption（kg/kiloton-nautical miles）	Average emissions per unit turnover（kg/kiloton-nautical miles）		
2019	103	2812	1592825	17353	31792	431170	7.18	26.52		
2020	98	2593	1368568	4270	34972	415727	7.36	24.22		
2021	102	3187	1475538	3571	31173	404853	6.75	24.6		
2022	107	3564	1568046	4205	34910	475796	6.67	21.98		

Source: COSCO Group Annual Report for Listed Companies

For liquefied gas tanker, chemical tanker, Bulk ship, In this paper, data such as vessel-based option1 (AER), average days at sea and average speed from the fourth IMO GHG Study 2020 will be used for calculation.Since the AER changes widely from year to year, this study will use the nearest AER in 2018 and corresponding average days at sea and average speed statistics for different tonnage.

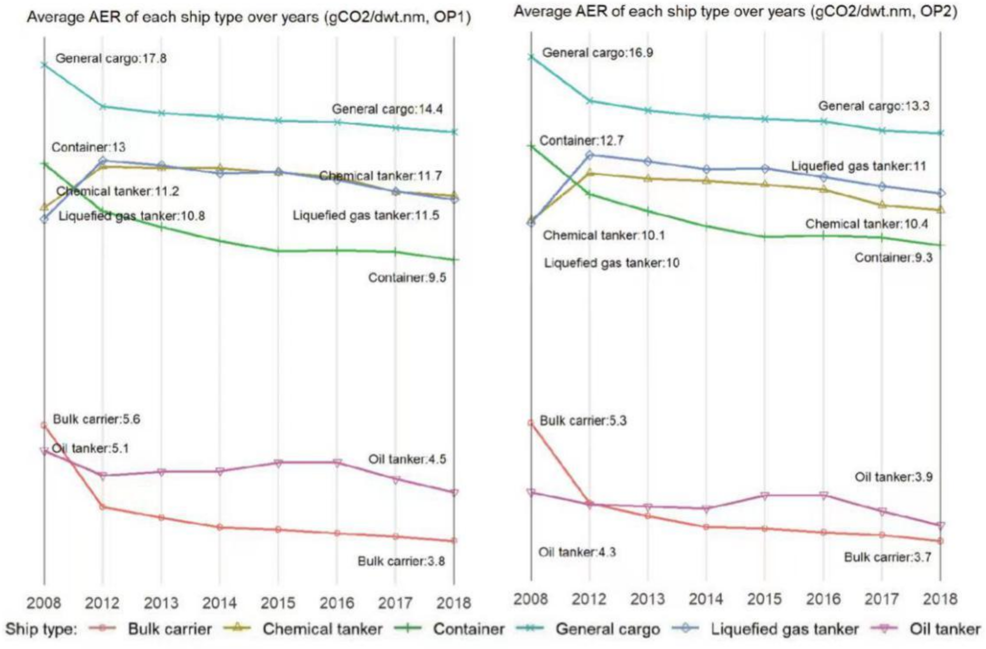
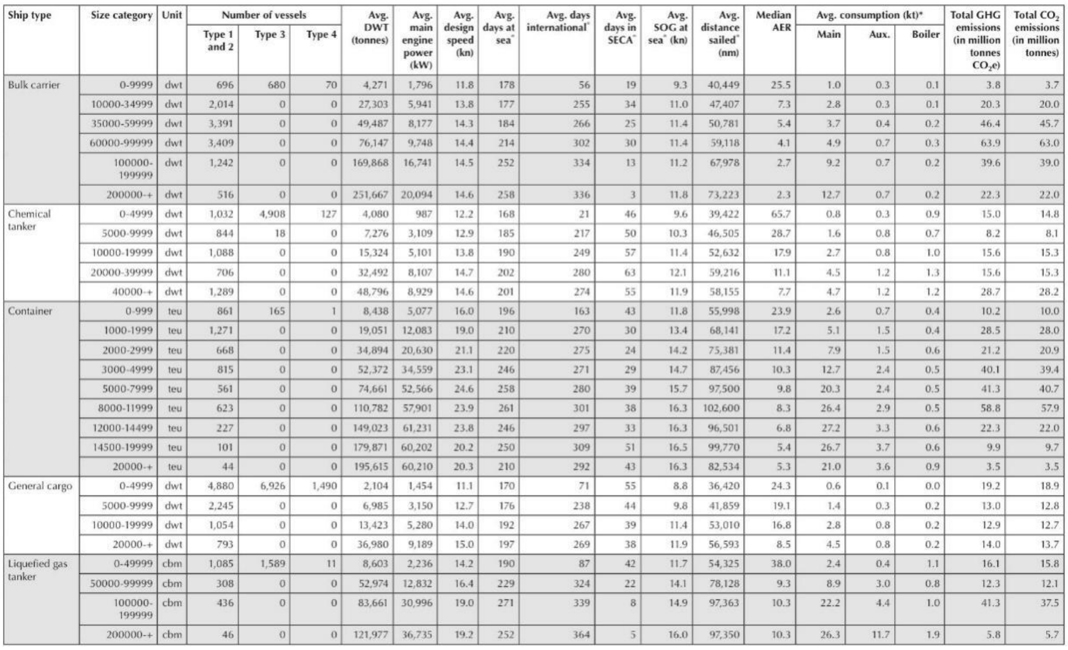


Figure 7- Carbon intensity levels of typical cargo ships over years (in ARE)

Source：IMO

Table 3- Detailed results for 2018 describing the fleet using the "bottom-up" method



Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea*	Avg. days international*	Avg. days in SECA*	Avg. SOG at sea* (kn)	Avg. distance sailed* (nm)	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4										Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	696	680	70	4,271	1,796	11.8	178	56	19	9.3	40,449	25.5	1.0	0.3	0.1	3.8	3.7
	10000-34999	dwt	2,014	0	0	27,303	5,941	13.8	177	255	34	11.0	47,407	7.3	2.8	0.3	0.1	20.3	20.0
	35000-59999	dwt	3,391	0	0	49,487	8,177	14.3	184	266	25	11.4	50,781	5.4	3.7	0.4	0.2	46.4	45.7
	60000-99999	dwt	3,409	0	0	76,147	9,748	14.4	214	302	30	11.4	59,118	4.1	4.9	0.7	0.3	63.9	63.0
	100000-199999	dwt	1,242	0	0	169,868	16,741	14.5	252	334	13	11.2	67,978	2.7	9.2	0.7	0.2	39.6	39.0
	200000-+	dwt	516	0	0	251,667	20,094	14.6	258	336	3	11.8	73,223	2.3	12.7	0.7	0.2	22.3	22.0
Chemical tanker	0-4999	dwt	1,032	4,908	127	4,080	987	12.2	168	21	46	9.6	39,422	65.7	0.8	0.3	0.9	15.0	14.8
	5000-9999	dwt	844	18	0	7,276	3,109	12.9	185	217	50	10.3	46,505	28.7	1.6	0.8	0.7	8.2	8.1
	10000-19999	dwt	1,088	0	0	15,324	5,101	13.8	190	249	57	11.4	52,632	17.9	2.7	0.8	1.0	15.6	15.3
	20000-39999	dwt	706	0	0	32,492	8,107	14.7	202	280	63	12.1	59,216	11.1	4.5	1.2	1.3	15.6	15.3
	40000-+	dwt	1,289	0	0	48,796	8,929	14.6	201	274	55	11.9	58,155	7.7	4.7	1.2	1.2	28.7	28.2
Container	0-999	teu	861	165	1	8,438	5,077	16.0	196	163	43	11.8	55,998	23.9	2.6	0.7	0.4	10.2	10.0
	1000-1999	teu	1,271	0	0	19,051	12,083	19.0	210	270	30	13.4	68,141	17.2	5.1	1.5	0.4	28.5	28.0
	2000-2999	teu	668	0	0	34,894	20,630	21.1	220	275	24	14.2	75,381	11.4	7.9	1.5	0.6	21.2	20.9
	3000-4999	teu	815	0	0	52,372	34,559	23.1	246	271	29	14.7	87,456	10.3	12.7	2.4	0.5	40.1	39.4
	5000-7999	teu	561	0	0	74,661	52,566	24.6	258	280	39	15.7	97,500	9.8	20.3	2.4	0.5	41.3	40.7
	8000-11999	teu	623	0	0	110,782	57,901	23.9	261	301	38	16.3	102,600	8.3	26.4	2.9	0.5	58.8	57.9
	12000-14499	teu	227	0	0	149,023	61,231	23.8	246	297	33	16.3	96,501	6.8	27.2	3.3	0.6	22.3	22.0
	14500-19999	teu	101	0	0	179,871	60,202	20.2	250	309	51	16.5	99,770	5.4	26.7	3.7	0.6	9.9	9.7
	20000-+	teu	44	0	0	195,615	60,210	20.3	210	292	43	16.3	82,534	5.3	21.0	3.6	0.9	3.5	3.5
General cargo	0-4999	dwt	4,880	6,926	1,490	2,104	1,454	11.1	170	71	55	8.8	36,420	24.3	0.6	0.1	0.0	19.2	18.9
	5000-9999	dwt	2,245	0	0	6,985	3,150	12.7	176	238	44	9.8	41,859	19.1	1.4	0.3	0.2	13.0	12.8
	10000-19999	dwt	1,054	0	0	13,423	5,280	14.0	192	267	39	11.4	53,010	16.8	2.8	0.8	0.2	12.9	12.7
	20000-+	dwt	793	0	0	36,980	9,189	15.0	197	269	38	11.9	56,593	8.5	4.5	0.8	0.2	14.0	13.7
Liquefied gas tanker	0-49999	cbm	1,085	1,589	11	8,603	2,236	14.2	190	87	42	11.7	54,325	38.0	2.4	0.4	1.1	16.1	15.8
	50000-99999	cbm	308	0	0	52,974	12,832	16.4	229	324	22	14.1	78,128	9.3	8.9	3.0	0.8	12.3	12.1
	100000-199999	cbm	436	0	0	83,661	30,996	19.0	271	339	8	14.9	97,363	10.3	22.2	4.4	1.0	41.3	37.5
	200000-+	cbm	46	0	0	121,977	36,735	19.2	252	364	5	16.0	97,350	10.3	26.3	11.7	1.9	5.8	5.7

Source: IMO

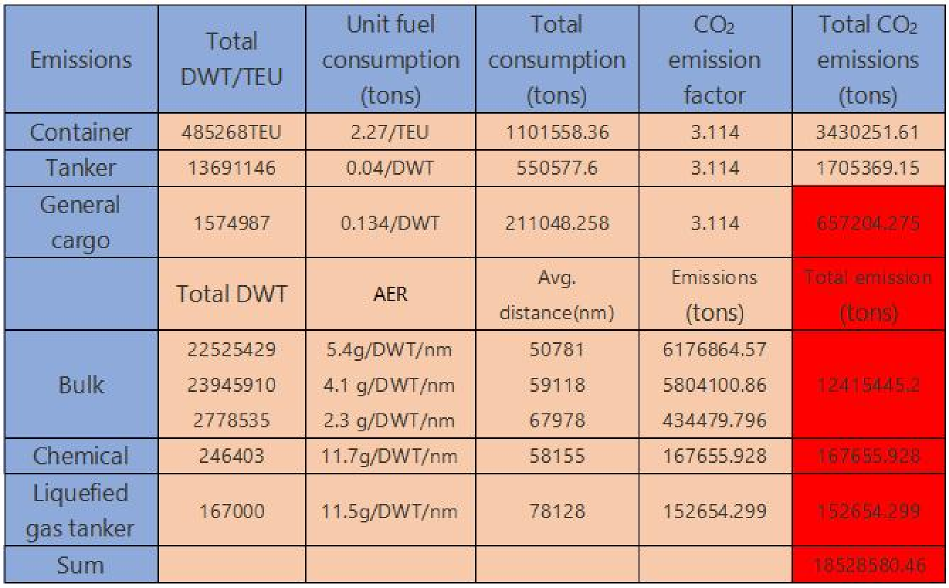
2.2 Estimation of CO_2 emissions from Chinese international ships

2.2.1Analysis of the CO_2 emissions from Chinese international ships based on the constructed model

According to equation (2), the measurement of CO_2 emission of Chinese flag international voyage ships is mainly based on the fuel consumption of six main ship types (container, bulk, tanker, General cargo, Liquefied gas tanker, Chemical), and the fuel consumption per DWT/TEU is obtained by using DWT/TEU as the denominator and multiplying it by the total DWT/TEU of the vessel type in Chinese international shipping statistics to obtain the total fuel consumption. The CO_2 emission factor of HFO, from the fourth IMO GHG Study 2020, is used in this computation since most international ocean-going vessels employ it.

$$E_{HFO} = \sum_j E_{HFO,j} = FC_{HFO,j} \cdot CF_{HFO} \tag{3}$$

Table 4- Calculation of CO_2 emissions after aggregation of similar types of ships



Emissions	Total DWT/TEU	Unit fuel consumption (tons)	Total consumption (tons)	CO_2 emission factor	Total CO_2 emissions (tons)
Container	485268TEU	2.27/TEU	1101558.36	3.114	3430251.61
Tanker	13691146	0.04/DWT	550577.6	3.114	1705369.15
General cargo	1574987	0.134/DWT	211048.258	3.114	657204.275
	Total DWT	AER	Avg. distance(nm)	Emissions (tons)	Total emission (tons)
Bulk	22525429 23945910 2778535	5.4g/DWT/nm 4.1 g/DWT/nm 2.3 g/DWT/nm	50781 59118 67978	6176864.57 5804100.86 434479.796	12415445.2
Chemical	246403	11.7g/DWT/nm	58155	167655.928	167655.928
Liquefied gas tanker	167000	11.5g/DWT/nm	78128	152654.299	152654.299
Sum					18528580.46

Source : self-made

Special note: The calculated values here are still somewhat different from the actual values because they involve the classification of ship types and ignore the effects of ship age and ship size on CO_2 emissions.

According to the calculation results of 2.2.1, the CO_2 emission share of the six major ship types of Chinese international ships is as follows:

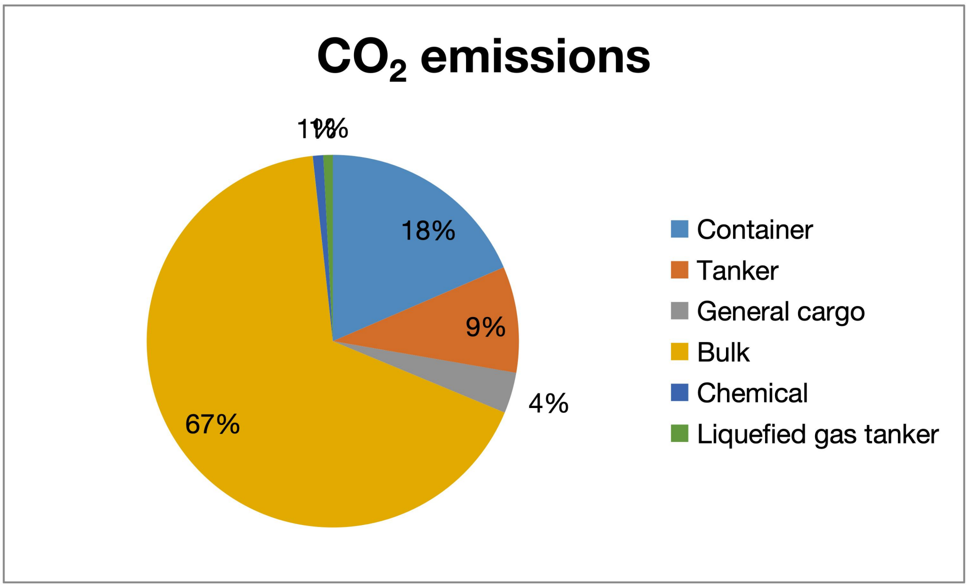


Figure 8- Emission share of the three major ship types

Source: self-made

2.2.2 Comparison of CO_2 Emissions from Chinese International Ships and Changes in Chinese Import and Export Shipping Volumes

The categories of imported and exported cargoes are categorized into 17 types of cargoes, which corresponds to a total of 8 types of ships, according to the Chinese commodities import and export data in the Clarkson maritime intelligence network. The following table shows the specific correspondence:

Table 5- Import and export cargo and ship type correspondence details

Cargo categories	Main streams	Ship types
Crude Oil	Imports/ Exports	Crude oil tanker
Oil Products	Imports/ Exports	Crude oil tanker
Containerisable	Imports/ Exports	Container ship
Chemical	Imports/ Exports	Chemical tanker
Liquid Gas	Imports/ Exports	Liquefied gas tanker
Specialized Liquid	Imports/ Exports	Liquefied gas tanker
Reefer Cargo	Imports/ Exports	Reefer ship
Grain (incl. soyabean)	Imports/ Exports	Bulk
Agribulks	Imports/ Exports	
Fertilisers	Imports/ Exports	
Metal Minor Bulk	Imports/ Exports	
Mineral Minor Bulk	Imports/ Exports	
Coal	Imports/ Exports	
Iron Ore	Imports	
Forest Products	Imports/ Exports	
Steel Products	Imports/ Exports	
Non-Container General Cargo	Imports/ Exports	General cargo

Source：Clarkson shipping intelligence network

Since the reefer ship's capacity is so little and it is not listed in the statistics table of international ships flying the Chinese flag, it will not be covered in this article. The changes obtained are given below by combining the import and export ocean freight volumes for each cargo by type (by container, tanker, bulk, chemical, liquefied gas, and general cargo):

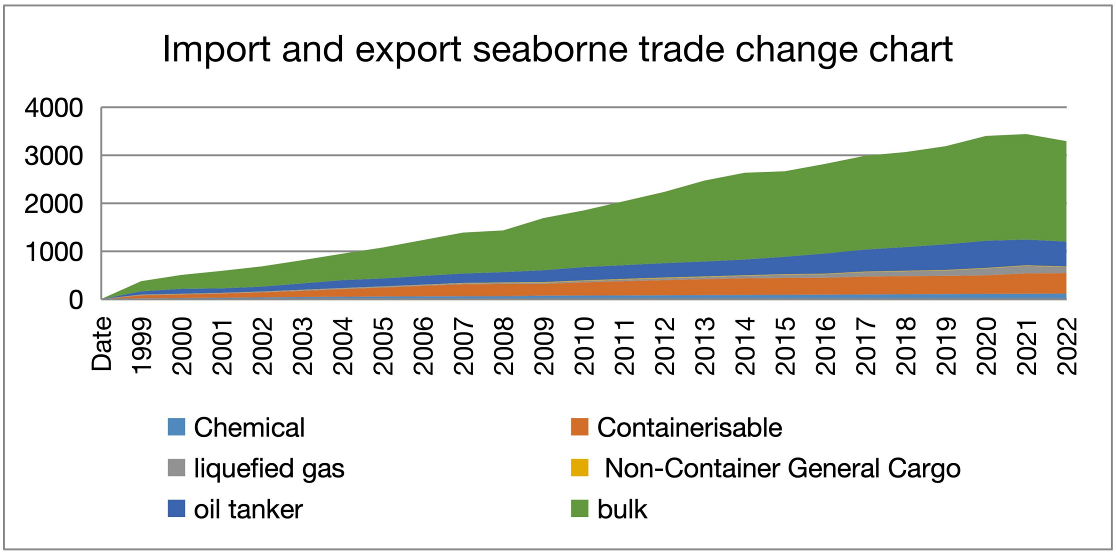


Figure 9- Volume of import and export of seaborne trade since 1999 - 2022

Source：Clarkson shipping intelligence network

The percentage of each type of sea freight cargo in the total volume of imports and exports is calculated in this study using five representative years: 2000, 2005, 2010, 2015, and 2022. The correlation between this percentage and the deadweight tonnage of the six main types of Chinese international ships in 2022 is then determined.

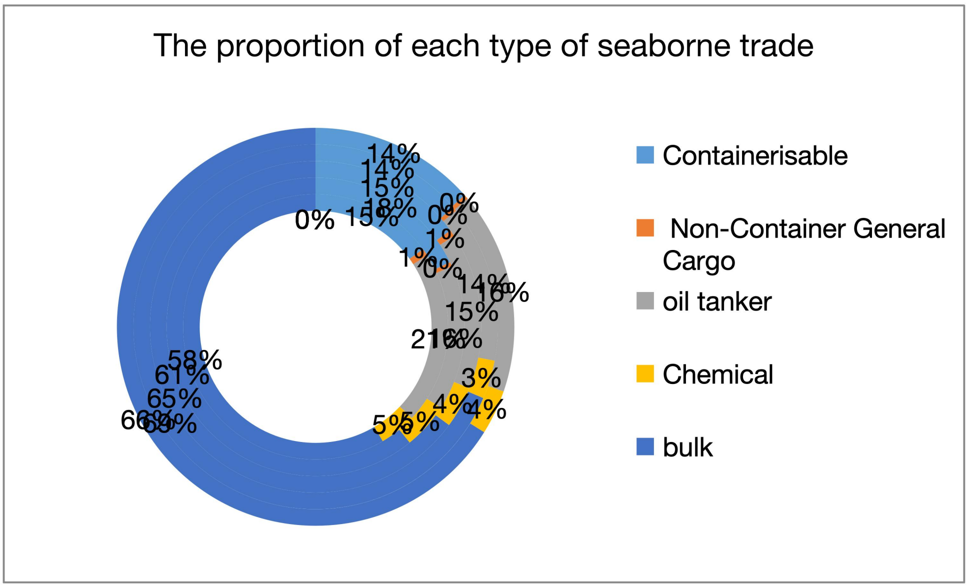


Figure 10- The proportion of various seaborne trade in 5 representative years

Source：Clarkson shipping intelligence network

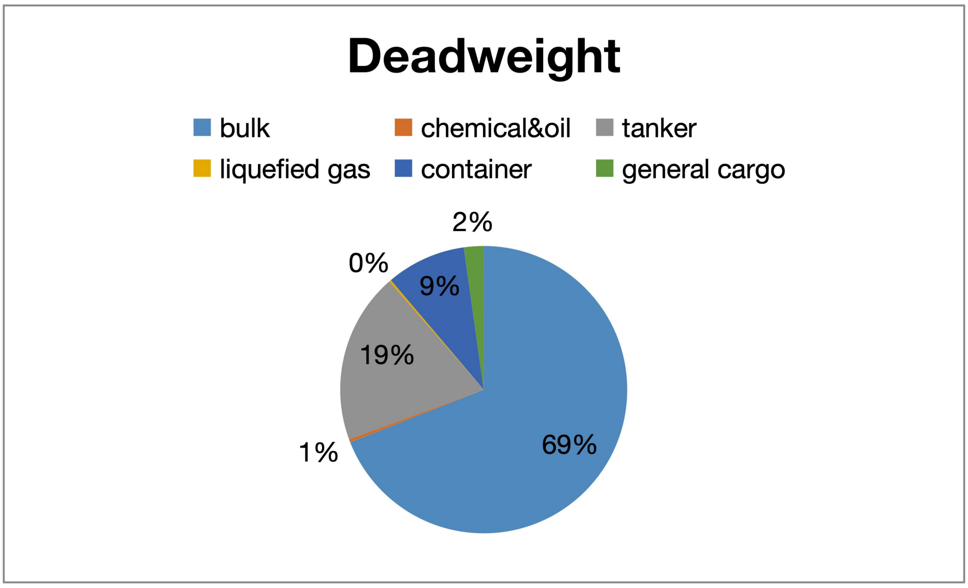


Figure 11- Comparison of deadweight tonnage of the six main ship types

Source：Clarkson shipping intelligence network

In the comparison of the two figures above, beside to the bulk ships that are the same, the dimensions of all other ships have all decreased to different degrees. Liquefied gas tankers and other high-value ships are returning to China more frequently, according figures from COSCO Holding, COSCO Sea Energy, and COSCO Specialized Transportation disclosed in their annual reports. But a sizable proportion of ships still fly the Hong Kong flag or another complacent flag. From the standpoint of Chinese corporations, these ships must undergo CO_2 emission reduction transformation; however, from the perspective of flag states, the existing ship survey regulations of China do not apply to such ships, so the emission reduction work of such ships is outside the purview of China's maritime authorities.

2.3 Summary of this chapter

This chapter calculates and analyzes CO_2 emissions from Chinese-flagged international ships. Based on data, a "top-down" and "bottom-up" CO_2 emission measuring model was created. Main data sources were listed company annual reports and Clarkson shipping intelligence network. The calculated results of the fourth IMO GHG Study 2020 were used to analyze the relationship between Chinese international sailing ships' total CO_2 emissions, ship type emission proportions, and import and export goods changes. The key implications of this chapter are as follows:

(1) There are significant differences in the contribution rates of various ship classes to overall CO_2 emissions. The three biggest sources of CO_2 emissions are dry bulk carriers, container ships, and oil tankers, with dry bulk carriers contributing 67%, container ships 18%, and oil tankers 9% respectively.

(2) Energy usage per unit turnover affects CO_2 emissions. When deadweight tons are low, container ships consume a lot of energy and emit a lot of CO_2.

(3) Chinese shipping companies and Chinese maritime authorities are also accountable for different CO_2 emission reduction responsibilities because the proportion of various ship types flying the Chinese flag differs from that of China's import and export of products. Chinese maritime authorities must create rules to help Chinese shipping company foster sustainable development while limiting CO_2 emissions within their authority.

CHAPTER 3 PREDICTION OF CO_2 EMISSIONS

Economy, energy, technology, legislation, and other factors affect ship CO_2 emission prediction. To create emission reduction policies and establish programs, nations and industry must develop reasonable projections of their future CO_2 emissions and environmental impact.

This chapter builds a future prediction model of CO_2 emissions from China's international shipping based on the IPCC environmental impact model and the IMO Marine CO_2 emission prediction model, estimates the emissions under various scenarios, and analyzes and predicts the trend.

Kaya's constant equation, developed by Japanese academic Yoichi Kaya (1989), connects CO_2 emissions to population, economy, and energy.

$$E = P * \frac{G}{P} * \frac{EC}{G} * \frac{E}{EC} \tag{4}$$

E: CO_2 emission; P: Population; G: GDP; EC: Energy consumption;

$\frac{G}{P}$: GDP per capita;

$\frac{EC}{G}$: energy consumption per unit of GDP;

$\frac{E}{EC}$: CO_2 emissions per unit of energy consumption;

Equation 4 shows how four factors—economy, population, transportation efficiency, and energy efficiency—influence CO_2 emissions. Since population and economic growth have a strong correlation on the maritime industry, they are fitted into one impact factor, so Equation 4 can be characterized as a collection of economic growth, fleet efficiency, and fuel emission factor, which matches IPCC's IPAT (I=P*A*T) environmental impact model. Thus, economic development, fleet efficiency, and fuel emission factor can anticipate CO_2 levels.

3.1 Correlation between economic growth and CO_2 emissions from ships

Seaborne trade is the main economic growth driver taken into account when estimating ship CO_2 emissions. The volume of maritime cargo transported is closely tied to population and GDP growth, so it's important to precisely forecast China's maritime transportation to estimate Chinese foreign ships' CO_2 emissions. You run the risk of making a serious error if you only employ the conventional linear equation with one variable to explain another variable. In order to examine the relationship between the changing trends of the independent and dependent variables, shipping turnover can be seen as the dependent variable and an exogenous variable as the independent variable, taking into account the complexity of the multi-factorial explanation. Compared to standard prediction models, multiple regression models' analysis and prediction are more systematic and diversified, and the change accuracy of dependent variables is higher.

A multiple regression model, which is frequently employed in the transportation industry, has the following fundamental equation:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \ldots + \alpha_n X_n + \varepsilon \quad (5)$$

Y: dependent variable;

X_i*: independent variable, i=1,2,……,n;*

α_0*: intercept of the regression equation;*

$\alpha_1 - \alpha_n$*: regression coefficients of the independent variables of interest;*

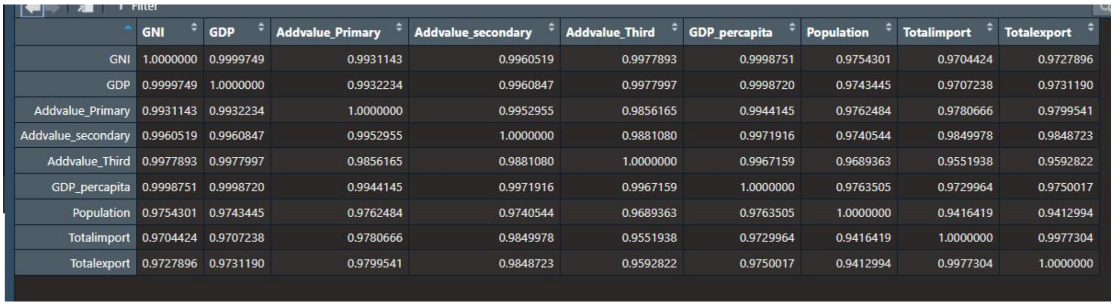
ε: *random error, which represents the difference between the observed value of y and the fitted value of the regression model, i.e., the reason why the regression model cannot be fitted exactly.*

At present, when forecasting future transportation demand and energy demand in the field of transportation, the original data are taken as logarithms during data processing to reduce the absolute number of data (Wang, et al., 2022; Hao, et al., 2015; Limanond, Jomnonkwao, & Srikaew, 2011), and a model is built on this basis to forecast. This paper uses a base of e to logarithmically process the data:

$$ln\ (Y) = \alpha_0 + \alpha_1 lnX_1 + \alpha_2 lnX_2 + \ldots + \alpha_n lnX_n + \varepsilon \tag{6}$$

This study predicts cargo turnover for oil tankers, chemical tankers, container ships, bulk ships, liquefied gas ships, and non-container general cargo ships. China's 2003–2023 GDP (X_1), population size (X_2), total import trade (X_3), and total export trade (X_4) are the independent variables. China Statistical Yearbook provides China's GDP, population size, total import trade, and total export trade for the past 20 years. Clarkson shipping intelligence network provides China's maritime transportation turnover basis data.

The multiple regression model must eliminate independent variable covariance. The computation findings show a high correlation between GDP and the other three independent variables, with correlation coefficients all exceeding 0.9. Multiple covariance will distort the model if these three independent variables are kept in the same model. The correlation coefficient statistics are given. Thus, to overcome the covariance problem, the covariance independent variables are manually eliminated and GDP is the only independent variable in the log-linear regression model.



	GNI	GDP	Addvalue_Primary	Addvalue_secondary	Addvalue_Third	GDP_percapita	Population	Totalimport	Totalexport
GNI	1.0000000	0.9999749	0.9931143	0.9960519	0.9977893	0.9998751	0.9754301	0.9704424	0.9727896
GDP	0.9999749	1.0000000	0.9932234	0.9960847	0.9977997	0.9998720	0.9743445	0.9707238	0.9731190
Addvalue_Primary	0.9931143	0.9932234	1.0000000	0.9952955	0.9856165	0.9944145	0.9762484	0.9780666	0.9799541
Addvalue_secondary	0.9960519	0.9960847	0.9952955	1.0000000	0.9881080	0.9971916	0.9740544	0.9849978	0.9848723
Addvalue_Third	0.9977893	0.9977997	0.9856165	0.9881080	1.0000000	0.9967159	0.9689363	0.9551938	0.9592822
GDP_percapita	0.9998751	0.9998720	0.9944145	0.9971916	0.9967159	1.0000000	0.9763505	0.9729964	0.9750017
Population	0.9754301	0.9743445	0.9762484	0.9740544	0.9689363	0.9763505	1.0000000	0.9416419	0.9412994
Totalimport	0.9704424	0.9707238	0.9780666	0.9849978	0.9551938	0.9729964	0.9416419	1.0000000	0.9977304
Totalexport	0.9727896	0.9731190	0.9799541	0.9848723	0.9592822	0.9750017	0.9412994	0.9977304	1.0000000

Figure 12- Calculation of correlation coefficients between independent variables

Source：Clarkson shipping intelligence network

This study uses statistical data from 2003-2023 to perform logarithmic regression analysis on the cargo turnover of six primary ship types. The fitted link between cargo turnover and GDP is shown below:

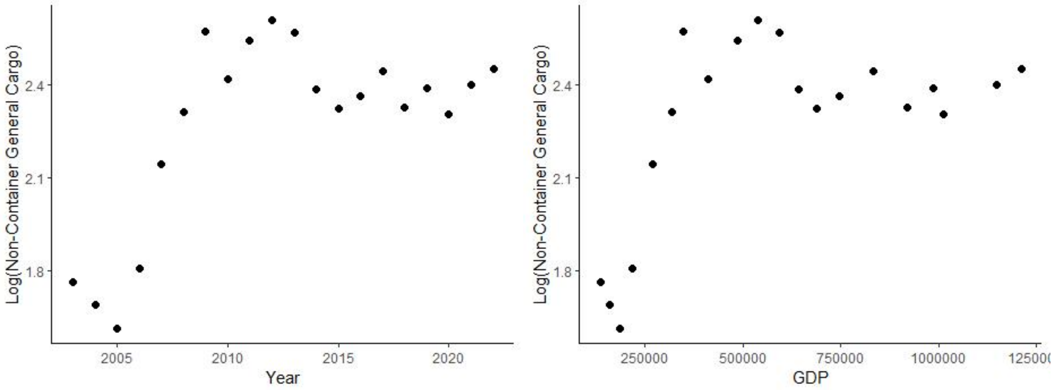
$$Ln(Y) = \alpha_0 + \alpha_1 * ln(GDP) \tag{7}$$

```
summary(lm(Chemical ~ log(GDP), Log_Data))
Call:
lm(formula = Chemical ~ log(GDP), data = Log_Data)

Residuals:
       Min         1Q    Median         3Q        Max
-0.056597  -0.013091  -0.006056   0.013376   0.074215

Coefficients:
              Estimate  Std. Error  t value  Pr(>|t|)
(Intercept)  -1.36418  (α0)0.13460   -10.13  7.27e-09  ***
log(GDP)      0.43617  (α1)0.01026    42.51   < 2e-16  ***
---
Signif. codes:   0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.03035 on 18 degrees of freedom
Multiple R-squared:  0.9901,        Adjusted R-squared:  0.9896
F-statistic:  1807 on 1 and 18 DF,  p-value: < 2.2e-16

> summary(lm(Contain ~ log(GDP), Log_Data))
Call:
```

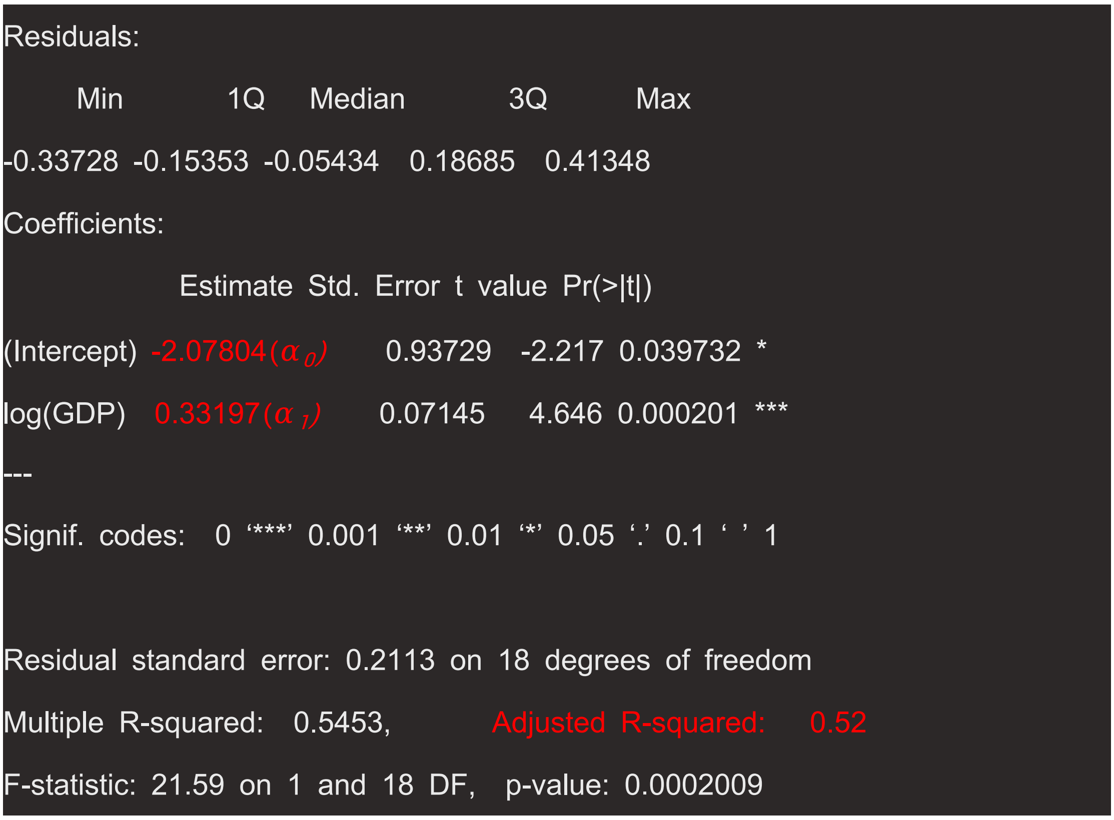
```
lm(formula = Contain ~ log(GDP), data = Log_Data)


Residuals:
       Min         1Q     Median         3Q        Max
-0.203821 -0.038106  0.008848  0.039574  0.118550


Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -0.50015(α0)0.32682   -1.53     0.143
log(GDP)     0.47113(α1)0.02491    18.91 2.53e-13 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


Residual standard error: 0.07369 on 18 degrees of freedom
Multiple R-squared:  0.9521,        Adjusted R-squared:  0.9494
F-statistic: 357.6 on 1 and 18 DF,  p-value: 2.529e-13


> summary(lm(Oiltanker ~ log(GDP), Log_Data))
Call:
lm(formula = Oiltanker ~ log(GDP), data = Log_Data)


Residuals:
       Min         1Q     Median         3Q        Max
-0.108920 -0.064085  0.008735  0.045961  0.139292


Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -2.87512 (α0)0.33374  -8.615 8.40e-08 ***
log(GDP)     0.65625 (α1)0.02544  25.794 1.15e-15 ***
---
```

```
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


Residual standard error: 0.07525 on 18 degrees of freedom

Multiple R-squared:  0.9737,        Adjusted R-squared:  0.9722

F-statistic: 665.3 on 1 and 18 DF,  p-value: 1.146e-15


> summary(lm(Bulk ~ log(GDP), Log_Data))

Call:

lm(formula = Bulk ~ log(GDP), data = Log_Data)


Residuals:

      Min        1Q    Median        3Q       Max

-0.17625 -0.05552  0.01315  0.05810  0.13175


Coefficients:

                Estimate Std. Error t value Pr(>|t|)

(Intercept) -2.26112 (α_0)0.35040  -6.453 4.52e-06 ***

log(GDP)     0.71990 (α_1)0.02671  26.950 5.31e-16 ***

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


Residual standard error: 0.07901 on 18 degrees of freedom

Multiple R-squared:  0.9758,        Adjusted R-squared:  0.9745

F-statistic: 726.3 on 1 and 18 DF,  p-value: 5.305e-16


GDP is better fitted the model than log(GDP)

(Log(Y) = α_0 + α_1*GDP)


> summary(lm(Liquidgas ~ GDP, Log_Data))

Call:
```

```
lm(formula = Liquidgas ~ GDP, data = Log_Data)


Residuals:
      Min        1Q    Median        3Q       Max
  -0.37517  -0.21682   0.01184   0.12953   0.37947


Coefficients:
                  Estimate  Std. Error  t value  Pr(>|t|)
(Intercept) -11.2684 (α0) 1.0219   -11.03  1.94e-09  ***
log(GDP)       1.1499 (α1)0.0779     14.76  1.69e-11  ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1


Residual standard error: 0.2304 on 18 degrees of freedom
Multiple R-squared:  0.9237, Adjusted R-squared:  0.9194
F-statistic: 217.9 on 1 and 18 DF,  p-value: 1.687e-11
```



```
> ####summary(lm(Non_Containercargo ~ log(GDP), Log_Data))
This function probably is not really reliable
Call:
lm(formula = Non_Containercargo ~ log(GDP), data = Log_Data)
```



```
Residuals:
     Min       1Q   Median       3Q      Max
-0.33728  -0.15353  -0.05434   0.18685   0.41348
Coefficients:
              Estimate  Std. Error  t value  Pr(>|t|)
(Intercept)  -2.07804(α0)   0.93729   -2.217  0.039732  *
log(GDP)   0.33197(α1)   0.07145    4.646  0.000201  ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2113 on 18 degrees of freedom
Multiple R-squared:  0.5453,     Adjusted R-squared:   0.52
F-statistic: 21.59 on 1 and 18 DF,  p-value: 0.0002009
```

As shown above, except for the low coefficient of determination $R^2=0.52$ for general cargo ship, the fitted equation $R^2>0.9$ for the other five ship types indicates that the regression curve is a good fit and that China's GDP is significantly correlated with their cargo turnover.

Calculation statistics for specific ship types:

Table 6- Logarithmic regression analysis calculation results for specific types of ships

Variables	α_0(intercept)	α_1(lg(gdp))	F-statistic	R^2	t value
Chemical	-1.36418	0.43617	1807	0.9896	42.51
Container	-0.50015	0.47113	357.6	0.9494	18.91
Oil tanker	-2.87512	0.65625	665.3	0.9722	25.794
Bulk	-2.26112	0.7199	726.3	0.9745	26.950
Liquid gas	-11.2684	1.1499	217.9	0.9194	14.76
General cargo	-2.07804	0.33197	21.59	0.52	4.646

Source : IMO, Clarkson, China National Statistical Yearbook

The CO_2 emissions forecast in this paper chooses to manually exclude general cargo ship and only forecast the future CO_2 emissions of the other five ship types because general cargo ship emissions only make up about 1% of the total CO_2 emissions.

3.2 Correlation between fleet efficiency and CO_2 emissions from ships

Fleet composition and ship size variations, fleet-specific emission rule requirements, and market-driven efficiency improvement are the key factors influencing fleet efficiency.

3.2.1 fleet composition and ship size

Since this article focuses on Chinese international ships, fleet composition does not expand and decline synchronously with China's import and export seaborne trade, and policies affect fleet composition, various assumptions must be made for projection. Thus, this paper anticipates that Chinese international ship fleets will remain unchanged. This document calculates the weighted average using the expected outcomes of the fourth IMO GHG study 2020 (save for container ships, bulk carriers, and liquefied gas carriers, other ships leave their size unaltered).The specific calculating formula is as follows:

$$CI = \sum_i AER_{i,j} * D_{i,j} * P_{i,j} \tag{8}$$

CI: average carbon emission intensity, unit: g/DWT for others g/TEU for container;

$AER_{i,j}$: average energy ratio in gram of *i* type ship in *j* size; unit: g/DWT/nm;

$D_{i,j}$: average distance sailed of *i* type ship in *j* size; unit: nm;

$P_{i,j}$: distribution of *i* ships over *j* size categories; unit: X%;

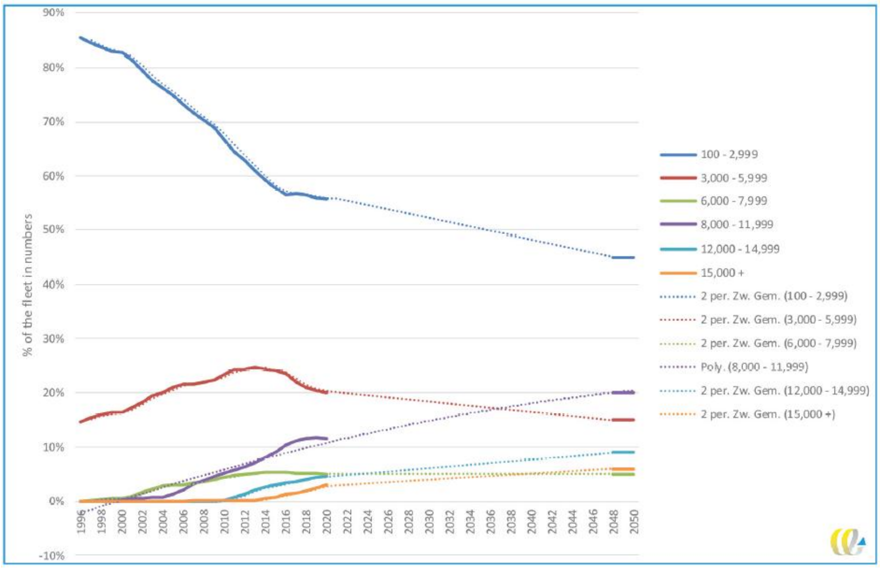


Figure 13- Size projections of containers

Source : the forth IMO GHG study 2020

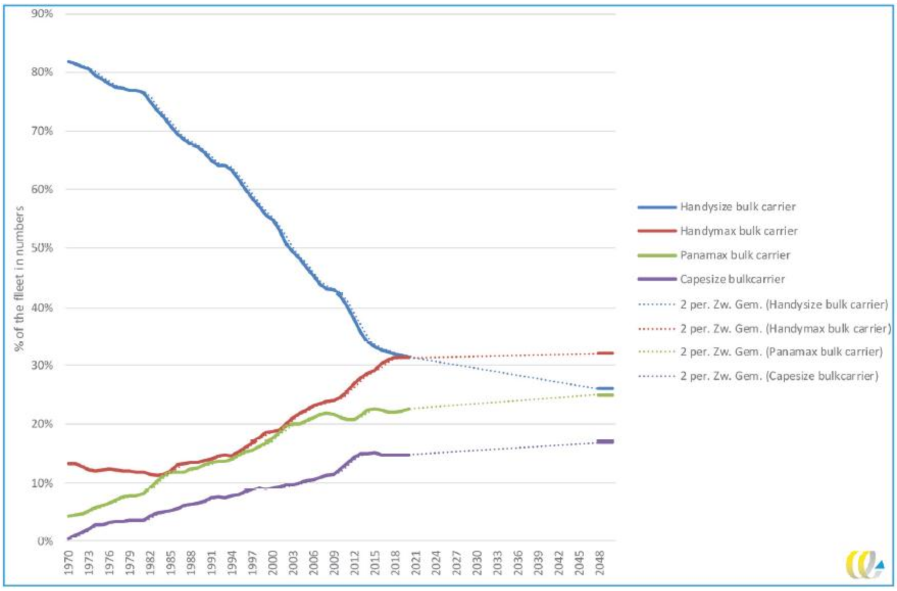


Figure 14- Size projections of bulk carriers

Source : the forth IMO GHG study 2020

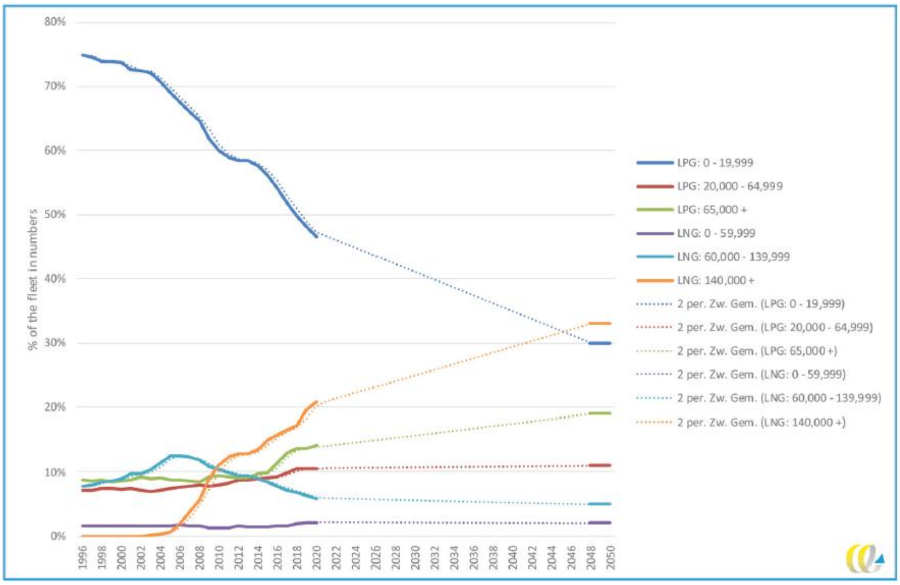
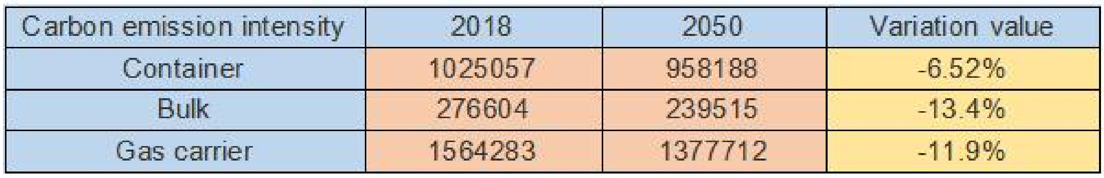


Figure 15- Size projections of gas carriers

Source : the forth IMO GHG study 2020

In this study, 2018 is the reference year and 2050 is the target. The ratio indicated in 3 Figures above is combined with the average energy ratio and average distance in table 3 to compute the change in the average carbon emission intensity of the three ship types. The table below displays calculation results:

Table 7- Variation value of average carbon emission intensity of three main ship types



Carbon emission intensity	2018	2050	Variation value
Container	1025057	958188	-6.52%
Bulk	276604	239515	-13.4%
Gas carrier	1564283	1377712	-11.9%

Source : the forth IMO GHG study 2020

3.2.2 requirements of emission rules on fleets

Under the Carbon Intensity Rules for International Shipping, the IMO promoted the EEDI for new ships, the EEXI and the CII for existing ships, primarily through the regulations connected to MARPOL Appendix VI "Prevention of Air Pollution from

Ships". Ships must meet EEDI, EEXI, and CII under the Carbon Intensity Rules for International Shipping. The energy efficiency regulations, which include EEDI, were approved at the 62nd MEPC meeting in July 2011 and went into effect on January 1, 2013, lasting ten years. EEXI, which will go into effect on January 1, 2023, is a significant extension of EEDI and uses the same calculation formula. It is applicable to ships of 400 GT and above. According to Huang, Jiang, and Lv (2023), the term "CII" refers to the actual operational carbon intensity index for ships, which takes effect on January 1, 2023, and applies to ships of 5,000 GT and higher.

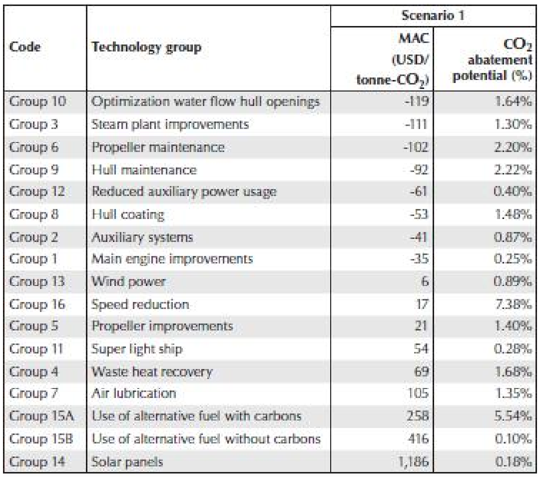
The goal of the EEDI, EEXI, CII, and SEEMP regulations is to accelerate the adoption of energy-saving and emission-reduction technologies on ships. The regulations themselves do not result in increased energy efficiency; rather, their precise effects depend on the advancement of technological levels and the application of energy-saving and emission-reduction measures. The influence of specific legislation on ship energy efficiency will not be explored separately in this section to avoid double counting as the next section will discuss the impact of the deployment of emission reduction measures (including technical methods) on fleet efficiency.

3.2.3 market-driven efficiency improvement

A total of 44 efficiency-improving technologies, which can be grouped into three categories, have been used to reduce CO_2 emissions in ships, according to the 2nd IMO GHG Study and the 4th IMO GHG Study. Energy-saving technology is the first category, followed by the usage of renewable energy and speed reduction.

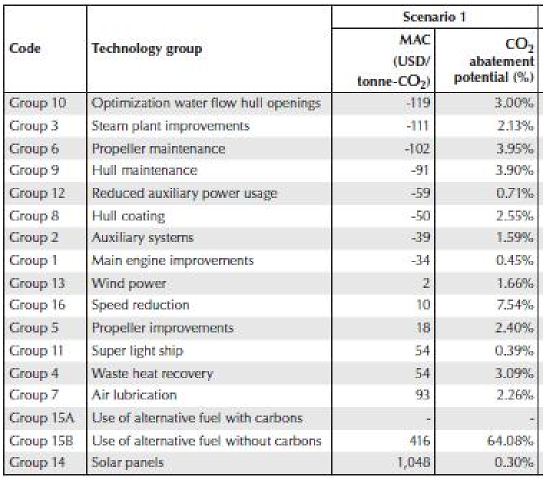
Speed reduction is an operational measure, but renewable energy entails low-carbon energy usage, hence this article mainly discusses efficiency gains through technological approaches. The use of abatement technology has a significant impact on CO_2 emission reductions in the practice of technical efficiency improvement. The ability of each technology to reduce CO_2 emissions is correlated with the projected penetration rate in 2030–2050 and the difference in 2018. The Fourth IMO GHG Study makes the following assumptions in this paper regarding the penetration rate of each type of abatement technology and the CO_2 energy saving and emission reduction effect under this penetration rate, taking into account the superposition and exclusion between energy saving and emission reduction technologies. The Fourth IMO GHG Study predicts the fleet efficiency under various growth models, as shown in the following table:

Table 8- Projections of fleet average efficiency improvements for scenarios



Code	Technology group	Scenario 1	
		MAC (USD/ tonne-CO_2)	CO_2 abatement potential (%)
Group 10	Optimization water flow hull openings	-119	1.64%
Group 3	Steam plant improvements	-111	1.30%
Group 6	Propeller maintenance	-102	2.20%
Group 9	Hull maintenance	-92	2.22%
Group 12	Reduced auxiliary power usage	-61	0.40%
Group 8	Hull coating	-53	1.48%
Group 2	Auxiliary systems	-41	0.87%
Group 1	Main engine improvements	-35	0.25%
Group 13	Wind power	6	0.89%
Group 16	Speed reduction	17	7.38%
Group 5	Propeller improvements	21	1.40%
Group 11	Super light ship	54	0.28%
Group 4	Waste heat recovery	69	1.68%
Group 7	Air lubrication	105	1.35%
Group 15A	Use of alternative fuel with carbons	258	5.54%
Group 15B	Use of alternative fuel without carbons	416	0.10%
Group 14	Solar panels	1,186	0.18%

2030



Code	Technology group	Scenario 1	
		MAC (USD/ tonne-CO_2)	CO_2 abatement potential (%)
Group 10	Optimization water flow hull openings	-119	3.00%
Group 3	Steam plant improvements	-111	2.13%
Group 6	Propeller maintenance	-102	3.95%
Group 9	Hull maintenance	-91	3.90%
Group 12	Reduced auxiliary power usage	-59	0.71%
Group 8	Hull coating	-50	2.55%
Group 2	Auxiliary systems	-39	1.59%
Group 1	Main engine improvements	-34	0.45%
Group 13	Wind power	2	1.66%
Group 16	Speed reduction	10	7.54%
Group 5	Propeller improvements	18	2.40%
Group 11	Super light ship	54	0.39%
Group 4	Waste heat recovery	54	3.09%
Group 7	Air lubrication	93	2.26%
Group 15A	Use of alternative fuel with carbons	-	-
Group 15B	Use of alternative fuel without carbons	416	64.08%
Group 14	Solar panels	1,048	0.30%

2050

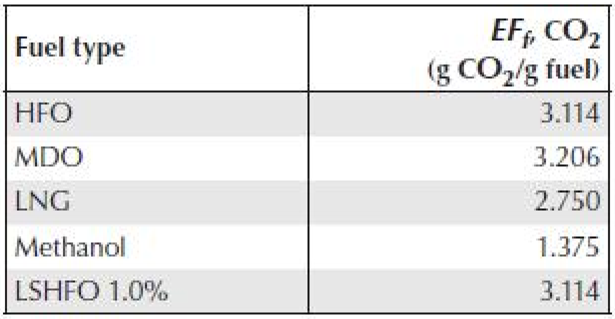
Source: the 4th IMO GHG study 2020

As can be seen from the above table, the growth of fleet average efficiency under all types of growth models is maintained at approximately 13.59% in 2030, which is taken to be 14% in this article, and at approximately 26.42% in 2050, which is taken to be 26% in this paper.

3.3 Correlation between fuel emission factor and CO_2 emissions from ships

The 2018 EEDI Guide already provides CO_2 emission factors for regularly used fuels, as shown in the table below. CO_2 emission factors are typically differentiated based on the kind of fuel.

Table 9- CO_2 fuel-based emission factors (EF_f)



Fuel type	EF_f, CO_2 (g CO_2/g fuel)
HFO	3.114
MDO	3.206
LNG	2.750
Methanol	1.375
LSHFO 1.0%	3.114

Source ： IMO

As illustrated above, certain fuels' CO_2 emission factors are relatively stable, and their contribution to a ship's total CO_2 emissions mostly comes from fuel blending. This paper will only discuss the blending of carbonaceous fuels like LNG and methanol, as hydrogen and ammonia have zero CO_2 emissions but no large ship engines. In the most optimistic scenario, all new ships will use carbonaceous fuels or dual fuel as their principal fuel, according to the 4th IMO GHG study. Since LNG is widely available and used, the penetration ratio between carbonaceous fuels is assumed to be LNG:methanol=3:1, and the weighted average of the pertinent variables in table 9 yields an emission factor of 2.40625 for mixed fuels. The 2050 fleet CO_2 emission factor is 2.731815 with 54% carbonaceous fuel.

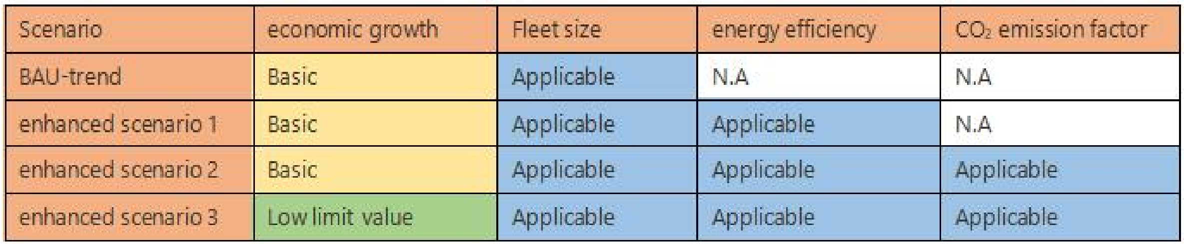
3.4 CO_2 emission prediction scenario setting

China's potential economic growth rate differs from the literature due to measuring methodologies (primarily the growth accounting method and the foreign experience analogy method), assumptions, parameter choices, etc. However, in general, the results for 2025 are mostly in the range of 5% to 6.5%, with individual results below 5% or above 7%; for 2035, the results are mostly in the range of 4% to 5%, with individual results below 4% or above 6%; for 2050, the results are roughly in the range of 2.5% to 4% (Lu, Cai, 2016; Liu Peilin,2015; Yi, Guo,2018; Bai, Zhang, 2017; Guo, Lu, 2018).For the convenience of calculation, the median of the interval is chosen as the average annual GDP growth rate, which is 5.75% in 2023-2025, 4.5% in 2025-2035, and 3.25% in 2035-2050.

The BAU-trend scenario describes a development that proceeds as usual, following the current trajectory and trend route without taking any new policies into account. China's GDP is anticipated to increase at an average annual rate of 5.75% in 2023-2025, 4.5% in 2025-2035, and 3.25% in 2035-2050 under the BAU-trend scenario. A linear regression model can predict the yearly maritime freight turnover of each vessel category from 2023 to 2050 under the BAU-trend scenario using the trend projection of the average annual growth rate of the independent variable GDP. The effect of changing fleet sizes must also be taken into account in the BAU-trend scenario.

On the basis of the BAU-trend scenario, the enhanced scenario 1 can be created by applying the fleet efficiency improvement technique widely; the enhanced scenario 2 can be created by adding the impact of low CO_2 emission factor fuels; An enhanced scenario 3 can be created based on the enhanced scenario 2, lowering the GDP growth rate projection by using the projections in this section's lower range, which are 5% in 2023–2025, 4% in 2025–2035, and 2.5% in 2035–2050. If this is done, the effects of economic growth, energy efficiency, and the CO_2 emission factor on total CO_2 emissions are taken into consideration. The following table is a construction of the specific scenarios:

Table 10- Scenario design



Scenario	economic growth	Fleet size	energy efficiency	CO_2 emission factor
BAU-trend	Basic	Applicable	N.A	N.A
enhanced scenario 1	Basic	Applicable	Applicable	N.A
enhanced scenario 2	Basic	Applicable	Applicable	Applicable
enhanced scenario 3	Low limit value	Applicable	Applicable	Applicable

Source: self-made

3.5 Trend prediction of CO_2 emission from ships

The effects of ship energy efficiency, CO_2 emission factor, and economic growth correspond to upgraded scenarios 1/2/3, respectively, in Section 3.4's scenarios. Then, under the scenarios of BAU-trend and upgraded scenario 1/2/3, the projected results of the total CO_2 emissions from Chinese international ships in 2050 may be obtained.

$$E = E_0 * G_i * V_s * E_e * CF_m \tag{9}$$

E: prediction results of CO_2 emission under different scenarios;

E_0: CO_2 emissions of different ship types in 2022;

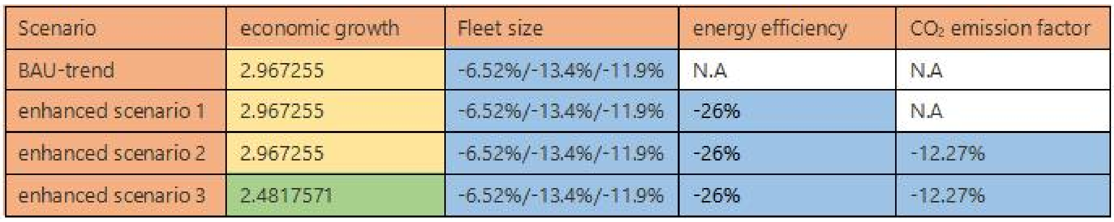
G_i: economic growth rate in BAU-trend and enhanced scenario 3;

V_s: predicted changes in fleet size;

E_e: variation value of ship energy efficiency;

CF_m: the change of CO_2 emission factor after the use of low-carbon fuel;

Table 11- Change value of each factor



Scenario	economic growth	Fleet size	energy efficiency	CO_2 emission factor
BAU-trend	2.967255	-6.52%/-13.4%/-11.9%	N.A	N.A
enhanced scenario 1	2.967255	-6.52%/-13.4%/-11.9%	-26%	N.A
enhanced scenario 2	2.967255	-6.52%/-13.4%/-11.9%	-26%	-12.27%
enhanced scenario 3	2.4817571	-6.52%/-13.4%/-11.9%	-26%	-12.27%

Source: IMO, Clarkson, China National Statistical Yearbook

3.5.1 Trend prediction of CO_2 emissions under BAU scenario

This research assumes that seaborne trade growth matches Chinese ship deadweight ton growth and that ship type structure remains intact except for natural size evolution. Reviewing the literature, China's economic development is forecasted, and the seaborne trade of five ship types is determined by linear regression. In the BAU scenario, seaborne trade of various ship types has grown. Seaborne trade in

2050 has increased 2.7 times from 2022, with liquid gas up 3.5 times and bulk up 2.6 times. Oil tanker freight grew 2.1 times, container 1.7 times, and chemical 1.6 times.

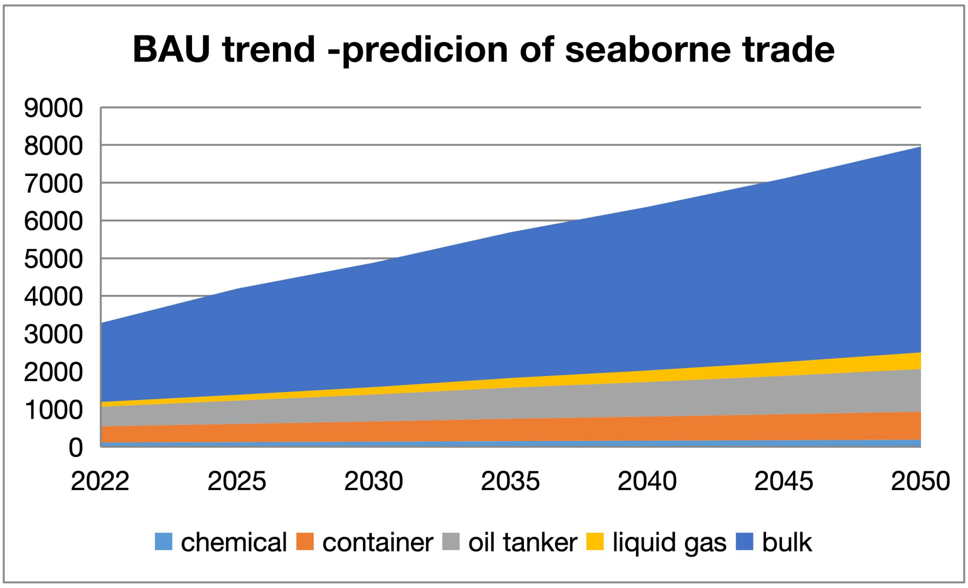


Figure 16- Seaborne trade growth forecast for 5 main goods

Source: Clarkson, China National Statistical Yearbook

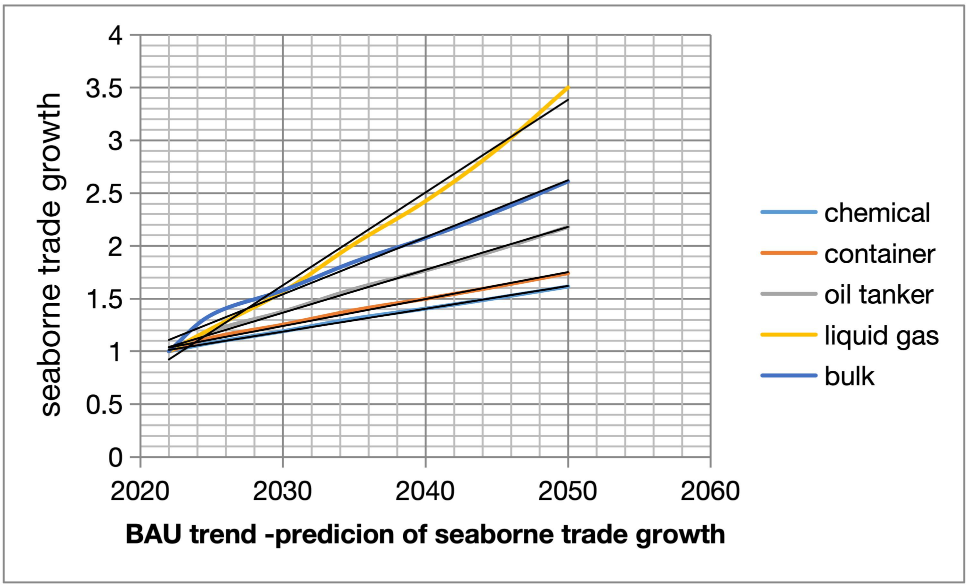


Figure 17- Growth rate of seaborne trade for 5 main goods

Source: Clarkson, China National Statistical Yearbook

Combined with the basic data in table 4, after converting seaborne trade with the same growth rate, the deadweight tons increase significantly, as shown in the figure below:

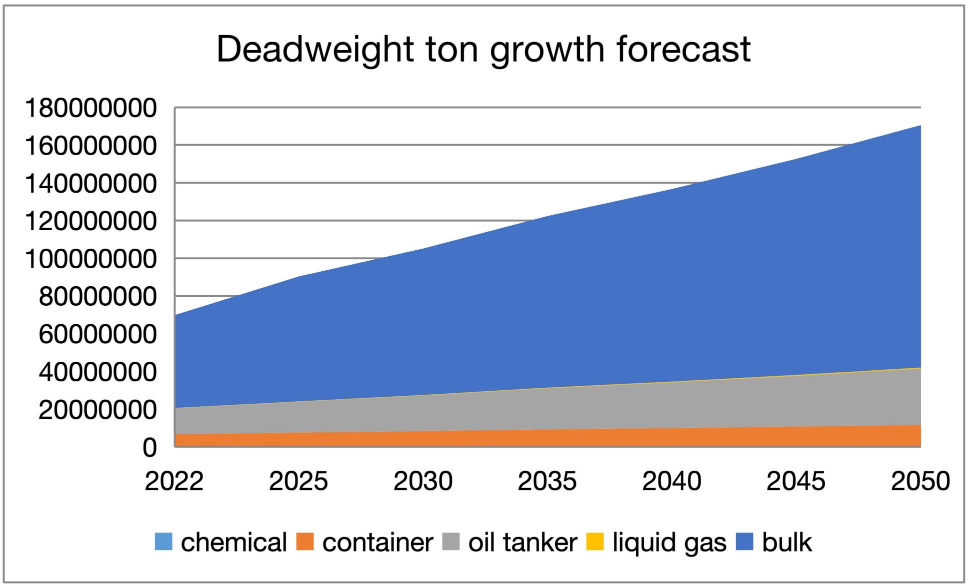


Figure 18- Deadweight ton growth prediction for 5 main ships

Source: Clarkson shipping intelligence network

With the exception of variations in unit energy consumption of container, bulk, and gas carriers brought on by changes in ship size (See table 7), other ship categories' unit energy consumption and CO_2 emission factors in the BAU scenario remain unchanged. The following picture illustrates the future CO_2 emission prediction of Chinese international ships as well as the CO_2 emission distribution ratio across various ship types, together with the rise in deadweight tonnage of each ship type:

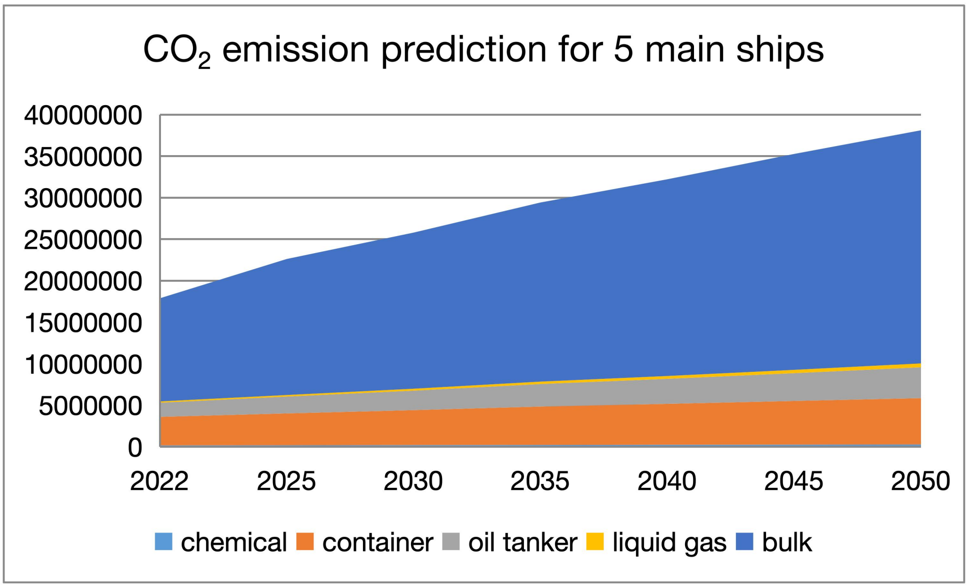


Figure 19- Future CO_2 emission prediction of Chinese international ships

Source: Clarkson shipping intelligence network, IMO

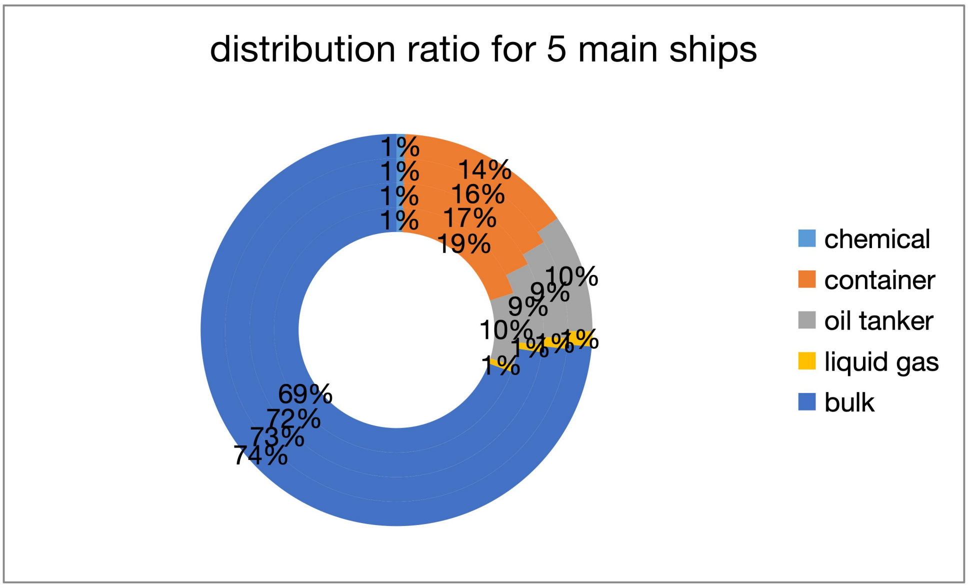


Figure 20- The CO_2 emission distribution ratio among different ships

Source: Clarkson shipping intelligence network, IMO

According to the BAU scenario, the CO_2 emissions of general cargo ships are calculated based on the same percentage of all emissions in 2022, and it is determined that the total CO_2 emissions of six major ships in 2050 will be 39,447,996.39 tons. It climbed by 212.9% compared to 18,528,580.46 tons in 2022, with chemical increasing by 161.4%, container increasing by 162.7%, oil tanker increasing by 217.8%, liquid gas growing at the quickest rate (308.4%), bulk increasing by 226%, and general cargo growing by 205.6%, as shown in the graph below:

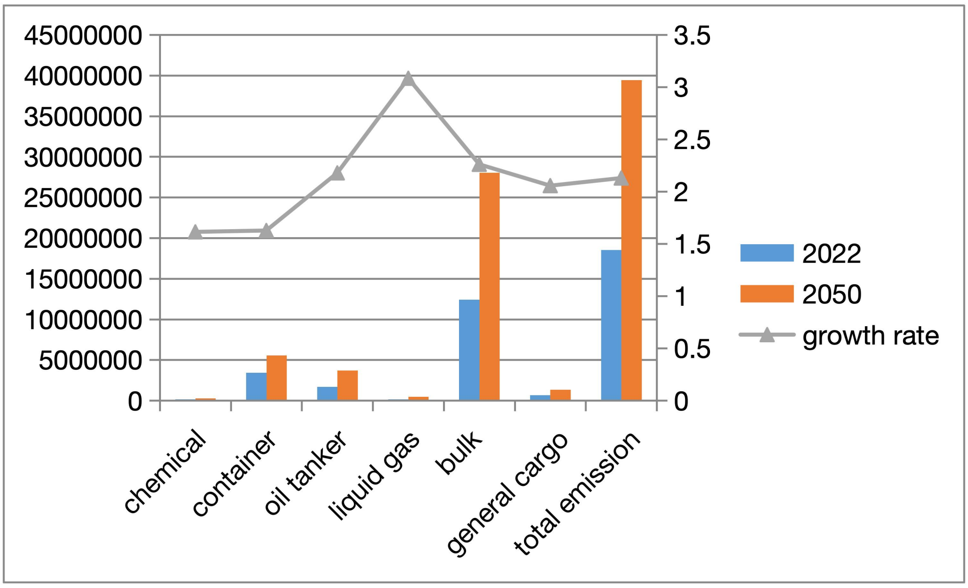


Figure 21- CO_2 emission and growth rate of each ship type

Source: Clarkson shipping intelligence network, IMO

3.5.2 Prediction of CO_2 emission trend under three enhanced scenarios

The overall predicted trend of China's international maritime CO_2 emissions from 2022 to 2050 is shown in the figure below. The BAU-trend scenario, which does not take policy changes into account, reflects the development of all factors in accordance with the existing situation (including the replacement of ship sizes according to the current path). The enhanced ship energy efficiency scenario, the use of clean energy scenario, and the low economic growth scenario that results in declining maritime demand are three scenarios that describe potential trends in China's international maritime CO_2 emissions, respectively.

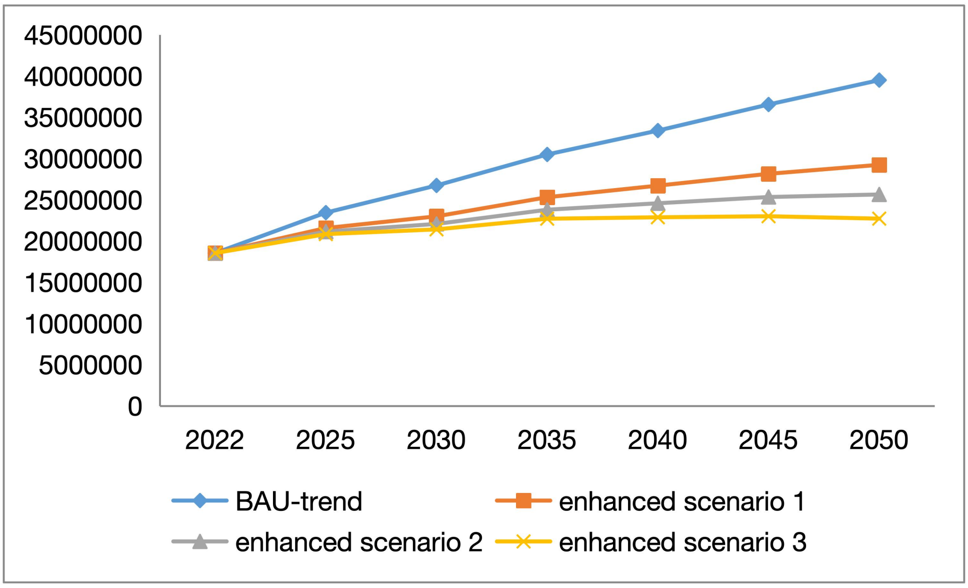


Figure 22- Prediction of CO_2 emission under different scenarios

Source: Clarkson, China National Statistical Yearbook

There are discrepancies in the precise growth rates of the emission reductions, but overall the enhanced scenario had a lower growth rate of CO_2 emissions from international shipping in China than the BAU-trend scenario did. In enhanced scenarios 1 and 2, the global trend of CO_2 emissions from international shipping continued to increase without experiencing a peak phenomenon; in enhanced scenario 3, CO_2 emissions from ships almost stopped growing in 2035, peaked in 2045, began to decline, and then returned to the 2035 emission level by 2050. The total CO_2 emissions in the BAU-trend are about 39.5 million tons, or 2.13 times what they will be in 2022. The total CO_2 emissions in improved scenario 1 are approximately 29.23 million tons, or 1.58 times what they will be in 2022. Around 25.63 million tons of CO_2 are emitted in enhanced scenario 2, which is 1.38 times more than in 2022. The total CO_2 emissions in the enhanced scenario 3 are about 22.7 million tons, which is about 1.23 times what it will be in 2022.

According to three enhanced scenarios, while switching from BAU-trend to enhanced scenario 1, enhanced scenario 1 transforms into enhanced scenario 2, and enhanced scenario 2 transforms into the enhanced scenario 3 with the best adjustment. In Scenario 3, it is predicted that decreasing sea freight turnover, using low-carbon fuel, and enhancing ship energy efficiency will lower China's international shipping's CO_2 emissions by 26%, 9%, and 7.5%, respectively, in 2050. Less CO_2 was emitted into the atmosphere in amounts of 10.3 million tons, 3.6 million tons, and 2.93 million tons, respectively.

3.6 Summary of this chapter

This chapter builds a prediction model for the trend of CO_2 emissions from Chinese international ships and forecasts the future trend of CO_2 emissions from international maritime transport in China based on changes in import and export cargo shipping volume derived from economic growth, ship energy efficiency, and CO_2 emissions. The model is based on the KAYA constant equation and the three variables proposed by IMO that affect the trend of CO_2 emissions from maritime transport. A number of matched adjustment scenarios, enhanced scenario 1/2/3 are developed for each variable based on the BAU-trend scenario, and the consequences of the CO_2 emission forecasting under various scenarios are evaluated using scenario simulation. The following are the main conclusions this chapter came to:

(1) Ship CO_2 emission forecasting should take into account the reduction in energy consumption brought about by the natural change in ship size, which occurs naturally with economic development without the need for policy formulation to promote or require it.

(2) The BAU-trend scenario predicts that CO_2 emissions from China's international ships will continue to rise quickly in the future. By 2050, CO_2 emissions from China's international maritime transport are predicted to be 39.5 million tons, or 2.13 times more than they were in 2022, growing at a rate of 2.74% annually. All other ship categories rose more than twice as quickly as liquid gas (up 308.4% from 2022 to 2050), with the exception of chemical tankers and container ships, which grew slowly. Dry bulk carriers remain consistently the largest source of CO_2 emissions, rising from 69% in 2022 to 74% in 2050.

(3) Between 22.7 million tons (enhanced scenario 3) and 29.23 million tons (enhanced scenario 1), the anticipated CO_2 emissions of Chinese international vessels under the three enhanced scenarios are lower by 2050 than those under the BAU-trend scenario. The upgraded scenario 3, which only projects a 36% rise in CO_2 emissions from 2022, is the best case scenario. The other upgraded scenarios also show a variety of effect variables, with the corresponding decreases in CO_2 emissions of 7.5%, 26%, and 9% coming from less import/export cargo movements, increased ship energy efficiency, and the use of low-carbon fuels.

CHAPTER 4 COMPARISON OF CO_2 EMISSION REDUCTION SCHEMES

Since 1997, IMO has created a number of obligatory regulations and guidance documents to encourage the marine sector's reduction of GHG emissions (Zhang S, et al., 2020). Among them, the IMO Initial Strategy for GHG Emission Reduction from Ships, adopted in 2018, sets the quantitative target of emission reduction as follows: compared with 2008, the average CO_2 emissions from international shipping per unit of transport activity will be reduced by at least 40% by 2030, and strive to reduce by at least 70% by 2050, 50% reduction in total CO_2 emissions by 2050(Chircop, 2019). China is the world's largest maritime emitter of carbon, thus meeting this challenging emission reduction target will be extremely difficult. Additionally, China formally pledged to "strive to reach peak CO_2 emissions by 2030 and strive to achieve carbon neutrality by 2060" by signing the Paris Agreement (China Daily, 2021). Studying the countermeasures for CO_2 reduction in China's international shipping is therefore urgently needed.

The current GHG working group debate resulted in a new GHG emission reduction target for the IMO, but it wasn't officially publicized until the submission of this article (IMO, 2023). Therefore, this research continues to use the IMO's 2018 emission reduction target as a constraint, backestimates a number of potential emission reduction paths to meet the target, and suggests a policy mix for Chinese international shipping to reduce CO_2 emissions. To support and serve as a source of data for the Chinese maritime authorities as they develop policies for reducing emissions.

4.1 IMO Stage Carbon Emission Reduction Target data Calculation (2050)

According to IMO's 2018 global maritime GHG emission reduction Roadmap, the "initial strategy" requires a 50% reduction in global maritime transport CO_2 emissions by 2050 compared to 2008 levels (Garcia, Foerster, & Lin, 2021). To do this, the subsequent debate and analysis will look at whether or not Chinese international ships will be able to satisfy the IMO's initial strategic aim by 2050 under various scenarios.

Sections 3.5.1 and 3.5.2 estimate Chinese-nationality ships' 2050 CO_2 emissions using historical data and the computation of their CO_2 emissions. This section uses historical data along with a forecast approach to determine the CO_2 emissions of Chinese ships in 2008. Then, a comparison and analysis of the anticipated values under various circumstances is performed.

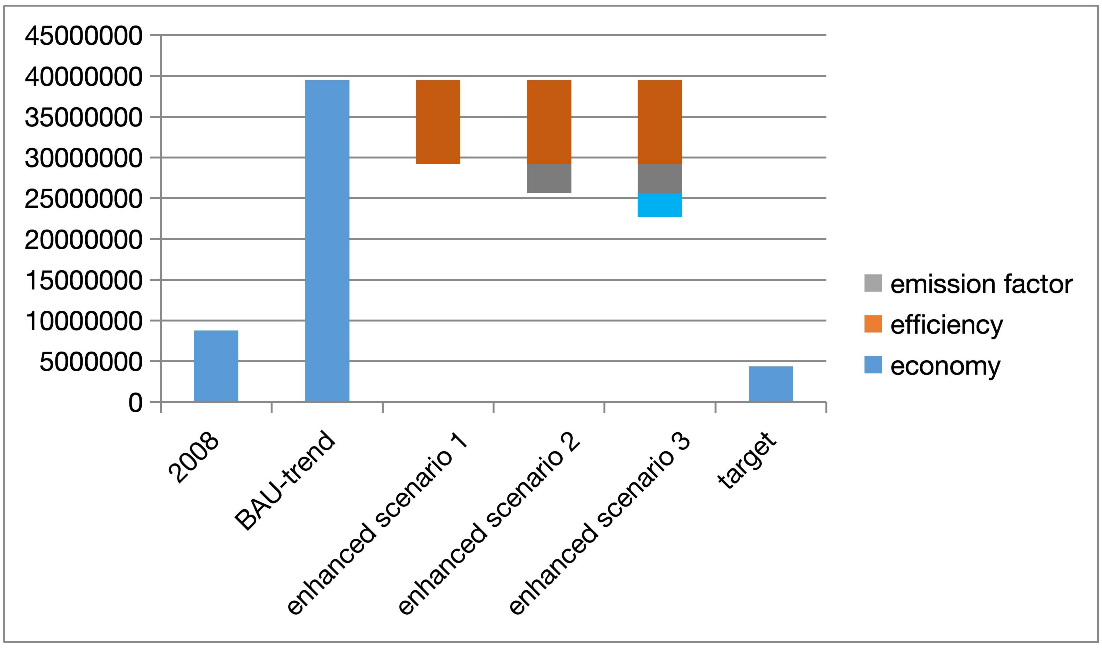


Figure 23- The comparison between CO_2 emissions under enhanced scenarios and reduction target of IMO in 2050

Source: Clarkson, China National Statistical Yearbook

FIG. 23 compares Chinese international ship CO_2 emissions under the BAU-trend scenario and three enhanced scenarios with the IMO CO_2 emission reduction target. According to the comparative findings, CO_2 emissions in 2050 will be 4.5 times higher than they were in 2008 under the BAU-trend scenario. The enhanced scenario 3 with the best emission reduction effect still releases 22.7 million tons of CO_2, despite the fact that CO_2 emissions are greatly decreased in the other enhanced scenarios. This is still 5.17 times the IMO's 2050 CO_2 reduction objective. In other words, even under the best-case enhancement scenario, the current emission reduction methods and measures cannot achieve the global CO_2 emission reduction target by 2050, whether it be to increase the efficiency of the current fleet, use low-carbon fuels, or account for the impact of the decreasing freight volume after the economic growth slowdown. Exploring innovative emission reduction plans and strategies for Chinese international ships is therefore vital.

4.2 Review of research on CO_2 emission reduction paths

According to a survey of the literature, technological advancements, operational changes, the use of eco-friendly fuels, and the utilization of alternative energy sources are the key ways for reaching CO_2 emissions target. Each technique includes multiple expressions for different ship sizes and kinds. The classification is broken down as follows:

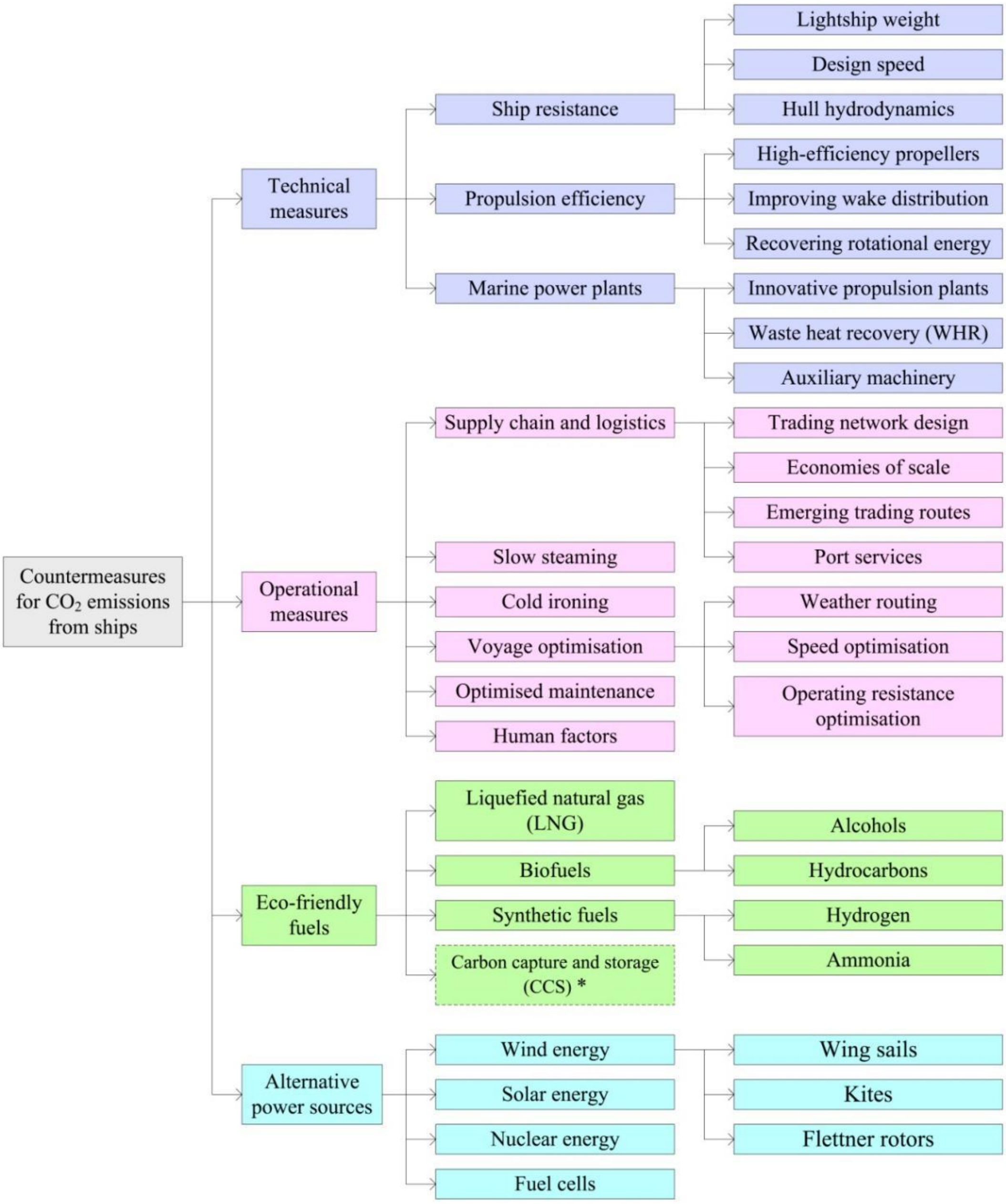


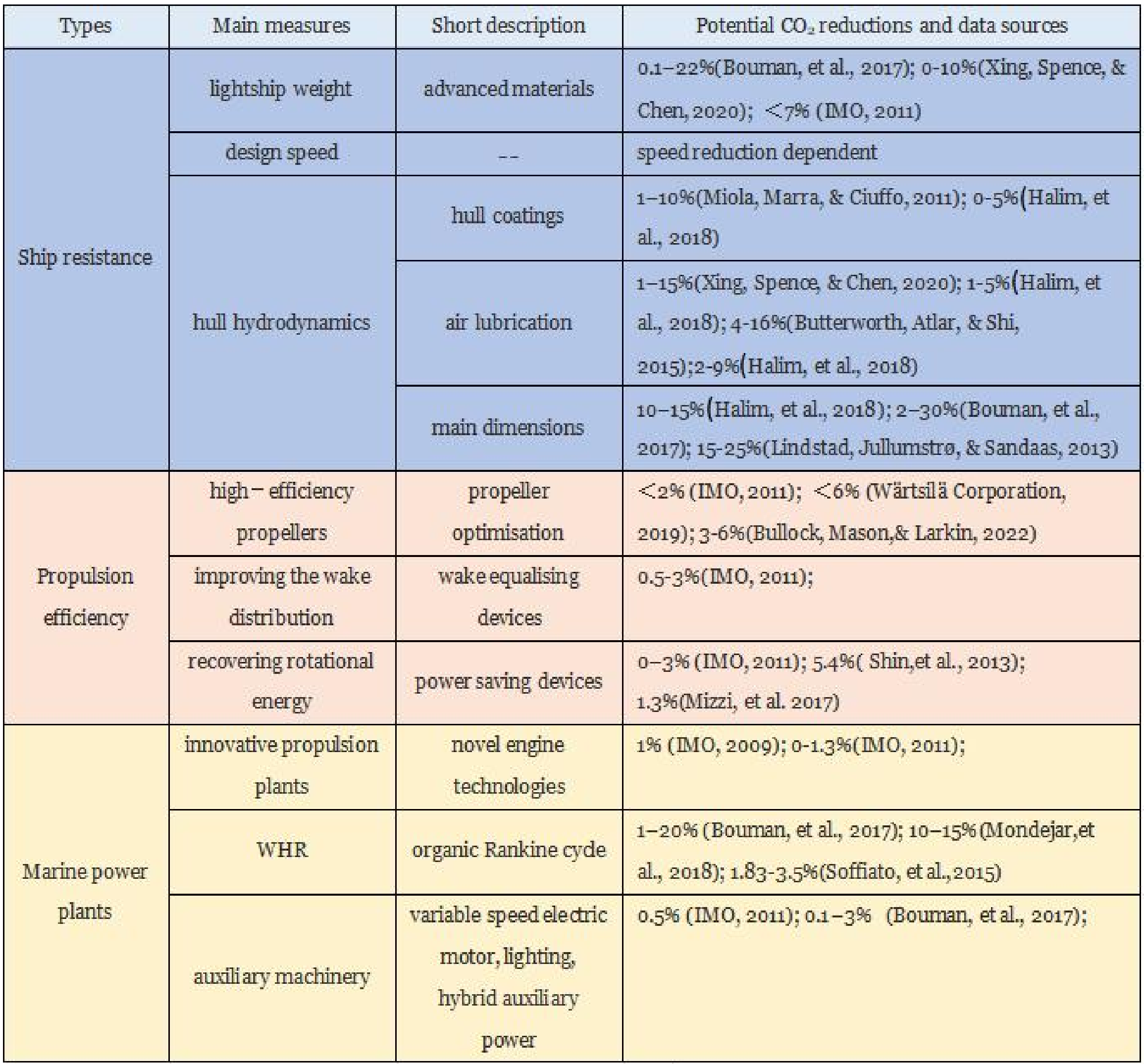
Figure 24- Potential measures for shipping CO_2 emissions reduction

Source: Science Direct

4.2.1 Technological solutions

Technically speaking, the hull, propeller, and marine power plant make up the marine propulsion system. Reducing ship resistance, increasing propulsion effectiveness, and increasing energy efficiency are the three primary ways to reduce ship emissions when taking energy consumption into account (Vidovi, et al., 2023). There are various realization approaches in each strategy. The CO_2 emission reduction of ships differs when the same technical measures are applied due to changes in ship types, weather circumstances, engine conditions, and operation conditions (Xing, Spence, & Chen, 2020). Additionally, technical methods are not always applicable to all ships due to variations in ship characteristics and renovation cost performance, thus their ability to reduce emissions also varies.The following technical measures have the potential to reduce CO_2 emissions:

Table 12- Technological solutions and potential CO_2 emissions reduction



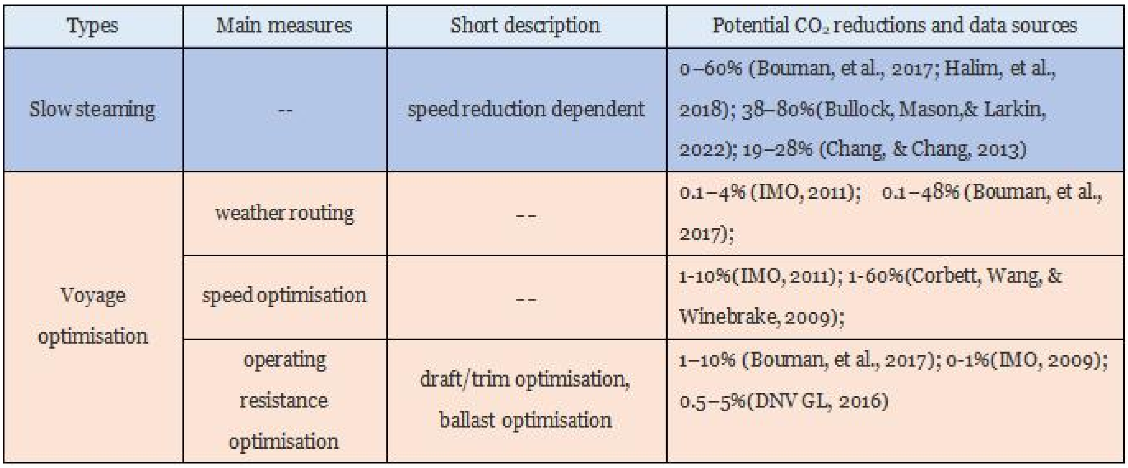
Types	Main measures	Short description	Potential CO_2 reductions and data sources
Ship resistance	lightship weight	advanced materials	0.1–22%(Bouman, et al., 2017); 0-10%(Xing, Spence, & Chen, 2020); ＜7% (IMO, 2011)
	design speed	--	speed reduction dependent
	hull hydrodynamics	hull coatings	1–10%(Miola, Marra, & Ciuffo, 2011); 0-5%（Halim, et al., 2018)
		air lubrication	1–15%(Xing, Spence, & Chen, 2020); 1-5%（Halim, et al., 2018); 4-16%(Butterworth, Atlar, & Shi, 2015);2-9%（Halim, et al., 2018)
		main dimensions	10–15%（Halim, et al., 2018); 2–30%(Bouman, et al., 2017); 15-25%(Lindstad, Jullumstrø, & Sandaas, 2013)
Propulsion efficiency	high – efficiency propellers	propeller optimisation	＜2% (IMO, 2011); ＜6% (Wärtsilä Corporation, 2019); 3-6%(Bullock, Mason,& Larkin, 2022)
	improving the wake distribution	wake equalising devices	0.5-3%(IMO, 2011);
	recovering rotational energy	power saving devices	0–3% (IMO, 2011); 5.4%(Shin,et al., 2013); 1.3%(Mizzi, et al. 2017)
Marine power plants	innovative propulsion plants	novel engine technologies	1% (IMO, 2009); 0-1.3%(IMO, 2011);
	WHR	organic Rankine cycle	1–20% (Bouman, et al., 2017); 10–15% (Mondejar,et al., 2018); 1.83-3.5%(Soffiato, et al.,2015)
	auxiliary machinery	variable speed electric motor, lighting, hybrid auxiliary power	0.5% (IMO, 2011); 0.1–3% (Bouman, et al., 2017);

Source : self-made

4.2.2 Operational measures

Operational methods reduce CO_2 emissions by lowering electricity demand and improving energy efficiency (Xing, Spence, & Chen, 2020). Operations take place during various cruise, maneuvering, and berthing stages and involve the crew, the ship, the ship company, the port, and other parties (Lindstad & Eskeland, 2015). This report only discusses ship emission reduction, not other major roles like supply chain and logistics optimization, human factors, maintenance, cold ironing, etc. The only topic covered in this section is the potential for slow steaming and trip optimization to reduce emissions. These specifics are provided:

Table 13- Operational measures and potential CO_2 emissions reduction



Types	Main measures	Short description	Potential CO_2 reductions and data sources
Slow steaming	--	speed reduction dependent	0–60% (Bouman, et al., 2017; Halim, et al., 2018); 38–80%(Bullock, Mason,& Larkin, 2022); 19–28% (Chang, & Chang, 2013)
Voyage optimisation	weather routing	--	0.1–4% (IMO, 2011); 0.1–48% (Bouman, et al., 2017);
	speed optimisation	--	1-10%(IMO, 2011); 1-60%(Corbett, Wang, & Winebrake, 2009);
	operating resistance optimisation	draft/trim optimisation, ballast optimisation	1–10% (Bouman, et al., 2017); 0-1%(IMO, 2009); 0.5–5%(DNV GL, 2016)

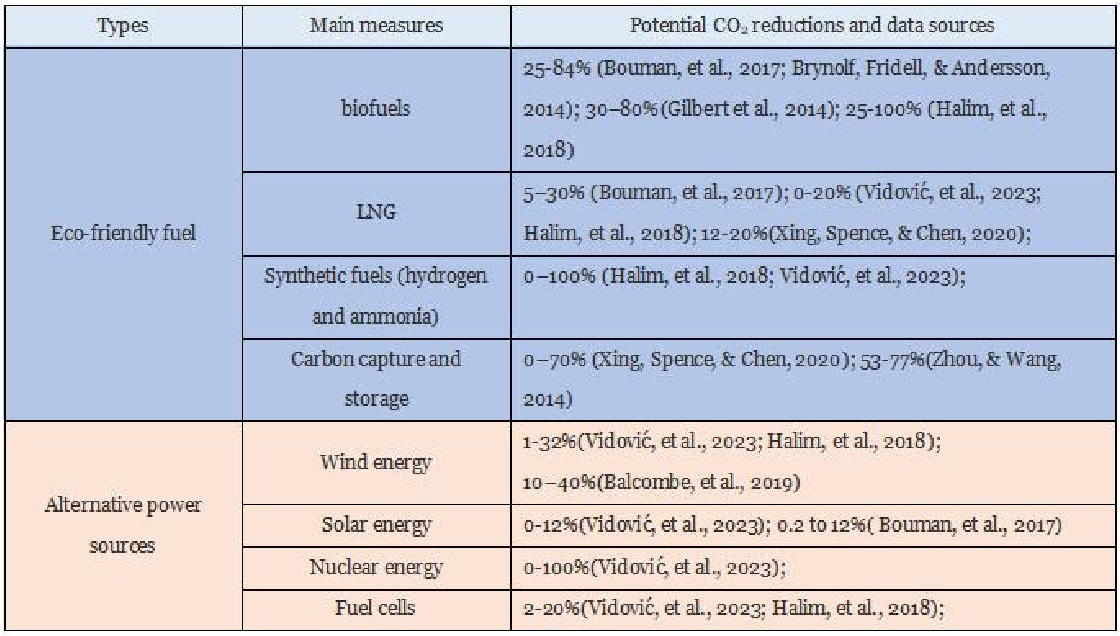
Source : self-made

4.2.3 Eco-friendly fuel& Alternative power sources

One of the crucial elements to achieving low-carbon shipping is diversifying ship fuels. Traditional fossil fuels should be gradually replaced by low- or zero-carbon fuels in order to reduce CO_2 emissions. In order to eventually replace conventional fuels, ships should also employ or experiment with LNG, biofuels, hydrogen, and ammonia as pure fuels or fuel blends.

Technical viability has been verified for a number of alternative marine fuels, the key obstacle is their economic viability (Xing, Spence, & Chen, 2020). Although a sizable amount of LNG has been used in the maritime industry, the need for future shipping to be carbon-neutral limits LNG's long-term potential. Due to the safety of the raw ingredients, bioethanol and biodiesel have a lower potential for use in the sea than methanol (Bouman, et al., 2017). Hydrogen and ammonia are projected to play a big part in the future of transporting fuel with the rise of the hydrogen economy (Halim, et al., 2018; Vidovi, et al., 2023), if the transportation and storage challenges can be better managed in the future. According to Xing, Spence, and Chen (2020), the current condition of alternative maritime fuels often contains the following drawbacks: high cost, a lack of infrastructure, and insufficient supply.

Table 14- Eco-friendly fuel & power sources and potential CO_2 emissions reduction



Types	Main measures	Potential CO_2 reductions and data sources
Eco-friendly fuel	biofuels	25-84% (Bouman, et al., 2017; Brynolf, Fridell, & Andersson, 2014); 30–80% (Gilbert et al., 2014); 25-100% (Halim, et al., 2018)
	LNG	5–30% (Bouman, et al., 2017); 0-20% (Vidović, et al., 2023; Halim, et al., 2018); 12-20%(Xing, Spence, & Chen, 2020);
	Synthetic fuels (hydrogen and ammonia)	0–100% (Halim, et al., 2018; Vidović, et al., 2023);
	Carbon capture and storage	0–70% (Xing, Spence, & Chen, 2020); 53-77%(Zhou, & Wang, 2014)
Alternative power sources	Wind energy	1-32%(Vidović, et al., 2023; Halim, et al., 2018); 10–40%(Balcombe, et al., 2019)
	Solar energy	0-12%(Vidović, et al., 2023); 0.2 to 12%(Bouman, et al., 2017)
	Nuclear energy	0-100%(Vidović, et al., 2023);
	Fuel cells	2-20%(Vidović, et al., 2023; Halim, et al., 2018);

Source : self-made

Due to the restricted output power of actual devices, several forms of hybrid power systems must be formed by combining auxiliary wind, solar photovoltaic, fuel cells, and diesel engine power systems (Vidovi, et al., 2023). Hybrid power ships provide safer and more environmentally friendly ship operating. However, hybrid power systems are a significant short- and medium-term goal of low-carbon shipping, not the only one, given the demand for zero carbon in the future.

4.3 Possible CO_2 emission reduction path selection

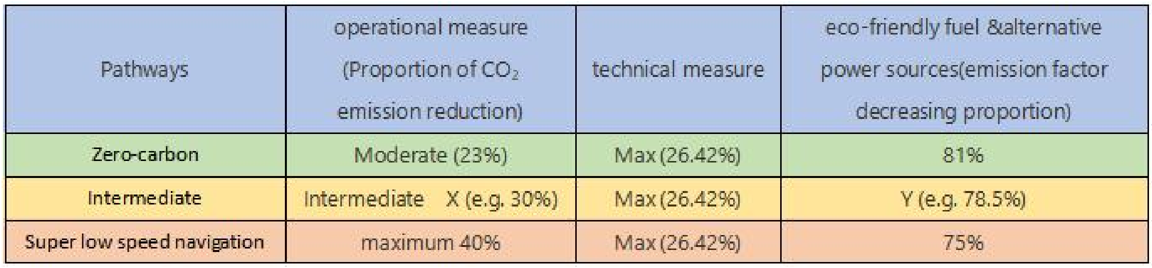
Chinese international ships' CO_2 emissions must be lowered by 89% from 39.5 million tons under BAU-trend to half of 2008's 4.4 million tons to meet the IMO initial strategy's CO_2 emission reduction objective. One emission reduction measure alone will not be able to meet the 2050 target, as shown by the findings anticipated in the third chapter of this study, regardless of technological measures, operational measures, or low-carbon fuel replacement. It is essential to adopt a variety of emission reduction schemes in order to meet the emission reduction target, even in the case of slow economic growth and the use of low-carbon fuel. (Special note: Since the impact of the larger ship sizes on lower unit energy consumption has already been taken into account in this paper's BAU-trend, the impact of the larger ship sizes on lower CO_2 emissions will not be discussed.)

Although technical measures are applicable to various systems, not all ships can benefit from them. For instance, the construction of huge ships cannot use aluminum from modern technologies. The application of cargo loading and shipping routes must also be taken into account while designing a slim hull (Ma, Yang, & Xing, 2018). As a result, when it comes to the adoption of technological measures, it is expected that the ship does its utmost to employ every technical option to conserve energy and cut emissions. As for operational measures, as mentioned above, the improvement of supply chain logistics and energy consumption in berthing state are not within the scope of this paper. However, the maximum emission reduction efficiency of the entire fleet increases by 26.42% with optimal technology penetration (100% new technology penetration), according to the fourth IMO GHG study data (IMO, 2020). Additionally, because they are arbitrary and challenging to thoroughly enhance, human factors and extensive maintenance are not included in the scope of operational measures. Speed reduction and trip optimization are the key operational measure variables employed in this section. In this study, the ship speed reduction and route optimization indexes are primarily obtained from IMarEST (Russell et al., 2011), where the ship speed reduction is chosen between two alternative speed reduction ranges: moderate (10%) and maximum (20%), which equate to CO2 reductions of 19% and 36%, respectively; Two operational action options—moderate (23%) and maximum (40%)—were created based on the direct selection of a maximum CO_2 reduction of 4% for route optimization (IMO, 2011).

Equation (3) states that in addition to technical and operational steps that can lower a ship's unit energy consumption, reducing the carbon emission factors of a ship's fuels, or using eco-friendly fuel and alternative power sources, is another option to lower a ship's CO_2 emissions. According to Table 14, nuclear energy, hydrogen, and ammonia can completely reduce CO_2 emissions, whereas biofuels, LNG, fuel cells, wind, and solar energy can only reduce emissions to varying degrees. The only variable altering the carbon emission variables used in the third chapter of this study for CO_2 emission prediction is LNG. The findings indicate that the IMO's aim for reducing CO_2 emissions cannot be met. Therefore, in order to meet the IMO's target, we must use additional environmentally friendly fuel and alternative power sources. The proportion of eco-friendly fuel to alternative power sources can be calculated based on the use of various technological and operational parameters.

The fraction of fuel replacement will change with the proportion of operational measures (ship speed decrease range), assuming that all technical measures are implemented. The particular composition plan to meet the goal of 89% CO_2 reduction is indicated in the table below:

Table 15- Different potential decarbonzation pathways and their components



Pathways	operational measure (Proportion of CO_2 emission reduction)	technical measure	eco-friendly fuel &alternative power sources(emission factor decreasing proportion)
Zero-carbon	Moderate (23%)	Max (26.42%)	81%
Intermediate	Intermediate X (e.g. 30%)	Max (26.42%)	Y (e.g. 78.5%)
Super low speed navigation	maximum 40%	Max (26.42%)	75%

Source : self-made

4.3.1 A path toward "zero-carbon" emission reduction

A "zero-carbon" emission reduction path requires that traditional HFO be primarily replaced as energy sources by eco-friendly fuel and alternative power sources under the conditions of moderate speed reduction of ships in order to achieve emission reduction targets from the perspective of lowering CO_2 emission factors.

Under this emission reduction approach, numerous ecologically friendly fuels and alternative energy sources are aggressively marketed, particularly zero-carbon energy sources like hydrogen and ammonia, which will quickly supplant traditional HFO in the ensuing 27 years. Fuel substitution, which will reduce the CO_2 emission factors of blended fuels by 81% by 2050, is the most crucial component in attaining the IMO emission reduction target.Clean energy has a greater impact on lowering CO_2 emissions than the combined effect of the other two emission reduction strategies, resulting in a reduction of 18.13 million tons of CO2 emissions. with this emission reduction approach, the ship only slowed down 10%, and its emission reduction effect was 8.03 million tons, similar to that of technological measures (with 100% penetration), which was 9.08 million tons. When the three emission reduction techniques are combined, it is anticipated that China's international ships will reduce their CO_2 emissions by 35.25 million tons in 2050, which will allow them to meet the target of a 50% reduction in CO2 emissions from 2008.

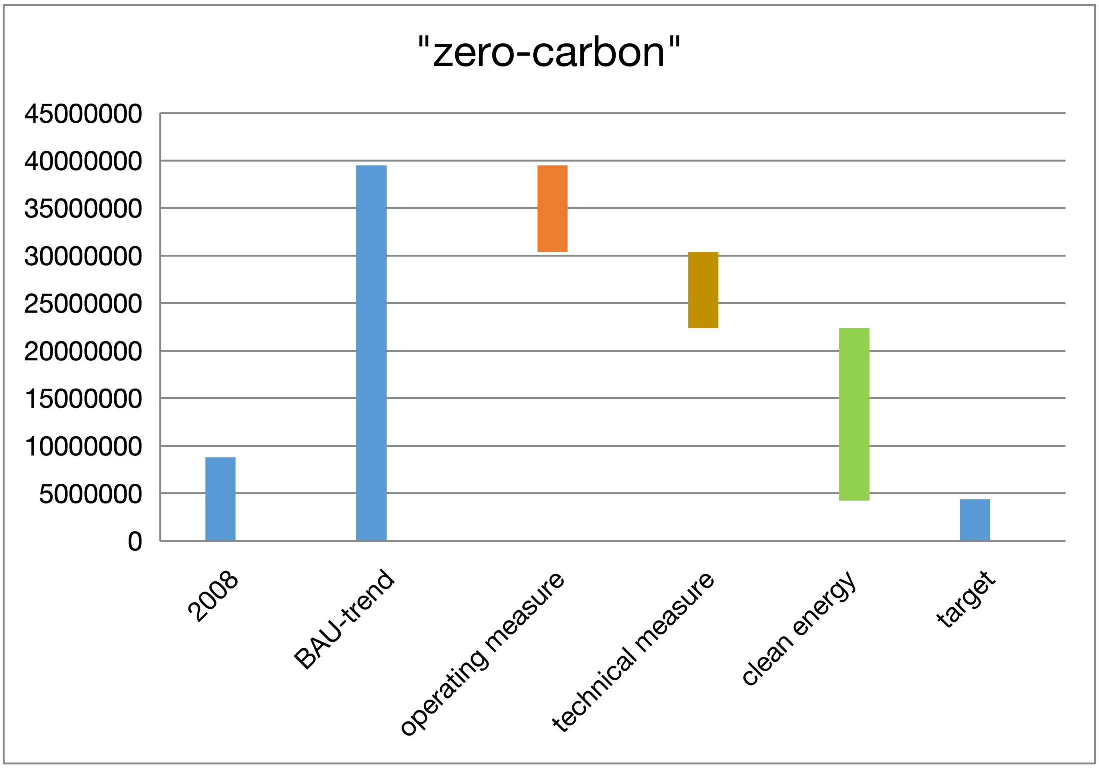


Figure 25- "zero-carbon" pathway CO_2 emissions reduction

Source: self-made

4.3.2 a path toward "ultra-low-speed navigation" emission reduction

Ultra-low-speed navigation primarily utilizes slow steaming to achieve the emission reduction target and reduce the efficiency of each ship type's CO_2 emissions.

Under this emission reduction path, all ship types will reduce ship speed to the maximum based on their own standard speed and greatly reduce CO_2 emissions according to the cubic relationship between ship speed and CO_2 emission, making ultra-low speed sailing within ships' normal operating range the most critical factor to meet the IMO emission reduction target. It is important to note that the large decrease in ship speed will have an impact on the effectiveness of wind assistance and hull optimization in reducing CO_2 emissions; however, the technical emission reduction deviation brought on by such an effect is not taken into account here. Even if the ship reduces its speed to the extent permitted by business needs, using zero-carbon fuel is still vital in terms of using environmentally friendly fuel and alternative power sources.

A significant amount of zero-carbon fuel is still required, as indicated in Table 15, to reduce the emission factor by more than 75%.

When compared to the 6.26 million tons of technical measures and the 13.08 million tons of clean energy, the CO_2 emission reduction achieved by significantly slowing down the ship's operating speed (20% deceleration) reached 15.8 million tons, making it the largest CO_2 emission reduction factor. The overall CO_2 emission is decreased by 35.14 million tons when the three actions are combined, compared to the expected CO_2 emission in the BAU-trend scenario, and the ideal emission reduction target of 50% relative to the 2008 level is also met.

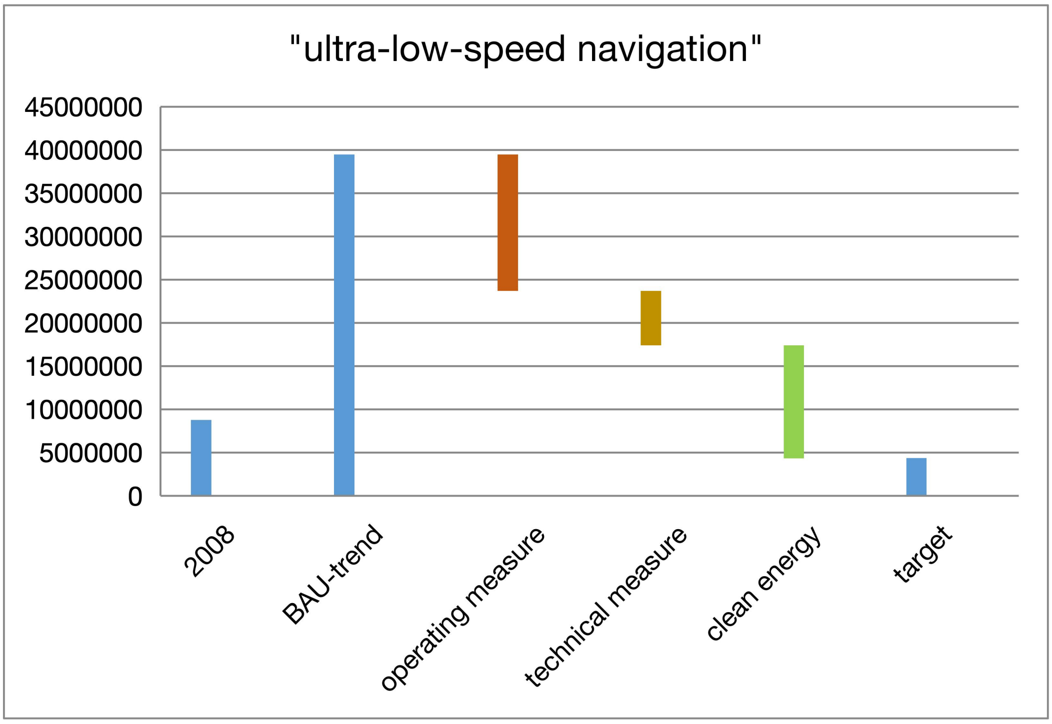


Figure 26- " ultra-low-speed navigation "pathway CO_2 emissions reduction

Source: self-made

4.4 Comparison of emission reduction paths under the reduction target

The comparison of the various emission reduction paths under the three paths of "zero-carbon" "ultra-low-speed Navigation" and “Intermediate” is shown in Fig. 27. The upper and lower limitations of the “Intermediate” path are based on the maximum deceleration and the maximum emission factor reduction stated in "zero-carbon" and "ultra-low-speed navigation," respectively. “Intermediate” path is a mix of CO_2 emission reduction approaches that can accomplish emission reduction targets. Figure 27 depicts a potential plan. In addition, the decline of shipping turnover due to the decline of economic growth or the enhancement of regional trade is not included in this path discussion, because the method discussed here is the most difficult situation to achieve the goal, and the decline of shipping turnover will directly lead to the decline of ship CO_2 emissions, so in the case of economic downturn, it is only necessary to reduce the intensity of the relevant emission reduction path.

Operational measures, technical measures, and clean energy are all covered by the "zero-carbon" and "ultra-low-speed navigation" emission reduction tracks, however the primary methods of reduction vary according on the path. "Zero-carbon" focuses on using clean energy to reduce CO_2 emission factors, and the CO_2 emission reduction impact produced by clean energy accounts for 51.4% of the total emission reduction, or more than half of the reduction in CO_2 emissions. The goal of "ultra-low-speed navigation" is to significantly reduce speed in order to meet emission reduction standards, doing so will result in a 45% reduction in ship CO_2 emissions. Since clean energy's application range is narrower than that of "zero-carbon" in this plan, it has a smaller impact on reducing emissions, which is why it only reduces emissions by roughly 37%.

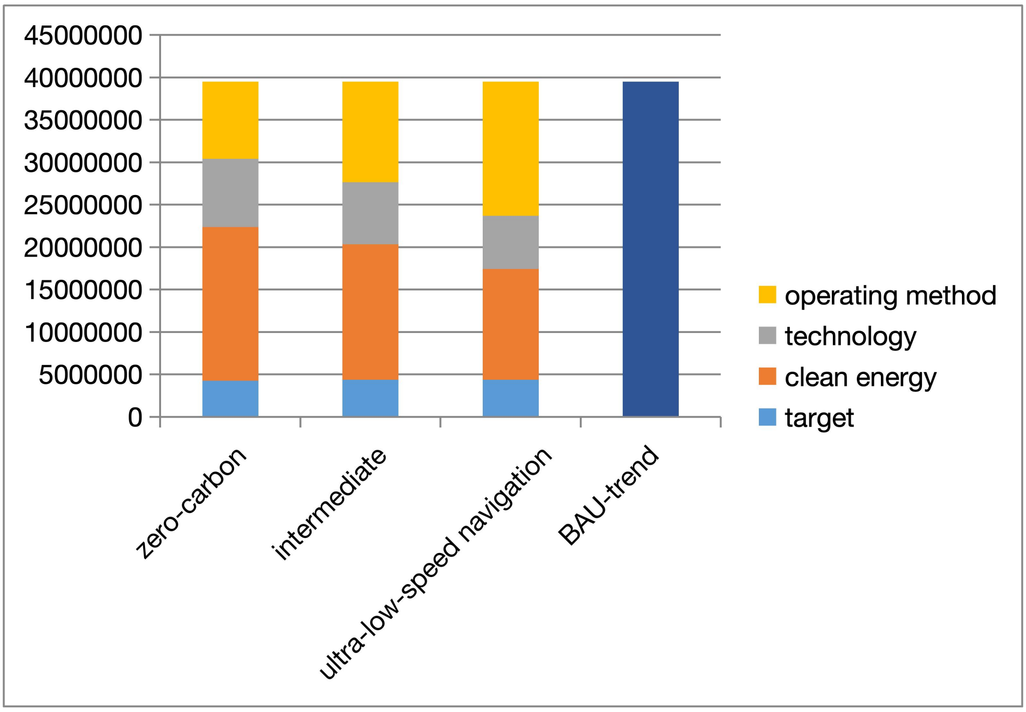


Figure 27- Comparison of three carbon emissions pathways

Source: self-made

4.5 Summary of this chapter

This paper analyzes the potential emission reduction paths and the potential emission reduction from three aspects: technical measures, operational measures, and clean energy, in order to explore the path of CO_2 emission reduction for China international ships that meet the IMO 2050 maritime emission reduction target. Back calculation quantifies two representative emission reduction approaches and one intermediate option to clarify China's future energy conservation and emission reduction work. The following are the primary conclusions:

(1) Although the CO_2 emission capacity of various emission reduction pathways differ, all of them largely rely on three strategies: technical measures, operational measures, and the use of clean energy sources. The selection of certain programs is strongly related to the objectives for lowering CO_2 emissions, but it is also significantly influenced by how quickly those programs are put into practice on Chinese ships.

(2) The emission reduction target of 2050 can be reached by combining the two representative emission reduction options and one intermediate path. In order to lower the CO_2 emission factor, "zero-carbon" primarily relies on clean energy to replace conventional heavy oil, this emission reduction effect accounts for 51.4% of the overall emission decrease. In order to reduce CO_2 emissions, "ultra-low-speed navigation" primarily relies on the significant slowdown of ships, and its emission effect accounts for 45% of the overall emissions. This intermediate path strikes a balance between "zero-carbon" and "ultra-low-speed navigation," which has not reduced speed and CO_2 emissions to their lowest point.

CHAPTER 5 COST-BENEFIT ANALYSIS OF CO_2 EMISSION REDUCTION PATH

Cost and policy have the biggest impacts on the decision-making process and actual reduction of CO_2 emissions. Shipping businesses won't be motivated to make adjustments unless there are enforceable policy requirements in place or they can profit from cost savings. For instance, following the implementation of the sulfur limit order, shipping companies started installing desulfurization towers and switching to low-sulfur oil, despite the fact that doing so would raise ship operating expenses. According to the discussion above, shipping businesses start to reduce CO_2 emission by reducing ship speed, improving ship energy efficiency, developing dual-fuel ships, and other methods after the IMO prescribes EEDI, EEXI, CII, SEEMP and other mandatory limits on CO_2 emission. Shipping companies will prioritize the CO_2 emission reduction option with the lowest marginal cost, which involves a cost-benefit analysis of the chosen emission reduction approach, provided they can meet the IMO's statutory goals.

5.1 The cost introduction of various emission reduction methods

5.1.1 Slow steaming

Due of the cubic link between ship speed and CO_2 emissions, reducing ship speed is viewed as a crucial option for shipping corporations to successfully cut emissions and fuel expenditures. Under the condition that products arrive consistently, shipping companies will reduce ship speed from design speed to optimal speed. The first is to increase cargo loading rate to make up for the decline in turnover speed caused by speed reduction (to load more cargo in a single voyage), but this method is subject to route and goods requirements, not for every scenario; the second is to add ships to maintain intervals (Corbett, Wang, & Winebrake, 2009). The first option, however, is still restricted by the long-term lease level and opportunity cost, i.e., the single voyage must pay more rent costs and the market opportunity costs, which results in slow steaming. Since opportunity cost is hard to determine, fixed mileage fuel savings are usually compared to higher rent and other costs (Jiao, 2019). The second approach objectively reduces fuel use, but it is limited by time charter, opportunity cost, and new ship construction and operational costs.

The above two strategies should additionally consider fuel tax as the carbon trading system matures. Shipping corporations prefer the first speed reduction approach because fuel tax encourages it. Following is a comparison of the two approaches:

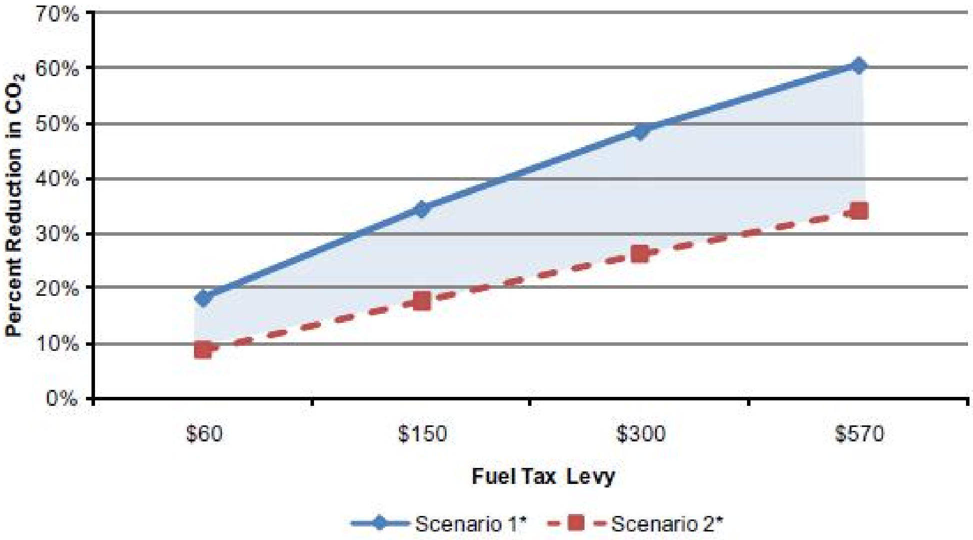


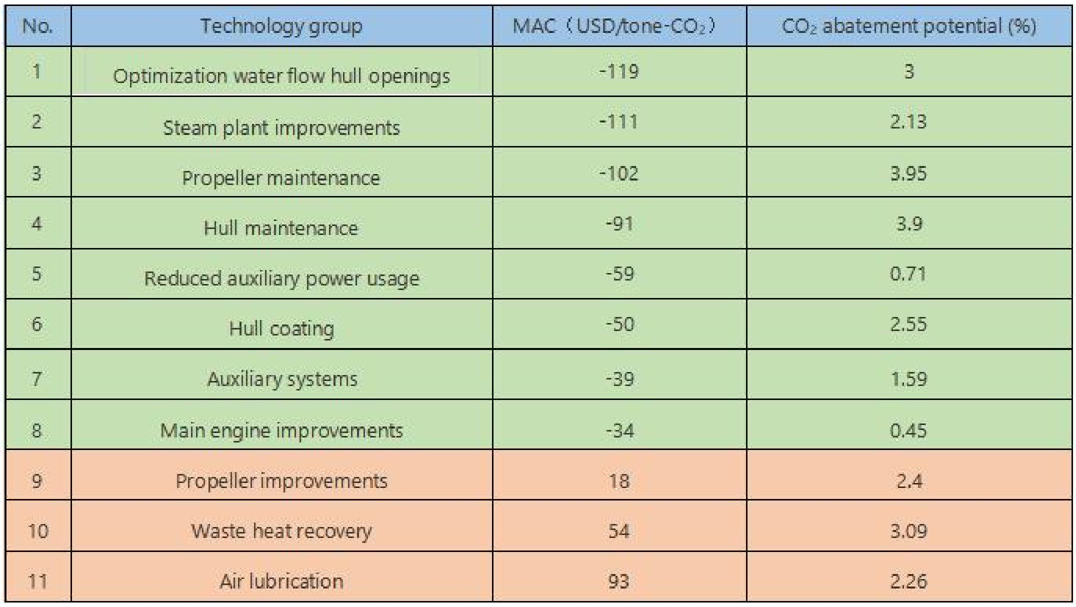
Figure 28- Impact of a fuel tax on CO_2 reductions

Source: Transportation Research

5.1.2 Technological solutions for energy efficiency

The expense of technical energy efficiency improvement solutions is primarily concentrated during the ship construction or transformation phase, and the main advantage of the technical solutions is fuel cost savings during the operation phase following the transformation (IMO, 2020).Therefore, whether the technical solution has positive benefits mainly depends on the length of operation time and fuel price. It is challenging to obtain the benefits of pollution reduction if the ship is elderly. The fourth IMO GHG study states that, assuming a 25-year service life, a fuel price of 375 USD/tonne, and a 4% discount rate, other technological solutions can yield positive emission reduction benefits(MAC < 0), with the exception of propeller improvement, waste heat recovery, and air lubrication. Given that the primary focus of this article is the reduction of all ship CO_2 emissions in 2050 (based on 100% technological penetration), the majority of technical approaches can successfully reduce emissions, as illustrated in the following table:

Table 16- Cost efficiency and abatement potential of technical solutions



No.	Technology group	MAC（USD/tone-CO_2）	CO_2 abatement potential (%)
1	Optimization water flow hull openings	-119	3
2	Steam plant improvements	-111	2.13
3	Propeller maintenance	-102	3.95
4	Hull maintenance	-91	3.9
5	Reduced auxiliary power usage	-59	0.71
6	Hull coating	-50	2.55
7	Auxiliary systems	-39	1.59
8	Main engine improvements	-34	0.45
9	Propeller improvements	18	2.4
10	Waste heat recovery	54	3.09
11	Air lubrication	93	2.26

Source : IMO

5.1.3 Clean energy

Shipping has long debated ship greening. Marine fuel is also steadily shifting from fossil fuel to renewable energy, with LNG serving as the transitional fuel and hydrogen, ammonia, and other zero-carbon fuels serving as the ultimate fuel craze (Liu, et al., 2021). Since hydrogen combustion in the engine is prone to tempering, early combustion, and knock, which affect engine operation and lead to low combustion efficiency, these problems are difficult to overcome and objectively slow the development of hydrogen internal combustion engines (Guo, et al., 2016), so the industry is more invested in hydrogen fuel cell research. The commercialization of nuclear-powered ships has been slow due to the low economic benefits and high management costs of nuclear energy (Jie, et al., 2021), so it will not be discussed in this section.

If ammonia is used as the main power source and hydrogen battery as the auxiliary power source, the total ownership cost of clean energy ships is the sum of the main power cost, auxiliary power cost, fuel storage tank cost, cost of adding new parts, fuel cost, maintenance cost, and loss of space (due to the low volume energy density of ammonia and hydrogen, the fuel tank volume is larger than oil fuel tank). Therefore, cargo tank loss caused by the increase of Ammonia fuel main engines, auxiliary power, and fuel cost more than typical ships, and new parts and cargo tank loss are new costs (Wang, & Wei, 2021).

5.2 Construction of a comparative model for the economics of different abatement paths

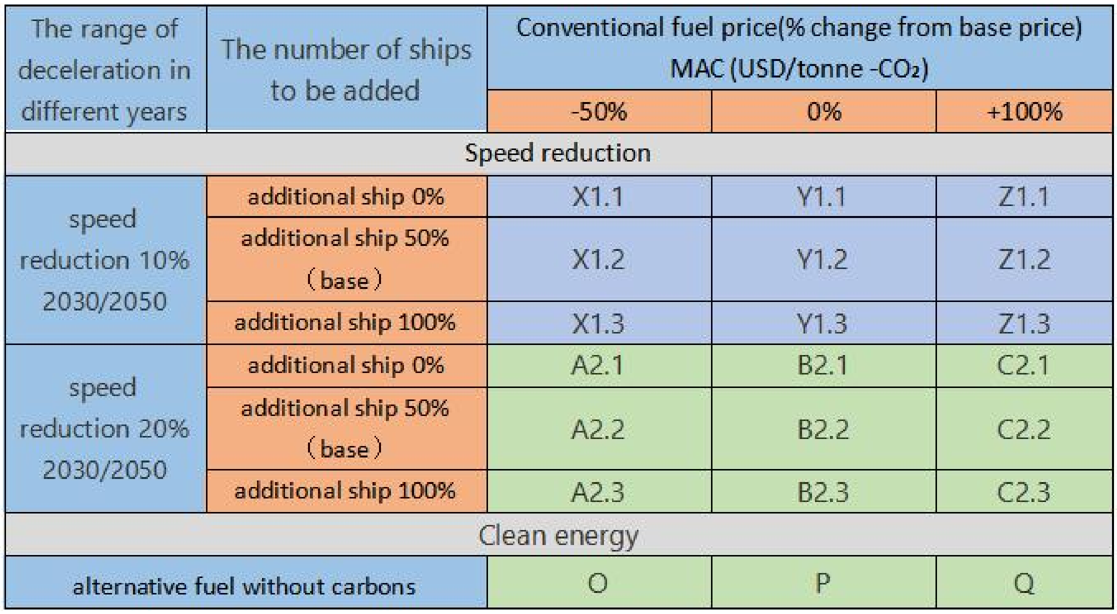
As seen in Chapter 4, IMO's CO2 emission reduction target requires technological, operational, and clean energy initiatives. Thus, this cost comparison is a comparative study of several paths that can achieve expected goals to find the most cost-effective practical path. "Zero-carbon" and "ultra-low-speed navigation" are compared since the "Intermediate" path costs in its middle position.

Technical measures cost the same in "zero-carbon" and "ultra-low-speed navigation" emission reduction options since technological penetration is expected to be 100%. No need for contrast. Just the cost difference between using clean energy and slow steaming is being compared here.

According to table 15, "zero-carbon" emission reduction reduces speed by 10% and CO_2 emission factor by 81%, while "ultra-low-speed navigation" reduces speed by 20% and CO_2 by 75%. To facilitate computations, the CO_2 emission factor reduction was instantly classified into the proportion of Chinese international ships that had successfully completed the switch to zero-carbon fuel. 81% of ships on the "zero-carbon" emission reduction program used zero-carbon fuel, while 19% did. 75% of ultra-low-speed navigation ships will utilize zero-carbon fuel, while 25% will use conventional fuel. After this transformation, comparing the economics of "zero-carbon" and "ultra-low-speed navigation" can be done by comparing the marginal cost of abatement per kilogram of CO_2 emissions.

In conjunction with section 5.1.1, the scenarios of speed reduction are primarily split into two groups: pure speed reduction, without an increase in freight capacity (i.e., no additional ship); and freight capacity reduction, with an increase in corresponding ships for a decrease in freight frequency as a result of the slowdown. These scenarios can be further divided based on the amount of increment, and here are two scenarios of 50% and 100% increm. In conjunction with section 5.1.3, this study focuses on three scenarios, such as maintaining the current price at its present level, 50% of the current price, and twice the current price. These scenarios illustrate how the MAC of clean energy changes with changes in the price of fossil fuels. This paper's model compares abatement path costs:

Table 17- Comparative modeling of the MAC of different abatement paths



The range of deceleration in different years	The number of ships to be added	Conventional fuel price(% change from base price) MAC (USD/tonne -CO_2)		
		-50%	0%	+100%
Speed reduction				
speed reduction 10% 2030/2050	additional ship 0%	X1.1	Y1.1	Z1.1
	additional ship 50% （base）	X1.2	Y1.2	Z1.2
	additional ship 100%	X1.3	Y1.3	Z1.3
speed reduction 20% 2030/2050	additional ship 0%	A2.1	B2.1	C2.1
	additional ship 50% （base）	A2.2	B2.2	C2.2
	additional ship 100%	A2.3	B2.3	C2.3
Clean energy				
alternative fuel without carbons		O	P	Q

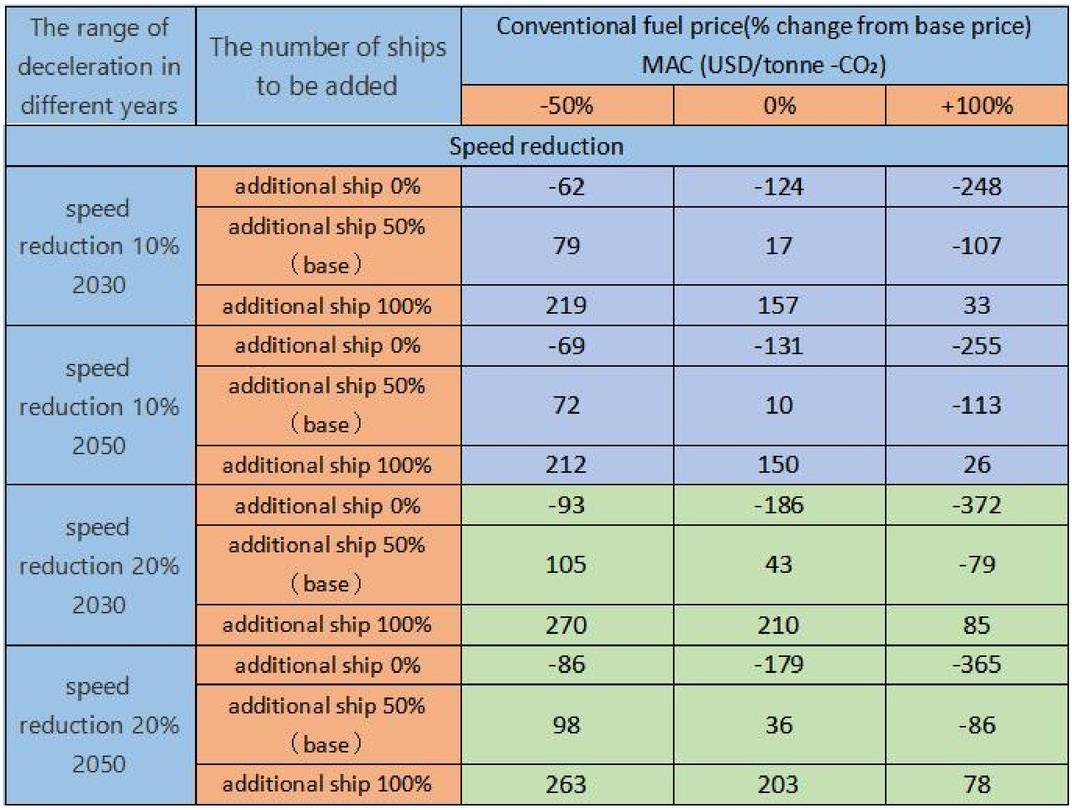
Source : self-made

Combining the above table, it is only necessary to compare the value of (X,Y,Z) + 81% (O,P,Q) with the value of (A,B,C) + 75% (O,P,Q) to obtain the cost effectiveness of emission reduction for different abatement paths.

5.3 Comparative cost-benefit analysis of different abatement paths

According to the data provided by the second & forth IMO GHG Study, IMarEST and Elsevier (IMO, 2009,2011,2017,2018 & 2020; Irena, Ernst, & Alexandros, 2021), the following table can be obtained by substituting the comparative model in Section 5.2:

Table 18- The MAC of speed reduction abatement

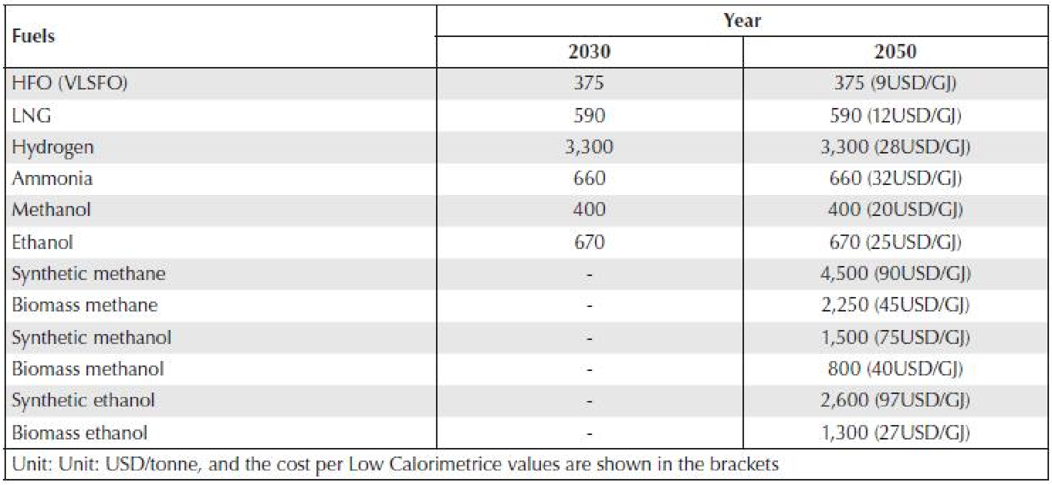


The range of deceleration in different years	The number of ships to be added	Conventional fuel price(% change from base price) MAC (USD/tonne -CO₂)		
		-50%	0%	+100%
Speed reduction				
speed reduction 10% 2030	additional ship 0%	-62	-124	-248
	additional ship 50% (base)	79	17	-107
	additional ship 100%	219	157	33
speed reduction 10% 2050	additional ship 0%	-69	-131	-255
	additional ship 50% (base)	72	10	-113
	additional ship 100%	212	150	26
speed reduction 20% 2030	additional ship 0%	-93	-186	-372
	additional ship 50% (base)	105	43	-79
	additional ship 100%	270	210	85
speed reduction 20% 2050	additional ship 0%	-86	-179	-365
	additional ship 50% (base)	98	36	-86
	additional ship 100%	263	203	78

Source : IMO, IMarEST and Elsevier

This paper follows the forth IMO GHG Study's assumption of constant prices for all types of fuels and uses the price values from that report, as shown in the following price list:

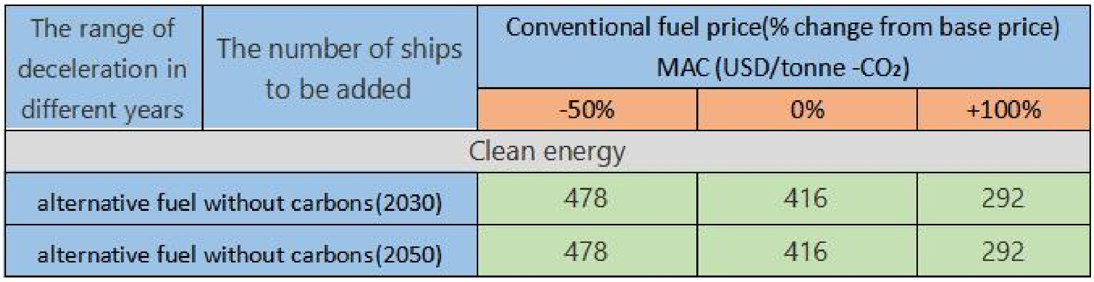
Table 19- Future costs fuel at 2030 and 2050



Fuels	Year	
	2030	2050
HFO (VLSFO)	375	375 (9USD/GJ)
LNG	590	590 (12USD/GJ)
Hydrogen	3,300	3,300 (28USD/GJ)
Ammonia	660	660 (32USD/GJ)
Methanol	400	400 (20USD/GJ)
Ethanol	670	670 (25USD/GJ)
Synthetic methane	-	4,500 (90USD/GJ)
Biomass methane	-	2,250 (45USD/GJ)
Synthetic methanol	-	1,500 (75USD/GJ)
Biomass methanol	-	800 (40USD/GJ)
Synthetic ethanol	-	2,600 (97USD/GJ)
Biomass ethanol	-	1,300 (27USD/GJ)
Unit: Unit: USD/tonne, and the cost per Low Calorimetrice values are shown in the brackets		

Source ： IMO

Table 20- The MAC of clean energy abatement



The range of deceleration in different years	The number of ships to be added	Conventional fuel price(% change from base price) MAC (USD/tonne -CO_2)		
		-50%	0%	+100%
Clean energy				
alternative fuel without carbons(2030)		478	416	292
alternative fuel without carbons(2050)		478	416	292

Source : IMO, IMarEST

The 2050 MAC data in table 18 & 20 are calculated and integrated according to the data calculation in section 5.2, and the detailed calculation results are shown in table 21 and the specific size comparison is shown in figure 29.

Table 21- The MAC of different abatement paths

The number of ships to be added	The range of deceleration in 2050	Conventional fuel price(% change from base price) MAC (USD/tonne-CO_2)		
		-50%	0%	+100%
additional ship 0%	Speed reduction 10%	466.18	353.96	129.52
	Speed reduction 20%	272.5	133	-146
additional ship 50% (base)	Speed reduction 10%	606.18	493.96	269.52
	Speed reduction 20%	456.5	348	133
additional ship 100%	Speed reduction 10%	318.18	205.96	-18.48
	Speed reduction 20%	621.5	515	297

Source : IMO, IMarEST

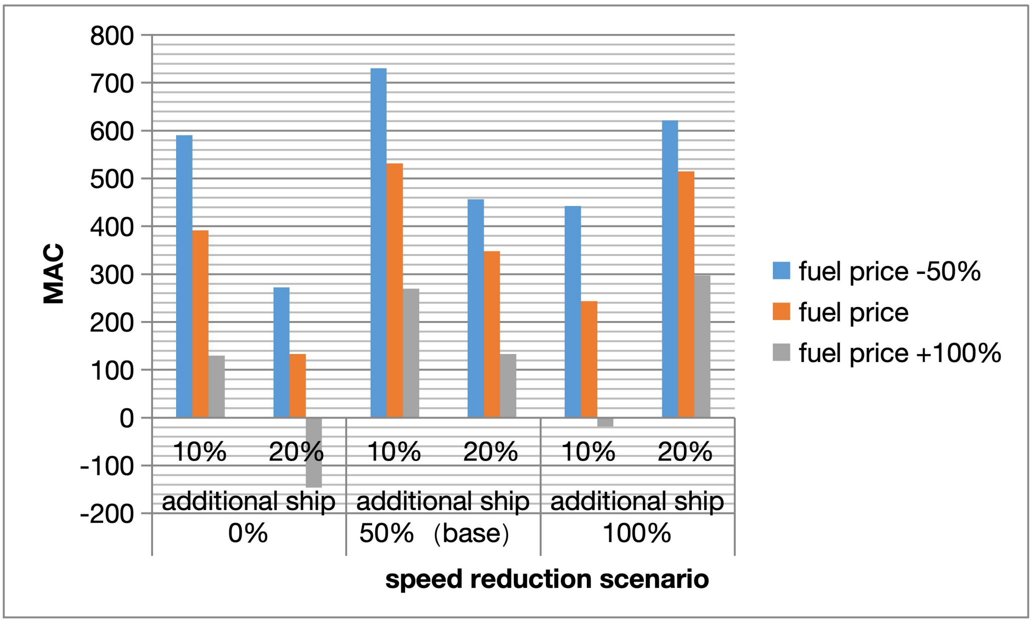


Figure 29- MAC comparison of different emission reduction paths

Source : IMO, IMarEST

Figure 29 illustrates that, regardless of fuel price changes, the economic efficiency of "ultra-low-speed navigation" is always superior to that of "zero-carbon" in the cases of no additional ships and 50% additional ships. It is also always superior to "zero-carbon" in the case of fully replenishing the capacity loss due to speed reduction (100% additional ships).

The IEA/OCED data indicate that as the amount of electricity produced by different new energy sources (hydropower, solar, wind, and nuclear) increases, the cost of per MWh electricity will decrease. The analysis above is primarily predicated on the assumption that the price of zero-carbon fuel will remain unchanged in the future. As a result, the cost of hydrogen and ammonia produced using renewable electricity will also go down (the precise downward trend is shown in Fig. 30 and 31). Additionally, the data will be simplified for ease of calculation (the cost of zero-carbon fuel is cut in half from its current cost), and its MAC will switch from Table 20 to Table 22.

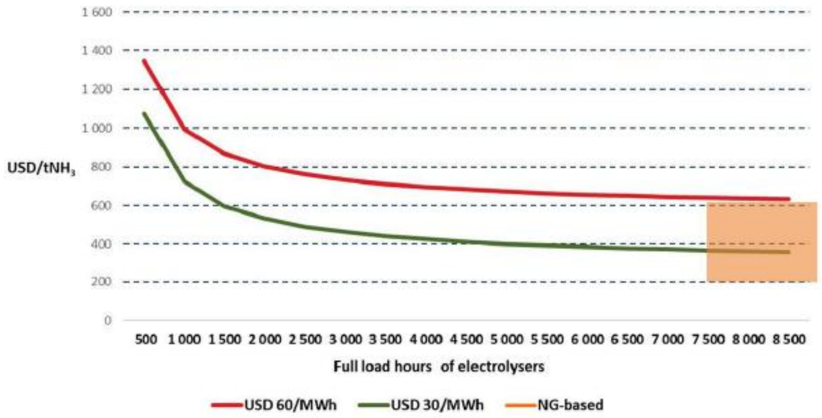


Figure 30- The cost of ammonia production at various electricity prices and electrolyser load factors

Source: Renewable Energy for Industry, IEA/OECD, 2017

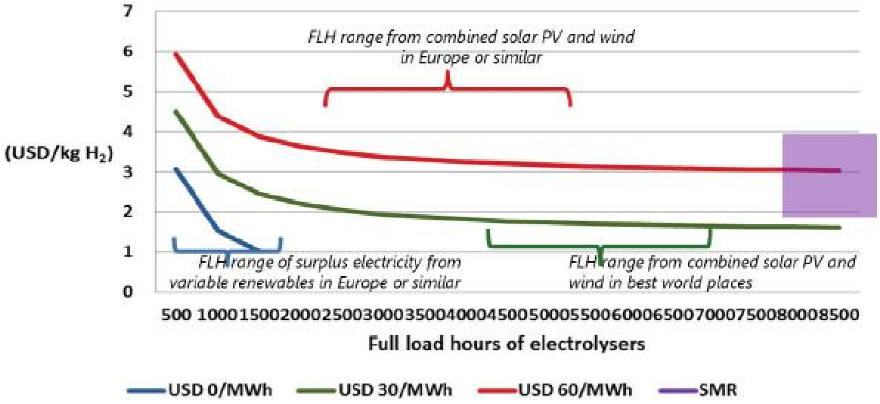


Figure 31- The cost of hydrogen production at various electricity prices and electrolyser load factors

Source: Renewable Energy for Industry, IEA/OECD, 2017

Table 22- The MAC of clean energy abatement (renewable electricity)

The range of deceleration in different years	The number of ships to be added	Conventional fuel price(% change from base price) MAC (USD/tonne -CO₂)		
		-50%	0%	+100%
Clean energy				
alternative fuel without carbons(2030)		478	416	292
alternative fuel without carbons(2050)		239	208	146

Source: IEA/OECD, IMO

Figure 32 shows the results of Section 5.2's computation on tables 18 and 22. Figure 32 reveals that after the significant decrease in zero-carbon fuel cost, "ultra-low-speed navigation" still has a lower abatement cost than the "zero-carbon" abatement path in the scenario where the ship is simply slowed down without additional ships, and the cost-benefit is better. Besides, the cost-benefit of "zero-carbon" emission reduction approach is better than that of "ultra-low-speed navigation" regardless of fuel price.

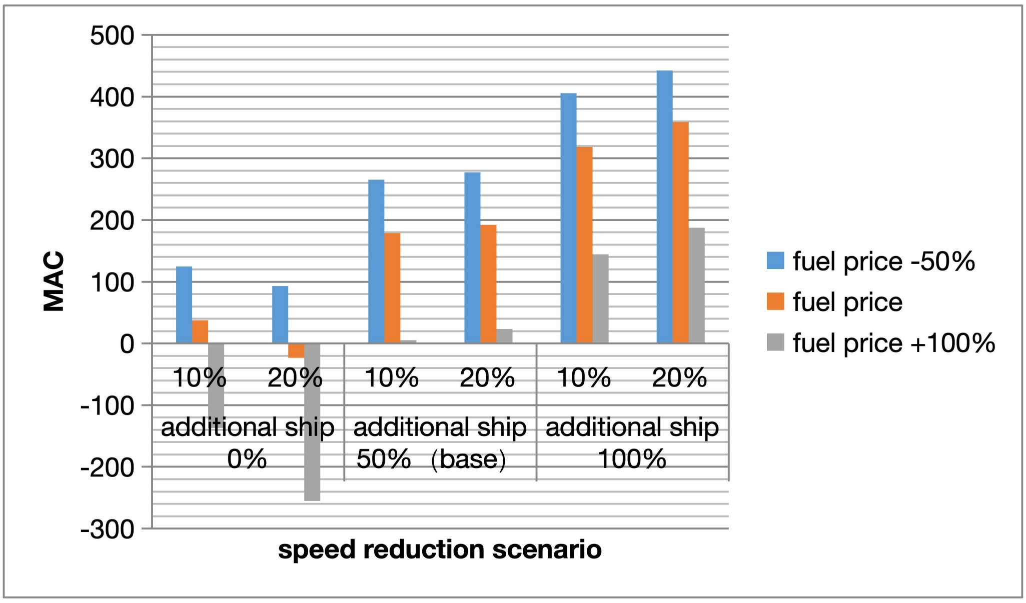


Figure 32- MAC comparison of different emission reduction paths (renewable electricity)

Source : IMO, IMarEST

5.4 Carbon emission reduction policy recommendations for Chinese international shipping

Chapters 2–5 demonstrate that current CO_2 emission reduction tactics and routes cannot fulfill the IMO's 2050 maritime CO_2 emission reduction target without zero-carbon fuels. The author highlighted that current CO_2 emissions primarily rely on empirical study to estimate, thus macro data can be obtained, but micro data like shipping enterprises' and ships' CO_2 emissions are difficult to collect. China's international shipping is mostly for the import and export of raw materials and industrial products, and bulk carriers, container ships, and tankers account for more than 80% of CO_2 emissions. Ship enlargement affects these three types of ships, hence it must be considered in emission reduction. China's economy is so large that one CO_2 emission reduction strategy won't be enough. We provide recommendations for reducing CO_2 emissions from China's foreign ships based on the empirical findings of this study, while also taking into account the existing status of the Chinese maritime authorities, in order to provide policy reference for decision-makers.

5.4.1 Establishment of ship data collection system

The goal of research on maritime CO_2 emissions is to lower CO_2 levels in order to promote the sustainable growth of maritime transportation, and the establishment of CO_2 reduction goals and mitigation strategies is based on reliable and real-world data on CO_2 emissions. The EU-MRV and IMO DCS requirements were added to the SEEMP requirements by the IMO in 2018, but this process is just getting started and only applies to ships above 5000 GRT (Kanberolu & Kökkülünk, 2021). As a major maritime nation, China needs a professional and precise data collecting system to collect and detect particular information on Chinese international ship shipping activities to save energy and reduce emissions. IMO also requires DCS, and China must create this system to effectively execute international conventions.

5.4.2 Promoting the application of technical measures

After IMO mandated EEDI, EEXI, CII, SEEMP, and other ship energy-saving and emission-reduction measures, shipping corporations reduced ship speed. However, the primary focus of speed reduction is to decrease the operating power of the engine. This has no positive impact on energy efficiency, and over time, it can even be hazardous to the ship's engine and related components (Rong, & Qian, 2014). As discussed in Chapter 4, many technical measures can reduce ship energy consumption, but ship owners are reluctant to retrofit due to cost, so competent authorities must set corresponding requirements or fund subsidies to promote energy-saving and emission-reducing technical measures. Additionally, the carbon emission trading system can be expanded to encompass shipping, leveraging the market's influence to encourage the adoption of technological CO_2 emission-reduction solutions.

5.4.3 Promoting clean energy use

The analysis of emission reduction strategies in Chapters 4 and 5 of this article reveals that clean energy must be used regardless of whether ultra-low speed navigation is employed in order to meet the IMO CO_2 emission reduction targets. This means that in order to lessen the burden on shipping companies and support the green and low-carbon sustainable development of the shipping industry, Chinese maritime authorities must support the development of clean energy-powered ships in terms of policy and facilitate the ship regulation system, ship inspection, ship registration, and company safety system management.

5.4.4 Boost the ship's ability to operate intelligently

Weather, route, wind, waves, longitudinal inclination of ships, and other factors all have an impact on how much CO_2 is emitted by ships. According to Corbett, Wang, and Winebrake (2009), it is untrue that the lower the speed, the less fuel is consumed. Many operational measures are listed in Chapter 4 of this paper that can raise the level of ship operation, including speed optimization, loading capacity optimization, route optimization, and others. Since these measures call for processing vast amounts of data and are not humanly feasible, the ship's intelligence level should be raised and its parameters should be changed in real time to maximize operation effect.

5.5 Summary of this chapter

This chapter builds MAC comparison models for several paths to assess the cost-effectiveness of "zero-carbon" and "ultra-low-speed navigation" under different situations and provides a scientific basis for Chinese international ship CO_2 emission reduction programs. This chapter examines cost-benefit analysis of emission reduction strategies. Main findings:

(1) Zero-carbon energy prices and the scale of the additional ship after a speed reduction are important factors in comparing emission reduction techniques. The

cost-benefit analysis of different emission reduction strategies will vary depending on the energy price and the scale of the new ship, so policymakers must constantly monitor these two factors.

(2) We should build ship DCS, promote technology measures, clean energy, and intelligent ship operation to implement relevant regulations and measures. Chinese ships must minimize emissions by combining numerous techniques, and the Chinese maritime authorities must monitor critical variables and act fast.

CHAPTER 6 CONCLUSION AND PROSPECT

This paper discusses the CO_2 emission share of various types of ships by measuring CO_2 emissions from Chinese international ships, predicts the future trend of CO_2 emissions under different scenarios, explores possible CO_2 emission reduction paths for Chinese international ships, compares the cost-benefit of different emission reduction paths, and provides path recommendations for Chinese international ship CO_2 emission reduction based on its findings.

6.1 Summary of research findings

This paper establishes a model for measuring and predicting CO_2 emissions from ships based on domestic and international research advancements, empirically analyzes the CO_2 reduction paths of Chinese international ships, compares the cost-benefit of various reduction paths, and clarifies the key factors influencing the reduction of MAC. The paper's main findings:

(1) A "top-down" and "bottom-up" CO_2 emission measurement model for Chinese international ships was created by categorizing and analyzing measuring methods. Clarkson Shipping Intelligence Network and listed company annual reports were used to quantify Chinese international ship CO_2 emissions. CO_2 emissions vary greatly by ship type. Dry bulk carriers emit 67% of CO_2, container ships 18%, and oil tankers 9%. Because foreign ships transport a large portion of Chinese import and export cargoes, they should be treated differently when enacting CO_2 emission reduction policies.

(2) Marine turnover, ship energy efficiency, and carbon emission factor are used to predict Chinese international shipping's CO_2 emissions. The four scenarios' emission forecasts are examined via scenario modeling. Each variable has a BAU-trend-based enhanced scenario. The study found that: ship massification has a non-negligible impact on ship CO_2 emissions; in the BAU-trend scenario, Chinese international ship CO_2 emissions are expected to increase to 39.5 million tons by 2050, with an average

annual growth rate of 2.74%; Under the three enhanced scenarios, the CO_2 emissions are expected to be between 22.7 and 29.23 million tons, and the CO_2 emissions are reduced by 7.5%, 26%, and 9% respectively, through the three approaches of erecting a lower maritime turnover, improving energy efficiency of ships, and reducing carbon emission factors.

(3) Three emission reduction paths—"zero-carbon," "ultra-low-speed navigation," and "intermediate"—were explored in conjunction with Chinese international ship CO_2 emission projections using a backward deduction method based on the IMO's CO_2 emission reduction target. Chapter 5 evaluates "zero-carbon" and "ultra-low-speed navigation" emission reduction approaches. According to studies, the cost-benefit of different emission reduction pathways will differ or even provide the opposite results, therefore policymakers must account for these changes and their relative relationship in real time. Establish a ship DCS, promote technical measures, boost clean energy consumption, improve ship intelligence, etc., while taking into account the relevant authorities' real circumstances.

6.2 Limitations and future research directions

In order to evaluate models for emission reduction paths and cost-benefit analysis on this topic, we must simplify the impact factors due to the difficulties of data collecting. As a result, the variety of pathway selection is insufficient. Additionally, the prediction analysis in this work uses a static model rather than a dynamic model, making it unable to assess the dynamic link between CO_2 emissions and affecting factors. Even though this research has generally done a more thorough investigation into the CO_2 emissions of Chinese international ships, the following areas still need improvement and in-depth investigation:

Accurate CO_2 emissions measurement for ships. This paper primarily chooses six major ship types for measuring CO_2 emissions, it does not analyze in detail the ship types with lower CO_2 emissions, particularly the ship types with larger cargo volume growth in recent years, which will have obvious changes in CO_2 emissions with economic development. Future research will allow for a more thorough collection of pertinent information and a more precise assessment of CO_2 emissions. Additionally, we can look into shipping companies in more detail and suggest policy changes that are more suited to their progress given their current challenges.

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