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Comparative analysis of SOx emission control technologies for container ships

Tongxu Zhang

WORLD MARITIME UNIVERSITY
Malmö, Sweden

COMPARATIVE ANALYSIS OF SO_x EMISSION CONTROL TECHNOLOGIES FOR CONTAINER SHIPS

By

Zhang Tongxu

China

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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.

(Signature): Zhang Tongxu

(Date): 24th September 2019

Supervised by: **Dr. Fabio Ballini (Ph.D.)**

Supervisor's affiliation: Assistant Professor- Maritime Economist

Maritime Energy Management Specialization

Maritime Energy Research Group

WORLD MARITIME UNIVERSITY

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Abstract

Title of Dissertation: Comparative analysis of SO_x emission control technologies for container ships

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Under the background of the new requirements for SO_x emission from ships to be implemented from January 1th, 2020, this dissertation made a comprehensive comparative analysis of various SO_x emission control technologies, which provided a decision-making reference for container ship owners to select appropriate SO_x emission control technology. Firstly, the dissertation analyzed the requirements of IMO, EU, USA and China for sulfur emission from ships, and identified various SO_x emission control technologies to be adopted to meet these requirements, which are also the comparison objects in this dissertation. Then, the PESTEL analysis model was established and various SO_x emission control technologies were comprehensively compared from 13 indexes of six aspects. In order to quantitatively compare the advantages and disadvantages of each SO_x emission control technology, this dissertation adopted grading-score method for the 13 evaluation indexes, and ranked various SO_x emission control technologies according to the integrated scores. On the basis of PESTEL analysis, this dissertation chose three SO_x emission control technologies with higher scores to carry out cost-environmental benefit analysis for container ships. In this dissertation, the calculation formulas of cost and environmental benefits of various SO_x emission control technologies were established with few ship parameters, which provided a general comparative tool for container ship owners to select suitable SO_x emission control technologies. Especially, the data regression method was used to establish the calculation formula of the average daily fuel consumption for container ships, which greatly simplifies the calculation of the fuel consumption for container ships. In order to apply the calculation formulas, this dissertation took an actual container ship as an example, and calculated its total cost, environmental benefit and benefit-cost ratio of the three SO_x emission control technologies. At the same time, combined with case study, the impacts of ship lifespan and fuel price on the total cost of SO_x emission control technologies were further analyzed. At the end of the dissertation, the conclusion of the research was summarized and numerous of recommendations are highlighted.

KEYWORDS : Ship emission, SO_x, Desulphurization technology, Container ship, PESTEL, Cost-benefit analysis

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List of Abbreviations

BCR	Benefit Cost Ratio
CO_2	Carbon dioxide
DECA	Domestic Emission Control Area
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
EMSA	European Maritime Safety Agency
EUAC	Estimated Uniform Annual Cost
GHG	Greenhouse Gas
HFO	Heavy fuel oil
IFO	Intermediate fuel oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LSO	Low Sulphur Oil
MEPC	Maritime Environment Protection Committee
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NO_x	Nitrogen Oxides

NPV	Net Present Value
ODS	Ozone Depleting Substances
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SDG	Sustainable Development Goal
SO_x	Sulphur dioxide
TEU	Twenty-foot Equivalent Unit
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compounds
WHO	World Health Organization

1 Introduction

1.1 Background

Shipping industry has made great contributions to the development of the world economy, but at the same time, it has also brought severe environmental pollution. The pollution from ships to the environment mainly includes the pollution to the sea water and the air. The pollutants to the air mainly include PM, NO_x, SO_x, GHG, VOC(volatile organic compounds) and ODS(ozone depleting substances). This dissertation mainly discusses the control measures of SO_x emission. The source of SO_x in ship exhaust gas is the combustion of sulfur-containing fuel oil. A report issued by the International Association of Independent Tanker Owners in 2016 showed that the international shipping industry consumes about 2 billion barrels of fuel oil annually, and SO_x emissions account for 20% of the global total emissions. In some developed port cities (such as Singapore, Hong Kong, Shanghai, etc.), the proportion is even as high as 30%-40%(Yang, G., 2016). A survey from Shenzhen Institute of Environmental Sciences of China in 2017 showed that if a larger container ship(5000-7000TEU) operated continuously for 24 hours with 70% maximum power using 3.5% sulphur fuel oil, its SO_x emissions would be equal to 210,000 trucks, and dozens of carcinogenic chemicals would also be produced into the air(Liu, C., 2017).

SO_x and other pollutants discharged into the air are harmful to human health and ecological environment. SO_x are also the main cause of acid rain. The UN attaches great importance to the control of air pollution. Among the 17 sustainable development goals(SDGs) of the UN, there are 5 SDGs which are directly related to air pollution control(NO.3 Good healthy and well-being, NO.7 Affordable and clean energy, NO.11 Sustainable cities and communities, NO.12 Responsible consumption and production, and NO.13 Climate action). The latest Air Quality Guidelines issued by WHO in 2005 set the upper concentration limits for SO_2(WHO, 2005). IMO has adopted step-by-step measures to restrict the SO_x emissions from ships. As early as 2010, the EU stipulated that ships berthing in EU ports should use fuel oil with sulphur content less than 0.1% m/m. In particular, the new SO_x emissions requirements for ships to be implemented from January 1, 2020 will bring great challenges to shipping industry. In addition, the United States, China and other countries or regions have also issued regional SO_x emission limitation requirements for ships. In order to protect the environment and human beings themselves, it is urgent to reduce SO_x emissions(Liu, C., 2017).

1.2 Problem statement

Facing the severe pressure of SO_x emissions reduction, shipping enterprises need to take effective measures to meet the emission limitation requirements of relevant international organizations, regions and countries. There are three methods to solve the problem: (1) using low-sulphur fuel oil. (2)using alternative clean fuel as ship power energy. (3)installing sulphur scrubbers, which includes dry scrubbers, seawater scrubbers, fresh water scrubbers and hybrid scrubbers. Each technology has its own characteristics and suitable working environment, and each technology also has its own advantages and disadvantages. Under the existing emission standards, it is a common practice for ships to carry two kinds of fuel oils with different sulfur content on board. Heavy oil is used in most navigation areas and low sulfur oil is used after entering the emission control areas(ECAs). However, the new SO_x emissions requirements for ships will be implemented from January 1, 2020. It will no longer be feasible to use heavy oil without any treatment of the exhaust gas. Shipping enterprises are facing new considerations in choosing SO_x reduction technology.

In the process of choosing the appropriate technology for controlling SO_x emissions from ships, the factors to be considered are very complex, such as ship type, navigation area, cost of modification, desulfurization effect, difficulty of modification, etc. Therefore, it is difficult to simply judge which desulfurization technology is most suitable for a particular ship. How to choose the most suitable technology of SO_x emissions from ships is a difficult problem for shipping enterprises.

1.3 Research objectives

The main objective of the research is to compare and analyze each SO_x emission control technology to help shipping enterprises choose the most suitable SO_x emission control technology. Considering that liner shipping has the characteristics of fixed routes and freight rates, the fuel consumption and cost statistics of container ships are relatively easy, so this research chooses container ships as the basis for comparison of various SO_x emission control technologies.

Specifically, the research will be looking;

□. to analyze the SO_x emission requirements of ships of IMO and different regions and countries.

□. to analyze the principles and characteristics of each SO_x emission control technology.

□. to establish a scientific evaluation system and make comprehensive evaluation of each SO_x emission control technology.

□. to analyze the cost-benefit of each SO_x emission control technology.

1.4 Research questions

To address the objectives of this research, the following questions must be answered.

□. What are the SO_x emission requirements for different regions at different times?

□. From what aspects to evaluate each SO_x emission control technology?

□. What are the characteristics of each SO_x emission control technology? And what are advantages and disadvantages of each SO_x emission control technology?

□. How to choose SO_x emission control technology for container ships from cost-benefit perspective?

1.5 Methods

The comparative analysis of SO_x emission control technology include qualitative comparison and quantitative comparison. Qualitative analysis mainly refers to establishing PESTEL evaluation model, quantitative analysis mainly refers to cost-benefit analysis of selected SO_x emission control technologies and data regression method. Data regression method is used to construct cost calculation formula in cost-benefit analysis.

Both quantitative and qualitative analysis require data collection and analysis. The data were obtained from primary and secondary sources. Primary data was collected from shipping companies and ship equipment manufacturing enterprises. Secondary data was gathered through journal articles, research papers from Google Scholar and WMU library, and official organization websites such as IMO, UNFCCC and others. The data collected was analyzed using a Microsoft Excel model and Eviews software, allowing the researcher to make cost-benefit analysis of various SO_x emission control technologies.

1.6 Research limitations

There are three main research limitations for this dissertation: (1) In the process of comparison of various SO_x emission control technologies using PESTEL method, the collected data mainly come from existing papers or reports, there are lacking of primary data and no questionnaire survey, therefore, the grade evaluation of various SO_x emission control methods is greatly influenced by the researcher's subjective judgement. (2) In order to compare the cost of various SO_x emission control technologies, general formulas for calculating the cost of fuel consumption of ships with different loading capacity, economic speed and route are constructed. However, these formulas based on data regression method are only rough calculations, which maybe different from the actual amount of fuel consumption. (3) The quantitative comparison of various SO_x emission control technologies are only for container ships, the comparison results for dry bulk carriers, tankers and other kinds of ships may be different.

1.7 Research outlines

This dissertation consists of seven chapters organized as follows,

Chapter one introduces the research topic, giving the background about SO_x emission control from ships, the problem statement, the research objectives, the research questions and the limitation of the research. In chapter two, existing literature on SO_x emission control technology is reviewed, summarizing the current research status of various ship SO_x emission technologies, and analyzing the shortcomings of current researches. Chapter three explains the comparative analysis method and data processing method used in the dissertation. Chapter four looks at the low sulphur fuel requirement and identify all the alternative SO_x emission control technologies, especially analyze the principles of each SO_x emission control technology. Chapter five establishes an evaluation system and makes a comprehensive comparison of each

SO_x emission control technology. On the basis of chapter five, chapter six chooses the three most excellent SO_x emission control technologies and makes cost-benefit analysis for container ships, so as to provide decision-making reference for shipping enterprises to choose the most suitable SO_x emission control technology. Finally, this dissertation summarizes the research results and makes some suggestions about control SO_x emission from ships. Figure 1.1 shows the vital steps of comparative analysis of SO_x emission control technologies for container ships.

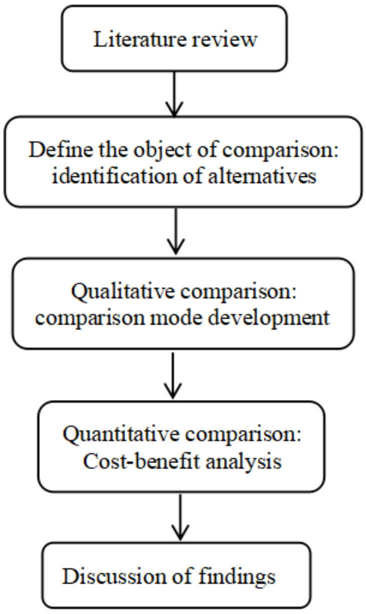


Figure 1.1: The vital steps of comparative analysis of SO_x emission control technologies

2 Literature reviews

IMO has adopted a phased and sub-regional implementation policy for SO_x emission requirements for ships. For the worldwide, from January 1, 2012, the requirement for sulfur content of ship fuel oil has been reduced from 4.5% to 3.5%, and from January 1, 2020, the requirement will be reduced from 3.5% to 0.5%. For ECAs, from July 1, 2010, the requirement of sulfur content of ship fuel oil has been reduced from 1.5% to 1.0%, and from January 1, 2015, the requirement has been reduced from 1.0% to 0.1%. Therefore, the year of 2020 is not the first time that IMO has put forward the requirement of reducing SO_x emissions from ships. In order to meet the IMO requirements of SO_x emission from ships, some studies on comparison and selection of various SO_x emission control technologies have been carried out in the past. However, it is undeniable that the SO_x emission control requirement of 2020 has greatly reduced the standard of SO_x emissions from ships and has a wider impact than any requirements in history. At present, the international attention to environmental pollution and people's awareness of environmental protection all over the world has reached an unprecedented height. This is also an important background for this research. This chapter will review previous studies conducted on comparison and selection of various SO_x emission control technologies.

There are much literature introducing the requirements of SO_x emission for ships. MARPOL Annex □ is the most authoritative statement. IMO has published ‘Frequently Asked Questions for the 2020 global sulphur limit’, which explained in detail the specific content of 2020 global sulphur limit, the implementation plan, the measures that shipowners can take, IMO's support policies, and expressed IMO’s determination to promote the reduction of SO_x emissions from ships(IMO, 2019). The EU, US California Air Resource Board, Ministry of Transport of China and other national and regional administrative organizations have introduced SO_x emission requirements for ships within their respective jurisdictions. LIU Chang-yu and others have made a detailed review of the SO_x emission requirements of ships in relevant regions and countries(Liu, C., 2017).

Various SO_x emission control technologies are the research objects of this dissertation. European Maritime Safety Agency has assessed the impact of the 0.1% sulphur in fuel requirement as from 1 January 2015 in SECAs, and introduced the selection of alternatives(EMSA, 2010). Zhou Song, Li Zheng and Shen Fei-xiang analyzed the working principles of open-loop, closed-loop and hybrid scrubbers and their application in ECA(Zhou, S., Li Z., & Shen, F., 2014). IMO has studied the feasibility and use of LNG as a fuel for shipping and analyzed the possible reduction of emissions by the introduction of LNG fuel(IMO, 2016). Pan Wei-peng analyzed the combustion characteristics of low sulfur oil and its impact on the environment(Pan, W., 2015). Li Yuan summarized the efficiency of using MGO, LNG duel fuel engines and scrubbers to remove SO_x, NO_x, CO_2 and PM respectively, but did not subdivide the emission reduction effects of various scrubbers(Li, Y., 2016).

MAN Diesel & Turbo compared the cost and payback time of using low sulphur oil, LNG and scrubbers, and concluded that the use of LNG as ship fuel promised a lower emission level and, given the right circumstances, lower fuel costs; the attractiveness of LNG as ship fuel compared to scrubber systems is dominated by three parameters: investment costs for LNG tank system, price difference between LNG and HFO, share of operation inside ECA(MAN Diesel & Turbo, 2012).

Herbert Engineering Corp. used Estimated Uniform Annual Cost (EUAC) method to analyze the cost of three primary fuel alternatives(Using MGO, LNG and HFO with scrubbers) solutions for meeting the ECA emission regulations for a variety of ship types and sizes operating in a selection of trades. The advantages and disadvantages of each fuel alternative are discussed, including the impact on emissions, and cost and benefit analyses are developed for a midsize tanker and midsize container ship(Herbert Engineering Corporation, 2018).

Ren Yuan chose a 2500TEU container ship sailing in Baltic waters and North waters as the studying project, researched the reports of class societies, equipment suppliers and famous research agents, and evaluated and compared the three SO_x emission control technologies from aspects of environmental-friendliness, supporting facilities, easy operation, power consumption and cost effectiveness, and finally expanded the comparison study to different vessel types(Ren, Y., 2016).

Yang Guo-shuai introduced the formation and harmfulness of SO_x emission from ships, summarized the main SO_x emission control technologies for ships and used the gray analytical hierarchy process(GAHP) to compare and analyze different SO_x emission control technologies from points of cost, environmental protection, operation and maneuverability(Yang, G., 2016).

Z. L. Yang developed a subjective generic methodology for providing ship owners with a transparent evaluation tool for selecting their preferred NO_x and SO_x control techniques, quantitatively analysed the merits of the control methods available in marine air pollution control practice using data collected from shipping companies, shipyards and maritime academies, also prioritized the applicable control techniques with respect to operational shipping environments(Yang, Z. L., Zhang, D., Caglayan, O., Jenkinson, I. D., Bonsall, S., Wang, J., & Yan, X. P., 2012).

Chengfeng Wang and others examined the potential costs and benefits of policy options for reducing offshore ship pollution using a meta-analysis of studies synthesized regionally for the US West Coast and concluded that combinations of fuel switching and control technology strategies provide the most cost-effective benefits from SECAs on the US West Coast and other world regions. Especially, the method of calculating environmental benefits proposed in this paper is of good property(Wang, C., & Corbett, J. J., 2007). Liping Jiang and others examined the costs and benefits of using MGO and scrubbers, provided a viewpoint by integrating the private abatement costs of ship owners and the social environmental benefits from emission reduction and observed that the NPV of MGO could fall quickly as the price spread between MGO and HFO increased(Jiang, L., Kronbak, J., & Christensen, L. P., 2014).

By collecting and analyzing relevant literature, it can be found that there are still some deficiencies in the current studies:

□. The existing literature mainly focused on comparing various ship SO_x emission control technologies from economy, environment or technology aspects, the evaluation system is not comprehensive. Therefore, there is a lack of comprehensive summary of the advantages and disadvantages of various ship SO_x emission control technologies.

□. Most of the papers compared various SO_x emission control technologies for specific ships, the estimation of environmental costs are usually subjective and lack of general and unified cost and benefit calculation formulas for container ships. Therefore, the calculation method of cost and benefit usually paid attention to individuality and lacked universalism.

□. Most of the current studies are static comparisons of cost and benefit of various SO_x emission control technologies, and lack of dynamic analysis of impact of ship lifespan and fuel price on the total cost of SO_x emission control technologies. Therefore, in the face of future fuel price changes, there is a lack of long-term consideration and relevant countermeasures.

3 Methodology

3.1 PESTEL analysis

PESTLE analysis is initially a concept in marketing principles, which is also used as a method by companies to track the environment they're operating in or are planning to launch a new project/product/service/technology etc. PESTEL analysis, also known as macro-environment analysis, is an effective tool for macro-environment analysis, which can identify all the factors that have an impact on the analysis object. PESTLE is a mnemonic which in its expanded form denotes P for Political, E for Economic, S for Social, T for Technological, L for Legal and E for Environmental. It gives a bird's eye view of the whole environment from many different angles that one wants to check or choose a certain idea/plan(Song, J., Sun, Y., & Jin, L, 2017). Because each SO_x emission control technology has its own advantages and disadvantages, in order to help shipping enterprises choose the most suitable technology, PESTEL analysis is used to compare various SO_x emission control technologies.

Political factors refer to international organizations, regional organizations or countries that have actual or potential impact on the choice of SO_x emission control technology and their related requirements. In order to distinguish from legal factors, the political factors in this dissertation focus on the future impact on SO_x emissions. Economic factors mainly refer to the cost of equipment installation and ship modification and cost of follow-up operation using a certain SO_x emission control technology. Social factors mainly refer to the effects of various SO_x emission control technologies on ship and human health. Technical factors mainly refer to the influence of technical characteristics of various SO_x emission control technologies on ship transport performance. Environmental factors mainly refer to the reduction of air pollution after using various SO_x emission control technologies. Legal factors mainly refer to the conformity of various SO_x emission control technologies to the current related SO_x emission requirements. In the process of analysis and comparison, it is necessary to refine and subdivide all aspects involved in PESTEL in order to establish a scientific evaluation system. Considering that there are many evaluation indexes for each SO_x emission control technology, in order to comprehensively evaluate each SO_x emission control technology, each evaluation index will be graded to quantify the evaluation results, and finally the integrated scores of each SO_x emission control technology will be obtained through summation.

3.2 Cost-benefit analysis

On the basis of PESTEL analysis of various SO_x emission control technologies, the cost and environmental factors will be quantitatively analyzed, which is cost-benefit analysis. In the fierce competition market, lower cost and higher net profit are the focus of attention of every enterprise. Cost-benefit analysis is an economic decision-making method to evaluate project/product/service/technology value by comparing the total cost and benefit of the project etc. The basic procedure of cost-benefit analysis is: firstly several schemes are put forward to achieve a certain goal, then calculate the cost and benefit of each scheme by using certain technical method, finally compare the cost and benefit of each scheme in order to find out how to maximize the benefit with the minimum cost in investment decision-making. When the cost and benefit of a project are calculated, all the items of costs and benefits will be listed and quantified(Pearce, D. W., 2016).

For the cost-benefit analysis in this dissertation, the cost includes the initial installation and transformation cost of SO_x emission control technologies, the subsequent maintenance and operation cost and fuel cost. The benefit refers to the environmental benefit, which is the environmental rehabilitation cost of reducing atmospheric pollutant emissions. To compare the cost and benefit of each SO_x emission control technology, the BCR is calculated. The BCR= the benefit /the cost. The bigger the BCR value is, the bigger the return of unit investment is, then the better the technology is.

3.3 Data regression method

As mentioned above, in the process of cost-benefit analysis of various SO_x emission control technologies, it is needed to calculate the fuel cost of a ship using the technology. In the process of calculating the fuel cost, it is needed to calculate the daily (24 hours) fuel consumption of the ship. The daily fuel consumption of a ship is related to its transportation capacity and speed. In order to establish a general formula for calculating the daily fuel consumption of a ship, it is necessary to use data regression method. The relationship between daily fuel consumption and ship transportation capacity, ship speed can be expressed as follows,

$$DFA = f(TEU,V)$$

Where;

DFA - Daily Fuel Assumption (tons)

TEU - Actual Number Of Standard Containers On Board (TEU)

V - Actual Speed of the ship (knot).

In the process of data regression analysis, the first step is to collect a certain number of data sets(DFA, TEU, V). In this dissertation, these data are primary data which were collected from shipping liner companies. The second step is to establish the formula model of DFA and TEU, V based on experience. The third step is to use the least square method to determine the coefficients in the formula model, so as to ensure the minimum error between the calculated DFA value and the actual DFA value. Eviews software will be used when the coefficients in the formula mode are calculated.

From the above it can been seen that PESTEL analysis and cost-benefit analysis are progressive relationships, and data regression method serves for cost-benefit analysis. The application of the three methodologies is shown in figure 3.1.

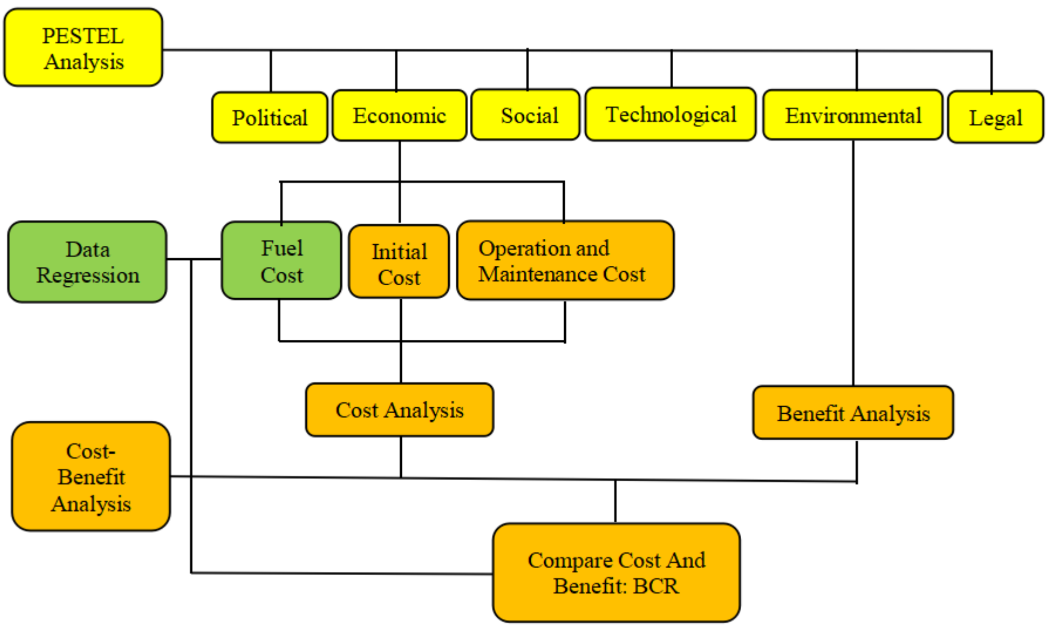


Figure 3.1: The application of the three methodologies

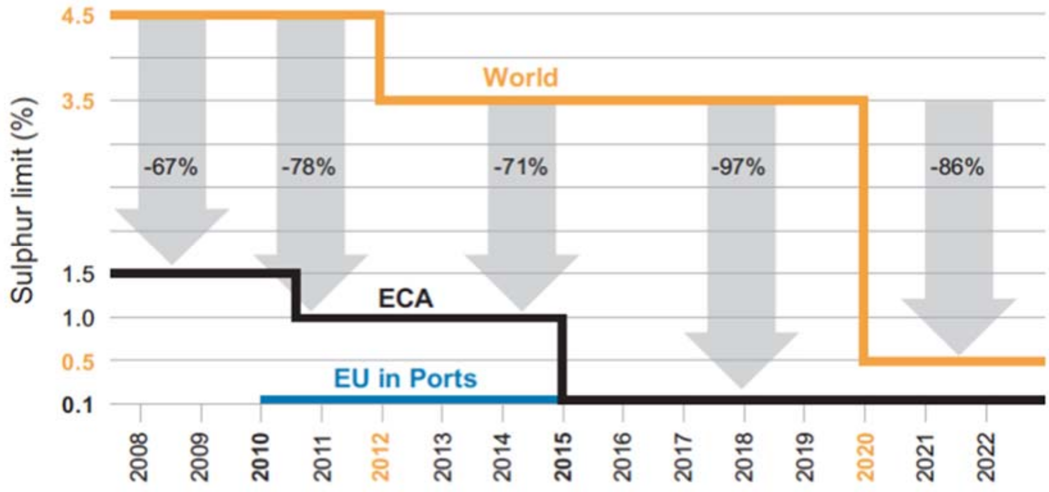
4 Low sulphur fuel requirements for ships and countermeasures

4.1 Low sulphur fuel requirements

In view of the great harm of SO_x, the control of SO_x emission has reached a point that can not be ignored. At present, there are two main types of regulations to limit SO_x emissions from ships, one is international emission control rules, which refers to

Annex VI of MARPOL Convention issued by IMO; the other is regional or national regulations, such as European Union control requirements, US Environmental Protection Agency decrees, and China's coastal emissions control requirements, etc.

MARPOL(The International Convention for the Prevention of Pollution from Ships) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes, which was set by IMO and now has six annexes. The annex □ is about the prevention of air pollution from ships, which entered into force on 19 May 2005 and amended several times after enforcement. According to MARPOL Annex □**,** all ocean-going ships of 400 gross tonnage and above should comply with the annex □ inspection codes and obtain the International Air Pollution Prevention Certificates. In non-emission control areas, the sulphur content of any fuel oil used on ships should not exceed 4.50% m/m prior to 1 January 2012, 3.50% m/m on and after 1 January 2012 and 0.50% m/m on and after 1 January 2020. In ECAs, the sulphur content of any fuel oil used on ships should not exceed 1.50% m/m prior to 1 July 2010, 1.00% m/m on and after 1 July 2010 and 0.01% m/m on and after 1 January 2015. At present, there are four ECAs set by MARPOL Annex □, (1) the Baltic sea area, (2) the North Sea, including the English Channel, (3) the United States Caribbean Sea area, (4)the North American area, including the sea area located 200 nautical miles off the coasts of the United States and Canada. At the same time, the MARPOL Annex □ also provides that for ships sailing in ECAs, the SO_x emission problem can be solved by two ways: one is to directly use fuels containing less sulfur than the emission requirements; the other is to reduce SO_x emissions through exhaust gas treatment systems. The timeline of limits on SO_x emissions from ship set by MARPOL Annex □ is shown in figure 4.1. The 2020 deadline was confirmed at the 70th session of IMO’s Marine Environment Protection Committee(MEPC) held in October 2016(IMO, 2019).



Source:Wartsila, 2018.

Figure4.1: IMO MARPOL annex sulphur limits timeline

In the EU, SO_x emissions from ships are regulated by EU Directive 2016/802. According to the Sulphur Directive, all ships at berth in EU ports should use fuel oil which meets with a 0.1% m/m maximum sulphur requirement from January 1, 2010. However, if the berthing time of the ship is less than 2 hours or the power supply of the ship is switched to shore power, it does not need to meet the requirements of the Sulphur Directive(Official Journal of the European Union, 2016).

In October 2016, the ministry of transport of China issued the implementation plan of controlling vessels exhaust gas emissions, which set three domestic emission control areas(DECAs) in China coastal areas, including the Pearl River delta, the Yangzi River delta and Bohai rim(Beijing, Tianjin, Hebei). According to this implementation plan, the sulphur content of any fuel oil used on board vessels entering the DECAs should not exceed 0.5% m/m on and after 1 January 2019. In December 2018, the ministry of transport of China issued the implementation scheme of the DECAs for atmospheric pollution from vessels, which expanded DECAs to all the coastal waters and the navigable waters of the main stream of the Yangtze River and the main stream of the Xijiang River. According to this implementation scheme, the sulphur content of any fuel oil used on board sea-going vessels operating in the DECAs should not exceed

0.5% m/m from 1 January 2019, the sulphur content of fuel oil used on board sea-going vessels should not exceed 0.1% m/m when operating in the inland river emission control areas from 1 January 2020, the sulphur content of any fuel oil used on board sea-going vessels should not exceed 0.1% m/m when operating in the coastal emission control area in Hainan waters from 1 January 2022. At the same time, this implementation scheme also agreed that the clean energy, new energy and exhaust gas cleaning systems can be used by vessels as alternative methods to meet the emission control requirements(MSA, 2018).

In addition, US California Air Resource Board has enacted a directive stipulating that the sulfur content of fuel oil used by ocean-going vessels within 24 miles of California coastline should not exceed 0.1% m/m(Yang, G., 2016).

Overall, compared with IMO requirements, China implemented the requirement that the sulfur content of fuel oil should not exceed 0.5% m/m one year ahead of IMO schedule in its coastal waters, the sulphur content of fuel oil used on board sea-going vessels entering the main stream of Yangtze River and Xijiang River after 2020 and entering Hainan waters after 2022 will be the same requirement as ECAs set by IMO and EU ports(0.1% m/m). Table 4.1 shows SO_x emission requirements for different times and different regions.

Table 4.1: SO_x emission requirements for different times and different regions

Unit: m/m

Time Region	China DECAs			ECAs set by IMO	EU ports	Non-emission control areas
	Coastal areas (exclude Hainan waters)	the main stream of the Yangtze and Xijiang River	Hainan waters			
2019.01.01-2019.12.31	0.5%	0.5%	0.5%	0.1%	0.1%	3.5%
2020.01.01-2021.12.31	0.5%	0.1%	0.5%	0.1%	0.1%	0.5%
2022.01.01-	0.5%	0.1%	0.1%	0.1%	0.1%	0.5%

Source: Official Journal of the European Union, 2016; MSA, 2018.

4.2 Identification of all alternative SOx emission control technologies

In order to meet the above low sulphur fuel requirements, there are three methods as follows,

□. Using low-sulphur fuel oil.

□. Using alternative clean fuel as ship power energy, such as LNG(liquefied natural gas), bio-fuels, methanol and etc. Because LNG is the most widely used among them, this dissertation takes LNG as the analysis object.

□. Installing sulphur scrubbers, which includes dry scrubbers, seawater scrubbers, fresh water scrubbers and hybrid scrubbers.

Among the three methods, using low-sulphur fuel oil and LNG belong to pre-treatment technologies, and installing sulphur scrubbers belong to after-treatment technologies. There are advantages and disadvantages for each method. Which method to choose to meet the low sulphur fuel requirement is a big challenge for shipping enterprises. Figure 4.2 shows the classification of ship SO_x emission control technologies.

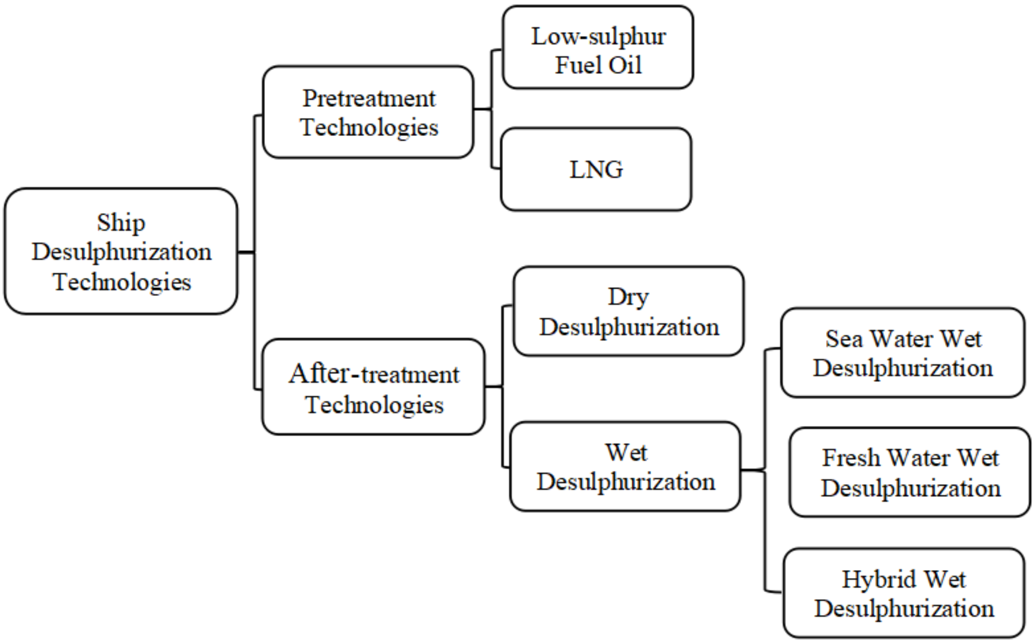


Figure 4.2: The classification of ship SO_x emission control technologies

Low sulphur fuel oil. Marine fuels can be classified as marine distillate fuel oil, marine residual fuel oil and intermediate fuel oil(IFO). Marine distillate fuel oil include marine gas oil(MGO) and marine diesel oil(MDO). Marine residual fuel oil is also called heavy fuel oil(HFO). Intermediate fuel oil is a blend of gas oil and heavy fuel oil, with less gas oil than marine diesel oil. ISO8217 has clear requirements for marine fuels classification and quality. The most frequently used marine fuels are listed as follows(ISO, 2017).

IFO380 - Intermediate fuel oil with a maximum viscosity of 380 centistokes. The sulphur content is less than 3.5%.

IFO180 - Intermediate fuel oil with a maximum viscosity of 180 centistokes.The sulphur content is less than 3.5%.

MDO - The main model is DMC with a maximum viscosity of 14 centistokes. The sulphur content of MDO used in ECAs should be less than 0.1%.

MGO - Including different models, such as DMX, DMA and DMB with a maximum viscosity of 11 centistokes. The sulphur content of MGO used in ECAs should be less than 0.1%(ISO, 2017).

Among the above four types of marine fuel, IFO380 and IFO180 are widely used now as high sulphur fuel oil, MDO and MGO are low sulphur fuel oil which can meet the requirement in ECAs, EU ports and China DECAs. In fact, there are two other kinds of low-sulfur oils in the market besides MDO and MGO. One is formed by further desulfurization on the basis of heavy oil, the other is formed by increasing the proportion of gas oil in the process of mixing gas oil and heavy oil to meet the requirement of less than 0.5% sulphur content. Because the forming processes of these two kinds of low sulfur oil are not uniform, their compositions are complex and different, they are less used less in the fuel market(Streibel, T., Schnelle-Kreis, J., Czech, H., Harndorf, H., Jakobi, G., Jokiniemi, J., ... & Müller, L., 2017). The low sulfur oil discussed in this dissertation mainly refers to MDO and MGO. Because MGO is more widely used than MDO, this dissertation will focus on the advantages and disadvantages of using MGO.

LNG fuel. LNG is formed by purification of natural gas produced in gas fields and liquefaction under atmospheric pressure at ultra-low temperature(-162℃). Natural gas liquefaction can greatly save storage and transportation space. The main components of LNG are CH_4 (more than 90%) and a small amount of ethane C_2H_6, C_3H_8 and N_2. LNG is colorless, tasteless, non-toxic and non-corrosive, and its volume is about 1/625 of that of gaseous natural gas. The main substances after LNG combustion are CO_2 and H_2O, which can reduce SO_x emissions almost 100% and other pollutants(such as PM) emissions at the same time. At present, the new building or refitted LNG powered ships mostly use dual-fuel diesel engines, which can be switched between fuel mode and gas mode at will(Yang, Z., Pei, L., & Zhu, J. 2018).

Ship LNG power engines have different classification methods according to different standards. According to the way of fuel use, it can be divided into single gas fuel engine, dual fuel engine and mixed combustion engine. According to the ignition mode, it can be divided into spark plug ignition and fuel ignition. According to the way of gas intake, it can be divided into in-cylinder intake and out-of-cylinder intake which can be further subdivided into different types. Figure 4.3 shows the different classification methods of LNG power engine. The world famous manufacturers of marine LNG engines are MAN, Wartsila and Rolls-Royce. MAN, Wartsila mainly produces dual fuel engines, Rolls-Royce mainly produces pure gas engines. Due to the low power of pure gas engine, which is usually less than 2000 KW for single engine, it is difficult to use in ocean transportation. Now the world's representative LNG engines used in ocean transportation are ME-GI series engines produced by MAN and DF series engines produced by Wartsila. They are all dual-fuel and fuel ignition engines. The difference is that the ME-GI series engines are high pressure direct injection engines, and DF series engines are low pressure direct injection engines(Yoo, B. Y., 2017). This dissertation will choose these two types of LNG engines as comparative objects.

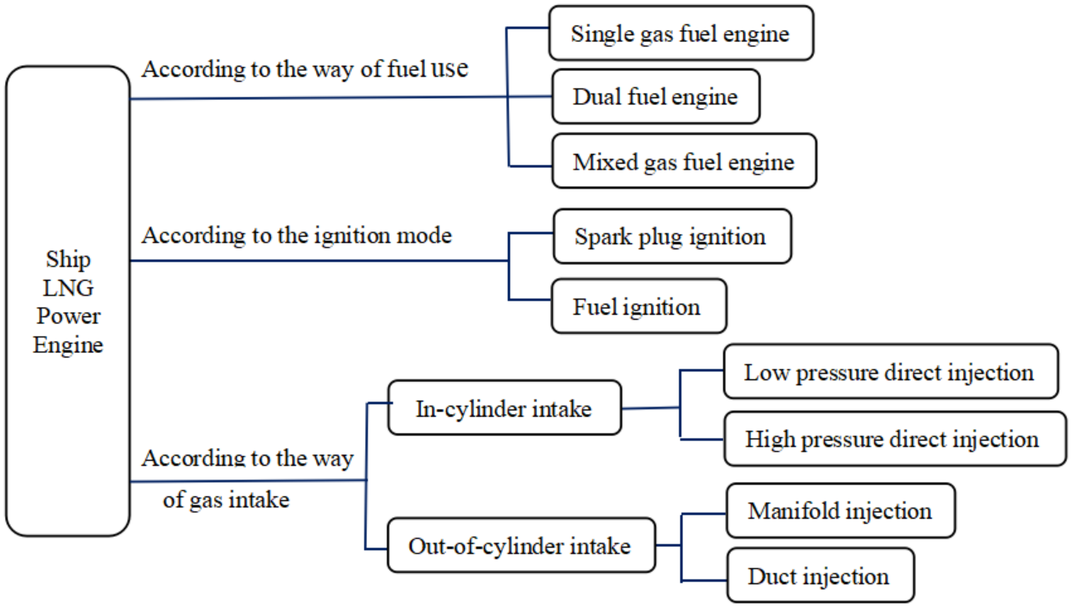


Figure 4.3: Different classification methods of LNG power engine

Dry desulfurization technology uses alkaline solid particles such as quicklime($CaCO_3$ and CaO) or $Ca(OH)_2$ as adsorbents, which react directly with SO_x in ship exhaust gas. Because adsorbents are dry solids, this technology is called dry scrubber. Dry scrubber has been studied by relevant companies, among which the most representative one is the dry desulfurization system developed by German companies Couple System and MAN. The main chemical reaction formulas are as follows,

$$SO_2+CaO \rightarrow CaSO_3, \quad SO_2+CaCO_3 \rightarrow CaSO_3+CO_2$$

$$SO_2+Ca(OH)_2 \rightarrow CaSO_3 + H_2O$$

The seawater desulfurization technology is to absorb SO_x in ship exhaust gas through pipelines equipped with seawater. On one hand, seawater can dissolve SO_x and form SO_3^{2-} and HSO_3^- in water, on the other hand, seawater is naturally weak alkaline and can react with dissolved SO_x to form sulfate. Because the seawater is not recycled and reused, this method is also called open-loop scrubber. The concentration of CO_3^{2-} and HCO_3^- in seawater used this technology should normally exceed 2200 μmol/L(Ren, Y., 2016).

The fresh water desulfurization technology is to add NaOH or MgO to fresh water to form alkaline solution, which can dissolve and neutralize SO_x in ship exhaust gas to desulfurize. When the PH value of the alkaline solution declines to a certain value, NaOH or MgO need to be added to ensure the desulfurization effect. Because alkaline solution can be recycled and reused, this method can greatly reduce the discharge of waste water and is also called closed-loop scrubber. Because NaOH is more widely used than MgO, this dissertation mainly compares and analyses the fresh water desulfurization technology using NaOH solution(Jiang, L., & Hansen, C. Ø., 2016).

Hybrid desulfurization technology is a desulfurization technology which combines seawater desulfurization technology and fresh water desulfurization technology. Hybrid desulfurization technology can operate in either open-loop mode with seawater or closed-loop mode with fresh water. In contrast, the use of seawater in the open-loop mode can save a lot of fresh water and reduce operating costs; when the concentration of CO_3^{2-} and HCO_3^- in seawater can not meet the requirement or discharging waste water is forbidden, the closed-loop mode should be used. This method is called hybrid scrubber(Jiang, L., & Hansen, C. Ø., 2016).

5 Evaluation of different ship SO_x emission control technologies

5.1 Establishment of Evaluation System

The working principles of various SO_x emission control technologies have described in chapter 4. According to the working characteristics of each SO_x emission control technology and based on PESTEL analysis method, the evaluation system of SO_x emission control technology is established as figure 5.1 shows. The evaluation system consists of 13 indexes from six aspects. In order to evaluate each index quantitatively, the evaluation results of each index are divided into five grades, with corresponding 5-1 score. The higher the grade, the higher the score. All comparisons except legal aspects are based on the use of IFO without exhaust gas treatment system, which is also the benchmark. For legal comparison, the benchmark is a set of various SO_x emission requirements, the evaluation results depend on the degree of conformity of the requirements.

For political, social, environmental and legal aspect, the five grade are ‘excellent’, ‘very good’, ‘good’, ‘fair’ and’ poor’. If the effect of the index is equal to that of the benchmark, the evaluation is ‘fair’, with corresponding score 2. If the effect of the index is lower than that of the benchmark, the evaluation grade is ‘poor’, with corresponding score 1. If the effect of the index is better than that of the benchmark, the evaluation grade is ‘good’, ‘very good’ or ‘excellent’, with corresponding score 3-5 respectively. The better the effect, the higher the score.

For economic, technological aspect, the five grade are 'save', 'fair', 'little more', 'more' and 'much more'. If the effect of the index is equal to that of the benchmark, the evaluation is 'fair', with corresponding score 4. If the effect of the index is lower than that of the benchmark, the evaluation grade is 'save', with corresponding score 5. If the effect of the index is higher than that of the benchmark, the evaluation grade is 'little more', 'more' or 'much more', with corresponding score 3-1 respectively. Five evaluation grades and corresponding scores are shown in Table 5.1.

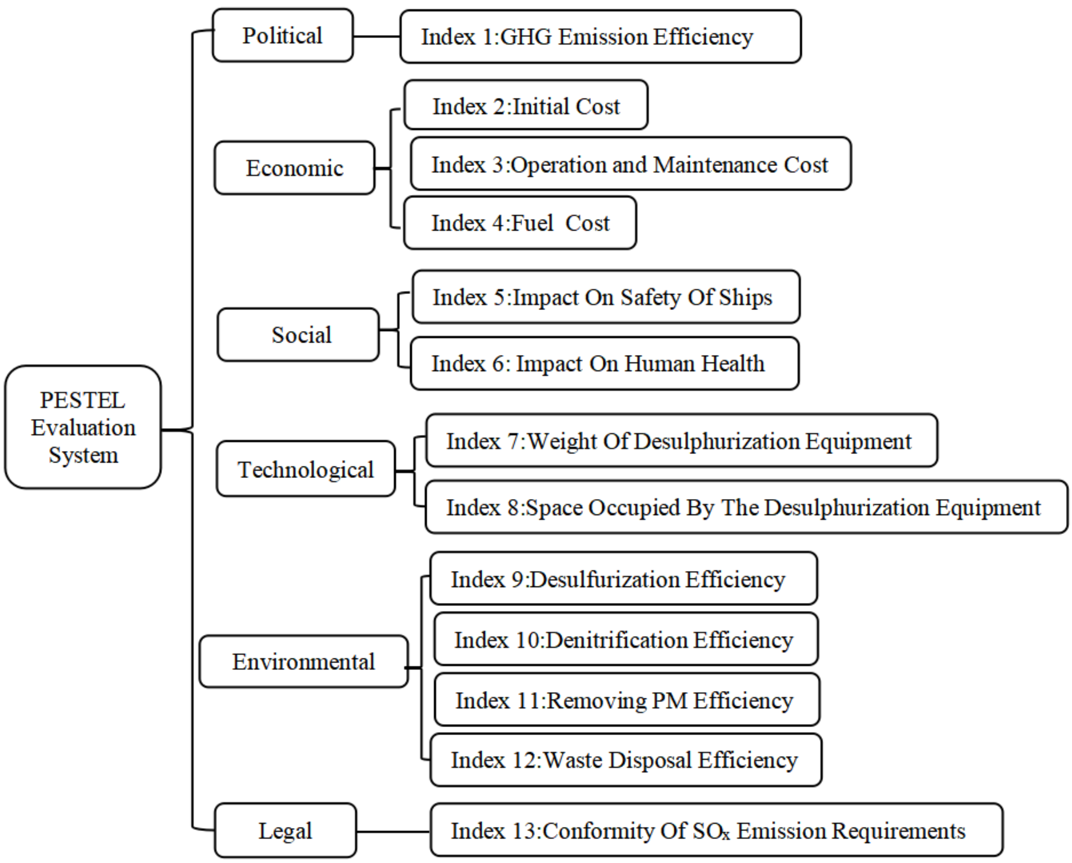


Figure 5.1: PESTEL evaluation system

Table 5.1: Five evaluation grades and corresponding scores

Grades	For P,S, E(environment),L	Excellent	Very Good	Good	Fair	Poor
	For E(economic),T	Save	Fair	Little more	More	Much more
Scores		5	4	3	2	1

5.2 Political

At present, the international community pays great attention to global climate change. The United Nations and IMO have longer-term planning and targets for GHG emissions than SO_x, NO_x and PM. In December 2015, the United Nations climate change conference held in Paris adopted the Paris Agreement, which reiterated the threat of GHG emissions to human beings and the global environment, and set the goal to keep a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius(UNFCCC, 2018). In April 2018, the Maritime Environment Protection Committee(MEPC) of IMO at its 72ed session adopted the Initial IMO Strategy on reduction of GHG emissions from ships, which represents the framework for further action by IMO, setting out a vision reiterating IMO's commitment to reducing CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and reducing the total annual GHG emissions by at least 50% by 2050 compared to 2008; achieving the goal of zero carbon emissions from ships by the end of this century.

Compared with IFO, the calorific value of MGO is 5% higher, in case of doing the same work, the consumption of MGO will be reduced by about 5%, thus the CO_2 emission will be reduced by about 5%. Although the calorific value of LNG is 17% lower than that of IFO, because of the different chemical composition of natural gas, in the case of doing the same work, using LNG will be reduced CO_2 by 20% compared with HFO. But there will be some unburned methane in the low pressure direct injection engine. Methane is the main component of natural gas, and its GHG impact is 25 times higher than CO_2, so methane escape offsets the reduction of CO_2 emission. Gas engines operated under high pressure direct injection have very low methane escape. Therefore, compared with oil fuel engines with the same output power, the overall CO_2 emission can be reduced by about 20%(LI Yuan, 2016). For dry scrubbers, if quicklime is used as absorbent, because CO_2 is produced in the reaction, CO_2 emissions will increase by about 10%(DONG Wei, 2013). Although wet scrubbers can absorb CO_2 from exhaust gas to some extent, the operation of scrubber will increase fuel consumption of ships, and the positive and negative effects are offset, so wet scrubbers will not reduce CO_2 emissions basically(Li, Y., 2016).

From the above analyses, it can be seen that wet scrubber and LNG low pressure direct injection engine have the same GHG emission effect with using IFO without exhaust gas treatment system, dry scrubber may generates more GHG, the GHG emission effect of using MGO is good, and the GHG emission effect of LNG high pressure direct injection engine is very good. The specific evaluation result of this index is shown in Table 5.2.

Table 5.2: GHG emission reduction effect of each SOx emission control technology

Evaluation	Low sulphur fuel oil	LNG fuel		Scrubber			
		Low pressure	High pressure	Dry	Sea water	Fresh water	Hybrid

Technologies		engine	engine				
GHG emission effect*	↓ 5%	No change	↓ 20%	↑ 10%	No change	No change	No change
Grade	Good	Fair	Very good	Poor	Fair	Fair	Fair
Score	3	2	4	1	2	2	2

Source:LI Yuan, 2016; DONG Wei, 2013.

5.3 Economic

5.3.1 Initial cost

Most ships using IFO can use MGO directly. If the fuel viscosity at the engine inlet is less than 3cST, fuel cooling system need to be installed to meet the working requirements of the main engines(Gao, C., Zheng, Y., 2010). In addition, for ships using both IFO and MGO before January 1, 2020, MGO storage tank should also be installed to separate IFO and MGO storage. But the cost of installing MGO cooling system and storage tank is relatively very low.

For using LNG fuel, compared with heavy oil, the increased initial cost mainly includes two parts, one is from the engine, the other is from the fuel tank and pipeline system. The powers required by container ships with different loading capacity are different, so the prices of LNG engines and fuel supply systems are also different. It is roughly estimated that the construction cost of LNG power ship is 15-30% higher than that of ordinary ship(Tian, H., 2016).

For seawater scrubber, the reacted water in seawater desulfurization system is discharged outboard directly without any treatment. The principle of the system is simple and the cost is relatively low. The closed-loop system in freshwater scrubber and hybrid scrubber is more complex than open-loop system. Compared with open-loop technology, closed-loop technology adds circulating pump, rehydration tank, rehydration pump, water treatment system and other devices, so the initial investment of refresh water scrubber and hybrid scrubber are relatively high(Seddiek, I. S., & Elgohary, M. M., 2014). The specific evaluation result of this index is shown in Table 5.3.

Table 5.3: Initial cost of each SO_x emission control technology

Evaluation Technologies	Low sulphur fuel oil	LNG fuel	Scrubber			
			Dry	Sea water	Fresh water	Hybrid
Grade	Fair	Much more	More	Little more	More	More
Score	4	1	2	3	2	2

Source: Tian, H., 2016; Seddiek, I. S., & Elgohary, M. M., 2014.

5.3.2 Maintenance and operating cost

For using MGO, ships may need to install cooling MGO system to increase fuel viscosity, but the maintenance and operating cost can be almost neglected.

According to the guide manual of L20DF duel fuel engine produced by Wartsila, the repair interval of piston, piston ring, cylinder liner, cylinder liner, intake valve, exhaust valve and jet pump is about 20000 hours. The life expectancy of intake valve, exhaust valve and jet pump is up to 40,000 hours, and that of piston and rigid sleeve is up to

60,000 hours, which is longer than that of diesel engine(Wartsila Finlan OY, 2018). Although extending the life of components can reduce costs, on the other hand, gas tanks, gas compressors and gas pipelines increase the maintenance cost. According to MAN statistics, the cost of spare parts and maintenance using LNG is about 10% higher than that of diesel engines(MAN Diesel & Turbo, 2012).

For scrubbers, the operating and maintenance cost of scrubbers mainly include the fuel consumption for scrubber operation, the absorbent cost and the maintenance cost of various pumps. All kinds of scrubbers has no effect on marine engine, and the cost of maintenance of the pumps are relatively low, which can be neglected. The cost of absorbents are very high, the price of quicklime is about 120 $/ton, the price of NaOH solution is about 250 $/ ton. At the same time, a large amount of absorbents will be consumed when dry scrubber runs and wet scrubber runs in closed-loop model, so the operation cost of dry scrubber, fresh water scrubber are very high(Sun, K., 2016). The specific evaluation result of this index is shown in Table 5.4.

Table 5.4: Maintenance and operating cost of each SOx emission control technology

Evaluation Technologies	Low sulphur fuel oil	LNG fuel	Scrubber			
			Dry	Sea water	Fresh water	Hybrid
Grade	Fair	More	Much more	Little more	Much more	More
Score	4	2	1	3	1	2

Source: MAN Diesel & Turbo, 2012; Sun, K., 2016.

5.3.3 Fuel cost

Fuel cost is related to unit fuel price and fuel consumption. But Fuel costs are only related to unit fuel prices when the same goods are transported for the same distance at the same speed. The unit fuel price here refers to the price of fuel that releases a unit energy. For shipping enterprises' decision-making reference, future fuel price is more meaningful than historical fuel price, but because future price is difficult to predict accurately, this dissertation chooses the recent period（the last one year） fuel price to compare. According to the data provided by Ship & Bunker website, the global average bunker price can be obtained from October 2018 to September 2019 on the first trading day of each month. By averaging 12 sets of data, the average fuel price of IFO and MGO can be obtained, which is shown in Table 5.5.

Table 5.5: The global average bunker price from October 2018 to September 2019

Date (year/month/day)	IFO380 ($ / ton)	IFP180 ($ / ton)	MGO ($ / ton)
2018/10/01	505.00	529.50	784.00
2018/11/01	511.50	535.50	784.50
2018/12/03	456.60	477.00	702.00

2019/01/01	405.50	420.50	661.50
2019/02/01	436.00	459.50	687.50
2019/03/01	470.50	490.50	714.50
2019/04/01	472.50	489.50	717.50
2019/05/01	478.50	507.00	732.00
2019/06/03	436.50	461.50	700.50
2019/07/01	447.00	473.00	698.50
2019/08/01	460.50	485.50	696.00
2019/09/02	404.00	427.00	673.50
Average price	457.01	479.67	712.67

Source: Ship & Bunker, 2019.

From the table 5.5, it can be seen that the average price of IFO380 is about 457.01 $/ton , the average price of IFO180 is 479.67 $/ton , and the average price of MGO is 712.67 $/ton. According as calorific value of IFO is 46 MJ/Kg and MGO is 48.3 MJ/kg, 1Btu equals to 1055.06J, it can be calculated that the average price of IFO380 is 10.48 $/MBtu, the average price of IFO180 is 11.00 $/MBtu, and the average price of MGO is 15.57 $/MBtu. The calculation process is as follows,

$$PF_{IFO380} = 457.01 \text{ \$/ton} = (457.01 / 46000) \times 1055.06 \text{ \$/MBtu} = 10.48 \text{ \$/MBtu}$$

$$PF_{IFO180} = 479.67 \text{ \$/ton} = (479.67 / 46000) \times 1055.06 \text{ \$/MBtu} = 11.00 \text{ \$/MBtu}$$

$$PF_{IFO380} = 712.67 \text{ \$/ton} = (712.67 / 48300) \times 1055.06 \text{ \$/MBtu} = 15.57 \text{ \$/MBtu}$$

Europe, East Asia and North America are the world's major natural gas trading centers. From 1th 10, 2018 to 1th 9, 2019, the average price of natural gas trading in American Henry Hub is 3.15 $/MBtu(U.S. Energy Information Administration, 2019), European gas hub prices for LNG is about 3.30$/MBtu, Asian spot prices for LNG is about 3.55 $/MBtu (Global LNG Hub, 2019). Then, the average LNG prices in the three places from from 1th 10, 2018 to 1th 9, 2019 is about 3.33 $/MBtu. The specific evaluation result of this index is shown in Table 5.6.

Table 5.6: The unit fuel cost of each SO_x emission control technology

Evaluation Technologies	Low sulphur fuel oil ($/MBtu)	LNG fuel ($/MBtu)	Scrubber ($/MBtu)			
			Dry	Sea water	Fresh water	Hybrid
Fuel cost	15.57	3.33	10.48-11.00	10.48-11.00	10.48-11.00	10.48-11.00
Grade	More	Save	Fair	Fair	Fair	Fair
Score	2	5	4	4	4	4

Source: Ship & Bunker, 2019; U.S. Energy Information Administration, 2019; Global LNG Hub, 2019.

5.4 Social

Social impact mainly includes two aspects, one is the impact on ship safety, the other is the impact on human health.

After desulfurization treatment, many physical and chemical properties of fuel oil have changed dramatically, such as high calorific value, low density, low viscosity, poor lubricity. Ship fuel oil supply system and engines are designed based on heavy oil. Long-term use of low-sulfur fuel oil will have a negative impact on marine main and auxiliary engines, specifically: the low viscosity and cold flow of low sulfur oil will lead to fuel leakage and worsen the main engine wear, and the conversion of low sulfur oil may lead to the failure of fuel system and equipment, and even the danger of losing power for ships. There have been some reports of accidents caused by the use of low-sulfur oil(Andersen, I. M. V., 2012). Compared with IFO, harmful substances such as ash, heavy metals and sulphur in MGO are greatly reduced, and the exhaust gas has less impact on human health. However, it is noteworthy that the sizes of PM formed by IFO and MGO combustion are quite different. Generally, the size of PM formed by MGO is PM1-PM2.5, while the PM formed by IFO are much larger than that of MGO(Andersen, I. M. V., 2012). The smaller the PMs are, the greater the harm to human beings will be. When the diameters of PMs are less than 2.5μm, they can be absorbed into alveoli and carried into the blood, leading to respiratory and cardiac diseases. Therefore, the total amount of PMs produced by MGO decreases, but these tiny PMs are more pathogenic. Generally speaking, compared with IFO, the use of MGO is 'Poor' to safety of ships and is 'Good' to human health.

The potential dangers of LNG mainly come from three aspects, (1) Low temperature. Because LNG is a ultra-low temperature(-163 ℃) liquid. If it leaks, people will be frostbitten and ship hull materials will be embrittled if they contact LNG directly. LNG pipeline system will shrink obviously due to the low temperature of internal LNG, which increases the risk of leakage. (2)Gasification expansion. The volume of LNG per unit increases about 600 times from liquid to gas. LNG gasification can lead to overpressure damage of closed sections/components or overpressure of fuel tank. (3) Inflammable and explosive. After LNG leak, if the diffusion of vapor cloud is limited, natural gas with 5%-15% concentration can be ignited and detonated. Although the danger of LNG is very high, once an accident occurs, it will be catastrophic, but through reasonable operation, the risk can be completely controlled. There are few reports of accidents of LNG power ship in the world until now(Adamchak, F., & Adede, A., 2013). In addition, LNG belongs to clean energy and has the smallest impact on human health. To have an integrative consideration, compared with IFO, the use of LNG is 'Poor' to safety of ships and is 'Very good' to human health.

In the aspect of ship safety, the use of strong alkali solution in freshwater scrubber and hybrid scrubber under closed-loop mode will have a certain corrosiveness to the ship and affect the safety of the ship. Therefore, the evaluation grade of the impact of freshwater scrubber and hybrid scrubber on ship safety is ‘Poor’. Dry scrubber and seawater scrubber have no significant impact on ship safety, so their evaluation grade is ‘Fair’. In the aspect of impact on human health, all kinds of scrubbers are generally safe and simple to operate, and the effects of SO_x and PM emission reduction are obvious. Compared with low sulphur oil and LNG fuel, the evaluation grade of impact on human health is ‘Good’. The specific evaluation result of this index is shown in Table 5.7.

Table 5.7: Social impact of each SOx emission control technology

Evaluation Technologies		Low sulphur fuel oil	LNG fuel	Scrubber			
				Dry	Sea water	Fresh water	Hybrid
Impact on ship safety	Grade	Poor	Poor	Fair	Fair	Poor	Poor
	Score	1	1	2	2	1	1
Impact on human health	Grade	Good	Very good	Good	Good	Good	Good
	Score	3	4	3	3	3	3

Source:Andersen, I. M. V., 2012; Adamchak, F., & Adede, A., 2013.

5.5 Technological

Technological aspect includes two indexes, one is the space occupied by desulphurization equipment, the other is the weight of desulphurization equipment.

Not all the ships using MGO need to install cooling system to increase fuel viscosity.

According to the parameters of marine chillers manufactured by York Refrigeration Marine, for the minimum power marine chillers(57Kw), the over dimension is 2538 mm × 1610 mm × 1850 mm, the weight is 980Kg, for the maximum power marine chillers(273Kw), the over dimension is 2804 mm × 1610 mm × 1850 mm, the weight is 1823Kg. That is to say, the engine room space occupied by York marine cooling system is about 7.6-8.4m^3, the weight of York marine cooling system is less than 2 tons(Gao, C., & Zheng, Y., 2010).

The calorific value of IFO is about 46 MJ/Kg and that of LNG is about 38 KJ/Kg(REN Y., 2016). That is to say, the calorific value of IFO is 1.2 times that of LNG. When the same combustion energy is obtained, the weight of LNG is 21% more than that of IFO. The density of LNG is about 0.42-0.46g/cm^3, and the density of IFO in 40℃is about 1g/cm^3(Ren, Y., 2016). That is to say, the density of IFO is 2.2-2.4 times that of LNG. It can be concluded that when the same combustion energy is obtained, the volume of LNG is 2.66-2.90 times that of IFO. Taking 8000TEU container ship commonly used in ocean transportation as an example, its fuel tank capacity can reach 10000m^3, and it can carry about 10000 tons of heavy oil. If the ship maintains the same endurance mileage, after using LNG fuel, the fuel tank capacity should be 26600-29000 m^3 and the fuel weight should be 12100 tons. In fact, in order to avoid sacrificing too much transport capacity, ships using LNG fuel usually tend to weaken its endurance capacity. Because the fuel pipeline system of LNG is more complex than that of heavy oil, the fuel pipeline system will occupy more ship space and increase ship weight after using LNG fuel. In short, compared with the use of heavy oil, for using LNG fuel, the occupied space and weight of ship will increased significantly.

The principle of dry scrubber is simple, but the volume and weight of the whole device are large. In addition, dry scrubber requires a large number of solid particles to be carried with the ship, which occupies a large space of the ship and increases the weight of the ship. Compared with seawater scrubber, freshwater scrubber adds circulating pump, rehydration tank, rehydration pump, water treatment system and other devices, which occupies more ship space and increases ship weight. Hybrid scrubbers use less fresh water than fresh water scrubbers, the increased weight and occupied space of hybrid scrubber is less than fresh water(Yang, G., 2016). The specific evaluation result of this index is shown in Table 5.8.

Table 5.8: Volume and weight of each SOx emission control technology

Source: Gao, C., & Zheng, Y., 2010; Ren, Y., 2016; Yang, G., 2016.

Evaluation Technologies		Low sulphur fuel oil	LNG fuel	Scrubber			
				Dry	Sea water	Fresh water	Hybrid
Space occupied	Grade	Little more	Much more	Much more	More	Much more	More
	Score	3	1	1	2	1	2
Increase weight	Grade	Little more	Much more	Much more	More	Much More	More
	Score	3	1	1	2	1	2

5.6 Environmental

5.6.1 Desulfurization efficiency

At present, the highest sulfur content of IFO and MGO is 3.5% and 0.1% respectively. According to the maximum value of sulphur content, compared with using IFO, using MGO with the same mass can reduce the sulphur emission by (3.5%-0.1%) / 3.5% = 97.1%. In addition, the calorific value of MGO is 5% higher than IFO, so when the same heat quantity is produced, the consumption of MGO will be reduced by about 5%, thus the reduced sulphur emission in total can be calculated as follows,

$$1- (1-97.1\%)(1-5\%) = 97.2\%$$

Natural gas usually contains H_2S. In order to prevent it from corroding transportation pipelines, refined desulfurization process is needed in its production process. A survey of LNG purchase and sale agreements conducted by Poten & Partners which is a natural gas consultant company, shows that the average content of sulfur in LNG is about 0.004%, which is far below the requirement of 0.1% in fuel oil. So when natural gas burns in the air, the SO_x produced after combustion can be considered to be almost zero. However, the SO_x emission of ship engine is not zero. Marine gas engines produced by Rolls Royce use spark plug ignition, which can reduce SO_x emissions by 100%. Dual-fuel engines produced by Wartsila and MAN need to be ignited by fuel oil, so the use of ignited oil and sulfur content of the ignited oil should be considered. For ME-GI series engines, the amount of ignition fuel is usually 3%-5% of the total fuel. Therefore, when using LNG fuel, if the ignition fuel is HFO, it can be inferred that the SO_x emission of high pressure engines is 95%-97% lower than that of HFO fuel engine without scrubber. For SDF series engines, the amount of ignition fuel is usually 1% of the total fuel. Therefore, it can reduce SO_x emissions by 99% than using HFO fuel engine without scrubber (Ma, Y., 2016).

According to the report of Couple System company, its Dry-EGCS scrubber system has been used on container ship ‘MS Timbus’, which can reduce SO_x emissions by 99%(Dong, W., 2013). For wet scrubbers, the effect of desulfurization is directly related to the PH value of absorbent liquid, the ratio of liquid to exhaust gas, the concentration of SO_x in the exhaust gas, and the type of filler etc. However, under specific working conditions, the scrubbers produced by various companies have clear scrubber effect values. According to Wartsila's report, the experiments proved that the seawater scrubber system and the freshwater scrubber system can reduce SO_x emissions by 90%-95% and 99% respectively. According to Aalborg's report, its EGCS hybrid scrubber system can reduce SO_x emissions by 98% in open-loop mode and reduce SO_x emissions by 99% in closed-loop mode(Dong, W., 2013). The specific evaluation result of this index is shown in Table 5.9.

Table 5.9: Desulfurization efficiency of each SO_x emission control technology

Evaluation Technologies	Low sulphur fuel oil	LNG fuel		Scrubber			
		Low pressure engine	High pressure engine	Dry	Sea water	Fresh water	Hybrid
SO_x emission effect	↓ 97.2%	↓ 99%	↓ 95-97%	↓ 99%	↓ 90-95%	↓ 99%	↓ 98-99%
Grade	Very good	Excellent	Very good	Excellent	Good	Excellent	Very good
Score	4	5	4	5	3	5	4

Source: Ma, Y., 2016; Dong, W., 2013.

5.6.2 Denitrification efficiency

The concentration of NO_x in exhaust gas is mainly determined by combustion temperature in the engine and the content of organic nitrogen in fuel. Using the same type of engine under the same working conditions, the combustion temperature in the engine is the same. Because the content of organic nitrogen in IFO is higher than that in MGO, the NO_x emission of using IFO is slightly higher than using MGO(Ren,Y., 2016). According to experimental data from the University of Richmond, in the case of doing the same work, the amounts of NO_x emission for different fuels are shown in Table 5.10.

Table 5.10: The amounts of NO_x emission for different fuels

The type of fuel	the amounts of NO_x emission (g/Kwh)	NO_x emission ratio (%)

IFO	9-12	100
MGO	8-11	88.9-91.7

Souce: Ren,Y., 2016.

Because ME-GI series engines adopt Diesel cycle, the combustion temperature is high, and the emission standard of NO_x can only reach Tier □, the exhaust gas recirculation(EGR) or selective catalytic reduction(SCR) system should be installed to meet Tier □. Because SDF series engines adopts Otto cycle, the combustion temperature is low, exhaust gas can reach Tier □ without treatment. According to the manufacturer's instructions, compared to using IFO without exhaust gas treatment system, ME-GI series engines can reduce NO_x by about 24%, SDF series engines can reduce NO_x by about 85%(Ma, Y., 2016).

Dry scrubber can only reduce SO_x in the exhaust gas, and can not reduce NO_x. Although wet desulfurization technologies can absorb NO_x to some extent, its effect is not obvious. Statistical reports from the European Maritime Safety Agency show that the denitrification efficiency of wet desulfurization technology is about 3-7%(European Maritime Safety Agency,2010). The specific evaluation result of this index is shown in Table 5.11.

Table 5.11: Denitrification efficiency of each SOx emission control technology

Evaluation Technologies	Low sulphur fuel oil	LNG fuel		Scrubber			
		Low pressure engine	High pressure engine	Dry	Sea water	Fresh water	Hybrid

NO_x emission effect*	↓ 8.3-11.1%	↓ 85%	↓ 24%	No change	↓ 3-7%	↓ 3-7%	↓ 3-7%
Grade	Good	Excellent	Very good	Fair	Good	Good	Good
Score	3	5	4	2	3	3	3

Source: Ren, Y., 2016; Ma, Y., 2016; European Maritime Safety Agency, 2010.

5.6.3 Removing PM efficiency

The formation of PM is related to impurity content in fuel and engine operating conditions. There are more impurities such as ash, heavy metals and sulfur in IFO than in MGO, thus using IFO will produce more PM than using MGO. According to the analysis of Herbert Engineering Corporation, in case of doing the same work, MGO can reduce PM emissions by about 50-85% compared with IFO(Herbert Engineering Corporation, 2018). For LNG fuel, because LNG contains few amounts of impurities, PM emissions are almost zero.

According to the report of Couple System company, its Dry-EGCS scrubber system can reduce PM emissions by 80%. According to Watsila's report, its seawater scrubber system and the freshwater scrubber system can reduce PM emissions by 80% and 30-60% respectively. According to Aalborg's report, its EGCS hybrid scrubber system can reduce PM emissions by 80% in both open-loop mode and closed-loop mode(Dong, W., 2013). The specific evaluation result of this index is shown in Table 5.12.

Table 5.12: Removing PM efficiency of each SOx emissions control technology

Evaluation Technologies	Low sulphur fuel oil	LNG fuel	Scrubber			
			Dry	Sea water	Fresh water	Hybrid
Removing PM Efficiency*	↓ 50-85%	Almost 0	↓ 80%	↓ 80%	↓ 30-60%	↓ 80%
Grade	Very good	Excellent	Very good	Very good	Good	Very good
Score	4	5	4	4	3	4

Source:Herbert Engineering Corporation, 2018; Dong, W., 2013.

5.6.4 Waste disposal efficiency

The combustion of low sulfur oil produces no liquid pollutants except a small amount of ash. For using LNG fuel, there is no liquid waste and solid waste generated. For dry scrubber, SO_x in exhaust gas are absorbed by quicklime, which generates solid waste. For wet scrubber, SO_x in exhaust gas are absorbed by sea water or fresh water, which generates liquid waste. In addition, in order to maintain a certain PH value of NaOH solution in closed loop model, it is necessary to remove sludge from the solution and add NaOH solute into the solution continuously, which will produce a certain amount of solid waste. According to Aalborg's calculation of its scrubber product−EGCS system, the sludge production amount is less than 0.5Kg/MW. The most controversial technology is the seawater scrubber, because the equipment is open-loop, it discharges waste water into the sea directly, which will pollute the marine environment.

Compared with using IFO without exhaust gas treatment system, using low sulfur oil obviously reduces ash generated after combustion, using LNG fuel doesn’t generate waste at all, dry scrubber converts gas waste into solid waste, wet scrubber converts gas waste into liquid waste and solid waste. The specific evaluation result of this index is shown in Table 5.13.

Table 5.13: Waste disposal efficiency of each SOx emission control technology

Evaluation Technologies	Low sulphur fuel oil	LNG fuel	Scrubber			
			Dry	Sea water	Fresh water	Hybrid
Waste Disposal Efficiency	Less ash	No waste	Solid waste	Liquid waste	Liquid and solid waste	Liquid and solid waste
Grade	Very good	Excellent	Poor	Poor	Poor	Poor
Score	4	5	1	1	1	1

Source:Aalborg, 2016.

5.7 Legal

Legal factors mainly refer to the conformity of various SO_x emission control technologies to the current related SO_x emission requirements.

At present, the highest sulfur content of IFO is 3.5%. IMO requires fuel oil with sulfur content not exceeding 0.5% in global waters from January, 1th, 2020. IMO and EU require the sulphur content of fuel does not exceeding 0.1% in ECAs and EU ports respectively. That is to say, compared with the using IFO, SO_x emissions in the global sea water should be reduced by 85.7%(=(3.5% - 0.5%)/3.5%) from January 1th, 2020, SO_x emissions in ECAs and EU ports should be reduced by 97.1%(=(3.5% - 0.1%)/3.5%) now. From Table 5.9, it can be seen that all SO_x emissions control technologies can meet the requirement of reducing SO_x emission by 85.7%. Except for LNG high pressure injection engine and seawater desulfurization technology, all the other SO_x emission control technologies can meet the requirement of reducing SO_x emission by 97.1%. When LNG high pressure injection engine is ignited with heavy oil, there is a risk that SO_x emissions will not meet the requirement in ECAs and EU ports. Therefore, for the sake of insurance, it is better to use low sulfur oil as ignition oil for LNG high pressure injection engines. When seawater scrubber is used, it will be high risky to meet the SO_x emissions requirements in ECAs and EU ports. Whether the seawater scrubber can meet the emission requirements in ECAs and EU ports depends on the specific sulfur content in the fuel oil. The specific evaluation result of this index is shown in Table 5.14.

Table 5.14: Legal conformity of each SO_x emission control technology

Technologies / Evaluation		Low sulphur fuel oil	LNG fuel		Scrubber			
			Low pressure engine	High pressure engine	Dry	Sea water	Fresh water	Hybrid
SO_x emission effect*		↓ 97.2%	↓ 99%	↓ 95-97%	↓ 99%	↓ 90-95%	↓ 99%	↓ 98-99%
Sulphur limit	0.5% (↓85.7%)	Well-conformity	Well-conformity	Well-conformity	Well-conformity	Conformity	Well-conformity	Well-conformity
	0.1% (↓97.1%)	Conformity	Well-conformity	Risky	Well-conformity	High-risky	Well-conformity	Well-conformity
Evaluation		Good	Excellent	Fair	Excellent	Poor	Excellent	Very good
Score		3	5	2	5	1	5	4

Source: Ma, Y., 2016; Dong, W., 2013.

5.8 Comprehensive evaluation results of each SO_x control technology

According to the above analysis, the scores of each SO_x control technology are shown in Table 5.15.

Generally speaking, the scores of various SO_x control technologies from high to low are LNG low pressure injection engine, low sulphur oil, LNG high pressure injection engine, hybrid scrubber, seawater scrubber, fresh water scrubber and dry scrubber. Because the weight of each index is not taken into account, the above scores are preliminary. Different decision makers attach importance to different factors, and the weight of each index is different. Therefore, the weight of each index varies greatly with different decision makers, so it is difficult to determine a unified weight for each index. For example, if decision makers pay more attention to economic factors, index 2-4 will account for a larger weight, if some decision makers pay more attention to environmental factors, index 1 and index 9-12 will account for a larger weight. In practice, shipowners pay more attention to economic factors.

Table 5.15: The scores of each SO_x emissions control technology

Evaluation Technologies		Low sulphur fuel oil	LNG fuel		Scrubbers			
			Low pressure engine	High pressure engine	Dry	Sea water	Fresh water	Hybrid
Political	Index 1	3	2	4	1	2	2	2
Economic	Index 2	4	1	1	2	3	2	2
	Index 3	4	2	2	1	3	1	2
	Index 4	2	5	5	4	4	4	4

Social	Index 5	1	1	1	2	2	1	1
	Index 6	3	4	4	3	3	3	3
Technological	Index 7	3	1	1	1	2	1	2
	Index 8	3	1	1	1	2	1	2
Environmental	Index 9	4	5	4	5	3	5	4
	Index 10	3	5	4	2	3	3	3
	Index 11	4	5	5	4	4	3	4
	Index 12	4	5	5	1	1	1	1
Legal	Index 13	3	5	2	5	1	5	4
Total scores		41	42	39	32	33	32	34

Based on the actual situation of market, it is found that low-sulfur oil is the most widely used to reduce SO_x emissions. Because of economic reasons, among all kinds of scrubbers, open-loop scrubbers are the most common solution for shipowners. Hybrid scrubbers have the advantages of both seawater scrubbers and fresh water scrubbers, which are usually chosen for shipowners that wants to be compliant in ports where there is a scrubber discharge ban. Fresh water and dry scrubbers are relatively less used because of high operating cost. LNG power ship occupies a certain proportion in the new shipbuilding. The actual situation is generally consistent with the evaluation results in this dissertation.

6 Cost-benefit analysis of different ship desulphurization technologies

In order to help shipping companies choose the most appropriate SO_x emission control technology, low sulphur oil, LNG fuel and scrubbers are needed to be further compared and analyzed from the perspective of cost-benefit. Based on the analysis in chapter 5, low pressure directly injection LNG engine and hybrid scrubber are selected to be compared because their higher total scores.

6.1 Cost analysis

6.1.1 Establishment of cost calculating formula

Generally, the total cost of SO_x emission control technologies include three parts, the initial cost, the maintenance cost and the fuel cost. The annual average total cost can be formulated as follows,

$$TC = IC/SL + MC + FC$$

Where;

TC - Annual Average Total Cost ($)

IC - Initial Cost ($)

SL - Ship lifespan (years).

MC -Maintenance Cost Per Year ($)

FC - Fuel Cost Per Year($).

And for container ships, the annual fuel cost can be formulated as follows,

$$FC = FCSV \times NOVPY$$

Where;

FCSV - Fuel Cost Of A Single Voyage ($)

NOVPY - Number Of Voyages / Year (times).

And for container ships, the fuel cost of single voyage can be formulated as follows,

$$FCSV = FASV \times PF = DFA \times DOV \times PF$$

Where;

FASV - Fuel Assumption Of A Single Voyage (tons)

PF - Price Of Fuel ($ / ton)

DFA - Daily Fuel Assumption (tons)

DOV - Sailing Days Of A Single Voyage (days).

According to the ship's working condition, the daily fuel consumption is directly related to its load and speed. Specifically, for container ships, the daily fuel assumption can be formulated as follows(ZHANG G., 2016),

$$DFA = \beta \times TEU \times V^3$$

Where;

TEU - Actual Number Of Standard Containers On Board (TEU)

V - Actual Speed of the ship (knot)

β - Coefficient of Correlation.

In order to calculate DFA, this dissertation uses data regression method to get the value of β. Fifty set of data(FASV, DOV, TEU, V) were obtained from COSCO SHIPPING Lines(Appendix A). Part of the selected data are shown in table 6.1. To be clear, (1) Because ships use low-sulfur oil in ECAs and EU ports, both the amount of low-sulfur oil and IFO were collected in FASV. (2) Because the actual number of containers on board of ships are different from one voyage to another, the values of TEU collected are the maximum capacity of ships, which is also the design capacity of ships. (3) Because a ship's actual speed is constantly changing, the V values collected are the economic speed of container ships. (4)The data regression method is used to form the DFA calculation formula of heavy oil firstly, then the consumption of low sulfur oil and LNG can be determined according to the calorific value ratios of different fuels.

Table 6.1 Collected raw data of (FASV, DOV, TEU, V)

NO.	**FASV(tons)**		**DOV(days)**	**TEU**	**V(knot)**
	IFO	**LSO**			
1	5247	689	85	10020	13
2	1477	221	59	3534	12
3	1708	123	65	3534	12
4	3322	459	70	4250	12
5	3196	419	63	4250	12
6	3200	620	63	4253	12
7	3603	338	63	4253	12
8	3250	492	71	4253	12
9	3449	540	64	4253	12
10	3040	526	63	4250	12
...					

Source:COSCO SHIPPING LINES, 2019

When data regression analysis is used, the consumption of low sulfur oil should be converted to IFO according to the calorific value ratio of two kinds of fuel. As mentioned in chapter 5.3.3, the calorific value of IFO is 46 MJ/Kg and MGO is 48.3 MJ/kg. Taking the first set of data as an example, if IFO is used for all the voyages, the amount of IFO required is,

$$FASV = 5247 \text{ tons} + 689 \text{ tons} \times (48.3 / 46) = 5970.45 \text{ tons}$$

And DFA = FASV / DOV = 5970.45 tons / 85 days = 70.24 tons/day.

Since β is multiplied by TEU in the formula, it is not necessary to multiply the collected TEU value by the average ship loading rate. This TEU values collected can be directly used for regression analysis. Then, according to the DFA calculation formula, the new data set are obtained after having the values of V to the power three, which is shown in table 6.2.

Table 6.2 Data used directly in regression method (DFA, TEU, V^3)

NO.	DFA	TEU	V^3
1	70.24	10020	2197
2	28.97	3534	1728
3	28.26	3534	1728
4	54.34	4250	1728
5	57.71	4250	1728
6	61.13	4253	1728
7	62.82	4253	1728
8	53.05	4253	1728
9	62.75	4253	1728

10	57.02	4250	1728
...			

Fifty sets of data(DFA, TEU, V^3) were imported into EViews, then DFA calculation formula was established in EViews. Finally, the value of β was obtained through EViews operation. The results of data regression analysis are shown in table 6.3.

Table 6.3: The results of regression analysis in EViews

Dependent Variable: DFA
Method: Least Squares (Gauss-Newton / Marquardt steps)
Date: 08/19/19 Time: 21:12
Sample: 1 50
Included observations: 50
DFA=C(1)*TEU*V3

	Coefficient	Std. Error	t-Statistic	Prob.
C(1)	2.71E-06	1.71E-07	15.82564	0.0000

R-squared	-1.430477	Mean dependent var	64.74011
Adjusted R-squared	-1.430477	S.D. dependent var	17.57053
S.E. of regression	27.39243	Akaike info criterion	9.478208
Sum squared resid	36766.92	Schwarz criterion	9.516448
Log likelihood	-235.9552	Hannan-Quinn criter.	9.492770
Durbin-Watson stat	0.370539		

From the above analysis results, it can be seen that the value of β is 1.71×10^{-7}, the ‘Probability’ is almost 0 which is less than 5%. The value of the ‘Probability’ indicates that the value of β is acceptable. The actual and regressive values of DFA and the gap between them are shown in figure 6.1.

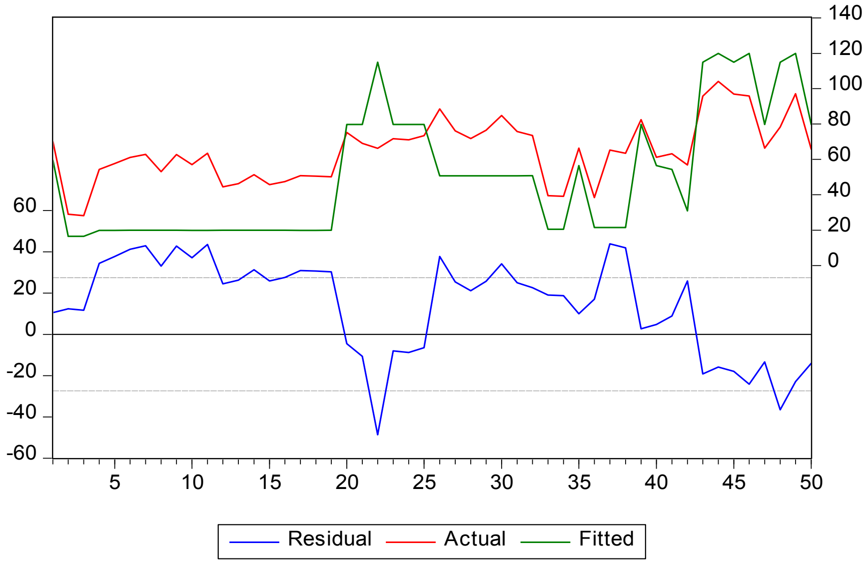


Figure 6.1: The actual and regressive values of DFA and the gap between them

Through regression analysis, the formulas for DFA calculation can be gotten as follows,

$$DFA = 1.71 \times 10^{-7} \times TEU \times V^3$$

6.1.2 The cost of using hybrid scrubber

IFO is still used for ships with hybrid scrubbers. According to the above analysis, the annual fuel cost of the ships with hybrid scrubbers(FC_{IFO}) is as follows,

$$FC_{IFO} = 1.71 \times 10^{-7} \times TEU \times V^3 \times DOV \times PF_{IFO} \times NOVPY$$

By consulting with Wartsila, normally there are only one scrubber installed on a vessel, and for output of engines from 1 MW to 70 MW, the price of the matching fresh water scrubber systems is from $1.67 million to $5.57 million. Assuming that the total power of a ship is proportional to the price of the scrubber system, and the main engines run on 70% load at maximum, the auxiliary engines runs on 85% load at maximum, then the initial cost of freshwater scrubbers can be obtained by the following formula.

$$IC_{HSC} = (0.0565 \times (P_M \times 70\% + P_A \times 85\%) + 1.615) \times 10^6$$

$$=(0.0396 \times P_M + 0.0480 \times P_A + 1.615) \times 10^6$$

Where,

IC_{HSC} - Initial Cost of Hybrid Scrubbers($)

P_M - The Main Engines Powers of A Ship(Mw)

PA - The Auxiliary Engines Powers of A Ship (Mw)

Maintenance cost of hybrid scrubbers mainly include the fuel consumption for scrubber operation, the cost of NaOH desulfurizer and maintenance cost of various pumps. As mentioned in chapter 5.3.2, the maintenance cost of various pumps can be ignored. Take Wartsila hybrid scrubbers as an example, the power consumption of the desulfurization equipment is about 1.5% of the auxiliary power(REN Y., 2016). The annual fuel cost for scrubber operation(MC_{FC}) is as follows,

$$MC_{FC} = FC_{IFO} \times \frac{P_A}{P_M + P_A} \times 1.5\%$$

$$= 2.565 \times 10^{-9} \times \frac{P_A}{P_M + P_A} \times TEU \times V^3 \times DOV \times PF_{IFO} \times NOVPY$$

Hybrid scrubbers have two working modes, open-loop and closed-loop. Closed-loop model is used in ports where there is a scrubber discharge ban, while open-loop mode can be used in areas without discharge restrictions. In the open-loop mode, the absorbent is seawater, the cost of which can be neglected. For Wartsila hybrid scrubbers, the consumption of NaOH solution under different output powers are shown in table 6.4. Assuming that the main engines run on 70% load at maximum, and the auxiliary engines runs on 85% load at maximum. The density of 50% NaOH solution is 1525kg/m^3. The price of 50% NaOH solution is about 250$/ton(Sun, K., 2016). When a ship is sailing, the main engines and auxiliary engines are work together. When ships are berthing in ports, only auxiliary engines are working. The proportion of a ship's sailing time to the total voyage time can be determined by the following formula,

$$\mathrm{SP} = \frac{(ND/V)/24}{DOV} = \frac{ND}{24 \times V \times DOV}$$

Where,

SP - The Proportion of A Ship's Sailing Time to The Total Voyage Time

ND - Navigation Distance per Voyage(nautical mile)

V - Economic Speed of Ships (knot)

DOV - Sailing Days Of A Single Voyage (days)

Table 6.4: NaOH solution consumption for different main powers

Output power (kw)	Assumption of 50% NaOH solution per hour (L/h)
5000	150
20000	600
40000	1200

Source: Sun, K., 2016.

For hybrid scrubbers, the cost of NaOH solution(MC_{SC}) in closed-loop model is,

$$MC_{SC} = (\frac{P_M \times 70\% + P_A \times 85\%}{5} \times 150) \times 10^{-3} \times 1.525 \times 250 \times 24 \times DOVR \times SP \times$$

$$NOVPY + (\frac{P_A \times 85\%}{5} \times 150) \times 10^{-3} \times 1.525 \times 250 \times 24 \times DOVR \times (1-SP) \times NOVPY$$

$$=(8.01 \times P_M \times \frac{ND}{V \times DOV} + 233.33 \times P_A) \times DOVR \times NOVPY$$

Where,

DOVR - Sailing Days Of A Single Voyage In Scrubber Discharge Ban Areas(days)

Hence, the average annual total cost of hybrid scrubbers is as follows,

$$TC_{HSC} = IC_{HSC}/SL + FC_{IFO} + MC_{FC} + MC_{SC}$$

$$=[(0.0396 \times P_M + 0.0480 \times P_A + 1.615) \times 10^6]/SL + (1.71 \times 10^{-7} + 2.565 \times 10^{-9} \times \frac{P_A}{P_M + P_A}$$

$$) \times TEU \times V^3 \times DOV \times PF_{IFO} \times NOVPY + (8.01 \times P_M \times \frac{ND}{V \times DOV} + 233.33 \times P_A)$$

$$\times DOVR \times NOVPY$$

Where;

TC_{HSC} - Annual Average Total Cost of Hybrid Scrubbers($)

IC_{HSC} - Initial Cost of Hybrid Scrubbers($)

SL - Ship lifespan (years)

FC_{IFO} - Fuel cost of using IFO ($)

MC_{FC} - Fuel Cost for Scrubber Operation($)

MC_{SC} - Solution Cost for Scrubber Operation($)

P_M - The Main Engines Powers of A Ship(Mw)

P_A - The Auxiliary Engines Powers of A Ship (Mw)

TEU - Ship Design Capacity (TEU)

V - Economic Speed of Ships (knot)

DOV - Sailing Days Of A Single Voyage (days)

PF_{IFO} - Price of IFO ($ / ton)

NOVPY - Number Of Voyages / Year (times)

ND - Navigation Distance per Voyage(nautical miles)

DOVR - Sailing Days Of A Single Voyage In Scrubber Discharge Ban Areas(days).

6.1.3 The cost of using low sulphur oil (MGO)

As mentioned in chapter 5.3.3, the calorific value of IFO is 46 MJ/Kg and MGO is 48.3 MJ/kg. The calorific value of IFO is 95.2% of MGO. If the same work is done, the consumption of MGO is 95.2% that of IFO. The annual fuel cost of using low sulphur oil is as follows,

$$FC_{MGO} = 1.71\times10^{-7} \times TEU \times V^3 \times 95.2\% \times DOV \times PF_{MGO} \times NOVPY$$

$$= 1.63\times10^{-7} \times TEU \times V^3 \times DOV \times PF_{MGO} \times NOVPY$$

Considering that not all ships need to install MGO cooling system, and the cost of the system is low, the initial cost of using MGO can be neglected. If MGO is used, the working life of some moving parts may be shortened because of the potential friction wear risk. Overall, the maintenance cost of using MGO is roughly the same as that of using IFO. Therefore, the total cost of using MGO is only the fuel cost, the calculation formula of which is as follows,

$$TC_{MGO} = FC_{MGO} = 1.63\times10^{-7} \times TEU \times V^3 \times DOV \times PF_{MGO} \times NOVPY$$

Where;

TC_{MGO} - Total Cost Of Using MGO ($)

FC_{MGO} - Fuel Cost Of Using MGO($)

TEU - Ship Design Capacity (TEU)

V - Economic Speed of Ships (knot)

DOV - Sailing Days Of A Single Voyage (days)

PF_{MGO} - Price Of MGO ($ / ton)

NOVPY - Number Of Voyages / Year (times).

6.1.4 The cost of using LNG low pressure injection engines

The calorific value of IFO is 46 MJ/Kg and LNG is 38 MJ/kg. The calorific value of IFO is 1.21 times that of LNG. If the same work is done, the consumption of LNG is 1.21 times that of IFO. For LNG low pressure injection engines, the amount of ignition fuel is usually 1% of the total fuel. Because the unit price of LNG is $/MBtu, after converting the required weight of LNG into heat energy, the annual fuel cost of using LNG low pressure injection engines is as follows,

$$FC_{LNG} = (1.71\times10^{-7} \times TEU \times V^3\times 1\% \times PF_{IFO} + 1.71\times10^{-7} \times TEU \times V^3\times 99\% \times 1.21 \times 38000\ MJ/ton \div 1055.06 MJ/MBtu \times PF_{LNG})\times DOV\times NOVPY$$

$$=(1.71\times10^{-9} \times PF_{IFO} + 7.38\times10^{-6} \times PF_{LNG})\times TEU \times V^3\times DOV\times NOVPY$$

According to Clarksons' data, the prices of new building ordinary container ships are shown in table 6.5. It is roughly estimated that the construction cost of LNG power ship is 15-30% higher than that of ordinary ship (taking the median value 22.5%). Based on the data in table 6.5, it can be calculated that the average cost of ordinary container ship is about $7360/TEU. Then the initial cost of using LNG power engines is as follows,

$$IC_{LNG} = \$7360 \times 22.5\% \times TEU$$

$$=1656 \times TEU$$

Table 6.5: Price of new building container ships

TEU	Build data	Builder	Owner	Price (M$)
23,000	2020-04	Daewoo (DSME)	HMM	155.40
20,988	2019-08	Jiangnan SY Group	COSCO Shipping Lines	140.32
15,300	2021-04	Hyundai HI (Ulsan)	HMM	121.60
14,952	2020-01	Hyundai HI (Ulsan)	Zodiac Maritime	102.30
11,000	2020-02	Samsung HI	Evergreen Marine	94.40

Souce: Clarksons Shipping Intelligence Network, 2019.

According to the experience accumulated by the Wartsila service department, the average annual maintenance cost of the main engine and its components is about \$40,000. According to the Wartsila W20 engines manual, the average annual maintenance cost of four W20 auxiliary engines is \$50,000. Therefore, for ships using heavy oil, the average annual maintenance cost of the main engine and auxiliary engine totals about \$90,000(Wartsila Finlan OY, 2019). According to MAN statistics, the cost of spare parts and maintenance using LNG is about 10% higher than that of diesel engines(MAN Diesel & Turbo, 2012). So the maintenance cost of using LNG high pressure injection engines is as follows,

$$MC_{LNG} = \$90{,}000 \times 10\% = 9000$$

By adding the initial cost, maintenance cost and fuel cost together, the total cost of using LNG low pressure injection engines is as follows,

$$TC_{LNG} = IC_{LNG}/SL + MC_{LNG} + FC_{LNG}$$

$$= (1656 \times TEU)/SL + 9000 + (1.71\times10^{-9} \times PF_{IFO} + 7.38\times10^{-6} \times PF_{LNG})\times TEU \times V^3 \times DOV \times NOVPY$$

Where;

TC_{LNG} -Average Annual Total Cost of Using LNG Low Pressures Injection Engines(\$)

IC_{LNG} - Initial Cost of Using LNG Low Pressures Injection Engines(\$)

SL - Ship lifespan (years)

MC_{LNG} - Maintenance Cost of Using LNG Low Pressures Injection Engines(\$)

FC_{LNG} - Fuel Cost of Using LNG Low Pressures Injection Engines(\$)

TEU - Ship Design Capacity (TEU)

PF_{IFO} - Price of IFO (\$/ton)

PF_{LNG} - Price of MGO (\$/MBtu)

V - Economic Speed of Ships (knot)

DOV - Sailing Days of A Single Voyage (days)

NOVPY - Number of Voyages / Year (times).

6.2 Analysis of environmental benefits

SO_x, NO_x, and PM all have great negative effects on natural environment, human health and the growth of animals and plants**.** CO_2 is the main source of GHG. Dealing with the environmental pollution caused by these pollutants requires a lot of money. The economic losses caused by these pollutants and the money needed for pollution treatment are defined as environmental costs in this dissertation. The environmental cost of each air pollutant are shown in table 6.6.

Table 6.6: Environmental cost of each air pollutant

Pollutants	SO_x	NO_x	CO_2	PM
Environmental cost ($/t)	13960	4992	26	465058

Source: Berechman J., 2012.

Different SO_x emission control technologies will reduce the emission of air pollutants to different degrees. The environmental costs of the reduced emission of various air pollutants are the benefits of this technology, which are called environmental benefits of this technology. The formula for calculating environmental benefits is as follows.

$$EB_i = \sum_j (EA_{IFO,j} - EA_{i,j}) \times EC_j$$

Where;

EB_i - Environmental Benefits of NO. i SO_x Emission Control Technology($)

$EA_{IFO,j}$ - Emission Amount of NO. j Air Pollutant for Using IFO Without Exhaust Gas Treatment(tons)

$EA_{i,j}$ - Emission Amount of NO. j Air Pollutant for Using NO. i SO_x Emission Control Technology (tons)

EC_j - Environmental Cost of NO. j Air Pollutant ($/t).

From the above formula, it can be seen that in order to get the environmental benefits of each SO_x emission control technology, it is necessary to calculate the emission amounts of various air pollutants. There are two commonly used methods for calculating the emission amounts of various air pollutants from ships. One is the top-down statistical method and the other is the bottom-up dynamic method(LI B., 2013). The top-down statistical method is based on the fuel consumption of ships directly. The annual fuel consumption of ships is multiplied by the emission coefficient of the kind of fuel to calculate the emission amounts of various air pollutants. The emission coefficients of different kinds of fuels are also different. The bottom-up dynamic method needs to know the specific information of powers, working time and speed of the main and auxiliary engines under different navigation conditions, and then calculate the emission amounts of various air pollutants under different conditions. Because the values of fuel consumption have been obtained when the cost of various SO_x emission control technologies were calculated, this dissertation will adopt top-down statistical method.

The formula for calculating the annual emission amounts of various air pollutants discharged from ships is as follows,

$$EA_{i,j} = C_{i,j} \times FASV_i \times NOVPY$$

Where;

$EA_{i,j}$ - Annual Emission Amount of NO. j Air Pollutant for Using NO. i Fuel(tons)

$C_{i,j}$ - Emission Coefficient of NO. j Air Pollutant for Using NO. i Fuel

$FASV_i$ - Fuel Assumption Of A Single Voyage for Using NO. i Fuel (tons)

NOVPY - Number Of Voyages / Year (times)

There are three types of fuel used in various SO_x emission control technologies: IFO, MGO and LNG. The average emission coefficients of IFO were given in 2006 IPCC guidelines for national greenhouse gas inventories, which is shown in table 6.7.

Table 6.7: Average emission coefficients of three air pollutants

Type of fuel	SO_x	NO_x	CO_2
IFO	1.02	4.8	72.6

Source: IPCC, 2006.

According to experiments conducted by the California Air Resources Board, a ton of heavy oil can produce 15,000 m^3 of flue gas after full combustion, and the PM produced by fuel with 3.5% sulfur content is about 250mg/m^3(Sax T., 2007). Thus, it can be estimated that a ton of heavy oil can produce about 0.00375 tons of PM after full combustion. That is to say, the emission coefficient of PM for using IFO is about 0.00375.

Based on the analysis in chapter 5.2 and 5.6, compared with using IFO without exhaust gas treatment, in case of doing the same work, using MGO will reduce SO_x, NO_x, CO_2

and PM by 97.2%, 8.3%-11.1%(taking the intermediate value 9.7%), 5% and 50-85%(taking the intermediate value 67.5%) respectively. Because the calorific value of MGO is 5% higher than that of IFO, in case of using the same mass of IFO and MGO, the emission coefficients for using MGO can be obtained by the following formulas,

$$C_{MGO,SO_x} = 1.02 \times [(1\text{-}97.2\%) / (1\text{-}5\%)] = 0.030$$

$$C_{MGO,NO_x} = 4.8 \times [(1\text{-}9.7\%) / (1\text{-}5\%)] = 4.57$$

$$C_{MGO,CO_2} = 72.6 \times [(1\text{-}5\%) / (1\text{-}5\%)] = 72.6$$

$$C_{MGO,PM} = 0.00375 \times [(1\text{-}67.5\%) / (1\text{-}5\%)] = 0.00128$$

Based on the analysis in chapter 5.2 and 5.6, compared with using IFO without exhaust gas treatment, in case of doing the same work, using LNG will reduce SO_x, NO_x, CO_2 and PM emissions by 100%, 85%, 20%, and 100% respectively. Because the calorific value of LNG is 17% lower than that of IFO, in case of using the same mass of IFO and MGO, the emission coefficients for using LNG can be obtained by the following formulas,

$$C_{LNG,SO_x} = 1.02 \times [(1\text{-}100\%) / (1\text{+}17\%)] = 0$$

$$C_{LNG,NO_x} = 4.8 \times [(1\text{-}85\%) / (1\text{+}17\%)] = 0.62$$

$$C_{LNG,CO_2} = 72.6 \times [(1\text{-}20\%) / (1\text{+}17\%)] = 49.64$$

$$C_{LNG,PM} = 0.00375 \times [(1\text{-}100\%) / (1\text{+}17\%)] = 0$$

In summary, the average emission coefficients of four air pollutants are shown in table 6.8.

Table 6.8: Average emission coefficients of four air pollutants

Type of fuel	SO_x	NO_x	CO_2	PM
IFO	1.02	4.8	72.6	0.00375
MGO	0.030	4.57	72.6	0.00128
LNG	0	0.62	49.64	0

Because both low sulfur oil and LNG fuel belong to combustion pretreatment technologies, the emission amount of air pollutants can be calculated directly by using the above formula. Hybrid scrubbers belong to post-combustion technology, the emission amount of air pollutants for using hybrid scrubbers can be obtained by the formula as follows,

$$EA_{HSC,j} = EA_{IFOB,j} \times ECF_{CLO,j} + EA_{IFON,j} \times ECF_{OPE,j}$$

Where,

$EA_{FWC,j}$ -Annual Emission Amount of NO. j Air Pollutant for Using Hybrid Scrubbers (tons)

$EA_{IFOB,j}$ - Annual Emission Amount of NO. j Air Pollutant for Using IFO Without Exhaust Gas Treatment in Scrubber Discharge Ban Areas(tons)

$ECF_{CLO,j}$ -Emission Control Factor of NO. j Air Pollutant for Using Hybrid Scrubbers within Closed-Loop Model. Based on the data in table 5.2, table 5.9, table 5.10 and table 5.11, it can be gotten that the ECF_{CLO,SO_x} is 0.01, the ECF_{CLO,NO_x} is 0.93-0.97(taking the intermediate value 0.95), the ECF_{CLO,CO_2} is 1, the $ECF_{CLO,PM}$ is 0.4-0.7(taking the intermediate value 0.55).

$EA_{IFON,j}$ - Annual Emission Amount of NO. j Air Pollutant for Using IFO Without Exhaust Gas Treatment in Non Scrubber Discharge Ban Areas(tons)

$ECF_{OPE,j}$ - Emission Control Factor of NO. j Air Pollutant for Using Hybrid Scrubbers within Open Loop Model. Based on the data in table 5.2, table 5.9, table 5.10

and table 5.11, it can be gotten that the ECF_{OPE,SO_x} is 0.05-0.1(taking the intermediate value 0.075), the ECF_{OPE,NO_x} is 0.93-0.97(taking the intermediate value 0.95), the ECF_{OPE,CO_2} is 1, the $ECF_{OPE,PM}$ is 0.2.

In summary, the final formulas for calculating the annual environmental benefits of various SO_x emission control technologies are as follows.

For hybrid scrubbers,

$EB_{HSC,SO_x} = 2.435\times10^{-3} \times TEU \times V^3 \times NOVPY\times(0.925\times DOV+0.065\times DOVR)$

$EB_{HSC,NO_x} = 2.049\times10^{-4} \times TEU \times V^3 \times NOVPY \times DOV$

$EB_{HSC,CO_2} = 0$

$EB_{HSC,PM} = 2.982\times10^{-4} \times TEU \times V^3 \times DOVR \times NOVPY \times (0.8\times DOV-0.35\times DOVR)$

$EB_{HSC} = EB_{HSC,SO_x} + EB_{HSC,NO_x} + EB_{HSC,CO_2} + EB_{HSC,PM}$

For MGO fuel,

$EB_{MGO,SO_x} = 2.367\times10^{-3} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO,NO_x} = 3.788\times10^{-4} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO,CO_2} = 1.510\times10^{-5} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO,PM} = 2.012\times10^{-4} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO} = EB_{MGO,SO_x} + EB_{MGO,NO_x} + EB_{MGO,CO_2} + EB_{MGO,PM}$

For LNG fuel,

$EB_{LNG,SO_x} = 2.411\times10^{-3} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{LNG,NO_x} = 3.423\times10^{-3} \times TEU \times V^3 \times DOV \times NOVPY$

EB_{LNG,CO_2} =5.523×10^{-5} × TEU × V^3 × DOV × NOVPY

$EB_{LNG,PM}$ =2.952×10^{-4} × TEU × V^3 × DOV × NOVPY

EB_{LNG}= EB_{LNG,SO_x} + EB_{LNG,NO_x} + EB_{LNG,CO_2} + $EB_{LNG,PM}$

Where,

$EB_{HSC,j}$ - Annual Environmental Benefits of NO. j Air Pollutant for Using Hybrid Scrubbers ($)

$EB_{MGO,j}$ - Annual Environmental Benefits of NO. j Air Pollutant for Using MGO ($)

$EB_{LNG,j}$ - Annual Environmental Benefits of NO. j Air Pollutant for Using LNG ($)

TEU - Ship Design Capacity (TEU)

V - Economic Speed of Ships (knot)

DOV - Sailing Days of A Single Voyage (days)

DOVR - Sailing Days Of A Single Voyage In Scrubber Discharge Ban Areas(days)

NOVPY - Number of Voyages / Year (times).

6.3 Comparison of cost and benefit

Because the total cost and environmental benefits of the three SO_x emission control technologies are different, this dissertation uses the benefit-cost ratio to compare the capital utilization efficiency of different SO_x emission control technologies. The benefit-cost ratio can be calculated by following formula,

$$BCR_i = EB_i / TC_i$$

Where,

BCR_i - Benefit-Cost Ratio of NO. i SO_x Emission Control Technology

EB_i - Annual Environmental Benefits of NO. i SO_x Emission Control Technology

TC_i - Total Cost of NO. i SO_x Emission Control Technology.

The bigger the BCR value is, the bigger the return of unit investment is, then the better the technology is.

6.4 Case study

Take a container ship 'COSCO Italy' sailing in Europe-China line as an example, the basic information of the ship are shown in table 6.9.

Table 6.9: The basic information of COSCO Italy

Ship name:COSCO Italy	Delivery date: 2014-04-29
Design capacity: 13386TEU	Main engine power: 72240Kw
Auxiliary engine power: 2648Kw *3 + 3530Kw*2	Economic speed: 13 knots
Rout:Tianjin-Dalian-Qingdao-Shanghai-Ningbo-Singapore-Piraeus-Rotterdam-Hamburg-Antwerp-Shanghai-Tianjin	
Navigation Distance of A Single Voyage: 15387 nautical miles	
Sailing Days of A Single Voyage: 77 days	
Number of voyages per year: 4.7	

Source: COSCO SHIPPING LINES, 2019.

The ship's age is currently five years, and it is assumed that the ship will be used for another 20 years. Because China coastal waters are scrubbers discharge ban areas, when hybrid scrubber is used in this ship, the scrubber should work in closed-loop mode along the coast of China and work in open-loop mode in other sea areas. The ship is in China coastal waters for about 20 day. According to the data in table 6.6 and analysis in chapter 6.1-6.3, the parameters which are needed to calculate the cost and benefits of various SO_x emission control technologies for this ship can be obtained. These parameters are shown in table 6.10.

Table 6.10: The specific parameters of COSCO Italy

TEU:13386	P_M :72.24Mw	P_A:15.004Mw
V:13 knots	ND:15387 nautical miles	DOV:77 days
DOVR: 20 days	NOVPY: 4.7	SL:20 years
PF_{IFO380}: 457.01 \$/ton	PF_{MGO}:712.67 \$/ton	$PF_{LNG:}$ 3.33 \$/MBtu

By substituting the above parameters into the formulas for calculating the cost and benefit of each SO_x emission control technology, the results are shown in table 6.11.

Table 6.11: Cost-benefit table for the three SO_x emission control technologies

	Cost-benefit analysis	Hybrid scrubber	MGO fuel	LNG fuel
Cost	IC ($)	5,195,896	0	22,167,216

analysis	SL (years)	20	20	20
	IC/SL ($)	259,795	0	1,108,361
	MC ($)	1,167,328	0	9,000
	FC ($)	831,747	1,236,362	269,877
	TC ($)	2,258,870	1,236,362	1,387,238
Environ-mental benefit analysis	EB_{SOx} ($)	24,590,311	25,192,294	25,660,592
	EB_{NOx} ($)	2,180,778	4,031,619	36,431,442
	EB_{CO2} ($)	0	160,711	587,820
	EB_{PM} ($)	2,250,500	2,141,398	3,141,853
	EB ($)	29,021,589	31,526,022	65,821,707
Comparison of cost and benefit - BCR		12.8	25.5	47.4

From table 6.8, it can be seen that, in terms of sub-item cost, the initial cost of using LNG is the highest, the maintenance cost of using hybrid scrubber is the highest, and the fuel cost of using MGO is the highest. Under the premise of 20 years' lifespan, the total cost of using hybrid scrubber is much higher than using MGO and LNG, and the total cost of using LNG is slightly higher than that of MGO. The main reason for the high total cost of hybrid scrubber is the high cost of NaOH solution consumption. Under the closed-loop operation mode, the NaOH solution consumption is very large and the unit price of NaOH solution is very high(more than half of the price of IFO380), which greatly increase the maintenance cost of hybrid scrubber.

In terms of SO_x emission benefit, there are no obvious difference between the three desulphurizaion technologies, but in terms of NO_x, CO_2, and PM emission benefit, using LNG has obvious advantages. The total environmental benefit of using LNG is more than twice that of the other two desulphurizaion technologies, the total environmental benefit of using MGO is slightly greater than that of hybrid scrubber.

In terms of comparison of cost and benefit, the BCR of using LNG is the highest, followed by using MGO, and the BCR of using hybrid scrubber is the lowest. That is to say, using LNG fuel has the highest capital utilization efficiency, followed by MGO, and using fresh water scrubber system has the lowest capital utilization efficiency.

The above results are based on 20 years' lifespan and the average fuel price of the last year. When lifespan and fuel prices are different, the analysis results will also be different. The impact of ship lifespan and fuel price on the total cost of various SO_x emission control technologies will be analyzed in depth below.

Taking 'COSCO Italy' as an example, with other parameters unchanged, the relationship between ship's lifespan and total cost of various SO_x emission control technologies are as follows.

$$TC_{HSC} = IC_{HSC}/SL + MC_{HSC} + FC_{IFO} = 5195.896/SL + 1167.328 + 831.747$$

$$= 5195.896/SL + 1999.075 \text{ (thousand \$)}$$

$$TC_{MGO} = FC_{MGO} = 1236.362 \text{ (thousand \$)}$$

$$TC_{LNG} = IC_{LNG}/SL + MC_{LNG} + FC_{LNG} = 22167.216/SL + 9 + 269.877$$

$$= 22167.216/SL + 278.877 \text{ (thousand \$)}$$

Trough calculation, it can be known that if $0 < SL \leqq 9.9$, $TC_{MGO} < TC_{HSC} \leqq TC_{LNG}$; if $9.9 < SL \leqq 23.2$, $TC_{MGO} < TC_{LNG} \leqq TC_{HSC}$; if $23.2 < SL$, $TC_{LNG} < TC_{MGO} < TC_{HSC}$.

That is to say, if the ship's life is short, the cost advantage of using MGO is obvious, but with the increase of ship's lifespan, the cost advantage of LNG is more obvious. Figure 6.2 shows the relationship between ship lifespan and total cost of various SO_x emission control technologies.

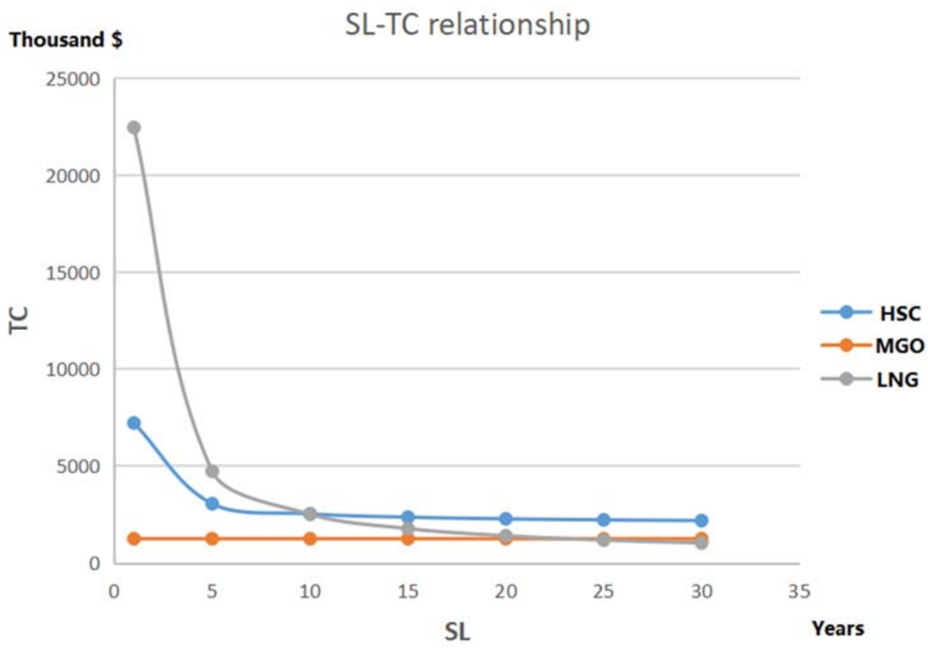


Figure 6.2: The relationship between ship lifespan and total cost of various SO_x emission control technologies

Taking 'COSCO Italy' as an example, with other parameters unchanged(SL=20 years), the relationship between fuel price and total cost of various SO_x emission control technologies are as follows(in order to compare easily, when LNG fuel is used, the cost of ignition oil is neglected, and the unit of LNF price is \$/ton here, 1\$/MBtu = 36.02 \$/ton).

$TC_{HSC} = IC_{HSC}/SL + MC_{FC} + MC_{SC} + \quad FC_{IFO}$

$= 259.795 + 4.695\times10^{-3}\times FC_{IFO} + 1165.183 + 1.820\times FC_{IFO}$

$=1.825\times FC_{IFO} + 1424.978$ (thousand \$)

$TC_{MGO} = FC_{MGO} = 1.735\times FC_{MGO}$ (thousand \$)

$TC_{LNG} = IC_{LNG}/SL + MC_{LNG} + FC_{LNG}$

$= 1108.361 + 9 + 2.182\times FC_{LNG}$

$=2.182\times FC_{LNG} + 1117.361$ (thousand \$)

The difference between TC_{HSC} and TC_{MGO} is as follows,

$TC_{HSC} - TC_{MGO} = 1.825\times FC_{IFO} - 1.735\times FC_{MGO} + 1424.978$ (thousand \$)

From the above formula, it can be seen that FC_{IFO} has positive affect to the difference between TC_{HSC} and TC_{MGO}, and FC_{MGO} has negative affect to the difference between TC_{HSC} and TC_{MGO}. The recent average price are $FC_{IFO380} = 457.01$ \$/ton, $FC_{MGO} = 712.67$ \$/ton, and $TC_{HSC} - TC_{MGO} = 1022.508$ thousand \$. If FC_{IFO} is unchanged, when FC_{MGO} increases, the difference between TC_{HSC} and TC_{MGO} will decrease. When $FC_{MGO} = 1302.02$ \$/ton, $TC_{HSC} - C_{MGO} = 0$, the total cost of using hybrid scrubber will be equal to the cost of using MGO. If $FC_{MGO} < 1302.02$ \$/ton, the cost of using MGO is lower than using hybrid scrubber.

The difference between TC_{HSC} and TC_{LNG} is as follow,

$TC_{HSC} - TC_{LNG} = 1.825\times FC_{IFO} - 2.182\times FC_{LNG} + 307.617$ (thousand \$)

From the above formula, it can be seen that FC_{IFO} has positive affect to the difference between TC_{HSC} and TC_{LNG}, and FC_{LNG} has negative affect to the difference between TC_{HSC} and TC_{LNG}. The recent average price are $FC_{IFO380} = 457.01$ \$/ton, $FC_{LNG} =$

119.95 \$/ton(3.33 \$/MBtu), and $TC_{HSC} - TC_{LNG}$ = 871.633 thousand \$. If FC_{IFO} is unchanged, when FC_{LNG} increases, the difference between TC_{HSC} and TC_{LNG} will decrease. When FC_{LNG} = 523.22 \$/ton(14.53 \$/MBtu), $TC_{HSC} - TC_{LNG} = 0$, the total cost of using hybrid scrubber will be equal to the cost of using LNG. If $FC_{LNG} <$ 523.22 \$/ton(14.53 \$/MBtu), the cost of using LNG is lower than using hybrid scrubber.

The difference between TC_{LNG} and TC_{MGO} is as follow,

$TC_{LNG} - TC_{MGO} = 2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361$ (thousand \$)

From the above formula, it can be seen that FC_{LNG} has positive affect to the difference between TC_{LNG} and TC_{MGO}, and FC_{MGO} has negative affect to the difference between TC_{LNG} and TC_{MGO}. The recent average price are FC_{MGO} = 712.67 \$/ton, FC_{LNG} = 119.95 \$/ton(3.33 \$/MBtu), and $TC_{LNG} - TC_{MGO}$ = 150.876 thousand \$. If $2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361=0$, there is no difference between the cost of using MGO and LNG. If $2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361>0$, the cost of using MGO is lower than using LNG. If $2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361<0$, the cost of using LNG is lower than using MGO. Figure 6.3 shows the relationship between fuel price and total cost of various SO_x emission control technologies. As can be seen from figure 6.3, the difference of total cost between using MGO and LNG is not significant at current fuel prices. If the price of LNG remains unchanged, the total cost of using MGO will be equal to the total cost of using LNG when the price of MGO rises by 11.4% to 794.87 \$/ton. If the price of MGO continues to rise, the cost advantage of using MGO will be lost.

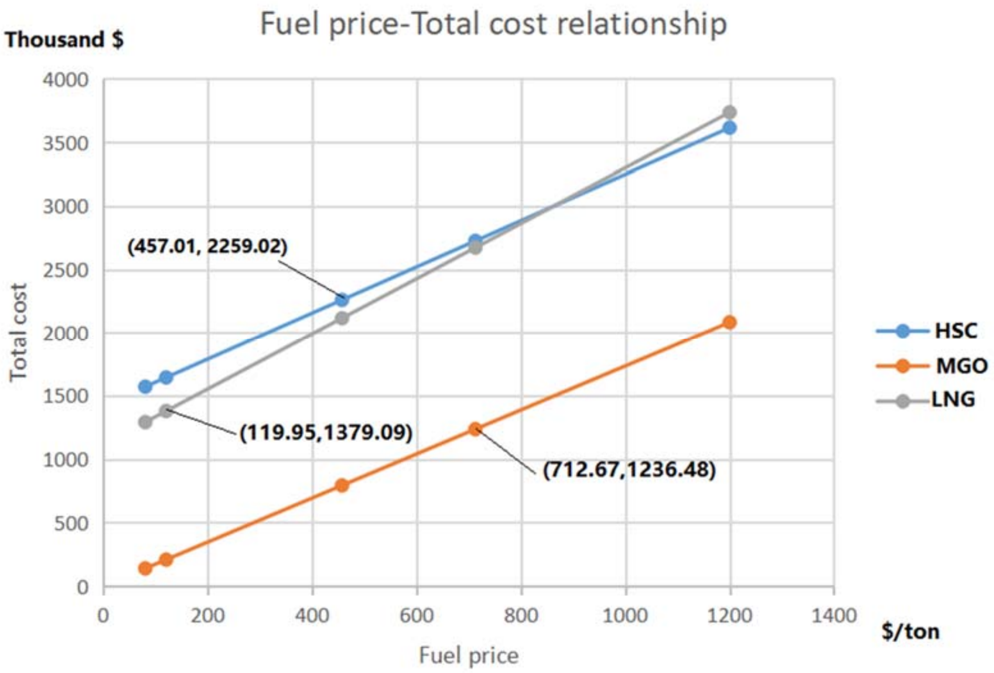


Figure 6.3: The relationship between fuel price and total cost of various SO_x emission control technologies

7 Conclusion and Recommendations

7.1 Conclusion

Under the current SO_x emission requirements, shipowners usually choose to use low-sulfur fuel oil in ECAs and other waters with special emission requirements, high-sulfur oil is still used in most sea areas in the world. According to the IMO requirement, the sulphur content of fuel oil used on ships should not exceed 0.50% m/m on and after 1 January 2020(or achieve equivalent SO_x emissions). Using high-sulfur oil without exhaust gas treatment will not be feasible any more. Shipowners have to reconsider which SO_x emission control technology to adopt.

By using PESTEL analysis method, various SO_x emission technologies were comprehensively compared from 13 indexes of six aspects. It is found that, high pressure directly injection LNG engine has the best effect on GHG emission reduction; the initial cost of using low-sulfur oil is the lowest, and that of using LNG fuel is the highest; the maintenance cost of using low sulfur oil is the lowest, the operation costs of dry scrubbers and fresh water scrubbers are the highest; the fuel cost of using LNG is the lowest, and that of using low-sulfur oil is the highest; the adverse effects of using dry scrubbers and seawater scrubbers on ships are lower than those of the other SO_x emission technologies; using LNG fuel has the least adverse impact on human health; using low-sulphur oil increases the least weight and occupies the smallest space for ships; the desulfurization effect of using low pressure directly injection LNG engine, dry scrubber and fresh water scrubber are better than the other SO_x emission control technologies; low pressure directly injection LNG engine has the highest denitrification efficiency; using LNG fuel has the highest removing PM efficiency and waste disposal efficiency; all SO_x emissions control technologies can meet the equivalent requirement of sulphur content below 0.5% m/m, but using high pressure directly injection LNG engine and seawater scrubber are risky to meet the equivalent requirement of sulphur content below 0.1% m/m.

Each SO_x emission control technology has its own advantages and disadvantages. If the weights of each index are equal, the comprehensive evaluation result of various SO_x emissions control technologies rank from high to low are LNG low pressure injection engine, low sulphur oil, LNG high pressure injection engine, hybrid scrubber, seawater scrubber, fresh water scrubber and dry scrubber. Different decision makers attach importance to different factors, and the weight of each index is different, the comprehensive evaluation result will also be different.

In order to quantitatively compare low sulphur oil, low pressure directly injection LNG engine and hybrid scrubbers, general formulas for calculating the cost, environmental benefits and benefit-cost ratio of the three technologies are established for container ships. Especially, the formula for calculating daily IFO fuel cost is obtained by using data regression method.The calculation formulas are as follows.

For use of hybrid scrubbers,

$DFA_{IFO} = 1.71\times10^{-7} \times TEU \times V^3$

$TC_{HSC} =[(0.0396 \times P_M + 0.0480\times P_A + 1.615)\times 10^6]/SL + (1.71\times10^{-7} + 2.565\times10^{-9} \times \frac{P_A}{P_M + P_A})\times TEU \times V^3 \times DOV \times PF_{IFO} \times NOVPY + (8.01\times P_M\times \frac{ND}{V \times DOV} + 233.33\times P_A) \times DOVR \times NOVPY$

$EB_{HSC,SO_x} = 2.435\times10^{-3} \times TEU \times V^3 \times NOVPY\times(0.925\times DOV+0.065\times DOVR)$

$EB_{HSC,NO_x} =2.049\times10^{-4} \times TEU \times V^3 \times NOVPY \times DOV$

$EB_{HSC,CO_2} =0$

$EB_{HSC,PM} =2.982\times10^{-4} \times TEU \times V^3 \times DOVR \times NOVPY \times (0.8\times DOV-0.35\times DOVR)$

$EB_{HSC}= EB_{HSC,SO_x} + EB_{HSC,NO_x} + EB_{HSC,CO_2} + EB_{HSC,PM}$

$BCR_{HSR} = EB_{HSR} / TC_{HSR}$

For use of MGO fuel,

$TC_{MGO} = 1.63\times10^{-7} \times TEU \times V^3 \times DOV \times PF_{MGO} \times NOVPY$

$EB_{MGO,SO_x} = 2.367\times10^{-3} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO,NO_x} = 3.788\times10^{-4} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO,CO_2} = 1.510\times10^{-5} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO,PM} = 2.012\times10^{-4} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{MGO} = EB_{MGO,SO_x} + EB_{MGO,NO_x} + EB_{MGO,CO_2} + EB_{MGO,PM}$

$BCR_{MGO} = EB_{MGO} / TC_{MGO}$

For use of LNG low pressure injection engine,

$TC_{LNG} = (1656 \times TEU) / SL + 9000 + (1.71\times10^{-9} \times PF_{IFO} + 7.38\times10^{-6} \times PF_{LNG}) \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{LNG,SO_x} = 2.411\times10^{-3} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{LNG,NO_x} = 3.423\times10^{-3} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{LNG,CO_2} = 5.523\times10^{-5} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{LNG,PM} = 2.952\times10^{-4} \times TEU \times V^3 \times DOV \times NOVPY$

$EB_{LNG} = EB_{LNG,SO_x} + EB_{LNG,NO_x} + EB_{LNG,CO_2} + EB_{LNG,PM}$

$BCR_{LNG} = EB_{LNG} / TC_{LNG}$

Where;

TC_{HSC} - Annual Average Total Cost of Hybrid Scrubbers($)

TC_{MGO} - Annual Average Total Cost Of Using MGO ($)

TC_{LNG} -Average Annual Total Cost of Using LNG Low Pressure Directly Injection Engines($)

SL - Ship lifespan (years)

P_M - The Main Engines Powers of A Ship(Mw)

P_A - The Auxiliary Engines Powers of A Ship (Mw)

TEU - Ship Design Capacity (TEU)

V - Economic Speed of Ships (knot)

DOV - Sailing Days Of A Single Voyage (days)

PF_{IFO} - Price of IFO ($ / ton)

PF_{MGO} - Price Of MGO ($ / ton)

PF_{LNG} - Price of MGO ($/MBtu)

NOVPY - Number Of Voyages / Year (times)

ND - Navigation Distance per Voyage(nautical miles)

DOVR - Sailing Days Of A Single Voyage In Scrubber Discharge Ban Areas(days)

$EB_{HSC,j}$-Annual Environmental Benefits of NO. j Air Pollutant for Using Hybrid Scrubbers ($)

$EB_{MGO,j}$ - Annual Environmental Benefits of NO. j Air Pollutant for Using MGO ($)

$EB_{LNG,j}$ - Annual Environmental Benefits of NO. j Air Pollutant for Using LNG ($)

Take a container ship 'COSCO Italy' sailing in Europe-China line as an example, if the lifespan is 20 years, the calculation results of the above formulas are as follows.

For use of hybrid scrubbers,

TC_{HSC} =2,258,870 $, EB_{HSC}=29,021,589 $, BCR_{HSR} =12.8.

For use of MGO fuel,

TC_{MGO} =1,236,362 \$, EB_{MGO}= 31,526,022 \$, BCR_{MGO} =25.5.

For use of LNG fuel,

TC_{LNG} = 1,387,238 \$, EB_{LNG}= 65,821,707\$, BCR_{LNG} =47.4.

It can be gotten that the total cost of using MGO is the lowest, the environmental benefit of using LNG is the highest, the benefit-cost ratio of using LNG is also the highest. Through further analysis of the impact of lifespan and fuel price on the total cost of each SO_x emissions control technology for 'COSCO Italy', it is found that if $0 < \text{lifespan} \leqq 9.9$, $TC_{MGO} < TC_{HSC} \leqq TC_{LNG}$, if $9.9 < \text{lifespan} \leqq 23.2$, $TC_{MGO} < TC_{LNG} \leqq TC_{HSC}$, if $23.2 < \text{lifespan}$, $TC_{LNG} < TC_{MGO} < TC_{HSC}$. The change of fuel price has obvious influence on the total cost comparison result of various SO_x emissions control technologies. Especially at the current fuel price, the total cost of using LNG and MGO are close. With the further increase of MGO price, the cost advantage of using MGO will be lost. When $2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361=0$, there is no difference between the cost of using MGO and LNG; when $2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361>0$, the cost of using MGO is lower than using LNG, when $2.182\times FC_{LNG} - 1.735\times FC_{MGO} + 1117.361<0$, the cost of using LNG is lower than using MGO.

7.2 Recommendations

At present, the 2020 global sulphur limit is about to be implemented, and the time left for the shipping enterprises is very limited. For the coming new SO_x emission restriction regulation, shipping enterprises and shipowner should prepare in advance. Some recommendations are as follows,

□. Shipping enterprises and shipowners should consider all kinds of factors to choose the most reasonable emission control technology, and formulate the implementation of 'sulfur limitation' plan (SIP) for each vessel as soon as possible according to the Guidelines for the Implementation Plan of the 2020 global sulphur limit issued by IMO (MEPC.1/Circ.878). Considering the special provisions of various countries and regional organizations, it is suggested that relevant procedures, such as training procedures, refueling procedures, fuel switching procedures and operation procedures, should be established for applicable ships, and relevant data should be recorded as required (e.g. starting/ending date/time, usage, longitude and latitude of ships, etc.), crew members on board should be familiar with and skilled in operation in advance, and keep fuel supply list, oil record book and other documents as required retention period.

□. When hybrid scrubber is used, the cost of alkaline solution consumption is very high under the closed-loop operation mode. In order to save costs, shipowners should use the open-loop operation mode as far as possible. Generally, for old ships(future service life is less than 20 years), using hybrid scrubber has a greater cost advantage, for new ships or new building ships, using LNG fuel has a greater cost advantage.

□. Under the selection of using low sulfur fuel oil, considering that the supply capacity of low sulfur fuel oil in the future is still uncertain, if it is not possible to purchase low sulfur fuel oil in time, or the fuel sold in certain ports can not meet the requirement, or because of mechanical failure, equipment failure and other reasons, the ship has to use the heavy fuel oil, these ships should contact the flag state authorities or relevant port authorities as soon as possible and keep the relevant documents on board as evidence.

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Appendices

Fuel Consumption Statistics of Ocean Container Ships

of COSCO SHIPPING LINES

NO.	Fuel assumption of a single voyage(tons)		Sailing days of a single voyage(days)	TEU	Economic speed(knot)
	IFO	LSO			
1	5247	689	85	10020	13
2	1477	221	59	3534	12
3	1708	123	65	3534	12
4	3322	459	70	4250	12
5	3196	419	63	4250	12
6	3200	620	63	4253	12
7	3603	338	63	4253	12
8	3250	492	71	4253	12
9	3449	540	64	4253	12
10	3040	526	63	4250	12
11	3222	741	63	4250	12
12	2750	383	71	4253	12
13	2747	469	70	4253	12

14	3169	402	70	4253	12
15	2911	279	70	4253	12
16	2896	407	70	4253	12
17	3082	455	70	4250	12
18	2766	401	63	4250	12
19	2908	291	64	4253	12
20	2897	321	43	13386	13
21	2887	345	47	13386	13
22	2941	292	49	19273	13
23	4242	333	64	13386	13
24	3782	797	65	13386	13
25	4286	321	63	13386	13
26	1600	1173	32	8501	13
27	2371	1369	50	8501	13
28	4887	131	70	8501	13
29	5195	151	70	8501	13
30	6382	223	78	8501	13
31	5592	228	77	8501	13
NO.	Fuel assumption of a single voyage(tons)		Sailing days of a single voyage(days)	TEU	Economic speed(knot)
	IFO	LSO			
32	5406	242	77	8533	13
33	2432	92	64	4360	12
34	2303	158	63	4360	12
35	7554	329	119	9469	13
36	1291	52	35	4578	12
37	3800	240	62	4578	12
38	3673	431	65	4578	12

39	5902	433	77	13386	13
40	4100	179	70	9472	13
41	4357	126	71	9115	13
42	3739	229	70	6600	12
43	5925	1378	77	19273	13
44	6986	985	77	20119	13
45	6240	1169	77	19273	13
46	6311	1020	77	20119	13
47	5536	232	87	13386	13
48	5657	805	83	19273	13
49	6550	879	77	20119	13
50	5100	402	84	13386	13

Note:

(1) A set of data for each ship;

(2) Different types of container vessels in Far East-Europe, Mediterranean, West America, Gulf of America, South America, Africa, Middle East Red Sea and Trans-Atlantic routes are selected, the data are derived from the ships' actual reports;

(3) According to the ships management experience, the economic speed of ships with capacities of more than 8000TEU is 13 knots, and the economic speed of ships with capacities of less than 8000TEU is 12 knots.