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# GHG Regulations of IMO 2020 and Optimum Countermeasures for Shipping Industry

# - Comparative Cost Analysis with Low Sulfur Oil and Scrubber for Container Shipping

By

David Kang

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## Abstract

The purpose of this study is to find a way to respond in the optimal direction to the sulfur oxide emission regulations introduced by the IMO in 2020. IMO 2020 introduced new sulfur oxide emissions controls to regulate greenhouse emissions in the maritime sector and limited the maximum emissions to be below 0.5% m/m. The shipping industry is currently considering introducing low sulfur oil, scrubbers, or alternative fuel propulsion ships. In the case of using VLSFO, it is found to be suitable for short-term response since there is no need for ship renovation. For introducing scrubbers, it is profitable in the mid-term since it can continuously use high sulfur oil that costs lower than VLSFO, however, installation and maintenance costs are expected. In the case of alternative fuel propulsion ships such as LNG, hydrogen, and ammonia, it should be introduced from a long-term perspective since the cost of manufacturing ships is remarkably high due to technical limitations at present. However, the introduction cost of VLSFO or the scrubbers may also vary by age and size of container ships. In other words, the payback period of the scrubber may change in a situation where oil prices fluctuate, and unit price fluctuations are predicted due to changes in demand and supply of the scrubber. Therefore, this study analyzed the optimal countermeasures to be taken by container shipping companies assuming each situation through scenario composition. As a result of the analysis, if oil prices continues to stay in 2022 level, scrubbers will lose its competitiveness in terms of cost. Only if the scrubber cost decreases by 50%, installing scrubber will be positively considered, otherwise it is beneficial to use VLSFO. However, if the HSFO and VLSFO prices increase in the past 3-year average trend, even if the scrubber price goes down in 50%, scrubbers lose competitiveness. In this case, VLSFO use is sought to be an optimum alternative. On the other hand, if HSFO and VLSFO prices follow with supply and demand prediction data, scrubber strategy gains competitiveness. Almost all containership except for those will be scrapped in 5 years, can be considered with installing scrubbers.

The study has found how payback period of scrubbers change due to price changes of VLSFO and the unit price of scrubbers and concluded the capabilities for shipping companies to predict these prices will be crucial for their businesses. In order to properly respond to changes in the market situation in the future, it is necessary to establish a countermeasure through appropriate scenario composition, and to flexibly respond to changes in the situation. By complying with greenhouse gas emission regulations and finding optimal countermeasures, both companies, individuals, and society will be able to create not only financial profits but also clean and sustainable environment.

# Table of Contents

Acknowledgements ........ ii

Abstract........ iii

List of Tables ........ vi

List of Figures........ vii

List of Abbreviations ........ viii

Chapter 1: Introduction........ 1

1.1 Research Background and Objectives ........ 1

1.2 Research Question and Sub-Research Questions ........ 2

1.3 Thesis Structure and Research Design ........ 3

1.4 Methodology of Approach........ 4

Chapter 2: IMO 2020 Regulatory Review........ 6

2.1 MARPOL Protocol Development Overview........ 6

2.2 MARPOL VI Review ........ 7

2.2.1 Annex 6, Chapter 3, Regulation 13 Nitrogen Oxide (NOx)........ 8

2.2.2 Annex 6, Chapter 3, Regulation 14 Sulfur Oxide (SOx) and Particulates ........ 9

2.3 Characteristics of IMO 2020 Sulfur Oxide Regulation ........ 9

2.3.1 Regulation Applies to all existing ships and new construction ships........ 9

2.3.2 IMO's High commitment to timely implementation........ 10

2.3.3 ECA Regional Expansion........ 11

2.4 Conclusions ........ 12

Chapter 3: Strategic Options as a Countermeasure against the Regulation ........ 14

3.1 Alternative Options for Shipping Companies ........ 14

3.1.1 Low Sulfur Oil........ 15

3.1.2 A Comparison of Low-Sulfur Oil Processing Methods in terms of Cost........ 16

3.1.3 VLSFO Use and its Limitations ........ 17

3.1.4 Exhaust Gas Cleaning System: Scrubber ........ 19

3.1.5 Open-Loop Scrubber (Sea Water Scrubber)........ 19

3.1.6 Closed-Loop Scrubber (Fresh Water Scrubber) ........ 20

3.1.7 Hybrid Scrubber ........ 20

3.1.8 Scrubber Installations and its Limitations ........ 21

3.2 Overall Advantages and Disadvantages of VLSFO and Scrubber Strategies ........ 22

3.3 Conclusion ........ 24

Chapter 4: Literature Review on Impacts of IMO 2020 and Responses from Industry ........ 26

4.1 Introduction ........ 26

4.2 Impacts on Fuel Oil and Shipping Industry ........ 26

4.3 Impacts on Market Concentrations and Competitions of Shipping Industry ......................27
4.4 Cost-benefit Analysis on Low Sulfur Oil and Scrubber Use................................................28
4.5 Low Sulfur Oil and Scrubber Strategy Comparison by Case Research ..............................30
4.5 Conclusion ............................................................................................................................34
4.6 Assumption Establishments Based on Literature Review ...................................................35
Chapter 5: Empirical Analysis: Cost Scenario Modeling..............................................................37
5.1 Dataset for Scenarios ............................................................................................................38
5.1.1 Oil Price and Bunker Fuel Oil Prices ...........................................................................38
5.1.2 Vessel Selections .............................................................................................................39
5.1.3 Scrubber Price.................................................................................................................40
5.1.4 Fuel Consumption............................................................................................................41
5.1.5 Scrubber Payback Period .......................................................................................................42
5.1.6 Containership Lifespan ..........................................................................................................43
5.2 <Scenario 1>: Cost Comparison Between VLSFO and Scrubber use with 2022 Oil Price .43
5.2.1 Empirical Modeling Analysis Results and Data..........................................................44
5.3 <Scenario 2>: Scrubber Price Decreases 50%, while VLSFO Price Stays .........................46
5.3.1 Empirical Modeling Analysis and Results ....................................................................46
5.4 <Scenario 3>: HSFO/VLSFO Price Increase Annually, while Scrubber Price Stays ..........49
5.4.1 Empirical Modelling Scenario Analysis and Results ...................................................49
5.5 <Scenario 4>: HSFO/VLSFO Prices Increase Annually, while Scrubber Price Decrease in 50%.........................................................................................................................................52
5.5.1 Empirical Modelling Scenario Analysis and Results ...................................................52
5.6 <Scenario 5>: VLSFO Price Increases By 8% Per Year.....................................................54
5.6.1 Empirical Modelling Scenario Analysis and Results ...................................................55
5.7 <Scenario 6>: Scrubber Price Decreases by 50%, VLSFO Price Increases by 8% Per Year ..........................................................................................................................................56
5.7.1 Empirical Modelling Scenario Analysis and Results ...................................................56
5.8 Summary and Conclusions for all Scenarios .......................................................................58
Chapter 6: Conclusions...................................................................................................................61
6.1 Conclusions and Recommendations .....................................................................................61
6.2 Limitation and Suggestions for the Future Research............................................................63
Annexes ..........................................................................................................................................65
Bibliography ...................................................................................................................................82

**List of Tables**


**Table 2. 1 MARPOL Annex VI NOx emission limits value**........................................................8

**Table 2. 2 Subjects and methods of application by environmental regulations** .....................10

**Table 2. 3 Regulation status of sulfur content of ship fuel by region**......................................12

**Table 3. 1 General Fuel Oil Types and Sulfur content for Ships** ............................................15

**Table 3. 2 Advantages and Disadvantages of producing Low Sulfur Oil by Process Methods** ...........................................................................................................................................16

**Table 3. 3 Bunker Fuel Demand (mb/d)** ........................................................................18

**Table 3. 4 Comparison of SOx Scrubber Technologies** ..........................................................21

**Table 3. 5 Advantages and Disadvantages of VLSFO and Scrubber use**................................22

**Table 4. 1 Advantages and Disadvantages of Low Sulfur Oil and Alternative Fuels**....... 27

**Table 4. 2 Yearly Savings in Fuel Costs compared with No Scrubbers (US $)**.......................30

**Table 5. 1 Scenario Overview**……………………………………………………………. ….37

**Table 5. 2 HSFO, VLSFO Bunker Prices (Rotterdam) and WTI Crude Oil Price**................38

**Table 5. 3 Container Vessel Selection for Scenarios and its Engine Power Output**..............40

**Table 5. 4 Estimated scrubber price in 2022 reflecting social discount rate based on scrubber price in 2012 (Price in $/kW)**.........................................................................................40

**Table 5. 5 Scrubber Prices by TEU Types** ..................................................................41

**Table 5. 6 Descriptive statistics for fuel consumption, distance, and sailing speed by ship size** ...........................................................................................................................................41

**Table 5. 7 Fuel Consumption for Selected Ships** ........................................................................42

**Table 5. 8 Summary of <Scenario 1> result**..............................................................................44

**Table 5. 9 Summary of <Scenario 2> Result**..............................................................................46

**Table 5. 10 Summary of <Scenario 3> Result**..........................................................................49

**Table 5. 11 Summary of <Scenario 4> Result**..........................................................................52

**Table 5. 12 Summary of <Scenario 5> result**..........................................................................55

**Table 5. 13 Summary of <Scenario 6> Result**..........................................................................56

**Table 5. 14 Empirical Scenario Modeling Result Summary** ....................................................59

**List of Figures**

**Figure 2. 1 MARPOL VI Regulation Overview**..........7
**Figure 2. 2 Emission Control Areas (ECAs) for NOx Emission Control** ..........8
**Figure 2. 3 Upper limit of SOx emission regulation** ..........9
**Figure 3. 1 VLSFO Bunker Prices: Rotterdam and Singapore ($/Ton)**..........18
**Figure 3. 2 Percentage of Scrubber Type Installed** ..........19
**Figure 3. 3 Regulations on the use of scrubbers** ..........22
**Figure 5. 1 <Scenario 1> Accumulative Cost with Scrubber Cost and Payback Period** ..........45
**Figure 5. 2 <Scenario 2> Accumulative Cost and Payback Period**..........47
**Figure 5. 3 <Scenario 3> Accumulative Cost and Payback Period**..........50
**Figure 5. 4 <Scenario 4> Accumulative Cost and Payback Period**..........53
**Figure 5. 5 <Scenario 5> Accumulative Cost and Payback Period**..........55
**Figure 5. 6 <Scenario 6> Accumulative Cost and Payback Period**..........57

**List of Abbreviations**

| | |
|---|---|
| **CAPEX** | Capital Expenditures |
| **ECA** | Emission Control Area |
| **EEDI** | Energy Efficiency Design Index |
| **EEOI** | Energy Efficiency Operational Indicator |
| **EGCSA** | Exhaust Gas Cleaning System Association |
| **EGR** | Exhaust Gas Reduction |
| **EIAPP** | Engine International Air Pollution Prevention Certificate |
| **ETS** | Emission Trading System |
| **FONAR** | Fuel Oil Non-Availability Report |
| **HDS** | Hydrodesulfurization |
| **IMO** | International Maritime Organization |
| **LNG** | Liquefied Natural Gas |
| **LSFO** | Low Sulfur Oil |
| **MARPOL** | Marine Pollution Treatment |
| **MBMs** | Market Based Measures |
| **MDO** | Marine Diesel Oil |
| **MEPC** | Marine Environment Protection Committee |
| **MGO** | Marine Gas Oil |
| **MOA** | Memorandum of Agreement |
| **NaOH** | Sodium Hydroxide |
| **NOx** | Nitrogen Oxides |
| **NPV** | Net Present Value |
| **ODS** | Oxidative Desulfurization |
| **OPEX** | Operating Expenses |
| **PM** | Particulate Matter |
| **PPR** | Pollution Prevention & Response |
| **SCR** | Selective Catalytic Reduction |
| **SECA** | Sulfur Oxides Emission Control Area |
| **SEEMP** | Ship Energy Efficiency Management Plan |
| **SMCR** | Specific Maximum Continuous Rating |
| **SO2** | Sulfur Dioxide |
| **SO3** | Sulfur Trioxide |
| **SOx** | Sulfur Oxides |

# Chapter 1: Introduction

## 1.1 Research Background and Objectives

In the shipping sector, environmental regulations targeting ports and seas around the world are being implemented centering on IMO. Accordingly, each company and country around the world is implementing environmental regulations on offshore passing and operating ships, including ports. In 2005, the IMO established regulations for reducing air pollutants in Chapter 3 of MARPOL Annex 6 (IMO, 2005), and in 2013, in Chapter 4 of Annex 6 (IMO, 2017). However, from the 1st of January 2020, the IMO has announced a new regulation to limit sulfur emissions from ships, and accordingly, shipping companies are taking steps to change or improve the energy sources of ships they have. Known as "IMO 2020", the rule limits the Sulfur in the fuel oil used on board ships operating outside designated emission control areas to 0.50% m/m (mass by mass) - a significant reduction from the previous limit of 3.5% (IMO, 2020). Among the air pollution emissions from ships, nitrogen oxides (NOx) have limited areas subject to the regulations, and regulatory standards are low for ships built before 2016. At present, the need for review is relatively low. However, in the case of sulfur oxide (SOx), it has been decided to lower the emission standard to 0.5% in general sea area and 0.1% in emission control area (ECA) from January 1, 2020, requiring all shipping companies to actively review countermeasures. Accordingly, global shipping companies are considering responding to this in mainly three ways. First, it is a method of replacing ship fuel with low sulfur oil from existing sulfur oil, secondly, a method of installing a scrubber, a desulfurization device, and thirdly, introducing a liquefied natural gas (LNG) propulsion ship. However, in the case of introducing LNG propulsion ships, there are technical limitations along with high capital costs, and general shipping companies are choosing to introduce low sulfur oil or install scrubbers.

On the one hand, according to the IEA, the demand for VLSFO is expected to increase to an average of 31.5% per year from 2020 to 2025, and from 1.3 mb/d to 2.1 mb/d (IEA, 2020). In addition, some refiners expected most oil trading to take place by blending, although they increased their production of VLSFO by increasing desulfurization facilities (ibid.,). Additionally, according to Wu and Lin, estimated fuel prices of VLSFO, LNG, and MGO will drop down since the supply of these fuels will go up (Wu and Lin, 2021). One the other hand, more than 1,200 ships are equipped with scrubbers every year, including 2019, before IMO 2020 was adopted and implemented. This is twice the size of the demand of 632 units in 2018, and demand has maintained a stable continuous trend in the past (DNV, 2022). In the case of low sulfur oil, supply can be increased at existing oil refineries by increasing the proportion of desulfurization in oil refineries or improving sulfur removal processes through additives, while scrubber manufacturers are expected to see a significant increase in price due to rising demand along with the limitation for companies to newly introduce their technology and simply increase the production volume with the current facility.

IMO is an organization that prepares regulations for all shipping-related companies and related workers. Therefore, IMO's new environmental regulations will exert a strong influence on the ship fuel and scrubber markets. In a situation where the demand and supply of ship fuel and scrubbers are rapidly changing, it is inevitable for global shipping companies to predict prices and set new management strategies according to scenario setting. In addition, since the entire industry in the shipping sector is expected to be affected by this movement of large shipping companies, cost comparison, forecast, and cost efficiency analysis research is not only academically but also industrially meaningful. Therefore, first, this paper analyzes the implications of IMO environmental regulations. Next, it researches the corresponding possible strategies that can be made against the regulation along with assumptions constructing a cost scenario for empirical analysis. In the empirical analysis part, it analyzes the cost effectiveness of low sulfur oil and scrubber usage costs. The cost of using scrubber and VLSFO changes since the oil price fluctuates and the unit price of scrubber could change from time to time depending on the supply and demand of the market. Therefore, this paper can analyze the change in the payback period of scrubbers according to fluctuations in oil prices and fluctuations in scrubber prices, and through this, it seeks an optimal operation strategy considering the type and age of container ships.

### 1.2 Research Question and Sub-Research Questions

- **Main Question: What is the most cost-effective, strategically optimal alternative to IMO 2020 regulation under the price fluctuations of low sulfur oil and scrubbers?**
- **Sub-Questions:**

1. **Why and how do shipping companies have to set countermeasures against MARPOL Annex VI regulation?**
2. **What are the advantages and disadvantages of using low sulfur oil and scrubbers?**
3. **What is the cost of using VLFSO for ship fuel compared to using HSFO with a scrubber in a current oil price?**

- What is the cost of using VLFSO and HSFO with Scrubber by the type of container ship?

4. **What is the Payback Period for the scrubber installation in container ships?**

- What is the cost difference between using Low Sulfur Oil and Scrubber, and how much is the payback period going to be?

5. **In several scenarios where the prices of the VLFSO and scrubber change due to its supply and demand fluctuations after IMO 2020, what is the best option considering economic feasibility?**

- What factors determine the trade-off between the alternatives for dealing with the IMO Low Sulfur regulations?
- Scenario: What is the best option within the combination fluctuating bunker fuel costs and scrubber costs? And how would the payback period of scrubber change?

### 1.3 Thesis Structure and Research Design

**Introduction**
- Research Background and Objectives
- Research Question
- Methodology

**IMO 2020 Regulatory Research and Literature Review**
- MARPOL Annex VI Review
- Implications of the Measures on the Industry

**Strategic Options for Countermeasures**
- Countermeasuring Strategies from Container Shipping Companies
- Bunker Adjustment Factors from Shipping Companies

**Empirical Analysis Using Cost Scenario Modeling**
- Base Scenarios (Static Model)
- Price Change Scenarios (Dynamic Model)

**Conclusion**
- Conclusion and recommendations

Following the introduction of Chapter 1, this study begins a review of the background of the implementation of IMO environmental regulations in Chapter 2 and a review of existing literature. In accordance with this trend, this paper conducts strategic evaluation and analysis focusing on the operation strategy of container ships under IMO 2020 environmental regulations, especially on the use of VLSFO and scrubbers. Therefore, in the Chapter 3, starting with a literature review on the regulation of greenhouse gas emissions reduction regulations in IMO 2020, the paper assesses a strategy that global shipping companies can respond to, that is, a comparative assessment on the use of VLSFO and scrubber. Additionally, it aims to investigate, compare, and analyze the response strategies of shipping companies currently in place. The analysis of accompanying costs will be examined in the next chapter. After the regulatory research and strategic assessments, Chapter 4 focuses on the cost effectiveness of low sulfur oil use or scrubber installation in container ships. The first goal is to compare and analyze costs considering oil prices, scrubber prices, container ship types, and secondly, to predict the optimal plan considering the scenario where oil prices rises due to increased demand of low sulfur oil, and the possible unit price changes in scrubbers due to demand and supply fluctuations. After analyzing the Base Scenario using a static model considering current VLSFO, HSO oil price, scrubber cost, and containership types, the paper analyzes the Price Change Scenario using a dynamic model considering the price fluctuating in the future. In the conclusion part, the overall scrubber payback period according to the type of container ship is discussed and the optimal method by the ship age is sought. In other words, the conclusion chapter discusses the optimal strategy that shipping companies should take according to container ship TEU type and ship age in the situation where low sulfur oil and scrubber prices fluctuate.

### 1.4 Methodology of Approach

The purpose of this study is to analyze the impact of IMO 2020 regulations on the shipping industry and container ship operation. Therefore, it uses quantitative research methods to analyze the cost-benefits of VLSFO and scrubber use for container ships. The assumptions are set by the literature review, in a sense that oil and scrubber price can change with a market fluctuation. Based on the assumptions made, empirical modeling is implemented to see the payback period of the scrubber comparing with VLSFO use situation. The detailed descriptions of the research method from each part proceeds as follows.

- The first is the IMO 2020 Regulatory Review and the MARPOL Annex VI Review, which are qualitative research including literature studies. This analyzes the characteristics and implications of regulation and studies the significances on the industry and shipping companies.

- The second is a study that reviews previous research data. This presupposes a strategic hypothesis for future ship operations through previous research that studied the impact of regulation on the industry and how the industry responded to it. This is a reference material for strategic analysis and empirical modeling to be conducted in this paper, and a part that seeks ways to study in the future based on the limitations of previous studies. Based on previous studies, it is possible to establish assumptions to be used in empirical analysis from the areas that was consistently presented, and areas that are not conducted in previous studies that require further research.
- Third, it seeks the optimal alternative as a strategy that shipping companies can choose. This part analyzes the status of markets, industries, and shipping companies responding to IMO regulations without presupposing artificial situation assumptions. The qualitative research methodology is adopted in that the meaning of regulation is extracted from the perspective of the shipping company, which is the subject of the study, and the phenomenon is explained, and countermeasures are sought as a whole.
- The fourth is an analysis through empirical modeling, and quantitative research methodology is adopted. Based on the situational assumptions that can be established from previous qualitative studies, it is a part that answers or verifies research problems or hypotheses that include quantitatively measurable characteristics. This is a quantitative study in that the situational assumption of price fluctuations according to market changes is reflected in the modeling to perform payback period calculations and cost-benefit analysis, and the actual significance is analyzed based on the results.

In conclusion, this paper uses qualitative research methodology in the case of regulatory research, literature review, and strategic option exploration and presentation. In addition, cost-benefit analysis and payback period calculation use quantitative research methodology with variable factors such as the ship's TEU type, oil price and scrubber price due to market fluctuations.

## Chapter 2: IMO 2020 Regulatory Review

### 2.1 MARPOL Protocol Development Overview

The IMO established the Marine Pollution Treatment (MARPOL) in 1973 as an agreement to prevent marine pollution (Shi, 2016). MARPOL is intended to prevent marine pollution caused by pollutants discharged from the normal operation of ships, and the protocol was adopted in 1978 and is sometimes marked as MARPOL 73/78 (ibid.,). The Convention first entered into force in 1983 and is now composed of six Annexes (Annex I–VI) (MARPOL, 1983). Annex VI, an annex to "air pollution," was newly established in 1997, and discussions began to be held to reduce sulfur oxides (SOx), nitrogen oxides (NOx), and fine dust (Campara, Hasanspahi ́c, Nermin and Vujici ́c, Srdan, 2018). NOx has decided to reduce the Emission Control Area (ECA) area in the North American and Caribbean by 80% compared to the current level since 2016, and SOx aims to reduce sulfur content by 0.5% at sea around the world from 2020 (ibid.,).

Enhanced sulfur oxide regulation by the International Maritime Organization (IMO) took effect on January 1, 2020. IMO, an international maritime organization under the UN, has decided to strengthen the sulfur content standard for ship fuel oil from 2020. The fuel sulfur content will be limited to 0.5 percent from the current 3.5 percent for ships that pass through all parts of the world (IMO, 2020). In particular, the new regulation added to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL), known as IMO 2020, focuses on reducing SOx emission. This is because the amount of SOx emitted from the sea is damaging enough to cause great harm to humans[1]. Ship fuel oil accounts for about 7% of the total transportation oil demand, however, about 90% of sulfur emissions from the transportation sector are generated in the maritime sector (Concawe, 2017). In this sense, the IMO seeks to implement this new regulation to reduce the amount of sulfur emitted from ships by 77%, equivalent to 8.5 million metric tons of SOx (IMO, 2019). Accordingly, the IMO aims to prevent people from suffering from cardiopulmonary diseases such as asthma and pulmonary due to sulfur emissions from ships in the atmosphere (ibid.,).

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[1] SOx, along with NOx, is a substance that was discussed from the United Nations in 1972 as an air pollutant that causes acid rain (Vasseur, 1973). Natural coal or petroleum contains sulfur, which generates sulfur oxides such as SO2 or SO3 during combustion (Kikuchi, 2001). Sulfur oxides react with water to form sulfuric acid and become acidic ratios (ibid.,). Sulfur oxides adversely affect the body's respiratory system and, when SOx are combined with air pollutants, produce sulfates, which form PM2.5 that causes heart disease and respiratory diseases (ibid.,).

## 2.2 MARPOL VI Review

Annex 6 consists of five chapters:

- Chapter 1: General – Application, Definitions, Exceptions and exemptions of the regulation are clarified.
- Chapter 2: Survey / Certification & Means of Control – Details of survey being done to ship owners and endorsements of certificates are specified. The form, duration, and validity of the certificate are specified, and detections of violations are regulated as well.
- Chapter 3: Requirements for control of Emissions – Ozone depleting substances, NOx, SOx, PM, Volatile Organic Compounds, Shipboard incineration & Reception facilities, Fuel quality and availabilities are regulated. Details of limits and control areas are clarified.
- Chapter 4: Regulations on the carbon intensity of international shipping - Carbon dioxide regulations are specified. Energy Efficiency Design Index (EEDI) for Ship Energy Efficiency Management Plan (SEEMP) are clarified. Its requirements, equations for calculations, and regulatory frameworks are specified.
- Chapter 5: Verification of compliance with the provisions of this Annex – Code for Implementation in the execution of this Annex and verification of compliance are specified.

Among these chapters, Practical Regulations for Operating Vessels are specified in Chapters 3 and 4 (Bazari, 2020). Figure 2.2 below summarizes the MARPOL regulation by substance, region, period, and range.

**Figure 2. 1 MARPOL VI Regulation Overview**

| Regulatory Substance | Regulation | Region | Period<br>'13 '14 '15 '16 '17 '18 '19 '20 '21 '22 | Range |
|---|---|---|---|---|
| **NOx** | MARPOL Annex VI Regulation 13 | ECA | Tier 2 → Tier 3 | For all new vessels |
| | | Global | Tier 2 | |
| **SOx** | MARPOL Annex VI Regulation 14 | ECA | 1.0% → 0.1% | For new and all existing vessels |
| | | Global | 3.5% → 0.5% | |

*Source: Own preparation, IMO*

### 2.2.1 Annex 6, Chapter 3, Regulation 13 Nitrogen Oxide (NOx)

Vessels with engine power of 130kw or more, built or modified since 1 January 2000, are subject to an Engine International Air Pollution Prevention Certificate (EIAPP) issued by the engine manufacturing plant for maintenance and periodic inspection for suitability (Campara, Hasanspahi´c, Nermin and Vujici´c, Srdan, 2018). Nitrogen oxide emission standards are divided into Tier I at the current level, Tier II at the current level, which reduces nitrogen oxide emissions by 15 to 22%, and Tier III at the current level, which reduces nitrogen oxide emissions by 80% (ibid.,). <Table 2.1> shows the criteria for allowing nitrogen oxide emission restrictions according to the ship's age.

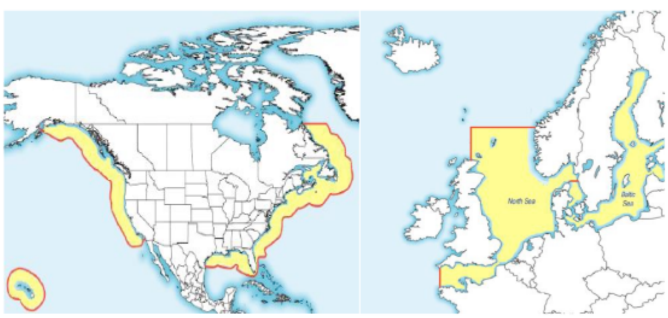
**Table 2. 1 MARPOL Annex VI NOx emission limits value**

| RPM (n = Rated Engine Speed) | Tier I | Tier II | Tier III |
|---|---|---|---|
| | 01.01.2001 ≤ Ship built < 01.01.2011 | 01.01.2011 ≤ Ship built < 01.01.2016 | After 01.01.2016 |
| **n < 130 rpm** | 17.0 g/kWh | 17.0 g/kWh | 17.0 g/kWh |
| **130rpm ≤ n < 2000rpm** | 45.0*n (-0.2) g/kWh | 44.0*n (-0.23) g/kWh | 9*n (-0.2) g/kWh |
| **2000 rpm ≤ n** | 9.8 g/kWh | 7.7 g/kWh | 2.0 g/kWh |

*Source: Own preparation, (Campara, Hasanspahi´c, Nermin and Vujici´c, Srdan, 2018), (KR, 2015)*

If the above conditions are not met, the vessel is inoperable, and to meet Tier III conditions in the emission control area, a separate selective catalytic reduction (SCR) may be mounted on the diesel engine to satisfy the conditions during navigation in <Figure 2.1>.

**Figure 2. 2 Emission Control Areas (ECAs) for NOx Emission Control**



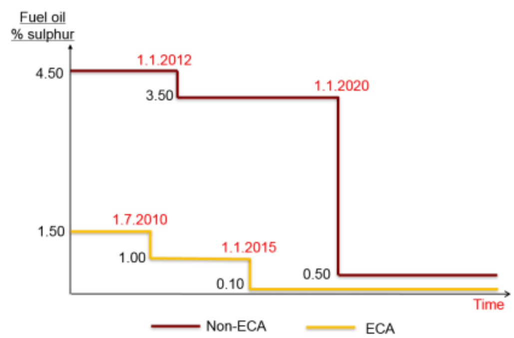
<North America, Caribbean ECA> <North Sea and Baltic Sea ECA>

*Source: IMO, (Bazari, 2020)*

### 2.2.2 Annex 6, Chapter 3, Regulation 14 Sulfur Oxide (SOx) and Particulates

In accordance with the regulations for reducing sulfur oxides, the sulfur content of fuel oil has been observed in general waters since January 1, 2012, and it was agreed at the 70th MEPC meeting in October 2016 to comply with the sulfur content of fuel oil less than 0.5% m/m from 2020. In the emission control area, the sulfur content of fuel oil has been maintained below 0.1% m/m since 2015. Vessels sailing in the emission control sea shall have a 'Fuel Oil Changeover Procedure' on the vessel and record the time, location, date, and time of low sulfur fuel conversion in the Engine Logbook. In addition, a method of installing an exhaust gas cleaning device issued with a compliance certificate on a ship may be used to navigate the emission control sea area and comply with the 2020 sulfur content limit.

**Figure 2. 3 Upper limit of SOx emission regulation**




*Source: IMO, (Bazari, 2020)*

## 2.3 Characteristics of IMO 2020 Sulfur Oxide Regulation

### 2.3.1 Regulation Applies to all existing ships and new construction ships

The most important feature of the IMO 2020 sulfur oxide regulation is that it applies not only to new ships but also to all ships operating in the zone. In addition, since there are methods other than physical modification methods for satisfying regulations, it is characterized that shipping companies do not necessarily need to modify ships to meet regulations. Physical modifications to meet regulations include installing sulfur oxide reduction devices, scrubbers, or completely replacing the ship's operating system with LNG propulsion ships. However, in addition to these physical modifications, shipping companies can meet the regulations simply by replacing ship fuel oil. This is what sets it apart from other existing ship environmental regulations. If the new regulations require physical modification, it is impossible to apply the regulation entirely to all existing lines, and the scope of the regulation was gradually and gradually expanded. For example, the difference is clear compared to the nitrogen oxide (NOx) emission regulation. IMO's NOx regulation divides the subject of regulation into Tier 1, Tier 2, and Tier 3 according to 'construction period' and 'operating area' (Bazari, 2020). Additional devices such as Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) are required on ships to meet emission regulations at each stage (ibid.,)

**Table 2. 2 Subjects and methods of application by environmental regulations**

| | **Target Ships** | | **Methods** | | **Regulation** |
|---|---|---|---|---|---|
| | Existing Ships | New Ships | Physical Modification | Non-Physical Modification | |
| **NOx** | ∆ | O | O | X | - Regulatory targets are subdivided into Tier 1, 2, and 3 according to the 'construction period', and 'operating area' of the vessel.<br>- Selective catalytic reduction or exhaust gas circulation is required on the vessel to meet emissions regulations. |
| **SOx** | O | O | O | O | - Applies to all existing vessels as well as to new construction<br>- Physical ship modifications are not essential to meet these regulations; simply replace ship fuel oil to meet ship regulations |

*Source: Own preparation, IMO* O: *Applicable* ∆: *Phased Application X*: *Non-Applicable*

However, as shown in Table 2.2, SOx regulation does not necessarily require physical modifications on the vessel. In other words, ships do not need to be modified or equipped an additional device to comply with environmental regulations in that it can be complied with by changing the fuel used. Therefore, it means that ships are not obligated to be equipped with exhaust gas cleaning devices such as scrubbers, and that fuel transition into low sulfur oil such as VLSFO or MGO can sufficiently comply with regulations.

### 2.3.2 IMO's High commitment to timely implementation

Drewry's survey data show that until 2018, most shippers and carriers were not ready for IMO 2020 and were not even aware of it (Damas, 2018). More than 90% of shipping companies did not conduct cost assessment following the enforcement of sulfur oxide regulations, and more than 4/5 shippers did not receive notice and clarification of freight increase from carriers (ibid.,). In addition, there is a precedent in which regulations have been delayed in protest of the IMO's decision. For example, Ballast Water Management Convention had been delayed for two years since it required all ships to be equipped with the device cleaning the ballast water (BEMA, 2021) (Riggio, 2019).

However, despite the unreadiness and unawareness of sulfur emission caps from shipping companies, and the risk of resistance from shipping companies such as BWMC regulatory delays, the intention to implement the regulation from IMO was remarkably high. In particular, through the 74th meeting of the MEPC (Marine Environment Protection Committee), which was held in May 2019, the IMO confirmed its willingness to implement sulfur oxide emission regulations in a timely manner. Prior to the 74th meeting, there were discussions on extending the timing of the regulation by five years, but the IMO concluded that there was no need for an extension after reviewing the possibility of regulatory enforcement of sulfur oxides, including the supply capacity of low sulfur oil (Saul, 2018). The IMO adopted guidelines for the implementation of consistent regulations through this MEPC 74th meeting, and the guidelines included the impact of the use of alternative oils on ships, responses to unregulated ships in individual port countries, and formats of FONAR (Fuel Oil Non-Availability Report) (European Commission, 2019). This does not deviate significantly from the PPR 6 (Pollution Prevention & Response) held in February 2019 and MEPC 73 held in October 2018 (IMO, 2019b). Hence, the uncertainty about the timely implementation of sulfur oxide emission regulations was greatly alleviated in the end. The summary of MEPC 74th meeting including major amendments can be found in <Annex 3>.

### 2.3.3 ECA Regional Expansion

Exhaust gas regulation is a sensitive issue that has a significant impact on the health of residents in coastal areas, and accordingly, major countries are very willing to participate in regulation. North America, the Baltic Sea, and the North Sea have already been designated as emission control areas (ECA), limiting the sulfur oxide content to less than 0.1% m/m1 (Svindland, 2018). Meanwhile, this ECA region is gradually expanding. On December 4, 2015, the Ministry of Transportation and Transport of China designated the Pearl River Delta, the Yangtze River Delta, and the Bohai Bay Rim areas as ECAs and gradually strengthened sulfur oxide emission regulations (Sun, Yang and Zheng, 2020). Until 2016, the use of fuel with a concentration of 0.5% or less was required at four major ports (Shanghai, Ningbo-Zhou Mountain, Suzhou, and Nantung) in the Yangtze Triangle (ibid.,). However, from 2018, the same regulations were strengthened to apply at all ports in the

ECA area (Urdahl, 2022a). From January 2019, the regulatory scope has been expanded to the entire area, and fuel with a sulfur content of less than 0.5% must be used not only for ships but also for all ships sailing in the area (Zis, Thalis P.V, 2021). In addition to IMO's ECA, there are also regulatory waters designated directly by the parties. The EU region will strengthen the sulfur content rates for all ships operating in ports and inland waterways in the EU region. By 2020, the upper limit of sulfur content will be regulated to 0.5% in all waters within the EU and 0.1% in EU ports (Urdahl, 2022b). In addition, Turkey, which is not a member of the EU, is forcing the use of fuel oil with a sulfur content of 0.1% or less on ships in port as well (Gard AS, 2011).

**Table 2. 3 Regulation status of sulfur content of ship fuel by region**

| | Area | Application Date | Sulfur Limit |
|---|---|---|---|
| **MARPOL Annex VI** | The whole sea area (except ECA) | 1.1.2012 | 3.5% |
| | The whole sea area (except ECA) | 1.1.2020 | 0.5% |
| | ECA | 1.1.2015 | 0.1% |
| **EU Directive 2005/33/EC** | At anchor in the European Union port | 1.1.2010 | 0.1% |
| | European waters outside the EU ECA | 1.1.2020 | 0.5% |
| **California OGV Fuel Regulation** | Within 24 miles of the California coast | 1.1.2014 | 0.1% |
| **Turkey** | At anchor in the harbor | 1.1.2012 | 0.1% |
| **Hong Kong** | At anchor in Hong Kong harbor | 1.7.2015 | 0.5% |
| **China** | At anchor in Shanghai, Ningbo, Zhou Shan, Suzhou, and Nantong ports | 1.4.2016 | 0.5% |
| | At anchor in Shenzhen Harbor | 1.10.2016 | 0.5% |
| | At anchor in Guangzhou, Zhuhai, Tianjin, Qinhuangdao, Tangshan and Huanghua ports | 1.9.2017 | 0.5% |
| | At anchor in the Pearl River Delta, Long Angle Delta and Bohai Sea waters | 1.1.2018 | 0.5% |
| | The Pearl River Delta, Long Angle Delta, and Bohai Sea waters from entry to departure | 1.1.2019 | 0.5% |

*Source: Own preparation, IMO, China Classification Society, EMSA, Indian Register of Shipping*

**2.4 Conclusions**

In conclusion, the regulation for the pollution in the maritime environment has been developing for nearly 50 years since the creation of the Maritime Pollution Treatment (MARPOL), and sulfur oxide regulations have been added since 2020. The regulation known as IMO 2020 is a part of MARPOL's Annex VI, which is the addition of sulfur oxide regulations after the regulation on nitric oxide was created. This sulfur oxide regulation has affected the shipping industry in various ways, which can be summarized as follows. IMO 2020 enforces the use of low sulfur oil, scrubber equipment, or alternative fuel for all vessels currently in operation and all vessels to be produced in the future. Despite the risks of resistance from shipping carriers and requesting regulatory delays, the IMO has decided to implement them in a timely manner, and all shipping companies must comply with the regulations as of January 2020. In the past, ECA existed locally and there were sulfur oxide regulations, however, the scope of regulation has been enlarged in that it has been expanded worldwide. Therefore, from the perspective of shipping companies, low sulfur oil such as VLSFO must be consumed inevitably, or a device such as scrubbers must be prepared to clean up exhaust gas to use high sulfur oil as it is. In addition, alternative fuel ships such as LNG and hydrogen will have to be introduced in the long run. It is inevitable that additional costs are incurred when all of the above measures are implemented, and it is necessary for shipping carriers to establish an optimal alternative in consideration of the accompanying costs and economic feasibility. In the case of VLSFO, appropriate oil price prediction is needed in that oil prices can float according to changes in market conditions, and if new equipment such as scrubbers is introduced, payback period should also be considered.

However, despite the additional costs involved to comply with the regulations are expected, this will promote sustainable development for a better environment and become a blueprint for the development of alternative fuels and ship technologies. In accordance with the implications of the regulations covered in this chapter, the next chapters will cover the strategies that shipping companies will choose in consideration of these regulations.

## Chapter 3: Strategic Options as a Countermeasure against the Regulation

In this chapter, the research focuses on the alternatives and strategies that shipping companies can take. First, alternative options for shipping companies are introduced including its characteristics, and limitations. Second, strategic evaluation is conducted by comparing and analyzing the advantages and disadvantages of each strategy. After that, thirdly, it discusses possible strategies that can be taken from the assessments presented in the previous parts. The goal of this chapter is to compare and analyze measures that shipping companies can adopt, and the optimal alternatives are calculated and clarified in the empirical modeling in the next chapter.

### 3.1 Alternative Options for Shipping Companies

Shipping companies can use three main methods to respond to regulations. The first is the use of low sulfur oil. It is an alternative for a variety of shipping companies since ship renovation costs are not expected, however, if the price difference between low-sulfur oil and high-sulfur oil in the future, there is a cost-bearing risk due to increased fuel costs. The second is the installation of scrubbers. Existing HSFO can be used continuously, and it removes the cost bearing risk of using VLSFO. However, the cost burden of installing scrubbers is high, and recently, risk factors are increasing as the number of open scrubbers prohibited areas increases. Third, LNG propulsion ships. Although it is in the spotlight as a clean fuel that can remove sulfur oxide emissions, the cost of investing in LNG ships is high, and LNG bunkering infrastructure is still insufficient. For renovation, according to Riviera, Hapag-Loyd reported that the cost of renovating the 15,000 TEU ship was $35 million (Snyder, 2021). For new ships, according to Clarkson Research, building new LNG Vessels costs $182 million to $303 million (2022 orderbook, 174,000 ㎥ size ships) (Clarkson Research 2022). In addition, since the tank in the LNG propulsion ship occupies more space than MGO and HSFO (DNV, 2014), it is inefficient in terms of ship loading capacity. Even if it is already renovated, it is still less competitive in operating maintenance costs, including fuel costs, than existing diesel propulsion ships. On top of that, additional ship management personnel must be hired under safety management, which will inevitably lead to an overall increase in costs. Moreover, only about 60 ports in North America, North Europe, and Northeast Asia can provide LNG bunkering at this point (Drewry, 2018a). In conclusion, at the moment, LNG propulsion ships are found to be expensive, high in cost for maintenance, and lacking bunkering sites leads to limitations in the shipping routes.

Therefore, this paper focuses on comparing low-sulfur oil use, and scrubber operations rather than incorporating LNG Propulsion Ship introductions. Accordingly, this section presents two possible countermeasures for shipping companies: the use of low sulfur oil and scrubbers.

### 3.1.1 Low Sulfur Oil

**Table 3. 1 General Fuel Oil Types and Sulfur content for Ships**

| Fuel Type | Sulfur Content |
|---|---|
| **ULSFO (Ultra-Low Sulfur Fuel Oil)** | Up to 0.1% |
| **VLSFO (Very-Low Sulfur Fuel Oil)** | Up to 0.5% |
| **HSFO (High Sulfur Fuel Oil)** | More than 1.0% |
| **MGO (Marine Gas Oil)** | 0.1~1.0% |

*Source: (Shell Marine, 2019)*

As summarized in <Table 3.1>, Ship Fuel Oil after IMO 2020 is divided into four types according to sulfur content. Fuel that meets the criteria set out by the IMO includes Marine Gas Oil (MGO), Low Sulfur Fuel Oil (including Ultra Low Sulfur Fuel Oil and Very Low Sulfur Fuel Oil), or mixed oil that meets the 0.5% criteria (Alfa Laval, 2019). The use of low sulfur oil is an alternative for a variety of shipping companies in a short term since the less burden of renovation costs compared to scrubbers or LNG propulsion ships is an attractive option. If low sulfur oil is used, there is no need to change the ship's engine or install other facilities, making no initial investment costs for shipping companies. Additionally, it is a relatively verified method since low sulfur oil has already been used in ECA waters since 2015. However, the excessive cost of fuel compared to the existing HSFO is expected to be a burden for shipping companies. The problem arises from the supply and demand of the products. Previously, low-sulfur oil purchased by shipping companies has been 0.1% MGO and 0.1% ULSFO to implement the 0.1% regulation of ECA waters announced since 2015 (ING, 2019). Among them, the MGO usage rate was high because of the lack of supply of ULSFO, and it is a product that lowered sulfur content to 0.1% by using a desulfurization device in the existing HSFO, which required refinery investment in desulfurization facilities. Additionally, there was not much demand for ULSFO from shipping companies since low sulfur oil was used only in ECA waters (ibid.,). As a result, refiners were not active in producing 0.1% ULSFO, and shipping companies often used MGO, a diesel with a slightly higher price (ibid.,). However, oil refineries have recently developed fuel oil with similar sulfur content as residual oil and mixed oil, and more oil refineries are expected to produce low-sulfur oil in the future. Through this, prices can be lowered through more supply expansion beyond making low-sulfur oil in the traditional method.

There are three methods for producing low-sulfur oil: a primary refinement of ultra-low-sulfur crude oil, a desulfurization of used-sulfur fuel oil, and a blending of low-sulfur heavy oil and other oils (Oil and Energy Trend, 2020). The profitability and characteristics of each process method are covered in the following section.

### 3.1.2 A Comparison of Low-Sulfur Oil Processing Methods in terms of Cost

As a factor that determines the price, in addition to the principle of supply and demand, the producer's production cost has a decisive effect on the price of the product. As low sulfur oil production is emerging, the process method and cost should be considered, and from the perspective of cost, the advantages and disadvantages of each process are summarized as shown in <Table 3.2>.

**Table 3. 2 Advantages and Disadvantages of producing Low Sulfur Oil by Process Methods**

| | Advantages | Disadvantages |
|---|---|---|
| **Low-Sulfur Light Crude Oil** | - Not necessary to invest in the facility | - Higher cost expected for manufacturing due to excessive costs of crude oil |
| **Desulfurization** | - Flexible adjustment of supply and demand for low-sulfur oil when it comes to market fluctuations | - Excessive costs of initial investment cost including building facilities. |
| **Blending** | - Minimize initial investment costs<br>- Flexible Adjustment of supply and demand of MGO, LFSO, and HSFO due to market fluctuations | - Concerns about poor compatibility between blending oils and possible quality problems such as sludge |

First, it is a method of producing low-sulfur oil by expanding the proportion of low-sulfur crude oil input. Crude oil is called "Sweet Oil" or “Light Oil” when it contains lower sulfur content, and "Sour Oil", or “Heavy Oil” in the case of high-sulfur oil (Yasin et al., 2013). According to statistics from the World Bank, light oil has an advantage in terms of cost since it does not require additional refining processes such as coking and cracking other than distillation (Bacon and Tordo, 2021a). Therefore, increasing the proportion of low-sulfur light oil, can increase the yield of light petroleum products including VLSFO. However, the cost of light crude oil is more expensive because of the scarcity and its usage on premium oil products (U.S. Energy Information Administration, 2016a).

In other words, to make VLSFO with light oil, a separate facility investment is unnecessary, and the input of crude oil can be adjusted according to the trend of low sulfur consumption, thereby flexibly responding to the demand for low sulfur oil. However, there is a disadvantage in that if the light crude oil prices increases, the cost of producing VLSFO will increase.

Second, it is a method of expanding desulfurization facilities. Refiners can convert high-sulfur crude oil into low-sulfur oil through the desulfurization process. In this case, it has an advantage since the cost of high sulfur crude oil is lower than the low-sulfur crude oil. According to U.S. EIA, the high sulfur crude oil is found to be low in price (U.S. Energy Information Administration, 2016b). Nevertheless, expanding new desulfurization facilities requires additional costs and investment decisions cannot be reversed once completed. Specifically, World Bank found that high sulfur crude oil is corrosive, and the production cost is high since the process is more complex (Bacon and Tordo, 2021b). In conclusion, if the price of low-sulfur crude oil falls and low-priced high-sulfur crude oil loses its price competitiveness, or if scrubbers are widely used and the demand for high-sulfur oil is high, the economic utility of the investment in desulfurization equipment may decrease.

Third, it is a method of producing regulatory compliance oil that meets the IMO 2020 standard by mixing low sulfur oil and high sulfur oil. Producing VLSFO with blending other existing oils is found to be the cheapest and easiest way for refineries (Díaz Delgado and Martínez de Osés, 2022). It is possible to make VLSFO by blending existing vacuum gas oil and low sulfur residue, and blending other existing oil can relieve the time and cost burden for refineries (Prajapati, Kohli and Maity, 2021). However, when the compatibility between blending oils is deteriorated, quality problems such as sludge may occur. It is found that VLSFO blends are paraffinic, increasing the risk of asphaltene precipitation during fuel-mixing operations (Kass et al., 2019). The asphaltene precipitation can occur sludges in the cold conditions, and if that happens in the engine, an additional cleaning process is required (ibid.,). Therefore, despite the advantages of being able to reduce prices from the supplier's point of view and being able to produce quickly, there is a risk that it can be avoided by shipping carriers due to quality problems.

#### 3.1.3 VLSFO Use and its Limitations

To conclude by summarizing the data described above, the use of low sulfur oil is a convenient alternative since it can respond to regulations within a brief period without additional investment, however, the shipping industry points out that applying low sulfur oil to engines that used high sulfur oil as their main fuel can cause various technical problems. Specifically, technical problems that may arise from the quality or variety of properties of low sulfur oil are also being discussed. The chemical make-up low sulfur fuels with variability will be a more issue than present-day fuels (Gulf Marine, 2019).

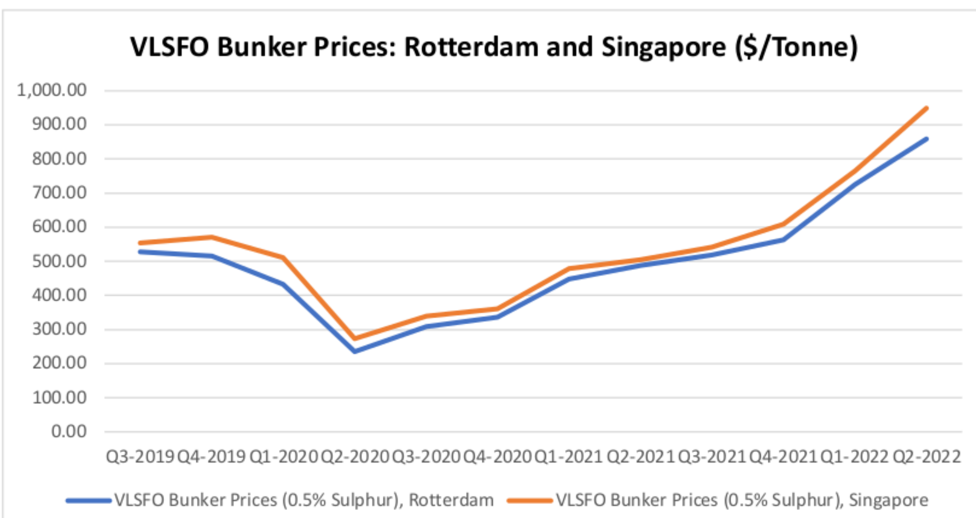
Another consideration for using low sulfur oil is that there is a risk of rising low sulfur prices depending on the supply and demand of low sulfur oil. For example, in the second half of 2019, ahead of the implementation of IMO 2020 regulations, the demand for low sulfur oil soared (see Table 3.3), and accordingly, the price of low sulfur oil also increased significantly. As shown in <Figure 3.1>, the spread between high sulfur oil and low sulfur oil traded at Singapore Port was at the level of $20/bbl. before the fourth quarter of 2019, but then soared to $60/bbl. in January 2020.

**Table 3. 3 Bunker Fuel Demand (mb/d)**

| Product | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | Annual % Growth | Annual Growth |
|---|---|---|---|---|---|---|---|---|---|
| Marine Gasoil | 0.9 | 1.3 | 1.2 | 1.1 | 1.1 | 1.0 | 1.0 | 2.5% | 2.3% |
| VLSFO | 0.2 | 1.3 | 1.6 | 1.8 | 1.9 | 2.0 | 2.1 | 51.0% | 31.5% |
| Marine HSFO | 2.9 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | -13.7% | -28.5% |
| Total Bunker | 3.9 | 3.8 | 4.0 | 4.1 | 4.2 | 4.2 | 4.3 | 1.3% | 5.2% |

*Source: (IEA, 2020)*

**Figure 3. 1 VLSFO Bunker Prices: Rotterdam and Singapore ($/Ton)**

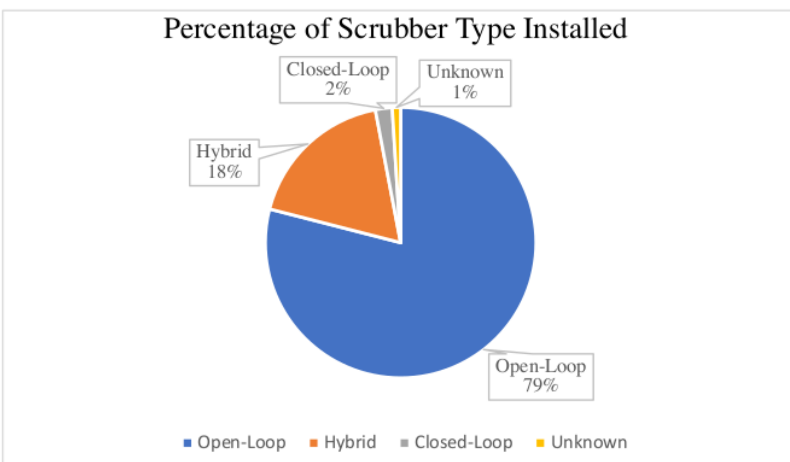



*Source: (Clarkson Research, 2022)*

### 3.1.4 Exhaust Gas Cleaning System: Scrubber

Scrubbers are equipment that reduces sulfur oxides for ships, and shipping companies can continue to use existing HSFO by installing scrubbers. In other words, it is an equipment for washing exhaust gas using water, which can be largely divided into an open-loop, a closed-loop, and a hybrid method. The open method is to dilute the acidity of sulfur oxide by spraying it to exhaust gas using seawater and discharge the seawater that has escaped the scrubber into the sea. The closed type purifies sulfur oxide using purified water to which sodium hydroxide (NaOH) is added, not seawater, and the purified water used is reused. A small amount of water containing impurities is a system that separates impurities and releases them into the sea. In general, the scrubber method preferred by shipping companies is 'open-loop' since the closed type is about twice as expensive to install than the open type. In fact, open type accounts for 79% of the global scrubber market. However, with the recent spread of the ban on the use of open scrubbers in each sea area, some shipping companies are adopting hybrid methods. The hybrid type is a method that uses both seawater and purified water and has the advantage of being able to use the closed type in areas where the open type cannot be used. According to the Norwegian Shipbuilding Association DNVGL, as of July 2019, open type accounted for the most at 79%. For hybrid type accounted for 18%, and closed type at only 2%. In addition, 74% of the existing ships were renovated to install scrubbers, and 26% of new shipbuilding ships.

**Figure 3. 2 Percentage of Scrubber Type Installed**




*Source: (DNVGL, 2019)*

### 3.1.5 Open-Loop Scrubber (Sea Water Scrubber)

Open-Loop Scrubber is the seawater-based exhaust cleaning system neutralizing the acidified exhaust gas using the natural alkalinity of seawater, and the seawater absorbs sulfur oxides of the exhaust gas and is separated into sludge and cleaning water through cleaning work, and the sludge is discharged to the sea and unloaded to the land receiving facility when the ship is anchored (Yang et al., 2021). The seawater-based exhaust gas cleaning system is applicable to both new ships and existing ships and can be used in all ship diesel engines (engine, auxiliary engines, boilers, etc.) (ibid.,), and is reported to have an excellent sulfur oxide reduction performance of about 99% and 50 to 70% (U.S. Environmental Protection Agency, 2021).

### 3.1.6 Closed-Loop Scrubber (Fresh Water Scrubber)

Closed-Loop Scrubber is the fresh water-based exhaust gas cleaning apparatus using caustic soda (NaOH) as a catalyst for absorption and reaction of sulfur oxides (Tran, 2017). It is useful when cleaning function is needed in seawater areas where natural alkalinity of seawater is insufficient. Fresh water absorbs sulfur oxides of exhaust gas using catalysts according to the same principle as seawater-based cleaning devices and is separated into sludge and cleaning water (ibid.,). However, sludge separated from the clean water-based exhaust gas cleaning device is stored on the main line and unloaded on land, just like the seawater cleaning device, however, Fresh Water, which is cleaning water, is recycled through a reprocessing machine and continuously used for sulfur oxide absorption (ibid.,). Additionally, the freshwater cleaning system is suitable for new ships, existing ships, and diesel engines, and cleaning the exhaust gas emitted when using fuel oil with a sulfur content of 3.5% m/m or less is equivalent to that of fuel oil with a sulfur content of 0.1% m/m, and particulate matter is reduced by 30-60% (Endres et al., 2018).

### 3.1.7 Hybrid Scrubber

Hybrid scrubbers are mostly used in open-loop mode at sea and are run in close-loop mode in ECA areas and ports for easy switching of applications (Indonesia Marine Equipment, 2020). It is reported that sulfur oxides of exhaust gas can be cleaned nearly 99% when using the complex system as a cleaning device that uses both seawater and fresh water, and particulate matter is reduced by 80% (Lloyd's Register Marine, 2015) (EGCSA, 2012). As mentioned above, in recent years, the use of Open Loop type scrubbers using seawater is limited within ECA, so the hybrid type has a great advantage.

**Table 3. 4 Comparison of SOx Scrubber Technologies**

| | Open Loop Scrubber | Closed Loop Scrubber | Hybrid Scrubber |
|---|---|---|---|
| **Main System Components** | - Scrubber<br>- Wash water piping<br>- Wash water pumps<br>- Wash water treatment Equipment<br>- Sludge handling Equipment | -Scrubber<br>-Wash water piping<br>-Wash water pumps<br>-Wash water processing Tank<br>-Wash water holding Tank<br>-Sodium hydroxide storage tank<br>-Wash water treatment Equipment<br>-Sludge handling equipment | -Scrubber<br>-Wash water piping<br>-Wash water pumps<br>-Wash water processing tank<br>-Wash water holding tank<br>-Sodium hydroxide storage tank<br>-Wash water treatment equipment<br>-Sludge handling equipment |
| **Operation in Fresh Water** | X | O | O |
| **Operation Without Discharge to sea** | X | For a limited time depending on the size of the wash waters holding tank | For a limited time depending on the size of the wash water holding tank |
| **Weight** | 30-55t | 30-55t | 30-55t |
| **Power Consumption** | 1-2% | 0.5-1% | 0.5-2% |
| **Scrubbing Chemical consumable** | X | Sodium hydroxide solution (≈6 l/MWh·%S) | Sodium hydroxide solution (≈6 l/MWh·%S) |
| **Particulate Matter Removal** | O | O | O |

*Source: (Lloyd's Register Marine, 2015)*

### 3.1.8 Scrubber Installations and its Limitations

The method of installing scrubbers meets the standards for regulating sulfur oxides strengthened in general waters while continuing to use low-sulfur oil. Since existing high-sulfur fuels can be continuously used, it is less risky than confronting low-sulfur oil price fluctuations. In addition to sulfur oxide, there is an advantage in that it is possible to reduce Particulate Matter. However, the biggest disadvantage is that the initial investment cost is high at $1 million to $8 million (Jotun, 2020), although the renovation cost varies by type. Moreover, it takes a considerable period to install, resulting in operational losses during the renovation period. In addition, a separate space is required to install the scrubber, which can reduce the shipping space of cargo, and since the weight is around 30-55 tons, there are disadvantages such as power consumption depending on the scrubber operation. Furthermore, even if a scrubber is installed, the possibility of confronting additional regulations cannot be excluded. In fact, the ban on open scrubber entry is expanding in major ports. To date, open scrubbers have been banned in Belgium, Germany, the Rhine River, Dublin, Ireland, Latvia, Lithuania, the United States (California and Connecticut ports and waters), the United Arab Emirates, Singapore, and Norway (see <Figure 3.3>) (EGCSA, 2022). Additionally, since January 2019, China has announced a ban on the discharge of open scrubber cleaning water from China's inland rivers and ECA areas that cover most coastal lines (Reuters, 2019). Even major ports such as Norway and Singapore prohibit the entry of open scrubber vessels, and ships equipped with scrubbers must use low sulfur oil in the underlying areas (North, 2022). Therefore, shipping companies currently considering installing scrubbers are facing uncertainty due to the possibility of expanding sanctions on open scrubbers. The IMO considered the environmental impact of cleaning water emissions and decided to discuss them at the 7th Sub-Commission on Pollution Prevention and Response (PPR), however, it was decided that the discharge water quality criteria would be reviewed when more data were accumulated (International Union of Marine Insurance, 2022). For this reason, the fact that there is uncertainty in sanctions in installing scrubbers acts as a risk.

**Figure 3. 3 Regulations on the use of scrubbers**


*Source: (Exhaust Gas Cleaning System Association, 2022)*

- *Green: Scrubber available, IMO criteria (MEPC).259 (68) Washable water can be discharged if satisfied.*
- *Yellow: Scrubber is available, additional criteria are applicable by country and region.*
- *Black: Scrubber available, do not discharge open loop scrubber cleaning water.*

### 3.2 Overall Advantages and Disadvantages of VLSFO and Scrubber Strategies

The advantages and disadvantages both VLSFO use, and scrubber use strategies can be summarized by combining the previous parts. Following <Table 3.5> shows the comparison between them.

**Table 3. 5 Advantages and Disadvantages of VLSFO and Scrubber use**

| | Advantages | Disadvantages |
|---|---|---|
| **VLSFO** | - Available for most ships.<br><br>- No need for physical modification, such as engine modification and additional equipment installation. This reduces<br><br>- Physical modification is not required, and it can be applied immediately without incurring initial investment costs compared to scrubber installation.<br><br>- Supply expansion is possible due to desulfurizing facilities from refineries will be completed in the coming years. | - Risk of rising oil prices (fuel costs) as demand increases. Low sulfur oil has a price range of about 40% higher than that of existing high sulfur oil.<br><br>- Quality assurance problems due to fuel conversion and application of existing engines.<br><br>- Risk of temporary shortage of supply and demand due to an increase in demand in the initial stages of regulatory enforcement and transitional periods. |
| **Scrubber** | - High-sulfur oil, which is relatively inexpensive compared to low-sulfur oil, can be used.<br><br>- Can be installed on an existing ship.<br><br>- Can reduce fine dust (PM (Particulate Matter)) as well as sulfur oxide (SOx)<br><br>- Flexible response to low sulfur oil price fluctuations. | - Initial investment costs are incurred, and operational losses are incurred during the installation period.<br><br>- A separate installation space is required, and the cargo capacity is reduced due to a decrease in the cargo space.<br><br>- Cannot install on small ships, low economic feasibility expected when installed on old ships.<br><br>- Additional power consumption and increased operational energy.<br><br>- (Open- Loop Scrubber) The existence of additional regulatory possibilities for scrubber cleaning water. |

*Source: Own preparation*

The VLSFO use strategy and the scrubber use strategy have opposite advantages and disadvantages, respectively. This is because each strategy uses different types of fuel oil, and the existence of initial investment costs contradicts. Therefore, shipping companies need to make appropriate choices according to the type, size, and age of the ship owned by the company. Large shipping companies can choose both strategy since they handle various types of ships and routes. In contrast, small and medium-sized shipping companies should choose strategies in consideration of the type of container ships and route length that each company focuses on.

Additionally, it is necessary to respond to future regulatory risks through the establishment of a flexible portfolio. As mentioned earlier, the prohibition of entry of open-loop scrubber equipped ships is being introduced by port officials in each country. The Singapore Maritime Port Authority (MPA) describes it as a "policy to protect the marine environment and maintain clean and continuous water quality at the port." (The Maritime Executive, 2018). Singapore's policy is recognized as a risk that other countries' restrictions on scrubber use could increase further in the future. Hence, there is a possibility that the use of open-type scrubbers will emerge as a risk. In line with changes in new environmental regulations in IMO and individual countries, domestic shipping companies should be able to reasonably adjust their strategies, and expand the flexibility for their optimal portfolio in consideration of their own shipping patterns.

### 3.3 Conclusion

In conclusion, each strategy should be comprehensively considered along with the cost of the opposite strategy. In other words, the installation of the scrubber or VLSFO use strategy will be determined by the cost of installing the scrubber, the price spread between low sulfur and high sulfur oil, and the amount of fuel consumed by the ship.

Firstly, the cost of installing the scrubber consists of the cost of the scrubber's own equipment, installation cost, and operational expenses, which vary depending on the type of ship, and manufacturer (Barleta and Sánchez, 2019). In addition to the various prices of scrubbers, the overall price can fluctuate as well. Increased demand for scrubbers can cause a rise in scrubber prices, however, prices may fall if supply expands. In other words, various factors determine the price of scrubbers, and shipping companies must accurately predict them to consider introducing strategies. As the initial investment cost accounts for a large portion of the scrubber's cost, the importance of this increases as well.

Secondly, the larger the price spread between high sulfur oil and low sulfur oil, the shorter the recovery period of scrubber installation costs, which is expected to increase the demand for scrubbers. Immediately after the implementation of IMO 2020, the price of low sulfur oil (LSFO) is expected to rise due to increased demand and insufficient supply from refineries, while the demand for high sulfur oil (HSFO) is expected to decrease, widening the price difference between the two fuel oils (Shuaibu, 2019). In this case, the recovery period of the scrubber installation cost will be shortened, and the demand for scrubbers will increase. On the other hand, an extension of the supply of VLSFO can decrease the price gap with HSFO. As such, high sulfur oil and low sulfur oil prices continue to fluctuate depending on market conditions. Therefore, accurately predicting the price of fuel oil will also be an important strategy for shipping carriers.

Thirdly, whether to install scrubbers will be determined according to ship types, engine specifications of it, fuel consumptions, and ship ages. Containerships have a variety of TEU types, sizes, and the engines mounted of each vessel are different as well. Since different types of engines will require different types of scrubbers, shipping companies should organize their portfolios in consideration of the various price factors described above. Additionally, Container ships have a lifespan, and the decision on whether to install scrubbers will vary depending on new and old ships.

All things considered, shipping companies will choose the strategy according to the scrubber price, the price of low-sulfur and high-sulfur oil, and the type and age of the ship they operate. Accordingly, this study aims to analyze the data by considering each element discussed above as a whole, and to discuss the optimal alternative that shipping companies can take through empirical modeling in the next chapter.

## Chapter 4: Literature Review on Impacts of IMO 2020 and Responses from Industry

### 4.1 Introduction

In this chapter, a literature review is conducted on the impact of IMO regulations and responses from the industry. This is to find out the effects of IMO 2020 and MARPOL VI amendments on the industry on top of the previous research: IMO regulations and their development overview, characteristics of the regulation, and its implications. In other words, this literature review analyzes the impact on the industry, the response of shipping companies, and the potential impact of this response from a cost perspective. Along with the conclusions, the assumptions for strategic analysis and empirical analysis to be discussed in the next chapter are presented.

### 4.2 Impacts on Fuel Oil and Shipping Industry

According to Vedachalam et al., it suggests that MGO/MDO, VLSFO or alternative fuels could be considered for compliance with IMO requirements. In the case of MGO/MDO, desulfurization is possible in various methods such as vacuum distillation and thermal cracking, however, this has a disadvantage in that the unit price is much more expensive than other fuel types (Vedachalam, Baquerizo and Dalai, Ajay K, 2022). In the case of VLSFO, in addition to the desulfurization process, crude oil from Australia, Nigeria, and Brazil can be refined, and in addition, it can be manufactured through blending with ULSFO, MGO, and residual oil, which has an advantage in securing supply (ibid.,). Moreover, it is predicted that supply expansion through more refining methods is possible since there are other refinery methods such as Hydrodesulfurization (HDS), Extrusive desulfurization, Oxidative desulfurization (ODS), and microbe desulfurization using hydrogen (ibid.,). The use of VLSFO and ULSFO has advantages in terms of time and cost for shipping companies in that there is no need to renovate or make new ships. However, energy transition into alternative energy has the advantages of reducing other greenhouse gas emissions including carbon dioxide and carbon monoxide other than SOx. LNG, hydrogen, alcohol, ammonia, biofuels, and solar power can be considered, although more research is needed to use them more cost-effectively since low energy densities and higher production costs are expected (ibid.,). To summarize this study, one the one hand, the study shows that it is necessary to introduce alternative fuel ships in a long-term and establish a plan to lower prices through gradual research and development. On the other hand, it shows that the introduction of VLSFO is cost-effective than alternative fuels from the current price perspective since the capital cost of introducing alternative fuel propulsion ship is remarkably high. Moreover, it implies that the possibility of increasing the production of low-sulfur oil through various refining technologies in the near future, and it can be expected that the extended supply will be able to meet the soaring demand.

**Table 4. 1 Advantages and Disadvantages of Low Sulfur Oil and Alternative Fuels**

| | Low Sulfur Oil | Alternative Fuels |
|---|---|---|
| **Advantages** | • **Supply Extension Available**: VLSFO can be produced due to many methods, so it is possible to expand the supply amount.<br><br>- Instead of using traditional vacuum distillation and thermal cracking methods, Hydrodesulfurization, extrusive desulfurization, Oxidative desulfurization, and microbe desulfurization using hydrogen may also be used.<br><br>- A blending method using existing oil with ULSFO, MGO, and residual oil can be used.<br><br>• **Crude Oil with Less Sulfur is Available:** In addition to the desulfurization method to produce low sulfur oil, it can be produced using crude oil from Australia, Nigeria, and Brazil with low sulfur content. | • **Environment Friendly:** In addition to sulfur oxide emissions, carbon dioxide, greenhouse gas, and particle matter can be reduced, which has advantages in the environment.<br><br>• **Advantageous to Further Regulations:** There is an advantage assuming that IMO's air environment regulations will be further strengthened in the near future. |
| **Disadvantages** | • **Expensive in Major Production Methods**: Desulfurization process with vacuum distillation and thermal cracking is expensive.<br><br>• **Limited to only SOx reductions:** Low sulfur oil has a small content of sulfur oxides but has a limitation in that it emits carbon dioxide, greenhouse gases, and particulate matter. | • **High Cost:** With current technology, the energy density is low, and the production cost is high to produce it<br><br>• **Technical Limitations on Voyage Routes:** Due to technical limitations, it is currently operated only for short operating distances on small ships.<br><br>• **Fuel Production is not Green:** Green ammonia, green methanol, and green hydrogen have to be developed to achieve complete carbon neutrality. |

*Source: Own Summary from Vedachalam, Baquerizo and Dalai, Ajay K, 2022*

### 4.3 Impacts on Market Concentrations and Competitions of Shipping Industry

According to Chrysouli A., it is found that the smaller the liner shipping companies are, the more passive they took on IMO 2020 regulations when it comes to fuel compliances (Chrysouli, 2018). This is the result of the fact that changing marine fuel is uncertain in efficiency and availability (ibid.,). Consequently, it predicted that the concentration of the market will be lowered, making a structure that more companies will be competing. However, it is analyzed that this is a phenomenon that occurs as a short-term. A number of small and medium-sized shipping companies will be able to compete with large shipping companies in the short term, however, large shipping companies will choose alternative fuel from a long-term perspective. Eventually, this will make a gap between the small companies in that they have a limited financial availability to introduce alternatives. As a result, it suggested that the market share of large shipping companies would rise again eventually, since following regulation compliance is the most efficient solution in that it cannot go against IMO's decision.

This study did not only a fragmentary analyzed that IMO's regulatory enforcement lowered the market concentration, but also suggested that more intense competition would occur when the market concentration is lowered. The reason is that the IMO regulation makes shipping companies have a tight time and cost challenges which eventually make the overall container shipping industry more competitive (ibid.,). Since shipping companies purchasing new alternative fuel propulsion ships, the overall renovation of the ship will not be implemented much in the short term, the research predicted that the Herfindahl-Hirschman Index, the market concentration index, will keep staying low for short and mid-terms.

**4.4 Cost-benefit Analysis on Low Sulfur Oil and Scrubber Use**

Various preceding studies have been conducted to analyze the economic feasibility of using low sulfur oil and scrubber. This is largely divided into two studies that compare and analyze the economic feasibility of using low sulfur oil and scrubber in general, and studies that focuses on specific regions or ports as examples. In addition, there is a study of selecting VLSFO with low sulfur oil, and a study of selecting MGO. However, previous studies suggest that there will be a change in the price of Fuel Oil in the future but not directly applying these in the scenarios, and some apply it directly in the price of low sulfur oil or a change in the price of scrubbers. Case research focuses on regional analysis; however, it is highly related to the study in this paper in that it compares the use of low sulfur oil and scrubbers.

First, according to the study of cost-benefit analysis on Low Sulfur Policy by Wu and Lin, it is found that the VLSFO strategy has a higher total incremental cost than the scrubber strategy in the first 4.14 years, but then, the trend is reversed (Wu and Lin, 2020). In addition, Cost-Benefit ratio of scrubber is found to be 3.3 years higher than the VLSFO strategy, which means that the VLSFO strategy is economical considering a period of more than 3.3 years (ibid.,). It indicates that scrubber for ocean route containership is short-term strategy within 3.3 years, and VLSFO strategy is less pollutant for periods longer than 3.3 years (ibid.,). This study determines a fixed route for one existing container ship and a bunker location to calculate the cost of using VLSFO. However, in the case of HSFO and VLSFO prices, it is calculated based on Drewry's 2020-2023 price forecast, which assumes that HSFO has little upward trend and VLSFO has a lower price. In other words, the price of VLSFO falls for five years, and the HSFO price is assumed to remain in nearly the original state. In the case of modelling, the Total Increment Cost is calculated, and for VLSFO, there is no CAPEX, and the price difference between VLSFO and HSFO is OPEX. On the contrary, Scrubber chose CAPEX as the installation cost, and OPEX selected the maintenance cost. This revealed that the value calculated by modelling the intersection of the Increment Cost was 4.14 years, and since then, the VLSFO strategy has been concluded to be a less costly strategy. Cost-benefit Analysis is calculated by comparing the cost of spending to reduce employment with the amount of GHG employment decreasing and concluded that the VLSFO strategy was economical for the first 3.3 years and the scrubber was economical thereafter. This suggests that scrubber has a more economical burden than VLSFO use initially. However, after 3 to 4 years, both methods show price stabilization, with additional costs decreasing.

This study focused on reality when it comes to ship selection since it set the scenario target with currently operating vessel data, bunkering areas. Additionally, it reflected the frequency and annual operating distances. Furthermore, the amount of greenhouse gases emitted was also calculated and reflected in the cost-benefit ratio, so it is possible to see how much greenhouse gas reduction the use of VLSFO and scrubber can achieve. However, for the oil price forecasts, there is a limitation in that they simply relied on Drewry's predictive data, hence, some could suggest a doubt about the reliability of the assumption that HSFO prices rarely change. In addition, VLSFO prices were predicted to fall, however in reality, the prediction was wrong since VLSFO prices rose from 2020 to 2022 (Clarkson Research, 2022). Misguided predictions evoke unrealistic results, although the data setting for the vessel and shipping routes were realistic. Therefore, to overcome the limitations of relying on forecast data, additional studies assuming that the trend of fluctuations in fuel oil prices from the past to the present is maintained are needed. Hence, this paper will be conducting the scenario modeling that includes the average trend of fuel oil price fluctuations from the past to the present in the following chapter.

Second, according to the research from Andersson et al.'s scrubber lifecycle and Cost Assessment, a combination of VLSFO and MGO showed a payback period of 5.4 years for open-loop scrubbers and 5.9 years for closed-loop scrubbers (Andersson, Jeong and Jang, 2020). If only MGO was used without VLSFO, the open-loop scrubber was calculated to be 3.2 years, and the closed-loop scrubber was calculated to be 3.6 years (ibid.,). This research attempted to calculate the emission potential by comprehensively considering the weight, operation cost, and installation cost of the scrubber, and the Life Cycle Assessment was conducted using the GaBi modeling method. As a result, although the Emission Potential is large for scrubbers, this suggests that design improvements are needed in terms of scrubber power consumption and transportation (ibid.,). The Cost Assessment assumes that fuel costs are based on bunkering costs in August 2020, scrubber costs are between about $4.5 million for open routes and between $3 million and $6 million for closed loops. Accordingly, the annual saving according to the scrubber type appears as follows.

**Table 4. 2 Yearly Savings in Fuel Costs compared with No Scrubbers (US $)**

| Fuel Combination | Open Loop | Closed Loop | No Scrubbers |
|---|---|---|---|
| **IFO 180 + MGO** | $ 5,135,101 | $ 5,094,667 | - |
| **IFO 380 + MGO** | $ 4,202,047 | $ 4,089,730 | - |
| **VLSFO + MGO** | - | - | $ 5,057,851 |
| **MGO** | - | - | $ 5,659,944 |

*Source: (Andersson, Jeong and Jang, 2020)*

This study is significant in that the payback period was calculated for each type of scrubber and the scrubber price was predicted through various previous research data. In addition, the use of MGO as well as the use of VLSFO was considered, and the assumption of using a mixture of them gives a difference from other scrubber strategy studies. However, this study has two limitations: first, the selection of scrubber types. There is a limitation in that open-loop scrubbers cannot be used in situations where they will be regulated. Moreover, only the closed-loop has been selected and the hybrid method has not been selected for its scenario compositions. Second, it is assumed that only MGO is used, but the scenario using VLSFO is not assumed to be used only with VLFSO, assuming that it is used in combination with MGO. Therefore, this paper will be conducting the study that includes the scenario analysis using hybrid and closed loop scrubbers and VLFSO in the following chapter.

### 4.5 Low Sulfur Oil and Scrubber Strategy Comparison by Case Research

Several studies show the VLSFO and Scrubber use strategies by case research. First, Fan,L. et al used Net Present Value model for evaluating fuel switch (to Low Sulfur Oil) and using hybrid-scrubbers in Chinese SECA (SOx Emission Control Area) area. For the NPV calculation, the number of voyages for the vessel and the TEU, loading factor, and freight rate are considered together. The ship was set as an anonymous ship listed on Clarkson's World Fleet Register, and the bunkering price was set as China's bunkering price in 2019. According to the results, it is more economical to use scrubbers if the rate of going through SECA areas during the shipping routes is more than 30%, and it is more cost-beneficial to use low sulfur oil if the price difference between high sulfur oil and low sulfur oil is less than 24% (Fan, Gu and Luo, 2020). Moreover, regarding the loading factors going above 65% and freight rates changing from $140/TEU to $240/TEU, the scrubber use is more beneficial if the scrubber cost goes down by 50% from the current level (ibid.,). Furthermore, it assumed 3%, 5%, 10% as discount rate respectively, and NPV calculation showed that 3% discount rate always showed higher NPV values. It means that lower the discount value is, the less the suitability for investing scrubbers. Therefore, in conclusion, it is advantageous to use low sulfur oil for container ships with long routes, and it is beneficial to use hybrid scrubbers for small and medium-sized container ships with a larger ratio of passing SECA among all routes (ibid.,).

This study suggests that economic feasibility changes according to ship size and type in that it analyzed the change in cost-benefit by the ratio passing through SECA. In addition, this study analyzed that the price difference between ULSFO and HSFO would be a critical factor for selecting scrubber strategies, and the larger the price difference between low-sulfur oil and high-sulfur oil, the more economical it is to use scrubbers. This paper is a study conducted by limiting the regional scope to China, however, it is also related to other countries and regions in that the Sulphur Emissions Control Area is distributed worldwide. For ship selection in the scenario, it uses a realistic data from the actual vessel running as a container vessel. In addition, the calculation result can be found to be more realistic in that NPV calculation was performed by considering TEU, Loading Factor, and Freight Rate in various ways. However, this study only analyzed the economic comparison between scrubbers and VLFSO use according to the rate of ships staying in SECA, and the extent of price drops for scrubbers make the VLSFO strategy more beneficial. Accordingly, there is a limitation in that the capital recovery period was not considered by analyzing the increase in costs to be borne by using scrubbers and VLSFO or the breakeven point of scrubber investment costs.

Second, according to Antturi et al., whether the use of low-sulfur oil including VLSFO and MGO and the use of scrubbers are economical can be calculated by the cost-benefit framework and sensitivity analysis (Antturi et al., 2016). In this paper, impact pathway analysis was used to analyze the impact on people by decreasing partial matter, and cost analysis was performed by comparing quantified estimation of health benefits with the cost of using low sulfur oil and scrubber. Accordingly, it was analyzed that a gain of €105 million and a loss of €465 million occurred (ibid.,). In other words, it was concluded that there was no benefit in terms of partial matter compared to the cost of low sulfur oil and scrubber investment. In addition, previous studies have refuted that the use of low sulfur oil has positive cost benefits to the Baltic and North Sea at the same time (E et al., 2015). Furthermore, it is found that sulfur regulation generates the profit from €17 M to €453M, from the worst case to the best case, respectively (Antturi et al., 2016). However, the cost is calculated to be from the worst case to the best case as €272 M to €671M, meaning that sulfur regulation is not cost-beneficial in the Baltic Sea area (ibid.,). The result came out based on cost analysis calculated by comprehensively considering shipping volume of Baltic countries, low sulfur oil and high sulfur oil prices, scrubber installation costs, and operating costs. The author agreed the previous research results that the use of low sulfur oil and scrubbers generally has a positive effect on the Baltic and North Sea regions but analyzed that the cost benefit is low if only the Baltic regions are analyzed separately (ibid.,). The reason that Baltic Sea Shipping area shows around four times more costs with sulfur regulation is that the regulation gives greater benefits to coastal areas near the SECA area or port cities used as major routes. Accordingly, the research suggests the benefits of regulation compliance are uneven in that countries far away in Central Europe will spend more, and countries that dominate major routes and markets will benefit greatly.

This study has a significance in that it quantifies and analyzes the total cost of using low-sulfur oil and scrubbers and the total gains on human health from a more holistic and broad perspective of the North Sea and Baltic Sea countries. Therefore, it is possible to compare not only the costs borne by shipping companies, but also the impact on society. However, the limitation of this study is that it analyzed only the particulate matter reduction effect and health benefit while analyzing the low sulfur oil and scrubber use strategy used to reduce sulfur. In addition, it is difficult to independently know the influence on shipping companies through the results of the paper, and it is a data that shows how large the loss will be nationally and regionally. Therefore, if there is a study focusing on the impact on shipping companies as an additional study, it will be possible to find out how low sulfur oil and scrubber use of shipping companies will affect companies and communities when considered together with this study.

Third, according to Shuaibu, using low sulfur oil is the best compliance solution and using high sulfur oil with the scrubber is found to be the second-best solution for shipping companies (Shuaibu, 2019). In other words, the study selected MGO as the low sulfur oil compliance method and using MGO is more proper than using scrubbers. The result comes from several statistical analysis and details are as follows. In TOPSIS scenario modeling, MGO was analyzed to be suitable for use with 0.47 normalized positive ideal point, and for 0.27 for HFO/Scrubber (ibid.,). This is the "Normalized Rating", a statistical result considering attributes such as fuel cost, freight rates, and cost of investment. Moreover, a sensitivity analysis including CAPEX, MGO, Freight Rates, HFO, and Bunker Costs showed that CAPEX is the biggest factor in setting up an alternatives considering cost. Accordingly, HFO/Scrubber use offer an economic advantage in a short term and mid-term, and it confirmed the economic feasibility of retrofit scrubbers. However, low sulfur oil including MGO does not require CAPEX, thus meaning that economic feasibility of these is the most cost-efficient.

Nevertheless, this study concluded that the price of low sulfur oil would be increased in price due to high demand and low sulfur oil has a risk of fuel quality since some refineries produce it with a mixture of high sulfur oil and other petroleum products. Low sulfur oil made by the blending method may generate sludge in the engine, causing engine failure (ibid.,). Moreover the study analyzed that the payback period of scrubber use would be 3 years and argued that scrubber use would be optimal when the operational cost limit is overcome in the future. This study is significant in that it analyzed the economic feasibility of low sulfur oil and scrubber by mathematical analysis methods such as sensitivity analysis and TOPSIS method, and derived results considering freight rate, bunkering cost, and CAPEX together. However, it has a limit since the author only considered MGO as a low sulfur oil even though VLSFO has been widely used for shipping companies complying IMO regulation. In addition, although it suggested that there would be a change in the price of low sulfur oil, it was not analyzed by reflecting this in the scenario. Therefore, further research is needed, including price fluctuations in low sulfur oil and in particular, VLSFO.

Fourth, according to the cashflow modelling from Panasiuk and Tukina, using scrubber is more effective in any scenario where the MGO fuel costs go up 170% and 340% (Panasiuk and Turkina, 2015). This increase is due to the fact that the price of all-time High Sulphur IFO and MGO rose between 30% and 250% by 2015, and the author predicted that there would be a greater price increase due to rising demand. This modeling investigated the scrubber capital recovery period at the time of oil price fluctuations in consideration of five years of NPV, and it is found that scenarios of continuing current MGO fuel price, 1.7 times, and 3.4 times of increase could all be converted into a surplus within two years (ibid.,). Modeling has been conducted on a particular vessel (DFDS Cargo Perry). In each scenario where the price of low sulfur oil rises, the method of using scrubbers generates profits of 216% and 522%, respectively (ibid.,). In addition, the payback period is analyzed from 0.5 years to a maximum of 1.75 years, which is relatively lower than those found from another research stated above. In conclusion, the payback period analyzed 1.57 years if the current price is maintained, 0.57 years if the MGO price rises 1.7 times, and 1.13 years if it rises 3.4 times.

This study shows significance in that the payback period of the scrubber can be calculated short within 2 years. However, since this study analyzed with a conclusive assumption that the use of MGO and scrubber is currently one of the most suitable methods, other low-sulfur oils such as VLSFO and ULSFO cannot be analyzed. There is a lack of concrete evidence that Low Sulphur MGO is the most suitable method, and assumptions with 170% and 340% price increases lack data evidence as well. Additionally, the price fluctuation of the scrubber is not considered in this study, hence making a necessity for future research on it. It is realistic in that the paper selected Danish shipping company DFDS' cargo ship that is being used in real life and calculated NPV and Payback Period of it. However, the information the specific ship used, what the ship's engine specifications are, and the unit price of the scrubber on board for that ship are insufficient. Therefore, in subsequent studies, it is necessary to calculate the scrubber price considering various types of cargo ships and the engine specifications of the ship, and through this, a more general and objective payback period can be calculated.

### 4.5 Conclusion

The preceding studies examined above are summarized as follows. First, with the advent of IMO 2020 regulations, the shipping industry needs to establish new fuel oil strategies such as MGO/MDO, VLSFO, scrubber, and LNG. Each strategy differs in investment cost (CAPEX) and maintenance cost (OPEX). To sort from high cost to low cost, it is summarized as follows. Investment costs incurred in the order of LNG, scrubber, and low sulfur oil strategies. In the case of maintenance costs, costs are incurred in the order of LNG, low sulfur oil, and scrubbers.

Second, if the following strategy is selected, various effects may occur, and from the operational point of view of shipping companies, the freight rate rises, and the market concentration decreases. In addition, from a cost perspective, differences occur depending on the major types of operations of the shipping company, the size and type of ships, and the setting of short and long-term standards. If the ship is a large ship that operates fixedly, LNG propulsion ships are suitable from a long-term perspective, hybrid scrubbers are used in the mid-term, and VLSFO strategies are suitable from a short-term perspective. In the case of small and medium-sized ships, LNG propulsion ships have exceedingly high investment costs and do not generate significant economic utility, and scrubbers are also the same, thus it is the most suitable to use VLSFO since it requires no initial investment costs.

However, thirdly, oil prices and scrubber prices are factors that vary depending on market conditions. Accordingly, it was analyzed that the larger the price difference between low-sulfur oil and high-sulfur oil, the shorter the payback period of scrubber use and the more cost-beneficial it is. According to Vedachalam, it has been clarified that VLSFO can be produced through many other processes with different technologies, thus the supply can be increased by oil refiners. Hence, if the price of low sulfur oil drops, then the economic feasibility of choosing VLSFO strategy is more suitable. In fact, Wu and Lin's study assumed that VLFSO would fall in price due to supply expansion and predicted that HSFO prices would remain at the current level, in which case Scrubber's payback period was found to be more than four years. However, studies by Shuaibu and Panasiuk predict that the price will rise above the current level as demand for low-sulfur oil increases in common, and that it will remain in an upward trend in the near future. Since the two studies were conducted before 2019 when VLSFO began to be produced, the data were used as MGO, not VLSFO. Therefore, although the results are shorter in general than the comparison between VLFSO use and scrubber use Payback Period shown in Wu and Lin's or Andersson et al.'s study, both studies predicted that there would be a continuous price increase due to increased demand for low sulfur oil. In addition, these studies constructed a scenario in which the price of low sulfur oil rises, however, only the use of MGO was assumed and the use of VLSFO was not assumed.

Based on the previous studies, considering the above three characteristics comprehensively, the strategies for using VLSFO, scrubber, and LNG can be considered as countermeasures for IMO sulfur oxide regulation, and the use of VLSFO and scrubber can be used in the mid and short-term. However, depending on market conditions, the price of low sulfur oil and scrubbers may rise or fall, and each strategy's investment economics may change. Previous studies mainly assumed that oil prices fell or rose over a fixed route, and as a result, scrubber payback period ranged from 0.5 to 2 years to 4 to 6 years. However, these studies lack diversity in ship composition in various scenarios, and when looking back at the current point in 2022, there are incorrect predictions, and no assumption has been made that the price of scrubbers fluctuates. Therefore, in this paper, in order to synthesize the phenomena that appeared based on previous studies and achieve additional research, assumptions can be established as in the following part.

### 4.6 Assumption Establishments Based on Literature Review

The assumptions that can be established through previous studies is as follows.

1. Scrubber's Payback Period and VLSFO's increment cost are variable factors that can change with oil price fluctuations.
2. Although VLSFO supply can be expanded, the price may increase due to its extensive demand since not big container ships but also small feeders will be highly likely choose it.
3. As Scrubber's demand increases, the price of the device may increase. However, the price can decrease as well if the scrubber supply increases.
4. Scrubber’s payback period can be increased when the price of low sulfur oil decreases and the price of scrubber devices increases.
5. In the opposite case, it decreases the scrubber payback period.
6. In conclusion, the best alternative will be chosen by considering the tradeoff between price fluctuations in VLSFO and scrubbers.

**Chapter 5: Empirical Analysis: Cost Scenario Modeling**

In this chapter, elements that can be assumed through previous regulatory analysis and literature review are modeled and analyzed as scenarios. In other words, it analyzes the change for the economic feasibility in the situation where market is changing and bunker oil, scrubber prices change. When the prices of HSFO, VLSFO, and scrubber change, the payback period of installing scrubber change, hence, it is possible to see what alternatives would be optimal for containerships selected on this scenario. Therefore, the scenario selects certain types of containerships, routes, fuel consumptions, scrubber prices, payback period formula, and average lifespan of the vessel. Prior to the modelling, each of the data elements will be assumed and calculated by reviewing previous statistical and literature data.

Next, the scenario modelling using above mentioned datasets will be conducted and it is consisted of a total of six. <Scenario 1> starts from the static scenario where the price of HSFO, VLSFO, and scrubber prices will not change. This scenario will serve as a standard for comparison with other scenarios dealing with dynamic analysis of fluctuating prices. <Scenario 2> considers the current scrubber demand and supply and assumes 50% decrease in scrubber price. However, in this scenario the bunker fuel oil prices will not change. However, in <Scenario 3> and <Scenario 4>, considering the overall bunker fuel oil prices and crude oil prices changes, it assumes annual increase of HSFO and VLSFO prices. The percentage of price increases will be assumed using Clarkson Research's time series data. The <Scenario 3> assumes that scrubber price will not change from the current level, however, <Scenario 4> assumes the price drop. For <Scenario 5> and <Scenario 6>, it considers the oil and bunker fuel supply and demand report predictions from IEA. For both scenarios, HSFO price is assumed to stay as current price, however, VLSFO price will be assumed to be increasing. However, in the case of <Scenario 6>, as considered in <Scenario 2> and <Scenario 4>, the situation in which the scrubber price decreases will be considered as well.

**Table 5. 1 Scenario Overview**

| Scenario | Variables | | |
|---|---|---|---|
| | **HSFO Price** | **VLSFO Price** | **Scrubber Price** |
| **Scenario 1** | Current Price | Current Price | Current Price |
| **Scenario 2** | Current Price | Current Price | 50% Decrease |
| **Scenario 3** | Annual 24% Increase | Annual 27% Increase | Current Price |
| **Scenario 4** | Annual 24% Increase | Annual 27% Increase | 50% Decrease |
| **Scenario 5** | Current Price | Annual 8% Increase | Current Price |
| **Scenario 6** | Current Price | Annual 8% Increase | 50% Increase |

### 5.1 Dataset for Scenarios

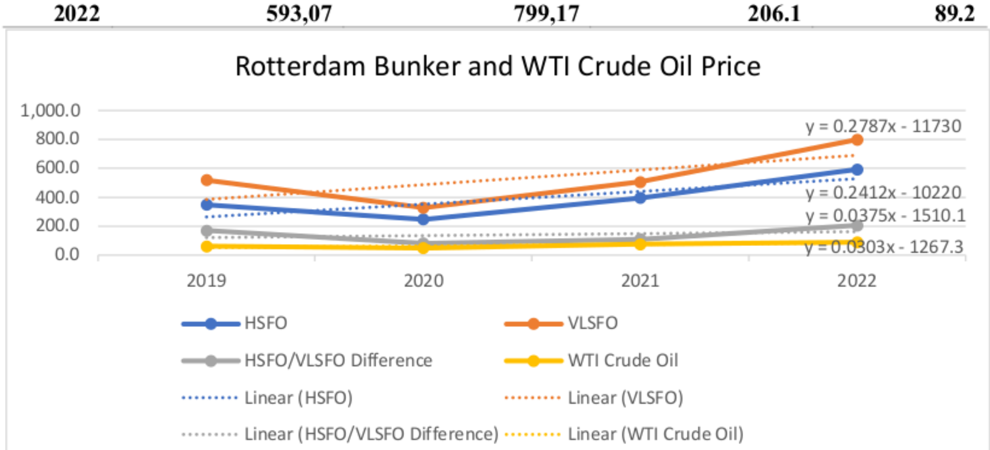
In order to maintain realistic and neutrality for the scenario, data setting is required by synthesizing statistical and literature analysis. This is carried out in the order of analyzing oil prices and bunker oil prices, selecting container ships for scenario composition, scrubber prices, fuel consumption of selected container ships, establishing scrubber payback period calculation methods, and setting container ship average lifespan.

#### 5.1.1 Oil Price and Bunker Fuel Oil Prices

This part aims to analyze the trend of bunkering prices, and the effect of the crude oil prices on bunkering prices. Since the scenario modelling is going to compare the scrubber use strategies that requires HSFO for its fuel with VLSFO use strategy, the <Table 5.2> shows HSFO and VLSFO Bunker prices (Rotterdam). In addition, to analyze if bunkering price trends are influenced by oil price fluctuations, and whether HSFO and VLSFO prices are moving together, HSFO/VLSFO price differences and WTI crude prices are presented in the table and graph. Prior to starting the analysis, the data starts from 2019 since VLSFO data exists from 2019. Since VLSFO was produced after the IMO 2020 implementation was adopted, data before 2019 do not exist.

**Table 5. 2 HSFO, VLSFO Bunker Prices (Rotterdam) and WTI Crude Oil Price**

| | HSFO Bunker Prices | VLSFO Bunker Prices | HSFO/VLSFO Price Difference | WTI Crude Oil Price |
|---|---|---|---|---|
| **Date** | $/Mt | $/Mt | $/Mt | $/bbl |
| **2019** | 349,14 | 518,93 | 169.78 | 61.14 |
| **2020** | 246,66 | 327,98 | 81.32 | 48.52 |
| **2021** | 396,11 | 505,59 | 109.48 | 75.21 |
| **2022** | **593,07** | **799,17** | **206.1** | **89.2** |




*Source: (Clarkson Research Services Limited, 2022)*

First, from the table and graph above, it can be verified whether fluctuations in oil prices directly affect bunker oil such as HSFO and VLSFO, and whether fluctuations in oil prices move with fluctuations in bunker oil. When the difference between HSFO and VLSFO is indicated as a trend line, the slope is 0.0375, and the slope of the trend line of the WTI crude oil price is 0.0303. This represents approximately the same slope value, and in conclusion, it can be seen that fluctuations in crude oil prices have a direct effect on fluctuations in bunker oil, fluctuating nearly proportionally. Therefore, it can be inferred that the reason why bunkering prices are formed at the highest level in 2022 is due to the fact that crude oil prices have reached their highest level since 2014 (Liadze et al., 2022).

Second, it can be seen whether fluctuations in HSFO prices and fluctuations in VLSFO prices move together. When the trend line of HSFO price and VLSFO price are displayed, the slope values are presented to be 0.2412 for HSFO and 0.2787 for VLSFO. This signifies that HSFO rose 27%, and VLSFO rose 24% on average from 2019 to 2022. In conclusion, the overall trend line moves together, however, it is analyzed that there is a difference of about 3%.

Overall, it can be concluded that HSFO and VLSFO prices move together with approximately the same value as the crude oil price fluctuates. This element can be reflected in the scenario components to be modeled in the following part.

### 5.1.2 Vessel Selections

Three types of container ships are selected for this scenario modeling, therefore, one of the ships of, New Panamax, Post-Panamax, and Panamax is selected for each ship category. The reason for choosing these three types of container ships is, firstly, that this scenario modeling assumes a fixed route, which will be set up as a ship crossing between Europe and Asia. Therefore, Feeder ships that are mostly cruising hinterlands were excluded. In the case of Ultra Large Container Vessel, since the vessel has been introduced in the early 2000s, most of the vessels are recently produced (Jungen et al., 2021). The assumptions consider both old and new ships, and so ULCV is excluded to consider old ships. In other words, among container ships crossing the continent, it was selected as a size category of three Panamax types, which are smaller than ULCV and larger than Feeder.

According to the Propulsion Trends report of MAN Energy Solution, TEU for each type of ship is specified. Panamax has a TEU of “2,800-5100”, post-Panamax “5,500-10,000”, New-Panamax “12,000-14,500” (MAN Energy Solution, 2019). Therefore, in this modeling, three vessels corresponding to each type with 14000, 10000, 4000 TEU are selected, and the reason why these are selected is to use the TEU type and corresponding engine data provided by the MAN Energy Solution. Specific maximum continuous rating (SMCR kW) of the engine installed on the vessel is summarized in <Table 5.3>. It is assumed that all of them follow the Europe-Asia (Hamburg to Shanghai) route since price comparison cannot be done if there is a difference in voyage routes.

**Table 5. 3 Container Vessel Selection for Scenarios and its Engine Power Output**

| Type | Capacity (TEU) | Power Output (kW) |
|---|---|---|
| **Neo Panamax** | 14,000 | 54,100 |
| **Post-Panamax** | 10,000 | 39,900 |
| **Panamax** | 4,000 | 20,900 |

*Source: (MAN Energy Solution, 2019)*

### 5.1.3 Scrubber Price

In the case of scrubber prices, it varies depending on manufacturer and market prices, and even if they are the same type, prices vary widely by brand. Therefore, to obtain a more neutral average price, this paper follows data from EGCSA, an association to which most scrubber manufacturers in the market are joined. According to 2012 data from EGCSA, Couple Systems stated that a 1 Mw engine scrubber costs USD 500k and a 20 Mw engine costs USD 4 million, and MES stated that each engine costs USD 1 million and USD 3 million (EGCSA, 2012). Accordingly, the scrubber price is calculated to cost 100 to 300 euros per kW of the ship's engine (In USD, it was calculated to be 125 to 375 USD per kW) (ibid.,). Therefore, the median price of EGCS using MGO and HFO is calculated as $250/kW (See Annex 4). However, as EGCSA's data are prior to the decade of 2012, the social discount rate must be applied to convert cost-benefit into the current value. This is the recommended criterion for calculating the Impact Assessment on an EU basis and is to be calculated by applying the '4%' (Freeman et al., 2021) (Groth, 2014). The 4% discount rate is used by the Danish Ministry of Finance as an energy-related social discount rate (Hermelink et al., 2015). The calculated values are shown in <Table 5.4 > below. In conclusion, the median value of the scrubber price estimated by calculating based on the social discount rate of 10 years was found to be $166/kW.

**Table 5. 4 Estimated scrubber price in 2022 reflecting social discount rate based on scrubber price in 2012 (Price in $/kW)**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Initial Price** | **250** | | | | | | | | | |
| **Discount Rate** | 4% | 4% | 4% | 4% | 4% | 4% | 4% | 4% | 4% | 4% |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Estimated Price** | 240 | 230,4 | 221,1 | 212,3 | 203,8 | 195,6 | 187,8 | 180,3 | 173,1 | 166,2 |
| **Year** | *1st* | *2nd* | *3rd* | *4th* | *5th* | *6th* | *7th* | *8th* | *9th* | *10th* |

Therefore, by multiplying the calculated scrubber price by the total engine power of the ship types selected above, the scrubber price per ship type can be obtained. This is calculated as shown in <Table 5.5> below.

**Table 5. 5 Scrubber Prices by TEU Types**

| Type | Capacity (TEU) | Power Output (kW) | Scrubber Price ($) |
|---|---|---|---|
| **Neo Panamax** | 14,000 | 54,100 | 8,980,600 |
| **Post-Panamax** | 10,000 | 39,900 | 6,623,400 |
| **Panamax** | 4,000 | 20,900 | 3,469,400 |

### 5.1.4 Fuel Consumption

Fuel consumption varies according to numerous factors such as operating distance and weather conditions according to the engine type mounted on the ship, the steaming speed, and other factors such as climates. Therefore, considering that each data sometimes could show an extreme result, this paper uses generalized data through statistical analysis for each container ship to use neutral data. According to Le et al., the fuel consumption analyzed by statistical analysis of 185 container ships in Korea is shown in the following table. This is a value obtained by dividing the type of container ship by TEU. It calculated the fuel consumption per voyage through big data of navigation information consisting of 38,687 voyages according to each container ship type (Le et al., 2020). This fuel consumption estimation model uses an average speed and sailing time, distance, and actual fuel consumption for main and auxiliary engines, and drew out the regression data (ibid.,).

**Table 5. 6 Descriptive statistics for fuel consumption, distance, and sailing speed by ship size**

| Ship Voyage Data | | | | Fuel consumption per voyage (Mt) | | |
|---|---|---|---|---|---|---|
| **Container ship capacity** | *No. of container ships* | *No. of voyages* | *Std dev.* | *Min.* | *Max.* | *Mean* |
| **Feeder (<3,000 TEU)** | 58 | 9492 | 43.6 | 0.6 | 494.5 | *39.31* |
| **Intermediate (3,000–5,999 TEU)** | 83 | 14257 | 201.0 | 2.5 | 3,270.2 | ***135.9*** |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Intermediate (6,000–7,999 TEU)** | 13 | 3473 | 209.6 | 3.1 | 1,693.5 | *159.9* |
| **Post-Panamax (8,000–11,999 TEU)** | 22 | 4331 | 348.0 | 11.5 | 2,159.5 | ***253.5*** |
| **Neo-Panamax (12,000–14,999 TEU)** | 9 | 2221 | 394.7 | 16.2 | 4,678.8 | ***386.2*** |

*Source: (Le et al., 2020)*

According to Verny and Grigentin, research of the navigation information of container ships sailing through the North Sea showed that container ships traveling from Hamburg to Shanghai took 37 days per voyage. Thus, this paper assumes that container ships operate 10 times a year from this data. By applying the findings from this data, it is possible to set the assumption that the containerships crossing Europe and Asia have 10 voyages per year. In conclusion, it indicates that it is possible to multiply 10 times from the fuel consumption found above to analyze yearly fuel consumption for each ship selected for the model. <Table 5.7> shows the summary of expected fuel consumptions for ships that are selected for following scenario modellings.

**Table 5. 7 Fuel Consumption for Selected Ships**

| Type | Fuel Consumption (Mt) |
|---|---|
| **Neo Panamax** | 3862 |
| **Post-Panamax** | 2535 |
| **Panamax** | 1359 |

### 5.1.5 Scrubber Payback Period

In order to obtain the payback period of the scrubber, the net present value can be considered by discounting the investment cost and cash flow at the market interest rate.

$$NPV = \sum_{t=0}^{T} \frac{P}{(1+i)^t} - C$$

According to Business Ratios and Formulas, NPV = ∑(P/ (1+i)t) – C, where “P” is net cash flow at time t, “i” is interest rate (return on investment), “t” is period of cash flow, and “C” is investment capital (Bragg, 2008). However, an important point when considering NPV is interest rates, and Europe Central Bank’s interest rate has currently maintained the 0% level for 10 years (European Central Bank, 2022). Referring to Annex 5, the ECB's market interest rate can be confirmed for 10 years, which maintains a market interest rate close to 0% from 2012 to 2022 and is currently 0%. Therefore, interest rate which is “i” can be determined to be 0.

Therefore, if the market interest rate is assumed to be 0%, Payback Period can be obtained by obtaining only P corresponding to Cash Flow and C corresponding to Scrubber Price.

$$Payback\ Period = Scrubber\ Price\ \div (Annual\ VLSFO\ Cost - Annual\ HSFO\ Cost)$$

Scrubber Price is equivalent to the cost of capital investment, and it can be recovered through the cost of using HSFO which is lower-cost than VLSFO. In other words, Cash Flow is the cost that can be saved by using HSFO instead of VLSFO. The reason is that the purpose of installing scrubbers is to achieve cost reduction by continuing to use low-priced HSFO and not using VLSFO which are determined to be higher than that of HSFO. In conclusion, the difference between the annual cost of using HSFO and VLSFO can be calculated, and the payback period is calculated by dividing this cost from Scrubber Price.

### 5.1.6 Containership Lifespan

According to US Army Corps of Engineers (USACE), the average lifespan of commercial containerships is found to be 20 to 25 years (Messer et al., 2022). Moreover, according to Clarkson Research data from 1996 to 2022, total containership demolition age is found to be average 26.26 years (Clarkson Research, 2022) (See Annex 6). Calculating the standard deviation of the sample is 4.5, so it can be seen that the data are distributed between about 21.76 and 30.7 years (ibid.,).

However, this is the data surveyed for all container ships, and the average size of all TEUs is calculated. According to Korean Maritime Safety Research, the lifespan of 5000 TEU ships is found to be 19 years (Jang, 2011). Furthermore, the research found that the greater the containership is, the longer the lifespan is (ibid.,). This paper conducts a study on three types of ships: Neo Panamax, Post-Panamax, and Panamax, which is to 14000, 10000 and 4000 TEU, respectively. Therefore, ships with a TEU capacity higher than 5000 TEU are being investigated as well, and since the economic feasibility of scrubbers is analyzed, it is necessary to set the appropriate average container ship lifespan as a reference point. In conclusion, taking account of the overall data studied above, the average ship life span is assumed to be 25 years.

## 5.2 <Scenario 1>: Cost Comparison Between VLSFO and Scrubber use with 2022 Oil Price

<Scenario 1> aims to examine the difference in cost in operating VLSFO or scrubber on the current basis by reflecting current oil prices. <Scenario 1> conducts a static analysis as a base scenario to

become a standard for comparing other scenarios to be analyzed in the following parts. Therefore, the accumulative cost and scrubber payback period are calculated on the assumption that HSFO, VLSFO, and scrubber prices are maintained as of 2022.

### 5.2.1 Empirical Modeling Analysis Results and Data

**Table 5. 8 Summary of <Scenario 1> result**

| **Type** | **Scrubber Price ($)** | **HSFO Price ($/Mt)** | **VLSFO Price ($/Mt)** | **Fuel Consumption (Mt)** |
|---|---|---|---|---|
| **Neo Panamax** | 8,980,600 | *593* | *799* | 3862 |
| **Post-Panamax** | 6,623,400 | *593* | *799* | 2535 |
| **Panamax** | 3,469,400 | *593* | *799* | 1359 |
| | **Annual HSFO Cost ($)** | **Annual VLSFO Cost ($)** | **Cost Diff**erence ($) | **Payback Period (Year)** |
| **Neo Panamax** | 2,290,166 | 3,085,738 | 795,572 | *11.2* |
| **Post-Panamax** | 1,503,255 | 2,025,465 | 522,210 | *12.6* |
| **Panamax** | 805,887 | 1,085,841 | 279,954 | *12.3* |

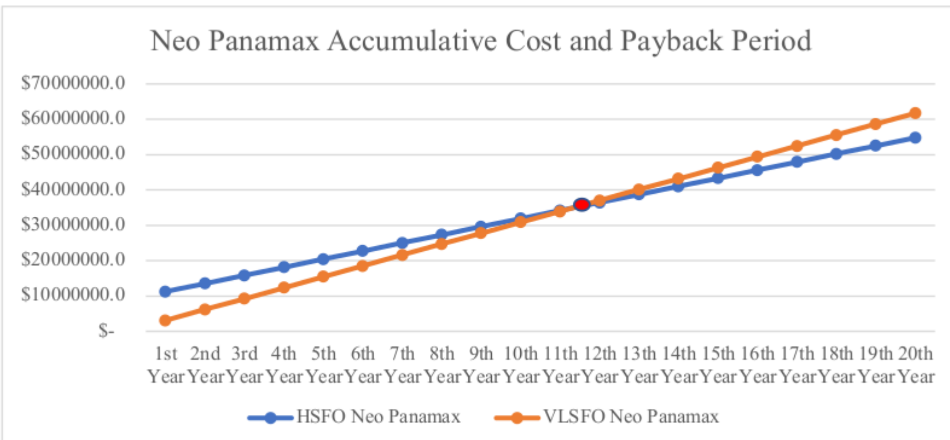
Annual HSFO and VLSFO usage costs can be calculated by considering the scrubber price, HSFO price, VLSFO price, and fuel usage analyzed in the previous part. Based on this, the accumulated value of each fuel use can be analyzed by modeling for 20 years, and the point where the total cost of using VLSFO and the total cost of using HSFO + Scrubber intersect can be analyzed as well. Accordingly, the intersection point is the total cost of using VLSFO exceeds the cost of using HSFO + Scrubber, hence, it indicates a Payback Period.

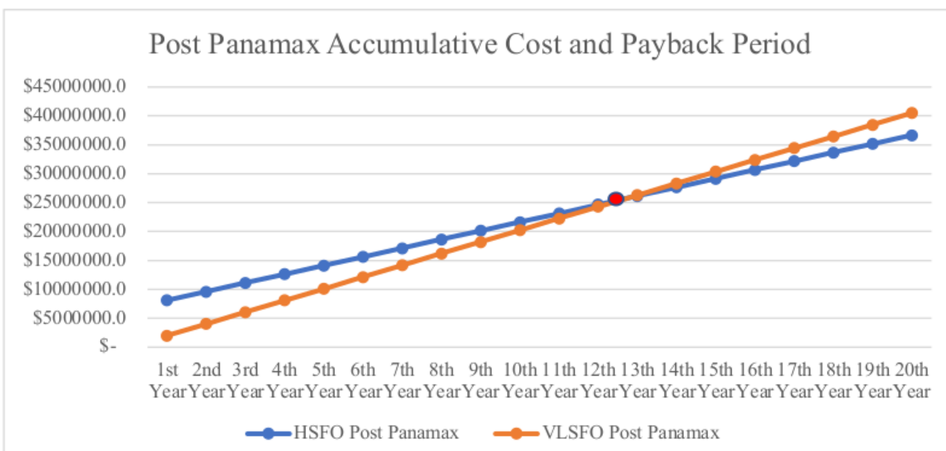
Referring to the summary of <Scenario 1> result presented in <Table 5.8>, the payback period of the scrubber is analyzed between about 11 and 12 years considering all ship TEU types of container ships. Considering that modern containerships have an average lifespan of 25 years, the period equivalent to half of the total life of the ship will be the payback period. Accordingly, it can be concluded under the assumption that the oil price will not change over time, it is economic to install vessels that are newly built. Furthermore, considering the ship's lifespan, retrofit scrubber installations for ships that are under 10 years old can be considered as well.

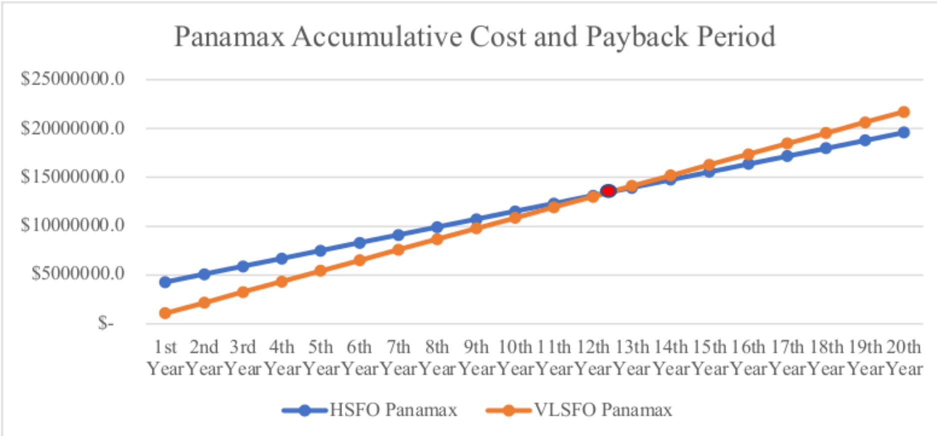
However, this analysis is considered in the hypothetical situation that the price difference between VLSFO and HSFO does not change at the current level, and the Payback Period may vary if there is a change in oil prices in the future. In other words, if the price difference between VLSFO and HSFO is predicted to widen further from the perspective of the shipping company, it is possible to consider installing scrubbers for vessels that are over 10 years as well. Therefore, in this scenario, it can be concluded that if the shipping companies predicts that current level of the oil price will stay, they will only choose to install scrubbers on new vessels. Whether to install scrubbers from the perspective of the shipping company in 2022 may vary depending on the future oil price prediction of the company.

The detailed accumulative cost curves and the intersection point that represents the payback period are presented in <Figure 5.1>. It is the graphic drawn from the simulation of the cost of using HSFO and VLSFO for 20 years.

**Figure 5. 1 <Scenario 1> Accumulative Cost with Scrubber Cost and Payback Period**






### 5.3 <Scenario 2>: Scrubber Price Decreases 50%, while VLSFO Price Stays

According to EGCSA's scrubber price data considered in the previous part, scrubber prices can fall and rise 50% from the median value (See 5.1.3 Scrubber Price and Annex 4). Therefore, this scenario assumes a scenario in which the scrubber price falls by 50%. According to DNV, about 1200 scrubbers are ordered annually and the volume of the order is continuing stably (DNV, 2018). In other words, although the excessive demand, there is a high possibility that the supply will expand as companies reaching scale of economy by mass productions. Referring to Annex 8, according to Clarkson Research, it is revealed that the number of scrubbers fitted on the vessel is constantly increasing (Clarkson Research, 2022). Furthermore, other than the current scrubber manufacturers, large container manufacturers such as Hyundai Heavy Industries and Mitsubishi Heavy Industries have entered the business of developing and manufacturing scrubbers, and both the scrubber market and supply can increase as their own scrubbers are likely to be installed on ships (Hyundai Global Service, 2019) (Mitsubishi Heavy Industries, n.d.). In conclusion, concerning the possibility of supply expansions from major scrubber manufacturers and higher competitions from more companies entering the business, this scenario assumes the price drop in scrubbers. It aims to analyze how the payback period changes if scrubber unit price decreases by 50%.

#### 5.3.1 Empirical Modeling Analysis and Results

**Table 5. 9 Summary of <Scenario 2> Result**

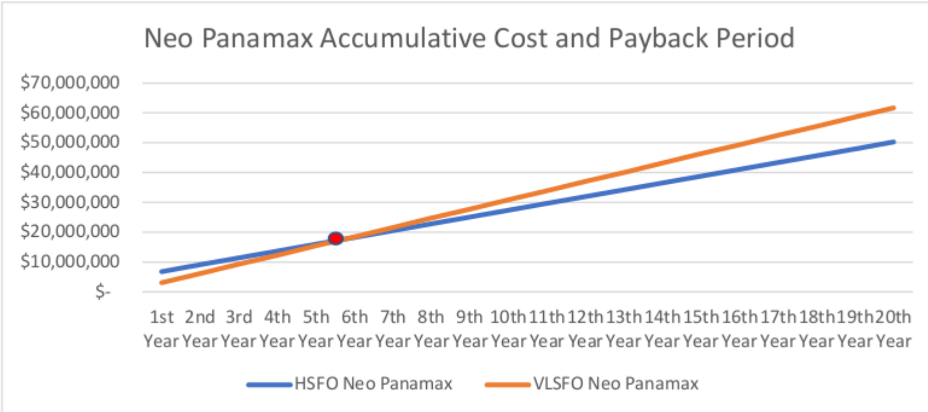
| Type | Scrubber Price ($) | HSFO Price ($/Mt) | VLSFO Price ($/Mt) | Fuel Consumption (Mt) |
|---|---|---|---|---|
| **Neo Panamax** | *4,490,300* | 593 | 799 | 3862 |
| **Post-Panamax** | *3,311,700* | 593 | 799 | 2535 |
| **Panamax** | *1,734,700* | 593 | 799 | 1359 |
| | **Annual HSFO Cost ($)** | **Annual VLSFO Cost ($)** | **Cost Difference ($)** | **Payback Period (Year)** |
| **Neo Panamax** | 2,290,166 | 3,085,738 | 795,572 | *5.64* |
| **Post-Panamax** | 1,503,255 | 2,025,465 | 522,210 | *6.34* |
| **Panamax** | 805,887 | 1,085,841 | 279,954 | *6.19* |

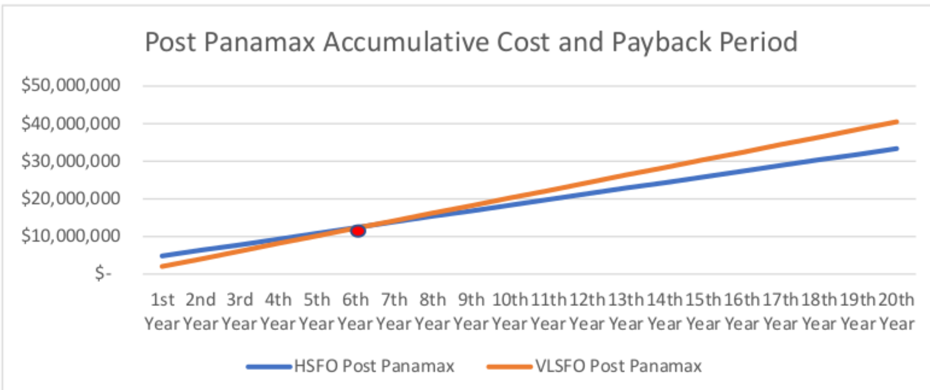
The prices of the scrubber assumed to be fell by 50%. And the payback period of Neo Panamax, Post Panamax, and Panamax are all calculated as 5.6, 6.34, and 6.19, respectively. Therefore, it can be summarized that the overall capital recovery period is calculated to be approximately 5-6 years. Since the lifespan of the container ship is 25 years on average, the plan to install scrubbers on newly built ships or ships made within 20 years can be positively considered. In fact, according to Clarkson Research, the average age of the ship that are installed with retrofit scrubbers from 2020 to 2022 is found to be 13.36 years (see Annex 10). However, as for the ships that are more than 20 years, it is appropriate to consider the use of low sulfur oil since the payback period may be longer than the remaining life of ships.

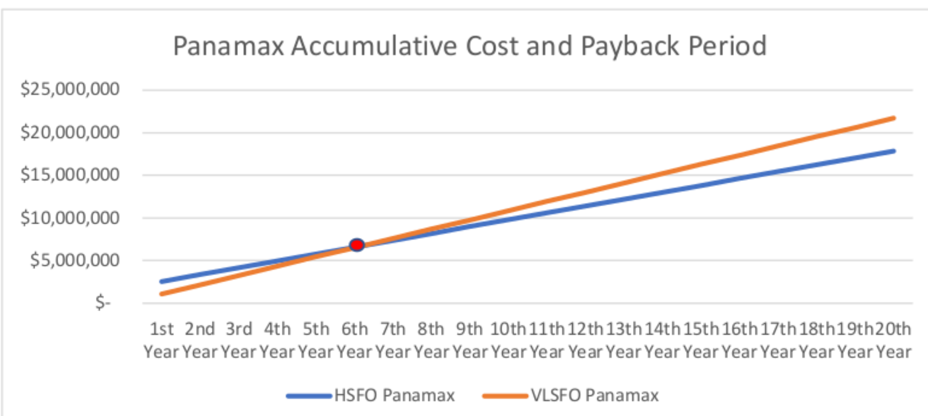
Since <Scenario 2> assumes that the price of VLSFO is fixed, the fluctuation of the VLSFO and HSFO prices are not considered. However, oil prices continue to fluctuate, and it might be too optimistic view to see future prices stay as the same as they are today. Therefore, in the next scenario, it is necessary to analyze the scenario by adding an assumption that oil prices rise and compare it with <Scenario 2>.

Details of the cost curve trendlines from the 20-year simulation and the payback period are presented in the <Figure 5.2>.

**Figure 5. 2 <Scenario 2> Accumulative Cost and Payback Period**




As such, the possibility of introducing scrubbers for almost all container vessels including new and old ships was confirmed in the case of <Scenario 2>. However, the scenario in which the scrubber increases by 50% will not be analyzed. The reason is that <Scenario 1> results have already shown that the scrubber payback period can exceed the half of the containership's lifespan, and if only the scrubber price increases, it will be an unrealistic scenario modeling. Furthermore, according to DNV, the demand is stably maintained at a level of more than 1,200 units per year in the past 3 years (DNV, 2018) (see Annex 11). Hence, considering the stable demand, assuming scrubber prices stay or going down would not be judged as unrealistic.

Apart from scrubber price, bunker price fluctuations are valid for both increase and decrease since it always had been fluctuated according to the data (see Table 5.2). Therefore, the next scenario consists of a scenario in which the bunker prices fluctuate.

### 5.4 <Scenario 3>: HSFO/VLSFO Price Increase Annually, while Scrubber Price Stays

Referring to the previous part of the comparative analysis of oil prices and bunkering prices, it can be inferred that prices fluctuate every year (see Table 5.2). In addition, from 2019 to 2022, HSFO prices increased by 24% on average, and VLSFO prices increased by 27% on average. Therefore, in this scenario, it establishes and models with assumption that HSFO and VLSFO rise 24% and 27% per year, respectively. In case of the price of a scrubber, it starts with the assumption that it maintains the current level.

#### 5.4.1 Empirical Modelling Scenario Analysis and Results

**Table 5. 10 Summary of <Scenario 3> Result**

| Type | Scrubber Price ($) | HSFO Price ($/Mt) | VLSFO Price ($/Mt) | Fuel Consumption (Mt) | Payback Period (Year) |
|---|---|---|---|---|---|
| **Neo Panamax** | 4,490,300 | *Annual 24% Increase from 2022 Price ($593)* | *Annual 27% Increase from 2022 Price ($799)* | 3862 | 12.8 |
| **Post-Panamax** | 3,311,700 | | | 2535 | 13.3 |
| **Panamax** | 1,734,700 | | | 1359 | 13.2 |

As a result of scenario modeling, the payback period of the scrubber was calculated to be 12.8 years for Neo Panamax, 13.3 years for Post-Panamax, and 13.2 years for Panamax. This is a result slightly higher than the assumption that the bunker price in 2022 will be maintained in <Scenario 1>. In other words, if the trend of rising bunkering prices continues to be maintained that is the average value of three years, the result is that the payback period of scrubbers will be longer, and the introduction of scrubbers will be disadvantageous. Even considering the average lifespan of the container ship that is 25 years, payback period takes the half of the lifespan. Therefore, scrubber installation can be positively considered for new ships, however, existing ships that are over 10-year-old are less economical for retrofit scrubbers.

**Figure 5. 3 <Scenario 3> Accumulative Cost and Payback Period**

<Scenario 3> does not increase the annual cost of using VLSFO by the same amount. This is due to the assumption that annual bunkering price rise by 24% and 27% per year, and a different approach should be taken from the method of calculating the payback period. <Scenario 1> and <Scenario 2> used by dividing the cost difference between HSFO and VLSFO by the price of the scrubber. However, for this scenario, HSFO and VLSFO prices rise in a curved form as shown in <Figure 5.>. Hence, the payback period can be obtained by drawing the trend line of the accumulative cost graph and obtaining the intersecting part through the equation. Accumulative cost graph for both HSFO and VLSFO are having a curvy shape, and equations can be formed in the form of polynomials. To obtain the intersection point, the root of the equation expressed in the form of a quadratic equation must be obtained, and to obtain this root, it can be obtained using univariate function. The function can be shown as follows.

$$f(x) = ax^2 + bx + c = a(x - r_1)(x - r_2)$$

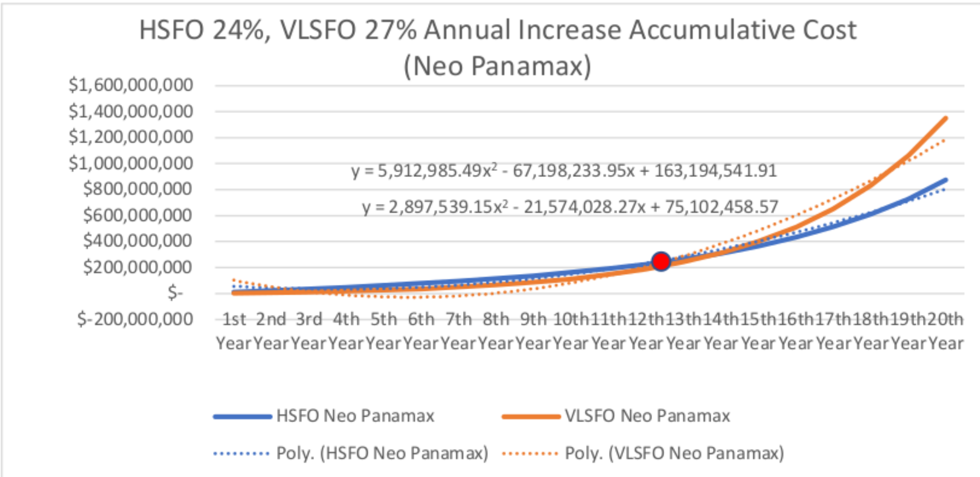
$$for\ which\ f(x) = 0,$$

$$Coefficients\ a, b, and\ c, are\ real\ or\ complex$$

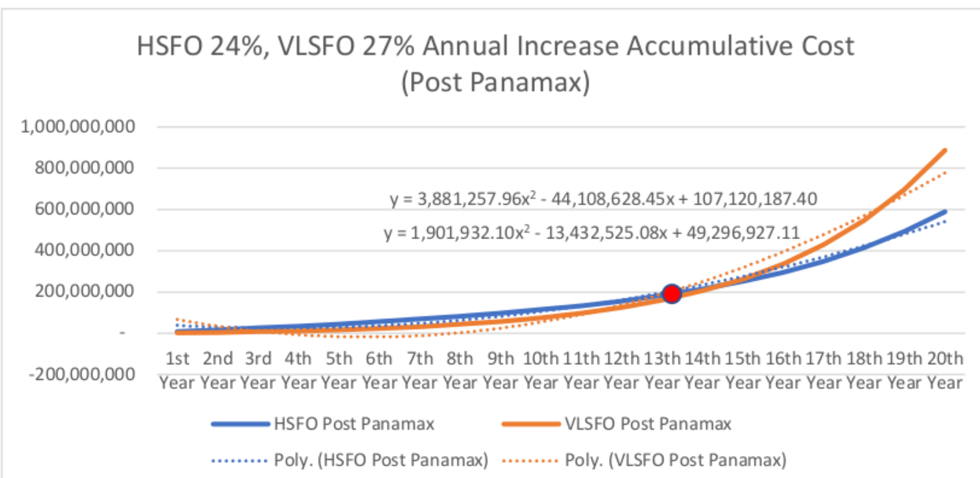
$$r_1 = \frac{-b - \sqrt{b^2 - 4ac}}{2a},$$

$$r_2 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}.$$

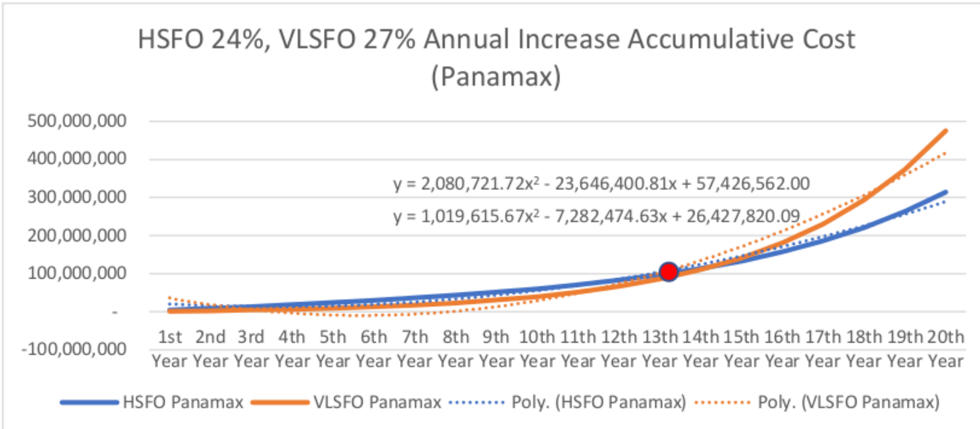
For both the cost curves of VLSFO and HSFO, the formula for obtaining two roots can be used since the coefficients are real numbers. In the quadratic equation, there are two intersections where the curve intersects with the x axis, so one of the roots can be in a negative number or a number that is very small. However, in this analysis, it cannot be negative since it is a value that calculates the payback period of scrubber which is in a yearly form that calculates the period for the future. Nor the aim is to get the intersection point of both cost curves, thus, the point where only trend lines intersect cannot be the payback period. Therefore, it can be concluded that out of the two roots, either the positive number or the bigger number are the payback period. Each payback period is displayed under the graph below and see Annex for specific calculations.




**X = 12.8 (See Annex 14)**




**X = 13.3 (See Annex15)**




**X = 13.2 (See Annex 16)**

### 5.5 <Scenario 4>: HSFO/VLSFO Prices Increase Annually, while Scrubber Price Decrease in 50%

In this scenario, as assumed in <Scenario 2, the situation where the price of the scrubber falls by 50% and the assumption of <Scenario 3> where the bunkering price rises were mixed and modeled. This is a scenario that can occur when maintaining the trend of rising bunkering prices for that has been observed from the past three-year data, expanding the supply of scrubbers, and achieving economies of scale by manufacturers.

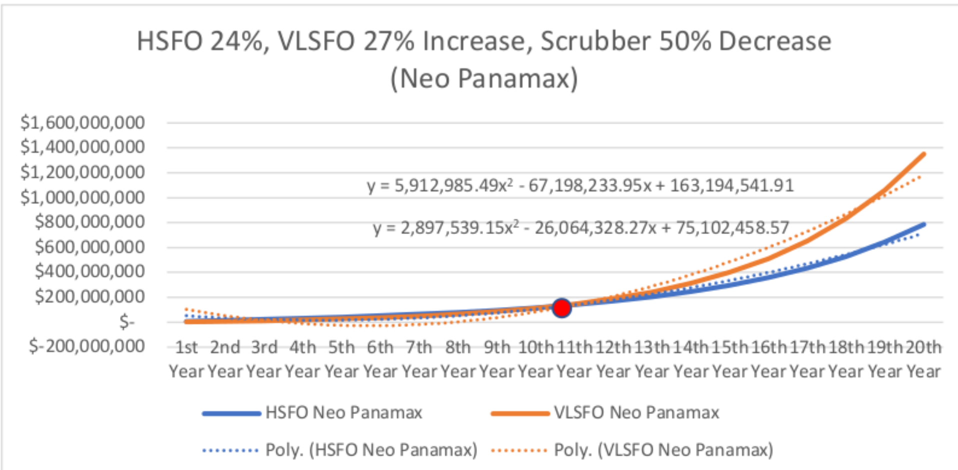
#### 5.5.1 Empirical Modelling Scenario Analysis and Results

**Table 5. 11 Summary of <Scenario 4> Result**

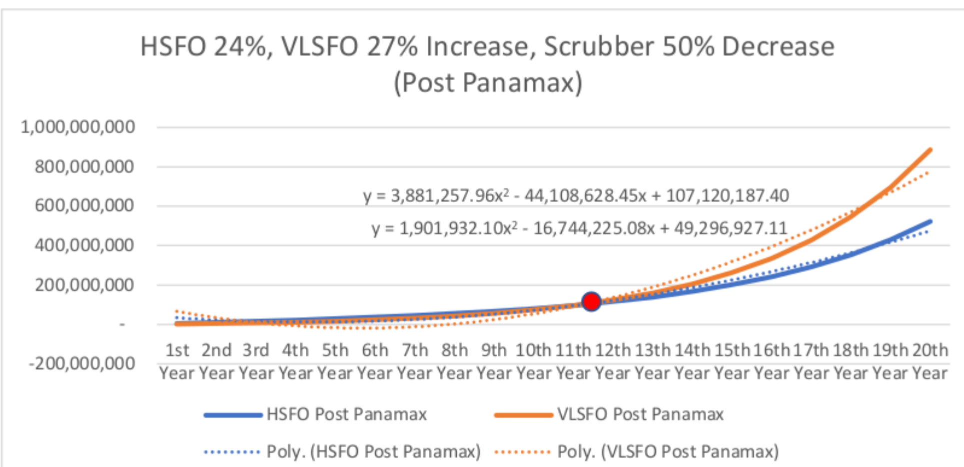
| Type | Scrubber Price ($) | HSFO Price ($/Mt) | VLSFO Price ($/Mt) | Fuel Consumption (Mt) | Payback Period (Year) |
|---|---|---|---|---|---|
| **Neo Panamax** | 4,490,300 | 593 | *Annual 8% Increase from 2022 Price ($799)* | 3862 | *10.98* |
| **Post-Panamax** | 3,311,700 | 593 | | 2535 | *11.22* |
| **Panamax** | 1,734,700 | 593 | | 1359 | *11.17* |

The result values of the scrubber Payback Period are calculated as Neo Panamax 10.98, Post-Panamax 11.22 and Panamax 11.17. This scenario assumes the situation of the trend of rising bunkering oil prices is maintained and scrubber demand is maintained at a similar level without significantly deviating from the recent three-year average as well. Additionally, it assumes scrubber manufacturers' competition, supply expansion, and economies of scale are achieved. However, the result of payback period came out to be similar to the base scenario <Scenario 1>. In other words, if the situation of rising oil prices and falling scrubber prices are mixed, scrubber payback periods are similar to the situation in which bunkering oil and scrubber prices are maintained at the current level in 2022. Thus, the installation of scrubbers on new ships and container ships aged less than 10 years can be positively considered as in <Scenario 1>.

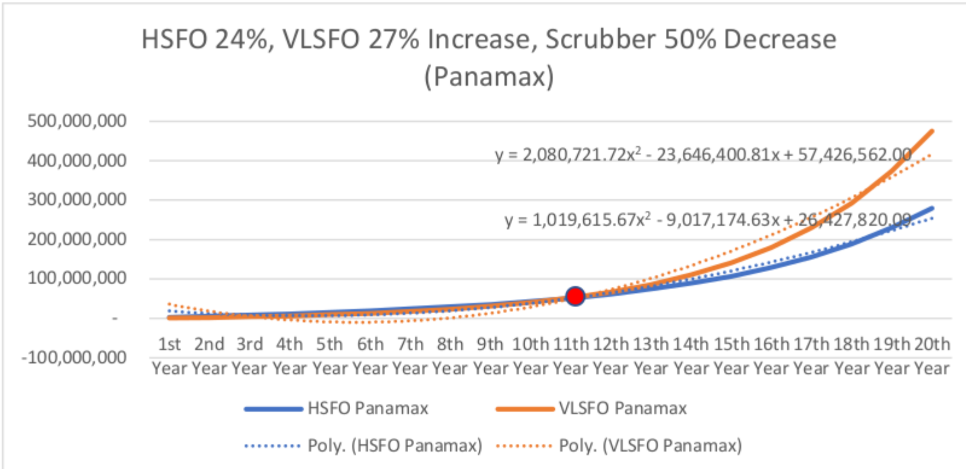
**Figure 5. 4 <Scenario 4> Accumulative Cost and Payback Period**




**X = 10.98 (See Annex 18)**




**X = 11.22 (See Annex 19)**




**X = 11.17 (See Annex 20)**

### 5.6 <Scenario 5>: VLSFO Price Increases By 8% Per Year

In this scenario, it is assumed that the price of VLSFO increases by 8% per year. According to a report on oil prices by the International Energy Agency in June 2022, global oil demand exceeded previous levels during the Pandemic period and predicted that it would reach 101.6mb/d by 2023 (IEA, 2022). Considering that the total oil demand in 2020 was 91 mb/d, and pre-pandemic year of 2019 was 99.7 mb/d, this means that demand for oil is increasing at a very steep rise (IEA, 2021). In addition, the IMO recently decided to revise the MARPOL again from 2023 to add Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) provisions. This is a decision to strengthen GHG regulations to reduce carbon dioxide as well as sulfur and nitrogen monoxide. Accordingly, the IEA also predicted that demand for VLSFO will rise from 1.4mb/d, the level of 2020, to 2.2mb/d by 2026 (ibid.,). This means that demand will grow 57.14 percent over six years, increasing by about 9 percent annually. However, IEA predicted that the supply is also expected to increase from OPEC but for 1 percent annually from 34 mb/d in 2020 to 35 mb/d in 2026, offsetting some increase in demand (ibid.,). Therefore, it can be concluded that the scenario can assume 8% Price increase in VLSFO annually. In addition, this is the basis for judging that the scrubber plan will be highly economical if the shipping company predicts that only the price of VLSFO will rise in the future, since it has been assumed that the price of VLSFO will be fixed based on 2022 in the <Scenario 2>.

### 5.6.1 Empirical Modelling Scenario Analysis and Results

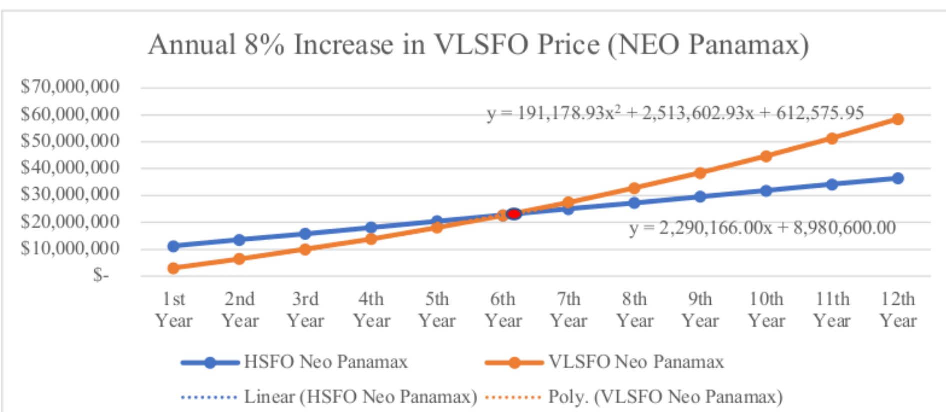
**Table 5. 12 Summary of <Scenario 5> result**

| **Type** | Scrubber Price ($) | HSFO Price ($/Mt) | VLSFO Price ($/Mt) | Fuel Consumption (Mt) | Payback Period (Year) |
|---|---|---|---|---|---|
| **Neo Panamax** | 8,980,600 | 593 | *Annual 8% Increase from 2022 Price ($799)* | 3862 | 6.05 |
| **Post-Panamax** | 6,623,400 | 593 | | 2535 | 6.48 |
| **Panamax** | 3,469,400 | 593 | | 1359 | 6.39 |

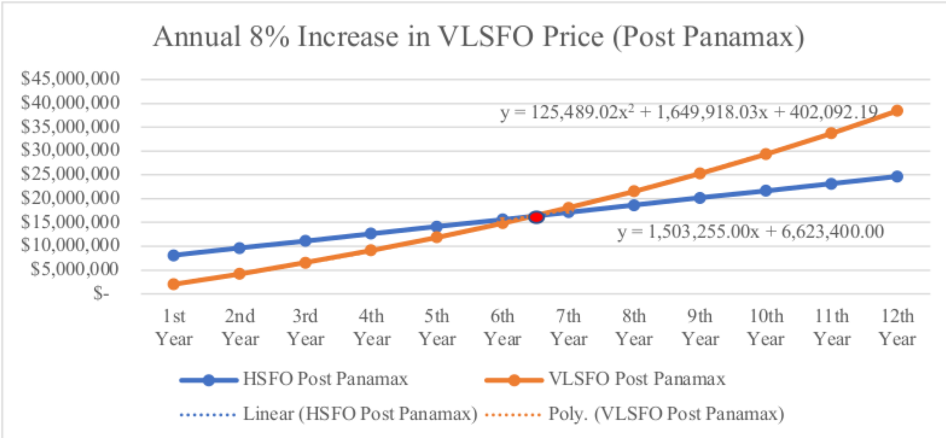
The payback period of the scrubbers for each type of the vessel came out to be 6.05 for Neo-Panamax, 6.48 for Post-Panamax, and 6.39 for Panamax. Therefore, if the annual oil price of low sulfur oil rises by 8%, the overall payback period for container ships takes 6 to 6.5 years. Accordingly, the container ship can benefit from the use of scrubbers for about 20 years in that the life span of the container ship is 25 years. This is a scenario in which both new and existing ships can positively consider the installation of scrubbers, and in the case of existing ships, it is economical only if the ship age is less than 20 years.

However, this is a scenario established by the assumption that the price of the scrubber does not change from the median of the average estimate, and if the price of the scrubber increases, the resulting value of the scenario may vary. Scenarios of varying scrubber prices will be covered in the next part.

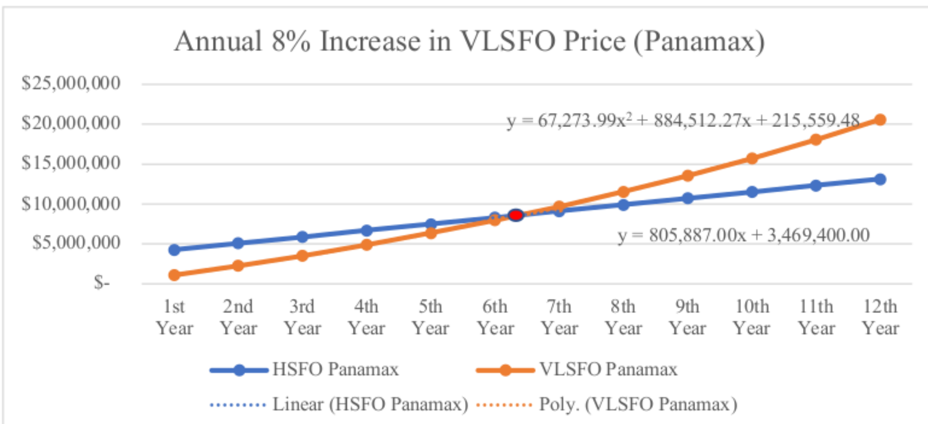
**Figure 5. 5 <Scenario 5> Accumulative Cost and Payback Period**




**X = 6.0573 (See Annex 22)**




**X = 6.4809 (See Annex 23)**




**X = 6.395 (See Annex 24)**

### 5.7 <Scenario 6>: Scrubber Price Decreases by 50%, VLSFO Price Increases by 8% Per Year

<Scenario 6> is a situation in which the price of the scrubber decreases by 50%, and the price of the VLSFO increases by 8%. This is a scenario where the supply of scrubbers expands whereas demand is maintained, and the demand for VLSFO increases as previously assumed, while HSFO maintains demand and supply.

#### 5.7.1 Empirical Modelling Scenario Analysis and Results

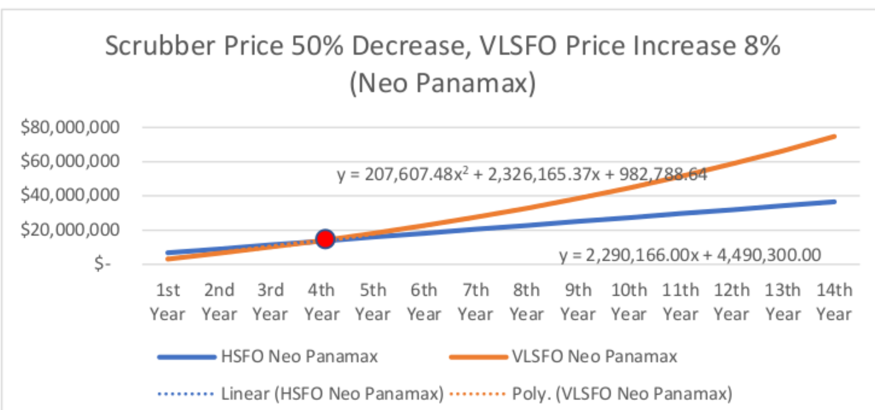
**Table 5. 13 Summary of <Scenario 6> Result**

| Type | Scrubber Price ($) | HSFO Price ($/Mt) | VLSFO Price ($/Mt) | Fuel Consumption (Mt) | Payback Period (Year) |
|---|---|---|---|---|---|
| **Neo Panamax** | 4,490,300 | 593 | *Annual 8% Increase from 2022 Price ($799)* | 3862 | *4.02* |
| **Post-Panamax** | 3,311,700 | 593 | | 2535 | *4.33* |
| **Panamax** | 1,734,700 | 593 | | 1359 | *4.27* |

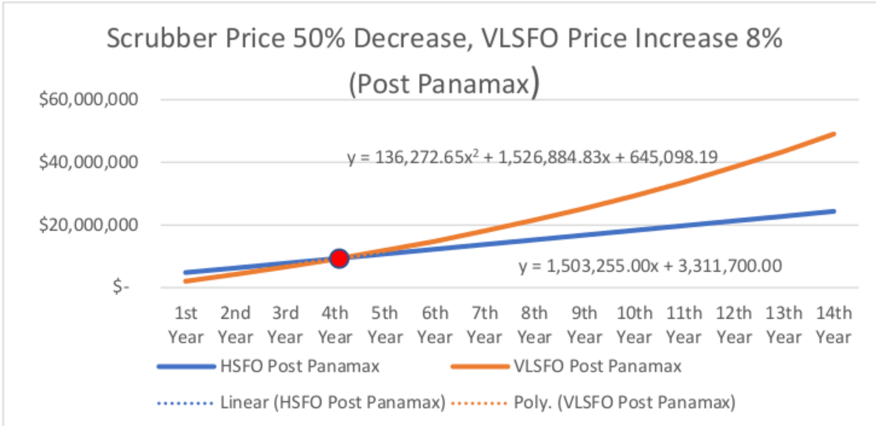
The Payback period was calculated as Neo Panamax 4.02, Post-Panamax 4.33, and Panamax 4.27. This result value is calculated as the shortest payback period throughout the previous scenario. Basically, while HSFO prices remain as they are now, only VLSFO prices rise, which is advantageous for scrubber economics. In addition, the decline in prices due to the supply of scrubber manufacturers and the expansion of competition is also very advantageous for the buyer, shipping companies. Accordingly, the shortest payback period was calculated.

In this scenario situation, the installation of scrubbers can be considered not only for newly created container ships but also for 20-year-old ships. In other words, it is a scenario in which the most ideal economic situation is assumed in the scrubber installation strategy.

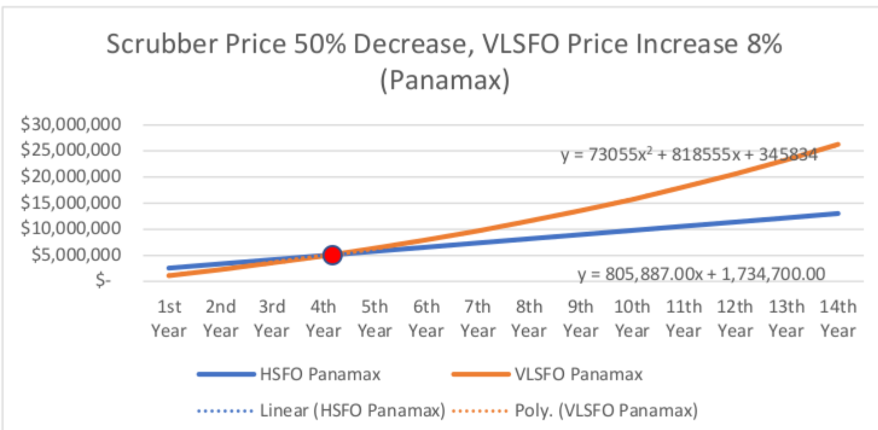
**Figure 5. 6 <Scenario 6> Accumulative Cost and Payback Period**




**X = 4.02 (See Annex 26)**




**X = 4.33 (See Annex 27)**




**X = 4.27 (See Annex 28)**

### 5.8 Summary and Conclusions for all Scenarios

**<Scenario 1>**: VLSFO price is set at the current level of price in 2022. The scrubber price is set as the median of the current base estimate. The payback period is calculated from 11 to 12 years, making it close to the half of the average lifespan of the containership that is 25 years. Therefore, both newly built ships and existing ships can be installed with the scrubber. However, for those ships that are more than 13 years old, it is better to consider using VLSFO strategy.

**<Scenario 2>**: VLSFO price is set to stay at the current price, and scrubber prices are set to decrease in 50% percent due to supply expansions and higher competitions due to more competitors entering into the market. “50%” decrease has been hypothesized from the data of EGCSA scrubber unit price estimates. Payback period has calculated to be around 5 years to 6 years, and it means that shipping companies can consider installing scrubbers for new ships and ships under 20 years old. Based on large container ships crossing Europe and Asia, VLSFO usage strategies are desirable if the age is 20 years or older.

**<Scenario 3>**: As a result of analyzing data from the past three years, the assumption was established based on the fact that crude oil and bunker oil prices moved together almost proportionally, and HSFO and VLSFO price fluctuations showed a difference of 3%. Therefore, it was assumed that HSFO increased by 24% per year and VLSFO increased by 27%. The payback period is calculated to be between 12 and 13, which is not much different from the base scenario <Scenario 1>. Therefore, this scenario can be concluded that it is desirable to install scrubbers on ships with a ship's age of less than 12-13 years, and above than that, the use of VLSFO is optimal.

**<Scenario 4>:** This scenario assumes the same incremental percentage for HSFO and VLSFO which is 24% and 27%, respectively. However, the scrubber price is assumed to be 50% decrease, as it has been assumed in <Scenario 2>. The payback period is analyzed at an average level of 11 years, and it is slightly reduced result value compared to <Scenario 3>, although there is no significant difference from the result value of <Scenario 1> which is the base scenario. In this case, the installation of scrubbers may be considered for ships manufactured for less than 15 years, and the use of VLSFO is appropriate for ships beyond that.

**<Scenario 5>**: VLSFO price is set to rise 8% every year, and scrubber prices are hypothesized to remain at the current level. "8%" has been hypothesized according to the supply and demand of VLSFO data from IEA. The Payback Period of the scrubber is calculated at the level of 6 to 6.5 years, suggesting that the installation of scrubbers could be considered for new ships and ships under the age of 20 years. Above 20 years aged ships are suitable to use VLSFO.

**<Scenario 6>**: VLSFO price is set to rise 8% every year, which is similar to <Scenario 5>. And the scrubber price is set to decrease 50% from the current unit price, which is the maximum value according to the data obtained from EGCSA Scrubber price estimates. The payback period is calculated to be more than 4 years, and this result is lower than the previous 5 scenarios. In this case, as in <Scenario 5>, the installation of scrubbers on ships with a ship age of 20 years or less can be positively considered, and in cases above that, the use of VLSFO is desirable. However, since the payback period is slightly lower than <Scenario 5>, the introduction of scrubbers can be considered more positively.

**Table 5. 14 Empirical Scenario Modeling Result Summary**

| Scenario | Variables | | | Scrubber Payback Period | | |
|---|---|---|---|---|---|---|
| | HSFO Price | VLSFO Price | Scrubber Price | Neo Panamax | Post Panamax | Panamax |
| **Scenario 1** | Current Price | Current Price | Current Price | 11.2 | 12.6 | 12.3 |
| **Scenario 2** | Current Price | Current Price | 50% Decrease | 5.64 | 6.34 | 6.19 |
| **Scenario 3** | Annual 24% Increase | Annual 27% Increase | Current Price | 12.8 | 13.3 | 13.2 |
| **Scenario 4** | Annual 24% Increase | Annual 27% Increase | 50% Decrease | 10.98 | 11.22 | 11.17 |
| **Scenario 5** | Current Price | Annual 8% Increase | Current Price | 6.05 | 6.48 | 6.39 |
| **Scenario 6** | Current Price | Annual 8% Increase | 50% Decrease | 4.02 | 4.33 | 4.27 |

# Chapter 6: Conclusions

## 6.1 Conclusions and Recommendations

This study began by considering which alternative would be the best option and what solution would be appropriate in terms of shipping companies' costs as IMO decided to enforce sulfur oxide emission regulations below 0.5% m/m in 2020. The IMO aims not to regulate sulfur alone, but to solve the climate change crisis by reducing greenhouse gases as a whole, create a clean atmosphere for the planet, and ultimately have a positive impact on humanity. Therefore, environmental regulations are gradually developed and strengthened, and from the perspective of the shipping industry, it is necessary to respond flexibly to this so that the business can be continuously operated.

Numerous shipping companies are considering introducing low sulfur oil, scrubbers, or alternative fuels such as LNG, hydrogen, ammonia, and methane, and it is a crucial decision for shipping companies even it is now two years after IMO 2020 introduction. Since alternative fuels have a prohibitive cost of introduction, they are considered for a longer-term, rather than mid and short term. However, the introduction and installation and operation of low sulfur oil are essential issues not only for existing ships but also for new ships, and the price of low sulfur oil fluctuates from time to time, and the price of scrubbers also fluctuates due to changes in supply and demand. As a result, shipping companies must choose cost-effective and strategically optimal alternatives to avoid losses, and differences are huge depending on how future scenarios are organized. Therefore, this paper explored and analyzed why and how shipping companies should choose countermeasures, what are the advantages and disadvantages of using low sulfur oil and scrubber, which method is more expensive at the current level, and how much payback period is calculated if scrubber is installed.

In the previous studies, it agreed in the point that low sulfur oil use has no additional device installation and maintenance cost since it does not cost capital costs. In addition, scrubbers are consistent in that HSFO can be used, which is less fuel-efficient. However, there were different positions on the economic feasibility and impact of the IMO 2020 response low sulfur oil and scrubber strategy. First, Cost-benefit Analysis analyzed that the annual maintenance reduction rate is similar to $5 million or calculated that scrubber payback period is 3.3 years by using oil price prediction data. However, this has limitations in that the oil price prediction data used as data for modeling and it goes against the average trend of oil price data from the past to the present. Second, case research analyzed the influence of low sulfur oil and scrubber use strategies in specific regions. These studies analyzed that the higher the rate of staying in SECA, the more advantageous it is to use scrubbers, the more advantageous it is to use low sulfur oil, and the less social cost it is to countries located adjacent to SECA. However, only the impact on the country and society was analyzed, and there was a limit to the effect on shipping companies. Third, it is statistical scenario analysis modeling. The best compliance solution was analyzed based on bunkering costs at the time of the study, and the economic feasibility of low sulfur oil and scrubber use strategies was analyzed when MGO prices increased 1.7 times and 3.4 times. This has a significance in that the modelling can be statistically analyzed, by calculating that the use of MGO is the most appropriate strategy or the payback period of the scrubber is three years. However, there were limitations such as not considering the use of VLSFO and the reason for assuming the increase in MGO prices by 1.7 times and 3.7 times was unclear. Therefore, this paper conducted a scenario analysis modeling to overcome all of the limitations described above and create a new research foundation.

In summary, shipping companies should introduce VLSFO, scrubbers, or alternative fuel propellants to comply with regulations and reduce global environmental pollution. However, in the case of LNG propulsion ships or hydrogen cell propulsion ships, manufacturers are limited and there are technical limitations, so they are not suitable for cost-effectiveness in a mid- to short-term. Therefore, as of now, this paper concluded that shipping companies are most likely to introduce VLSFO or scrubbers in the medium or short term. The advantages and disadvantages of low sulfur oil and scrubbers are as follows. For low sulfur oil, it can be simply introduced only by switching fuel without having to modify ships or install new devices. However, the disadvantage is that blending oil has a risk of sludge occurring, and economic efficiency is low if the increase is high due to the rising trend of low sulfur oil prices. On the contrary, in the case of scrubbers, TEU is reduced in container ships because new equipment needs to be installed on existing ships, initial introduction costs are about 5-10 million dollars depending on the size of the ship, and if demand is high, the sea area regulating Open-Loop scrubbers is increasing, and additional maintenance costs. However, it is advantageous to increase the price of low-sulfur oil in that existing high-sulfur oil can be used, there is no risk of having sludge and engine failure as blending oil is not used, and if more scrubber suppliers are entering the market, a drop in price can be expected. In order to determine the most optimal solution either introducing VLSFO or installing and operating scrubbers, it is necessary to consider the price burden and economic feasibility from the perspective of shipping companies. However, prices reflect market conditions, and it is difficult to predict how they will change in the future. Therefore, this paper sought an optimal countermeasure by setting six scenarios. This paper analyzed and utilized the research data of IEA, EGCSA, Clarkson Research, and MAN Energy Solution as a whole to assume the future price estimations. Hence, in the case where HSFO and VLSFO prices fluctuate together, the increase has been assumed to be 24% and 27% respectively. On the other hand, in the case where considering only market demand

and supply, annual increase of 8% for VLSFO price is settled and HSFO to stay unchanged. The scrubber price is assumed to either stay as in the current price or decrease in 50% considering current market demand and supply. The payback period is calculated by the combinations of these prices, and the best optimal solutions have been discussed for each scenario.

To conclude by summing up overall five scenarios, if the current oil prices are assumed to continue constantly without any changes, the scrubber's economic feasibility is only advantageous to ships that are under 13 years. Ships that are above 13 years are suitable to use VLSFO. However, if the scrubber price goes down 50%, the payback period halved, and scrubber would be advantageous for containerships aged less than 20 years. However, if the shipping company expects future oil prices to rise to an average of 5 years trend, scrubber's economic feasibility worsens. Even if scrubber price goes down in 50%, it shows similar results with the scenario where no changes in price are assumed. Therefore, VLSFO use will be widely concerned. On the other hand, if the shipping companies considers market demand and supply prediction data other than previous oil price trends, scrubber use strategies are found to be more advantageous compared to other scenarios. Especially if the scrubber price drops down, which is the situation assumed based upon the supply and demand predictions, scrubber strategy will be the most beneficial for almost all containerships running except for ships that will be scrapped in 5 years.

By comprehensively considering all of these scenarios, shipping companies can see what the worst case and the best-case scenario would be considering all price variables. Being able to choose the most optimal decision, it will not only achieve greenhouse gas emission reductions but also maximize their profits. This way will enable businesses, individuals, and all of us related to the shipping world to enjoy environmental and economic prosperities.

### 6.2 Limitation and Suggestions for the Future Research

In previous studies, alternatives to regulations on sulfur oxide emission reduction were conducted through specific navigation routes, countries, or companies. However, comprehensive research according to changes in ship characteristics, operation characteristics, and cost of countermeasures of container ship shipping companies is limited. Accordingly, this study can predict and analyze the cost change according to the change in the scenario, and it can be seen that it has laid the foundation for selecting the optimal alternative. However, this study has limitations in that it analyzed the scenario by categorically assuming the demand and supply of the scrubber market, where the price and increase or decrease of VLSFO are uncertain from time to time. In other words, assumed scenario of VLSFO price increasing 8% annually and 50% decrease in scrubber unit price have a limitation since it is an estimated assumption. Additionally, scenarios where HSFO and VLSFO price rise as in 5-year average value cannot be concluded that it is perfectly realistic. Oil prices and bunker fuel prices fluctuate, and predictions are difficult to make. Therefore, if VLSFO price data becomes large and scrubber prices can be widely provided as open sources, it will be possible to predict more accurate scenarios through big data analysis or machine learning. In other words, if only a large amount of data can be collected, more accurate research will be possible with more advanced technologies. However, it is unknown whether the exact price of scrubbers, which are one of the corporate secrets, can be disclosed. Hence the study that estimates them most accurately can be a study that suggests the most realistic alternative.

**Annexes**

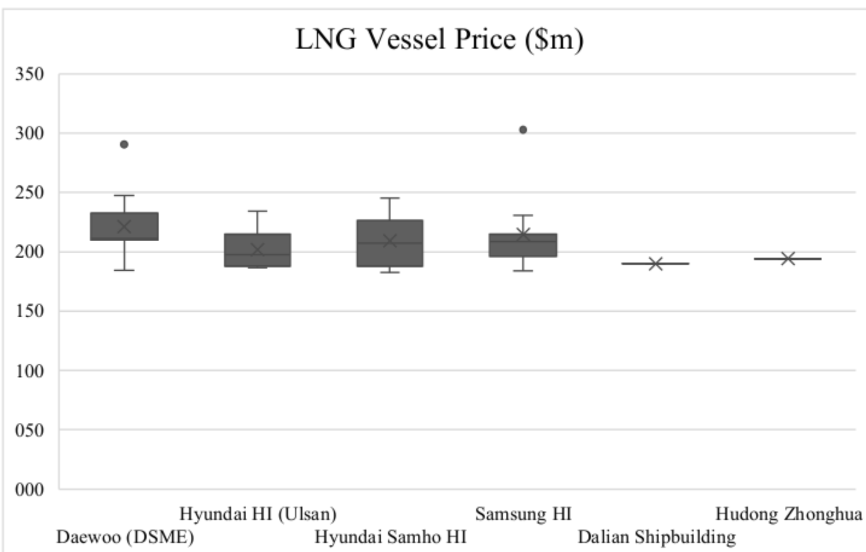
**Annex 1 – Comparative Evaluations of Proposed Market-Based Measures**

| Proposed Measures | Proposed Country | Key Contents | Evaluations |
|---|---|---|---|
| International Fund for Greenhouse Gas emissions from ships (GHG Fund) | Denmark | Fund formation and operation by imposing a uniform tax per ton of fuel (impose to the fuel supplier or shipowner). | The implementation of the system is the easiest and the response of many Member States. |
| Leveraged Incentive Scheme (LIS) | Japan | GHG Fund contributions are collected in marine bunkers, where a portion of the contributions are refunded and marked as a "superior performance vessels" for vessels meeting or exceeding the agreed efficiency benchmarks. | It is primarily designed to reduce CO2 emissions from shipping directly. Additional funds are expected to help fund management. |
| Port State Levy | Jamaica | Port Authority Imposes Tax on Shippers of Arriving Vessels. | Due to the international nature of IMO, the possibility of realizing regulations on shippers from individual ports is low. |
| Ship Efficiency and Credit Trading (SECT) | US | Provide points to ships below EEDI emission acceptance standards and sell points to other industrial sectors. | Can be an excessive dependence on non-international shipping. |
| Vessel Efficiency System (VES) | World Shipping Council | Mandatory efficiency standards are set on new and existing ships to determine how low the average efficiency is, by the grade and size of each ship. This standard will be gradually stricter, and ships that do not meet the standards will be charged a fee that applies to fuel consumption. | Excessive cost of renovation is expected for old existing vessels to meet technical standards. |
| Global Emission Trading System (ETS) | Norway | Allocation and mutual transaction of emission rights by ship or ship, determining the total annual or five-year international shipping sector emissions. | Advantages for countries with existing experience in areas such as Europe and North America |
| Global Emissions Trading System (ETS) | UK | Two differences from Norway's proposal: a national emission allowance allocation method instead of | The shift to the domestic unit may ease the bias of competitiveness in Europe and North |
| Emissions Trading System (ETS) | France | | |

| | | | |
|---|---|---|---|
| | | a global auction, and an approach to setting the emission cap for long-term reduction trajectories. | America at the international level, but it is still advantageous to countries with experience in enforcing regulations. |
| Market-Based Instruments: a penalty on trade and development | Bahamas | Payment of contributions based on the amount of cargo in each country to raise funds equivalent to 3.3% of the total global emissions in the shipping industry. | Can be an Incentives applicable to emissions trading or carbon taxes. |
| Rebate Mechanism (RM) | IUCN | Fund is provided to developing countries by raising funds equivalent to the proportion of developing countries to the total global trade volume based on the amount. | Can be an Incentives applicable to emissions trading or carbon taxes. |

*Source: Own preparation, (IMO, 2011), (Psaraftis, Zis and Lagouvardou, 2021)*

**Annex 2 – LNG Vessel Price**




*Source: Clarkson Research (2022)*

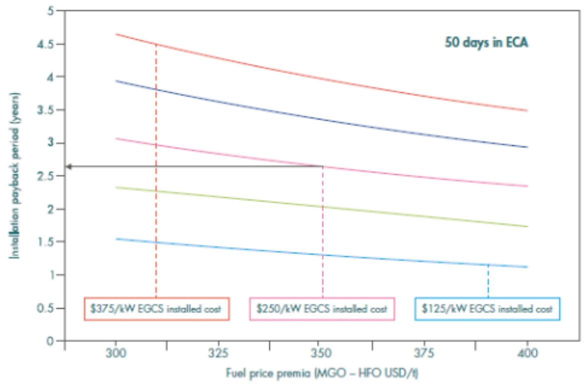
**Annex 3 – Summary of IMO MEPC 74th Meeting**

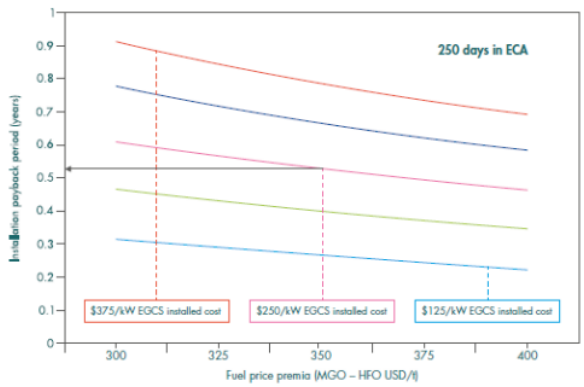
| Major Agenda | Amendments |
|---|---|

| | |
|---|---|
| **Adoption of the Amendment** | • Preparation of electronic records (approval required for fuel procurement, cargo, waste disposal, Nox, SOx related records, from October 1, 2020)<br><br>• Adopted regulations for discharge control of residual floating substances and tank cleaning-related substances (from January 1, 2021<br><br>• Regulation of energy efficiency design index related to ice structural lines (from October 1, 2020)<br><br>• Revision of rules related to Nox, and revision of rules related to drying and facilities for hazardous chemical carriers |
| **Reducing greenhouse gas emissions** | • Initial research starts to reduce greenhouse gas emissions from ships. Full-fledged discussion on short-term and medium-term measures to reduce emissions<br><br>• The IMO plans to reduce carbon dioxide emissions by at least 40% in 2030 compared to 2008 and by 70% in 2050<br><br>• Total greenhouse gas emissions reduced by more than 50% by 2050 |
| **Introduction of SOx regulations** | • Adopting guidelines for regulations with a sulfur content of 0.5% or less of ship fuel to take effect on January 1, 2020<br><br>• Refers to guidelines and technical considerations for each low-sulfur product<br><br>• Major measures of the administration and port countries to check compliance with regulations<br><br>• Control of fuel suppliers through sample surveys, notification of nonconforming ships, and sharing information to the IMO<br><br>• Fuel Oil Non-Availability Report (FONAR): Declaration documents to be prepared if fuel oil is not supplied despite appropriate efforts |

*Source: (Class NK, 2019)*

**Annex 4 – Fuel Price Premia and Installation Payback Period of Scrubbers**



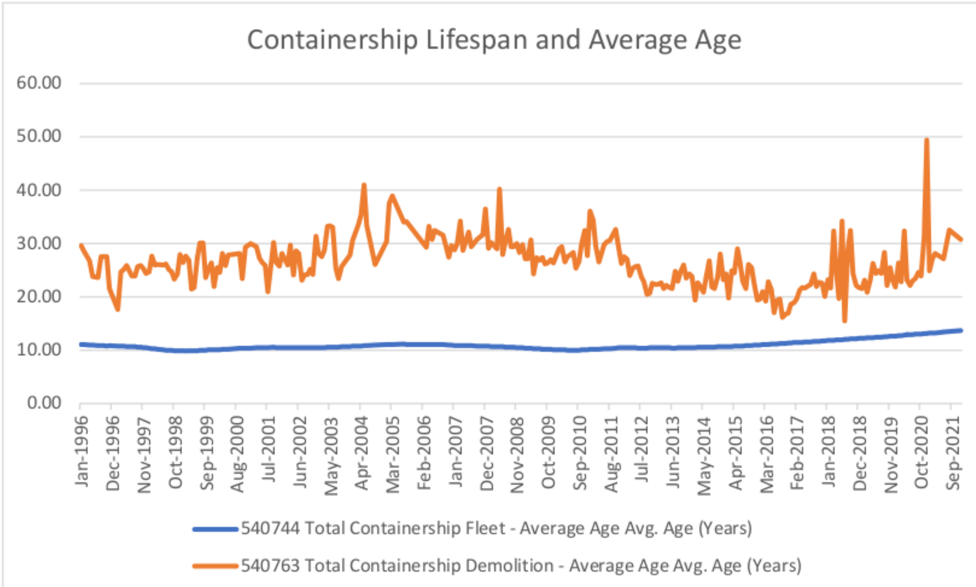




**Annex 5 – 10 Years of European Central Bank Interest Rate Overview**

| Date (with effect from) | | Deposit facility | Fixed rate tenders Fixed rate |
|---|---|---|---|
| **2022** | 27 Jul. | 0.00 | 0.50 |
| **2019** | 18 Sep. | −0.50 | 0.00 |
| **2016** | 16 Mar. | −0.40 | 0.00 |
| **2015** | 9 Dec. | −0.30 | 0.05 |
| **2014** | 10 Sep. | −0.20 | 0.05 |
| | 11 Jun. | −0.10 | 0.15 |
| **2013** | 13 Nov. | 0.00 | 0.25 |
| | 8 May. | 0.00 | 0.50 |
| **2012** | 11 Jul. | 0.00 | 0.75 |

*Source: (European Central Bank, 2022)*

**Annex 6 – Containership Lifespan and Average Age**




*Source: (Clarkson Research, 2022)*

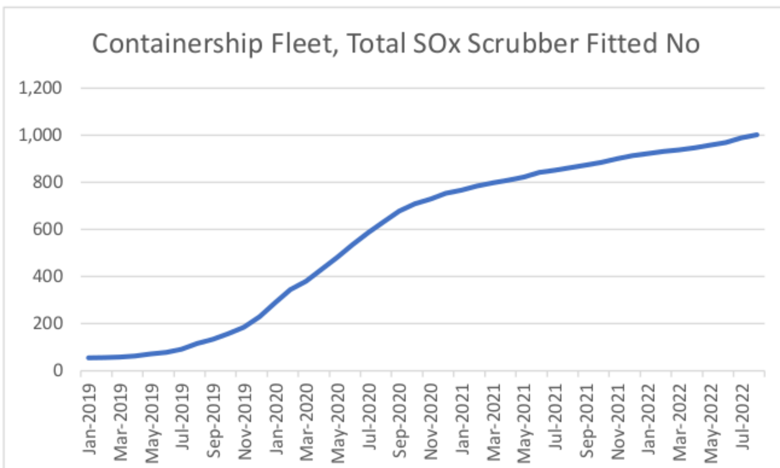
**Annex 7 – <Scenario 1> 20 Years Accumulative Fuel Cost Including Scrubber Cost**

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Neo Panamax | VLSFO Neo Panamax |
| 1st Year | $ 11,270,766 | $ 3,085,738 |
| 2nd Year | $ 13,560,932 | $ 6,171,476 |
| 3rd Year | $ 15,851,098 | $ 9,257,214 |
| 4th Year | $ 18,141,264 | $ 12,342,952 |
| 5th Year | $ 20,431,430 | $ 15,428,690 |
| 6th Year | $ 22,721,596 | $ 18,514,428 |
| 7th Year | $ 25,011,762 | $ 21,600,166 |
| 8th Year | $ 27,301,928 | $ 24,685,904 |
| 9th Year | $ 29,592,094 | $ 27,771,642 |
| 10th Year | $ 31,882,260 | $ 30,857,380 |
| 11th Year | $ 34,172,426 | $ 33,943,118 |
| 12th Year | $ 36,462,592 | $ 37,028,856 |
| 13th Year | $ 38,752,758 | $ 40,114,594 |
| 14th Year | $ 41,042,924 | $ 43,200,332 |
| 15th Year | $ 43,333,090 | $ 46,286,070 |
| 16th Year | $ 45,623,256 | $ 49,371,808 |
| 17th Year | $ 47,913,422 | $ 52,457,546 |
| 18th Year | $ 50,203,588 | $ 55,543,284 |
| 19th Year | $ 52,493,754 | $ 58,629,022 |
| 20th Year | $ 54,783,920 | $ 61,714,760 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Post Panamax | VLSFO Post Panamax |
| 1st Year | $ 8,126,655 | $ 2,025,465 |
| 2nd Year | $ 9,629,910 | $ 4,050,930 |
| 3rd Year | $ 11,133,165 | $ 6,076,395 |
| 4th Year | $ 12,636,420 | $ 8,101,860 |
| 5th Year | $ 14,139,675 | $ 10,127,325 |
| 6th Year | $ 15,642,930 | $ 12,152,790 |
| 7th Year | $ 17,146,185 | $ 14,178,255 |
| 8th Year | $ 18,649,440 | $ 16,203,720 |
| 9th Year | $ 20,152,695 | $ 18,229,185 |
| 10th Year | $ 21,655,950 | $ 20,254,650 |
| 11th Year | $ 23,159,205 | $ 22,280,115 |
| 12th Year | $ 24,662,460 | $ 24,305,580 |
| 13th Year | $ 26,165,715 | $ 26,331,045 |
| 14th Year | $ 27,668,970 | $ 28,356,510 |
| 15th Year | $ 29,172,225 | $ 30,381,975 |
| 16th Year | $ 30,675,480 | $ 32,407,440 |
| 17th Year | $ 32,178,735 | $ 34,432,905 |
| 18th Year | $ 33,681,990 | $ 36,458,370 |
| 19th Year | $ 35,185,245 | $ 38,483,835 |
| 20th Year | $ 36,688,500 | $ 40,509,300 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Panamax | VLSFO Panamax |
| 1st Year | $ 4,275,287 | $ 1,085,841 |
| 2nd Year | $ 5,081,174 | $ 2,171,682 |
| 3rd Year | $ 5,887,061 | $ 3,257,523 |
| 4th Year | $ 6,692,948 | $ 4,343,364 |
| 5th Year | $ 7,498,835 | $ 5,429,205 |
| 6th Year | $ 8,304,722 | $ 6,515,046 |
| 7th Year | $ 9,110,609 | $ 7,600,887 |
| 8th Year | $ 9,916,496 | $ 8,686,728 |
| 9th Year | $ 10,722,383 | $ 9,772,569 |
| 10th Year | $ 11,528,270 | $ 10,858,410 |
| 11th Year | $ 12,334,157 | $ 11,944,251 |
| 12th Year | $ 13,140,044 | $ 13,030,092 |
| 13th Year | $ 13,945,931 | $ 14,115,933 |
| 14th Year | $ 14,751,818 | $ 15,201,774 |
| 15th Year | $ 15,557,705 | $ 16,287,615 |
| 16th Year | $ 16,363,592 | $ 17,373,456 |
| 17th Year | $ 17,169,479 | $ 18,459,297 |
| 18th Year | $ 17,975,366 | $ 19,545,138 |
| 19th Year | $ 18,781,253 | $ 20,630,979 |
| 20th Year | $ 19,587,140 | $ 21,716,820 |

**Annex 8 – Total SOx Scrubber Fitted Number**




*Source: (Clarkson Research, 2022)*

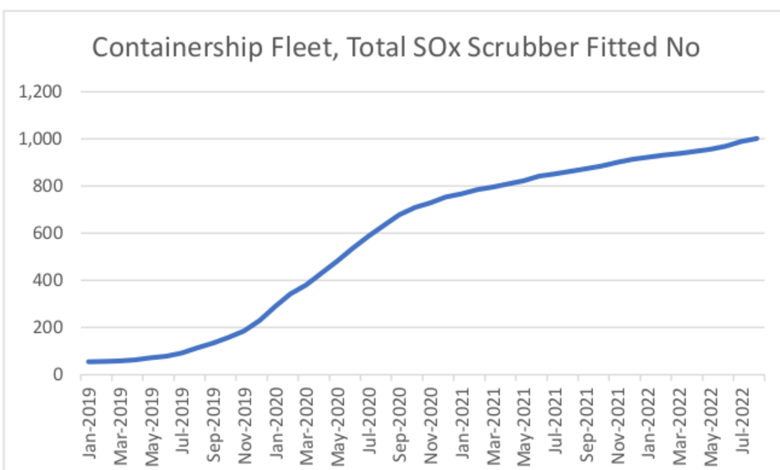
**Annex 9 – <Scenario 2> 20 Years Accumulative Fuel Cost Including Scrubber Cost**

| Accumulative Fuel Cost Including Scrubber Cost | | |
| --- | --- | --- |
| | HSFO Neo Panamax | VLSFO Neo Panamax |
| 1st Year | $ 6,780,466 | $ 3,085,738 |
| 2nd Year | $ 9,070,632 | $ 6,171,476 |
| 3rd Year | $ 11,360,798 | $ 9,257,214 |
| 4th Year | $ 13,650,964 | $ 12,342,952 |
| 5th Year | $ 15,941,130 | $ 15,428,690 |
| 6th Year | $ 18,231,296 | $ 18,514,428 |
| 7th Year | $ 20,521,462 | $ 21,600,166 |
| 8th Year | $ 22,811,628 | $ 24,685,904 |
| 9th Year | $ 25,101,794 | $ 27,771,642 |
| 10th Year | $ 27,391,960 | $ 30,857,380 |
| 11th Year | $ 29,682,126 | $ 33,943,118 |
| 12th Year | $ 31,972,292 | $ 37,028,856 |
| 13th Year | $ 34,262,458 | $ 40,114,594 |
| 14th Year | $ 36,552,624 | $ 43,200,332 |
| 15th Year | $ 38,842,790 | $ 46,286,070 |
| 16th Year | $ 41,132,956 | $ 49,371,808 |
| 17th Year | $ 43,423,122 | $ 52,457,546 |
| 18th Year | $ 45,713,288 | $ 55,543,284 |
| 19th Year | $ 48,003,454 | $ 58,629,022 |
| 20th Year | $ 50,293,620 | $ 61,714,760 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
| --- | --- | --- |
| | HSFO Post Panamax | VLSFO Post Panamax |
| 1st Year | $ 4,814,955 | $ 2,025,465 |
| 2nd Year | $ 6,318,210 | $ 4,050,930 |
| 3rd Year | $ 7,821,465 | $ 6,076,395 |
| 4th Year | $ 9,324,720 | $ 8,101,860 |
| 5th Year | $ 10,827,975 | $ 10,127,325 |
| 6th Year | $ 12,331,230 | $ 12,152,790 |
| 7th Year | $ 13,834,485 | $ 14,178,255 |
| 8th Year | $ 15,337,740 | $ 16,203,720 |
| 9th Year | $ 16,840,995 | $ 18,229,185 |
| 10th Year | $ 18,344,250 | $ 20,254,650 |
| 11th Year | $ 19,847,505 | $ 22,280,115 |
| 12th Year | $ 21,350,760 | $ 24,305,580 |
| 13th Year | $ 22,854,015 | $ 26,331,045 |
| 14th Year | $ 24,357,270 | $ 28,356,510 |
| 15th Year | $ 25,860,525 | $ 30,381,975 |
| 16th Year | $ 27,363,780 | $ 32,407,440 |
| 17th Year | $ 28,867,035 | $ 34,432,905 |
| 18th Year | $ 30,370,290 | $ 36,458,370 |
| 19th Year | $ 31,873,545 | $ 38,483,835 |
| 20th Year | $ 33,376,800 | $ 40,509,300 |

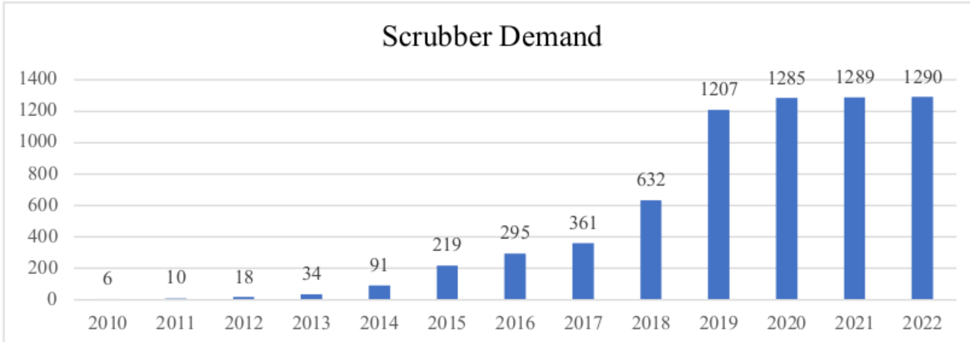
| Accumulative Fuel Cost Including Scrubber Cost | | |
| --- | --- | --- |
| | HSFO Panamax | VLSFO Panamax |
| 1st Year | $ 2,540,587 | $ 1,085,841 |
| 2nd Year | $ 3,346,474 | $ 2,171,682 |
| 3rd Year | $ 4,152,361 | $ 3,257,523 |
| 4th Year | $ 4,958,248 | $ 4,343,364 |
| 5th Year | $ 5,764,135 | $ 5,429,205 |
| 6th Year | $ 6,570,022 | $ 6,515,046 |
| 7th Year | $ 7,375,909 | $ 7,600,887 |
| 8th Year | $ 8,181,796 | $ 8,686,728 |
| 9th Year | $ 8,987,683 | $ 9,772,569 |
| 10th Year | $ 9,793,570 | $ 10,858,410 |
| 11th Year | $ 10,599,457 | $ 11,944,251 |
| 12th Year | $ 11,405,344 | $ 13,030,092 |
| 13th Year | $ 12,211,231 | $ 14,115,933 |
| 14th Year | $ 13,017,118 | $ 15,201,774 |
| 15th Year | $ 13,823,005 | $ 16,287,615 |
| 16th Year | $ 14,628,892 | $ 17,373,456 |
| 17th Year | $ 15,434,779 | $ 18,459,297 |
| 18th Year | $ 16,240,666 | $ 19,545,138 |
| 19th Year | $ 17,046,553 | $ 20,630,979 |
| 20th Year | $ 17,852,440 | $ 21,716,820 |

## Annex 10 – Average age of Container Ships that are installed with Retrofit Scrubbers

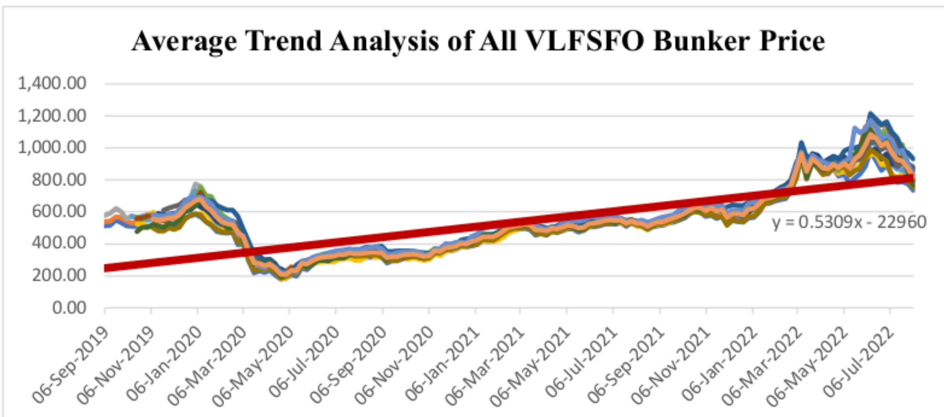



*Source: (Clarkson Research, 2022)*

**Annex 11 – Scrubber Demand Overview**




**Annex 12 – Average Trend Analysis of All VLSFO Bunker Price (2019 Sep. – 2022 Jul.)**




*Source: (Clarkson Research, 2022)*

**Annex 13 - <Scenario 3> 20 Years Price Increase (Annual Increase for both HSFO/VLSFO)**

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Neo Panamax | VLSFO Neo Panamax |
| 1st Year | $ 11,270,766 | $ 3,085,738 |
| 2nd Year | $ 23,091,172 | $ 7,004,625 |
| 3rd Year | $ 35,593,131 | $ 11,981,612 |
| 4th Year | $ 48,940,217 | $ 18,302,385 |
| 5th Year | $ 63,335,259 | $ 26,329,767 |
| 6th Year | $ 79,029,767 | $ 36,524,543 |
| 7th Year | $ 96,335,613 | $ 49,471,907 |
| 8th Year | $ 115,639,518 | $ 65,915,060 |
| 9th Year | $ 137,421,016 | $ 86,797,864 |
| 10th Year | $ 162,274,730 | $ 113,319,026 |
| 11th Year | $ 190,937,991 | $ 147,000,900 |
| 12th Year | $ 224,325,090 | $ 189,776,882 |
| 13th Year | $ 263,569,750 | $ 244,102,378 |
| 14th Year | $ 310,077,784 | $ 313,095,757 |
| 15th Year | $ 365,592,402 | $ 400,717,350 |
| 16th Year | $ 432,275,185 | $ 511,996,772 |
| 17th Year | $ 512,806,491 | $ 653,321,639 |
| 18th Year | $ 610,509,967 | $ 832,804,220 |
| 19th Year | $ 729,506,933 | $ 1,060,747,097 |
| 20th Year | $ 874,907,827 | $ 1,350,234,551 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Post Panamax | VLSFO Post Panamax |
| 1st Year | 8,126,655 | $ 2,025,465 |
| 2nd Year | $ 16,614,091 | $ 4,597,806 |
| 3rd Year | $ 25,548,896 | $ 7,864,678 |
| 4th Year | $ 35,038,438 | $ 12,013,606 |
| 5th Year | $ 45,215,854 | $ 17,282,745 |
| 6th Year | $ 56,246,234 | $ 23,974,551 |
| 7th Year | $ 68,334,290 | $ 32,473,145 |
| 8th Year | $ 81,733,862 | $ 43,266,359 |
| 9th Year | $ 96,759,716 | $ 56,973,740 |
| 10th Year | $ 113,802,159 | $ 74,382,115 |
| 11th Year | $ 133,345,172 | $ 96,490,752 |
| 12th Year | $ 155,988,892 | $ 124,568,719 |
| 13th Year | $ 182,477,489 | $ 160,227,739 |
| 14th Year | $ 213,733,734 | $ 205,514,693 |
| 15th Year | $ 250,901,861 | $ 263,029,125 |
| 16th Year | $ 295,400,722 | $ 336,072,454 |
| 17th Year | $ 348,989,695 | $ 428,837,482 |
| 18th Year | $ 413,850,405 | $ 546,649,067 |
| 19th Year | $ 492,688,069 | $ 696,269,780 |
| 20th Year | $ 588,857,156 | $ 886,288,086 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Panamax | VLSFO Panamax |
| 1st Year | 4,275,287 | $ 1,085,841 |
| 2nd Year | 8,743,986.88 | $ 2,464,859 |
| 3rd Year | 13,452,518.73 | $ 4,216,212 |
| 4th Year | 18,458,442.23 | $ 6,440,430 |
| 5th Year | 23,833,131.36 | $ 9,265,187 |
| 6th Year | 29,665,089.89 | $ 12,852,629 |
| 7th Year | 36,064,062.46 | $ 17,408,680 |
| 8th Year | 43,166,132.45 | $ 23,194,864 |
| 9th Year | 51,140,043.24 | $ 30,543,319 |
| 10th Year | 60,195,036.62 | $ 39,875,856 |
| 11th Year | 70,590,572.41 | $ 51,728,178 |
| 12th Year | 82,648,380.78 | $ 66,780,627 |
| 13th Year | 96,767,407.17 | $ 85,897,237 |
| 14th Year | 113,442,343.89 | $ 110,175,333 |
| 15th Year | 133,286,609.43 | $ 141,008,513 |
| 16th Year | 157,060,842.69 | $ 180,166,653 |
| 17th Year | 185,708,235.93 | $ 229,897,490 |
| 18th Year | 220,398,347.56 | $ 293,055,654 |
| 19th Year | 262,581,429.97 | $ 373,266,521 |
| 20th Year | 314,055,796.16 | $ 475,134,323 |

**Annex 14 - <Scenario 3> Neo-Panamax Bunker Price Increase Payback Period Calculation**

a = 3015446.34, b = -45624205.68, and c = 88092083.34

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(-45624205.68) \pm \sqrt{(-45624205.68)^2 - 4(3015446.34)(88092083.34)}}{2(3015446.34)}$$

$$x = \frac{45624205.68 \pm \sqrt{2.0815681439309E+15 - 1.0625478011623E+15}}{6030892.68}$$

$$x = \frac{45624205.68 \pm \sqrt{1.0190203427686E+15}}{6030892.68}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{45624205.68 + \sqrt{1.0190203427686E+15}}{6030892.68}, x_1 = 12.858180011935$$

$$x_2 = \frac{45624205.68 - \sqrt{1.0190203427686E+15}}{6030892.68}, x_2 = 2.2719866485669$$

**Annex 15 - <Scenario 3> Post-Panamax Bunker Price Increase Payback Period Calculation**

a = 1979325.86, b = -30676103.37, and c = 57823260.29

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(-30676103.37) \pm \sqrt{(-30676103.37)^2 - 4(1979325.86)(57823260.29)}}{2(1979325.86)}$$

$$x = \frac{30676103.37 \pm \sqrt{9.4102331796693E+14 - 4.5780429760603E+14}}{3958651.72}$$

$$x = \frac{30676103.37 \pm \sqrt{4.8321902036089E+14}}{3958651.72}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{30676103.37 + \sqrt{4.8321902036089E+14}}{3958651.72}, x_1 = 13.302091315778$$

$$x_2 = \frac{30676103.37 - \sqrt{4.8321902036089E+14}}{3958651.72}, x_2 = 2.1961669497917$$

**Annex 16 - <Scenario 3> Panamax Bunker Price Increase Payback Period Calculation**

a = 1061106.05, b = -16363926.18, and c = 30998741.91

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(-16363926.18) \pm \sqrt{(-16363926.18)^2 - 4(1061106.05)(30998741.91)}}{2(1061106.05)}$$

$$x = \frac{16363926.18 \pm \sqrt{2.6777808002449E+14 - 1.3157181033236E+14}}{2122212.1}$$

$$x = \frac{16363926.18 \pm \sqrt{1.3620626969213E+14}}{2122212.1}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{16363926.18 + \sqrt{1.3620626969213E+14}}{2122212.1}, x_1 = 13.210117103281$$

$$x_2 = \frac{16363926.18 - \sqrt{1.3620626969213E+14}}{2122212.1}, x_2 = 2.2114575640201$$

**Annex 17 - <Scenario 4> 20 Years Price Increase (Annual Increase for both HSFO/VLSFO) and Decrease for Scrubber in 50%**

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Neo Panamax | VLSFO Neo Panamax |
| 1st Year | $ 6,780,466 | $ 3,085,738 |
| 2nd Year | $ 14,110,572 | $ 7,004,625 |
| 3rd Year | $ 22,122,231 | $ 11,981,612 |
| 4th Year | $ 30,979,017 | $ 18,302,385 |
| 5th Year | $ 40,883,759 | $ 26,329,767 |
| 6th Year | $ 52,087,967 | $ 36,524,543 |
| 7th Year | $ 64,903,513 | $ 49,471,907 |
| 8th Year | $ 79,717,118 | $ 65,915,060 |
| 9th Year | $ 97,008,316 | $ 86,797,864 |
| 10th Year | $ 117,371,730 | $ 113,319,026 |
| 11th Year | $ 141,544,691 | $ 147,000,900 |
| 12th Year | $ 170,441,490 | $ 189,776,882 |
| 13th Year | $ 205,195,850 | $ 244,102,378 |
| 14th Year | $ 247,213,584 | $ 313,095,757 |
| 15th Year | $ 298,237,902 | $ 400,717,350 |
| 16th Year | $ 360,430,385 | $ 511,996,772 |
| 17th Year | $ 436,471,391 | $ 653,321,639 |
| 18th Year | $ 529,684,567 | $ 832,804,220 |
| 19th Year | $ 644,191,233 | $ 1,060,747,097 |
| 20th Year | $ 785,101,827 | $ 1,350,234,551 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Post Panamax | VLSFO Post Panamax |
| 1st Year | 4,814,955 | $ 2,025,465 |
| 2nd Year | $ 9,990,691 | $ 4,597,806 |
| 3rd Year | $ 15,613,796 | $ 7,864,678 |
| 4th Year | $ 21,791,638 | $ 12,013,606 |
| 5th Year | $ 28,657,354 | $ 17,282,745 |
| 6th Year | $ 36,376,034 | $ 23,974,551 |
| 7th Year | $ 45,152,390 | $ 32,473,145 |
| 8th Year | $ 55,240,262 | $ 43,266,359 |
| 9th Year | $ 66,954,416 | $ 56,973,740 |
| 10th Year | $ 80,685,159 | $ 74,382,115 |
| 11th Year | $ 96,916,472 | $ 96,490,752 |
| 12th Year | $ 116,248,492 | $ 124,568,719 |
| 13th Year | $ 139,425,389 | $ 160,227,739 |
| 14th Year | $ 167,369,934 | $ 205,514,693 |
| 15th Year | $ 201,226,361 | $ 263,029,125 |
| 16th Year | $ 242,413,522 | $ 336,072,454 |
| 17th Year | $ 292,690,795 | $ 428,837,482 |
| 18th Year | $ 354,239,805 | $ 546,649,067 |
| 19th Year | $ 429,765,769 | $ 696,269,780 |
| 20th Year | $ 522,623,156 | $ 886,288,086 |

| Accumulative Fuel Cost Induding Scrubber Cost | | |
|---|---|---|
| | HSFO Panamax | VLSFO Panamax |
| 1st Year | 2,540,587 | $ 1,085,841 |
| 2nd Year | 5,274,586.88 | $ 2,464,859 |
| 3rd Year | 8,248,418.73 | $ 4,216,212 |
| 4th Year | 11,519,642.23 | $ 6,440,430 |
| 5th Year | 15,159,631.36 | $ 9,265,187 |
| 6th Year | 19,256,889.89 | $ 12,852,629 |
| 7th Year | 23,921,162.46 | $ 17,408,680 |
| 8th Year | 29,288,532.45 | $ 23,194,864 |
| 9th Year | 35,527,743.24 | $ 30,543,319 |
| 10th Year | 42,848,036.62 | $ 39,875,856 |
| 11th Year | 51,508,872.41 | $ 51,728,178 |
| 12th Year | 61,831,980.78 | $ 66,780,627 |
| 13th Year | 74,216,307.17 | $ 85,897,237 |
| 14th Year | 89,156,543.89 | $ 110,175,333 |
| 15th Year | 107,266,109.43 | $ 141,008,513 |
| 16th Year | 129,305,642.69 | $ 180,166,653 |
| 17th Year | 156,218,335.93 | $ 229,897,490 |
| 18th Year | 189,173,747.56 | $ 293,055,654 |
| 19th Year | 229,622,129.97 | $ 373,266,521 |
| 20th Year | 279,361,796.16 | $ 475,134,323 |

**Annex 18 - <Scenario 4> Neo-Panamax Bunker Price Increase, Scrubber price decrease Payback Period Calculation**

a = 3015446.34, b = -41133905.68, and c = 88092083.34

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(-41133905.68) \pm \sqrt{(-41133905.68)^2 - 4(3015446.34)(88092083.34)}}{2(3015446.34)}$$

$$x = \frac{41133905.68 \pm \sqrt{1.6919981964911E+15 - 1.0625478011623E+15}}{6030892.68}$$

$$x = \frac{41133905.68 \pm \sqrt{6.2945039532882E+14}}{6030892.68}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{41133905.68 + \sqrt{6.2945039532882E+14}}{6030892.68}, x_1 = 10.980589311382$$

$$x_2 = \frac{41133905.68 - \sqrt{6.2945039532882E+14}}{6030892.68}, x_2 = 2.6604777287962$$

**Annex 19 - <Scenario 4> Post-Panamax Bunker Price Increase, Scrubber price decrease Payback Period Calculation**

a = 1979325.86, b = -27364403.37, and c = 57823260.29

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(-27364403.37) \pm \sqrt{(-27364403.37)^2 - 4(1979325.86)(57823260.29)}}{2(1979325.86)}$$

$$x = \frac{27364403.37 \pm \sqrt{7.4881057179607E+14 - 4.5780429760603E+14}}{3958651.72}$$

$$x = \frac{27364403.37 \pm \sqrt{2.9100627419003E+14}}{3958651.72}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{27364403.37 + \sqrt{2.9100627419003E+14}}{3958651.72}, x_1 = 11.221828167799$$

$$x_2 = \frac{27364403.37 - \sqrt{2.9100627419003E+14}}{3958651.72}, x_2 = 2.6032846764302$$

**Annex 20 - <Scenario 4> Post-Panamax Bunker Price Increase, Scrubber price decrease Payback Period Calculation**

a = 1061106.05, b = -14629226.18, and c = 30998741.91

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-(-14629226.18) \pm \sqrt{(-14629226.18)^2 - 4(1061106.05)(30998741.91)}}{2(1061106.05)}$$

$$x = \frac{14629226.18 \pm \sqrt{2.140142586256E+14 - 1.3157181033236E+14}}{2122212.1}$$

$$x = \frac{14629226.18 \pm \sqrt{82442448293239}}{2122212.1}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{14629226.18 + \sqrt{82442448293239}}{2122212.1}, x_1 = 11.171837429633$$

$$x_2 = \frac{14629226.18 - \sqrt{82442448293239}}{2122212.1}, x_2 = 2.6149336287358$$

**Annex 21 - <Scenario 5> 14 Years Accumulative Fuel Cost Including Scrubber Cost**

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Neo Panamax | VLSFO Neo Panamax |
| 1st Year | $ 11,270,766 | $ 3,085,738 |
| 2nd Year | $ 13,560,932 | $ 6,418,335 |
| 3rd Year | $ 15,851,098 | $ 10,017,540 |
| 4th Year | $ 18,141,264 | $ 13,904,681 |
| 5th Year | $ 20,431,430 | $ 18,102,794 |
| 6th Year | $ 22,721,596 | $ 22,636,755 |
| 7th Year | $ 25,011,762 | $ 27,533,433 |
| 8th Year | $ 27,301,928 | $ 32,821,846 |
| 9th Year | $ 29,592,094 | $ 38,533,332 |
| 10th Year | $ 31,882,260 | $ 44,701,736 |
| 11th Year | $ 34,172,426 | $ 51,363,613 |
| 12th Year | $ 36,462,592 | $ 58,558,440 |
| 13th Year | $ 38,752,758 | $ 66,328,853 |
| 14th Year | $ 41,042,924 | $ 74,720,900 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Post Panamax | VLSFO Post Panamax |
| 1st Year | $ 8,126,655 | $ 2,025,465 |
| 2nd Year | $ 9,629,910 | $ 4,212,967 |
| 3rd Year | $ 11,133,165 | $ 6,575,470 |
| 4th Year | $ 12,636,420 | $ 9,126,972 |
| 5th Year | $ 14,139,675 | $ 11,882,595 |
| 6th Year | $ 15,642,930 | $ 14,858,668 |
| 7th Year | $ 17,146,185 | $ 18,072,826 |
| 8th Year | $ 18,649,440 | $ 21,544,117 |
| 9th Year | $ 20,152,695 | $ 25,293,111 |
| 10th Year | $ 21,655,950 | $ 29,342,025 |
| 11th Year | $ 23,159,205 | $ 33,714,852 |
| 12th Year | $ 24,662,460 | $ 38,437,505 |
| 13th Year | $ 26,165,715 | $ 43,537,971 |
| 14th Year | $ 27,668,970 | $ 49,046,474 |

| Accumulative Fuel Cost Including Scrubber Cos | | |
|---|---|---|
| | HSFO Panamax | VLSFO Panamax |
| 1st Year | $ 4,275,287 | $ 1,085,841 |
| 2nd Year | $ 5,081,174 | $ 2,258,549 |
| 3rd Year | $ 5,887,061 | $ 3,525,074 |
| 4th Year | $ 6,692,948 | $ 4,892,921 |
| 5th Year | $ 7,498,835 | $ 6,370,196 |
| 6th Year | $ 8,304,722 | $ 7,965,653 |
| 7th Year | $ 9,110,609 | $ 9,688,746 |
| 8th Year | $ 9,916,496 | $ 11,549,686 |
| 9th Year | $ 10,722,383 | $ 13,559,502 |
| 10th Year | $ 11,528,270 | $ 15,730,103 |
| 11th Year | $ 12,334,157 | $ 18,074,353 |
| 12th Year | $ 13,140,044 | $ 20,606,142 |
| 13th Year | $ 13,945,931 | $ 23,340,474 |
| 14th Year | $ 14,751,818 | $ 26,293,553 |

**Annex 22 - <Scenario 5> Neo-Panamax VLSFO Price 8% Increase Payback Period Calculation**

a = 191178.93, b = 223436.93, and c = -8368024.05

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-223436.93 \pm \sqrt{(223436.93)^2 - 4(191178.93)(-8368024.05)}}{2(191178.93)}$$

$$x = \frac{-223436.93 \pm \sqrt{49924061687.825 + 6399159536373.1}}{382357.86}$$

$$x = \frac{-223436.93 \pm \sqrt{6449083598060.9}}{382357.86}$$

The discriminant $b^2-4ac > 0$ so, there are two real roots.

$$x_1 = \frac{-223436.93 + \sqrt{6449083598060.9}}{382357.86}, x_1 = 6.0573298192432$$

$$x_2 = \frac{-223436.93 - \sqrt{6449083598060.9}}{382357.86}, x_2 = -7.2260618024172$$

**Annex 23 - <Scenario 5> Post-Panamax VLSFO Price 8% Increase Payback Period Calculation**

a = 125489.02, b = 146663.03, and c = -6221307.81

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-146663.03 \pm \sqrt{(146663.03)^2 - 4(125489.02)(-6221307.81)}}{2(125489.02)}$$

$$x = \frac{-146663.03 \pm \sqrt{21510044368.781 + 3122823280781}}{250978.04}$$

$$x = \frac{-146663.03 \pm \sqrt{3144333325149.8}}{250978.04}$$

The discriminant $b^2-4ac > 0$ so, there are two real roots.

$$x_1 = \frac{-146663.03 + \sqrt{3144333325149.8}}{250978.04}, x_1 = 6.4809008051063$$

$$x_2 = \frac{-146663.03 - \sqrt{3144333325149.8}}{250978.04}, x_2 = -7.6496327786288$$

**Annex 24 - <Scenario 5> Panamax VLSFO Price 8% Increase Payback Period Calculation**

a = 67273.99, b = 78625.27, and c = -3253840.52

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-78625.27 \pm \sqrt{(78625.27)^2 - 4(67273.99)(-3253840.52)}}{2(67273.99)}$$

$$x = \frac{-78625.27 \pm \sqrt{6181933082.5729 + 875595338416.3}}{134547.98}$$

$$x = \frac{-78625.27 \pm \sqrt{881777271498.87}}{134547.98}$$

$$x_1 = \frac{-78625.27 + \sqrt{881777271498.87}}{134547.98}, x_1 = 6.3947797135267$$

$$x_2 = \frac{-78625.27 - \sqrt{881777271498.87}}{134547.98}, x_2 = -7.5635117896233$$

**Annex 25 - <Scenario 6> 14 Years Accumulative Fuel Cost Including Scrubber Cost**

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Neo Panamax | VLSFO Neo Panamax |
| 1st Year | $ 6,780,466 | $ 3,085,738 |
| 2nd Year | $ 9,070,632 | $ 6,418,335 |
| 3rd Year | $ 11,360,798 | $ 10,017,540 |
| 4th Year | $ 13,650,964 | $ 13,904,681 |
| 5th Year | $ 15,941,130 | $ 18,102,794 |
| 6th Year | $ 18,231,296 | $ 22,636,755 |
| 7th Year | $ 20,521,462 | $ 27,533,433 |
| 8th Year | $ 22,811,628 | $ 32,821,846 |
| 9th Year | $ 25,101,794 | $ 38,533,332 |
| 10th Year | $ 27,391,960 | $ 44,701,736 |
| 11th Year | $ 29,682,126 | $ 51,363,613 |
| 12th Year | $ 31,972,292 | $ 58,558,440 |
| 13th Year | $ 34,262,458 | $ 66,328,853 |
| 14th Year | $ 36,552,624 | $ 74,720,900 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Post Panamax | VLSFO Post Panamax |
| 1st Year | $ 4,814,955 | $ 2,025,465 |
| 2nd Year | $ 6,318,210 | $ 4,212,967 |
| 3rd Year | $ 7,821,465 | $ 6,575,470 |
| 4th Year | $ 9,324,720 | $ 9,126,972 |
| 5th Year | $ 10,827,975 | $ 11,882,595 |
| 6th Year | $ 12,331,230 | $ 14,858,668 |
| 7th Year | $ 13,834,485 | $ 18,072,826 |
| 8th Year | $ 15,337,740 | $ 21,544,117 |
| 9th Year | $ 16,840,995 | $ 25,293,111 |
| 10th Year | $ 18,344,250 | $ 29,342,025 |
| 11th Year | $ 19,847,505 | $ 33,714,852 |
| 12th Year | $ 21,350,760 | $ 38,437,505 |
| 13th Year | $ 22,854,015 | $ 43,537,971 |
| 14th Year | $ 24,357,270 | $ 49,046,474 |

| Accumulative Fuel Cost Including Scrubber Cost | | |
|---|---|---|
| | HSFO Panamax | VLSFO Panamax |
| 1st Year | $ 2,540,587 | $ 1,085,841 |
| 2nd Year | $ 3,346,474 | $ 2,258,549 |
| 3rd Year | $ 4,152,361 | $ 3,525,074 |
| 4th Year | $ 4,958,248 | $ 4,892,921 |
| 5th Year | $ 5,764,135 | $ 6,370,196 |
| 6th Year | $ 6,570,022 | $ 7,965,653 |
| 7th Year | $ 7,375,909 | $ 9,688,746 |
| 8th Year | $ 8,181,796 | $ 11,549,686 |
| 9th Year | $ 8,987,683 | $ 13,559,502 |
| 10th Year | $ 9,793,570 | $ 15,730,103 |
| 11th Year | $ 10,599,457 | $ 18,074,353 |
| 12th Year | $ 11,405,344 | $ 20,606,142 |
| 13th Year | $ 12,211,231 | $ 23,340,474 |
| 14th Year | $ 13,017,118 | $ 26,293,553 |

**Annex 26 - <Scenario 6> Neo-Panamax VLSFO Price 8% Increase, Scrubber 50% Decrease Payback Period Calculation**

a = 207607.48, b = 35999.37, and c = -3507511.36

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-35999.37 \pm \sqrt{(35999.37)^2 - 4(207607.48)(-3507511.36)}}{2(207607.48)}$$

$$x = \frac{-35999.37 \pm \sqrt{1295954640.3969 + 2912742378083.9}}{415214.96}$$

$$x = \frac{-35999.37 \pm \sqrt{2914038332724.3}}{415214.96}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{-35999.37 + \sqrt{2914038332724.3}}{415214.96}, x_1 = 4.0245565496966$$

$$x_2 = \frac{-35999.37 - \sqrt{2914038332724.3}}{415214.96}, x_2 = -4.1979576718527$$

**Annex 27 - <Scenario 6> Post-Panamax VLSFO Price 8% Increase, Scrubber 50% Decrease Payback Period Calculation**

a = 136272.65, b = 23629.83, and c = -2666601.81

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-23629.83 \pm \sqrt{(23629.83)^2 - 4(136272.65)(-2666601.81)}}{2(136272.65)}$$

$$x = \frac{-23629.83 \pm \sqrt{558368865.8289 + 1453539580574}}{272545.3}$$

$$x = \frac{-23629.83 \pm \sqrt{1454097949439.8}}{272545.3}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{-23629.83 + \sqrt{1454097949439.8}}{272545.3}, x_1 = 4.337737646549$$

$$x_2 = \frac{-23629.83 - \sqrt{1454097949439.8}}{272545.3}, x_2 = -4.5111387655557$$

**Annex 28 - <Scenario 6> -Panamax VLSFO Price 8% Increase, Scrubber 50% Decrease Payback Period Calculation**

a = 73055, b = 12668, and c = -1388866

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{-12668 \pm \sqrt{(12668)^2 - 4(73055)(-1388866)}}{2(73055)}$$

$$x = \frac{-12668 \pm \sqrt{160478224 + 405854422520}}{146110}$$

$$x = \frac{-12668 \pm \sqrt{406014900744}}{146110}$$

$b^2 - 4ac > 0$ so, there are two real roots.

$$x_1 = \frac{-12668 + \sqrt{406014900744}}{146110}, x_1 = 4.2743479946616$$

$$x_2 = \frac{-12668 - \sqrt{406014900744}}{146110}, x_2 = -4.4477515946889$$

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