University of South-Eastern Norway

# The Influence of MARPOL Annex VI on Global Ship Emission: A Study Based on the Impact in the ECAs

**Candidate name:** Ashwin Chettri

**University of South-Eastern Norway**
Faculty of Technology, Natural Sciences, and Maritime Sciences

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## Abstract

The International Maritime Organization's MARPOL Annex VI focuses on reducing global ship emission of Sulphur Oxides (SOx) and Particulate Matter (PM) from 3.50% to 0.50% from January 2020. However, the emission control areas (ECAs) have already set the limit of SOx emission to 0.10% since 2015. This means that the vessels operating in these regions (ECAs) have reduced their emission down to 0.10% by adopting various emission reduction technologies. The major concern arises when the MARPOL Annex VI will come into force from January 2020, resulting in global emission reduction down to 0.50%. This thesis focuses on air pollution caused by vessels by using bunker fuels with high sulphur content in the ECA regions, identifying various options adopted by the shipowners operating in the ECA to reduce the emission.

For the vessels to abide by the MARPOL Annex VI regulations, the ship-owners have adopted the option of installing a Scrubber system on their vessels, which allows the vessel to keep running on Heavy Fuel Oil (HFO) which has high sulphur content. The other common compliance options that have been adopted are using LNG as propulsion fuel, changing or switching the fuel for propulsion from HFO to distillates (Marine Gasoil), and using low-emission fuels and technologies, *i.e.,* batteries, hydrogen, methanol.

Using literature study as the method for collecting the data, secondary data like various research articles, conference papers, journals, news, and reports will be used to collect in-depth information. Based on the findings and the strategies adopted by the ship-owners in the ECA regions, few options that global ship-owners and operators could adopt to comply with the MARPOL Annex VI effective from January 2020, will be analyzed in this study.

Keywords: IMO, MARPOL Annex VI, Emission Control Areas, Sulphur Oxide (SOx), Nitrous Oxide (NOx), Particulate Matter, Scrubbers, LNG, Heavy Fuel Oil, Marine Gasoil.

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## List of Abbreviations

| | |
|---|---|
| $CH_4$ | Methane (one atom of Carbon, four atoms of Hydrogen) |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| CSA | Clean Shipping Alliance |
| cSt | Submultiple Centistokes |
| DNV-GL | Det Norske Veritas – Germanischer Lloyd |
| ECA | Emission Control Area |
| EGCS | Exhaust Gas Cleaning System |
| FGSS | Fuel Gas Supply System |
| GHG | Greenhouse Gas |
| GPS | Global Positioning System |
| GVU | Gas Valve Unit |
| HFO/HSFO | Heavy Fuel Oil / High Sulphur Fuel Oil |
| IFO | Intermediate Fuel Oil |
| IMCO | Inter-Governmental Maritime Consultative Organization |
| IMO | International Maritime Organization |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MARPOL | Maritime Pollution (International Convention for the Prevention of Pollution from Ships) |
| MDO | Marine Diesel Oil |
| MEPC | Marine Environment Protection Committee |
| MGO | Marine Gasoil |
| NIS | Norwegian International Ship Register (Norsk Internasjonalt Skipsregister) |
| $NO_x$ | Nitrogen/Nitric Oxides |
| NPV | Net Present Value |
| pH | Pouvoir Hydrogène (Power of Hydrogen) |
| PM | Particulate Matter |
| ppm | Parts Per Million |
| RO-RO | Roll-on / Roll-off Ships |
| $SO_x$ | Sulphur Oxides |
| SOLAS | Safety of Life at Sea |
| STCW | Standards of Training, Certification, and Watchkeeping |
| UHC | Unburnt Hydrocarbons |
| ULCC | Ultra Large Crude Carriers |
| VOC | Volatile Organic Compound |
| VLCC | Very Large Crude Carriers |

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# Chapter 1

## 1.1 Introduction

Maritime transportation is one of the most preferred modes of transportation worldwide. Due to its capacity to transport cargoes in bulk at a reasonable price, international shipping transports more than 80% of global trades to various places around the world. "*It provides a dependable, low-cost means of transporting goods globally, facilitating commerce and helping to create prosperity among nations and peoples*" (IMO, 2019d). Being one of the busiest and most preferred modes of transportation, maritime transportation contributes rather significantly to global air pollution.

Most of the world's fleet is operating in diesel engines as they operate with relatively lesser fuel than the other propulsion systems available. The major bunker fuels to power these diesel engines are Marine Gas Oil (MGO), which is a distillate, and Heavy Fuel Oil (HFO), which is almost a pure residual oil with high sulphur content. Shipping industry consumed around 350 million tonnes of fuels in the year 2007, out of which 250 million tonnes were residual fuels (Brynolf, Magnusson, Fridell, & Andersson, 2014). The main reason why ship-owners prefer to use residual fuels is because of its availability and cheap costs. This, however, comes with a greater price. These residual fuels contain a high amount of sulphur in it, and when these fuels are burnt, it releases sulphur oxides (SOx) and other particulate matter (PM) into the air, causing a major source of air pollution. As a result, Čampara, Hasanspahić, & Vujičić (2018) estimated that maritime transportation is responsible for annual emission of 3.3 million tons of nitrogen oxides, 2.3 million tons of sulphur oxides and 250,000 tons of harmful particulate matter, and emission has increased by 40% - 50% between 2000 to 2020. Certain factors other than the type of fuel used for propulsion, such as the deadweight of the vessel, shipping route, engine type and the condition of the vessel itself determines the level of emission (Jiang, Kronbak, & Christensen, 2014).

Since the emission level from maritime transport is noteworthy, a specialized agency of the United Nations known as the *International Maritime Organization* (IMO) have set standards to reduce the emission from ships. The IMO has adopted International Convention for the Prevention of Pollution from Ships (MARPOL Annex VI) in 1997 and entered into force on 19$^{th}$ May 2005, with an aim to reduce the ship emission. The MARPOL Annex VI was further revised and adopted the revised version in October 2008 which focused on reducing the emissions of SOx, NOx and particulate matter. The MARPOL Annex VI limits the emission of SOx and particulate matter in some designated areas known as the Emission Control Areas, from 1.0% m/m to 0.10% m/m on and after 1st January 2015. The regulation also sets the emission limit globally from the current 3.50% to 0.50%. The global limit shall be effective on and after 1st January 2020 (IMO, 2018).

Since the Emission Control Areas has already implemented the emission limit since 2015, this thesis focuses on studying various problems that the ship-owners faced, and their strategies adopted in order to comply with the emission regulation. Based on this study, different strategies/technologies for global ship-owners can adopt to comply with the MARPOL Annex VI, will also be identified in this study.

## 1.2 Objective

The objective of this thesis is to focus on the International Maritime Organization's Maritime Pollution Annex VI (IMO MARPOL Annex VI) which focuses on limiting global emission of Sulphur oxides (SOx), Nitrogen oxides (NOx) and other Particulate Matter. The MARPOL Annex VI legislation sets the limit for the amount of SOx and other particulate matter that a vessel can emit. Since the present global Sulphur cap is 3.50% m/m (mass by mass) causing various health and environmental threats, the International Maritime Organization now focuses on mitigating those threats by reducing the global Sulphur cap from 3.50% to 0.50% m/m effective from 1 January 2020 (IMO, 2019g).

The IMO has already established a much stricter limit for SOx and other particulate matters in the Emission Control Areas (ECAs) which came into effect 1 January 2015 (IMO, 2018). The emission of Sulphur oxides and other particulate matters has been reduced to 0.10% m/m (mass by mass) in the established ECA regions since January 2015, which is much stricter as compared to the global 0.50% m/m that shall be effective from 1st January 2020. Areas that constitutes Emission Control Areas are the Baltic Sea areas, the North Sea area, the North American area (designated coastal areas of the USA and Canada) and the United States Caribbean Sea areas, as shown in Figure 1.

Heavy Fuel Oil (HFO) also known as bunker oil or heavy diesel oil, is one of the major types of fuel that ships use for its propulsion. Heavy fuel oil is a mixture of residual fuel and distillate diluent (e.g., marine gas oil) and contains sulphur in heavy amounts which sooner or later leads to shipping emission once it has passed through the engines (Fritt-Rasmussen et al., 2018).

This thesis focuses on studying the influence of the Sulphur cap regulation on the ECA regions, investigate the approaches adopted by the ship-owners to comply with the regulation and identify some technologies that can be adopted by the global ship-owners.

## 1.3 Research Question

The primary objective of this thesis is to study and understand the effects caused by Sulphur cap regulation on Emission Control Areas (ECAs) established by the International Maritime Organization (IMO) which came into effect from 1 January 2015. Furthermore, based on the measures adopted by the ship-owners operating in the ECAs to overcome the Sulphur cap regulation, possible solutions that are available for global ship-owners will be analyzed in this paper.

The fundamental Research Question(s) that this study aims to answer are as follows:

**Research Question:**

What are the main emission reduction measures adopted by the ship-owners to comply with the MARPOL Annex VI regulations in the Emission Control Areas (ECAs)?

**Sub Research Question:**

Based on the ECAs study, what are different possible options available for the global ship-owners to comply with the MARPOL Annex VI that shall be effective from 1st January 2020, and what could be the most efficient and economic emission reduction technique?

## 1.4 Thesis Structure

*Chapter 1*: A brief introduction of this thesis paper will be explained in this chapter of the thesis. It also contains the objective and the research question(s) that shall be addressed later in this study.

*Chapter 2*: The following section will give an outlook of the literature that has been used in the study. This covers various topics like IMO, MARPOL Annex VI, ECA regions, SOx & NOx emissions, etc.

*Chapter 3*: The third chapter contains the methodology section. This describes the various methods used to collect and analyze the data needed to form concrete findings.

*Chapter 4*: This chapter covers the actual implementation of the methods described in the previous chapter. Data collected (findings) using the methods will be presented in this chapter.

*Chapter 5*: This chapter contains the discussion and re-addressing the research question(s) stated in chapter 1. Limitations and difficulties found during the research will also be addressed in this chapter.

*Chapter 6*: The final chapter of this thesis paper contains the conclusion of this study. Furthermore, it also contains some of the topics that were not covered in this paper and suggestion for further study will be pointed out here.

# Chapter 2

## 2.1 Background and Literature

### 2.1.1 *International Maritime Organization (IMO)*

"*It has always been recognized that the best way of improving safety at sea is by developing international regulations that are followed by all shipping nations*" (IMO, 2019a).

International Maritime Organization also known as IMO is the specialized agency of the United Nations, which sets global shipping standards for the safety, security and prevent maritime pollution of any nature. Apart from setting standards for international shipping, their major objective is to ensure that the standards are fair and effective for the ship-owners to comply and to ensure that it is implemented by all (IMO, 2019d).

Since maritime transport constitutes more than 80 percent of global trade, the world depends upon the efficiency, safety, and security of the shipping industry. Therefore, the IMO sets and regulates those standards to ensure that the international shipping industry meets those expectations.

IMO was established in 1948 at an international conference held in Geneva, initially known as Inter-Governmental Maritime Consultative Organization (IMCO), which was later changed to International Maritime Organization (IMO) in 1982 (IMO, 2019a). The IMO is currently regulated by the membership of 174 member states and 3 associate members who meet every two years. There are various conventions adopted and regulated by the IMO, and the main bodies responsible for adopting and implementing conventions are: Maritime Safety Committee, Facilitation Committee, Legal Committee, Marine Environment Protection Committee, along with the Assembly and the Council (IMO, 2019e). These conventions are adopted and implemented for different purposes like safety and security, maritime pollution, liabilities etc., out of which, Convention for the Safety of Life at Sea (SOLAS), Maritime Pollution (MARPOL) and Standards of Training, Certification, and Watch-keeping for Seafarers (STCW) are the key IMO conventions (IMO, 2019e).

### 2.1.2 *MARPOL Annex VI*:

International Convention for the Prevention of Pollution from Ships, also known as the MARPOL Convention was first adopted on 2 November 1973, solely for the purpose of preventing marine pollution which is either caused by operation or accidental causes (IMO, 2019c). After the adoption of MARPOL, there were various Annexes introduced to restrict the pollution of the marine environment caused by ships. However, these annexes were not substantial enough to restrict the air pollution caused by the ships.

Over the past few years, large factories, plants, and road vehicles were considered as the major source for air pollution, whereas ships, being far from the coast, were given considerably less significance as a source of air pollution. While the vehicles and plant's emission were being watched and regulated, the emission of harmful gases and particulate matters from ships became vulnerable and started contributing more to global air pollution (Čampara et al., 2018). This led the International Maritime Organization to take necessary steps to reduce the emission caused by ships which further led to the introduction of MARPOL Annex VI.

The MARPOL Annex VI was first adopted in 1997 following its entry into force on 19 May 2005, whose main objective was to limit the harmful exhaust gases (Sulphur and Nitrous Oxides) from ships. Apart from the emission regulation, MARPOL Annex VI also monitors and regulates the incineration from shipboard and emission of Volatile Organic Compounds (VOC) from tanker vessels (IMO, 2018).

In 2005, the Marine Environment Protection Committee (MEPC) at its 53rd session decided to revise the MARPOL Annex VI in order to tighten the emission limits. After years of close examination, the MEPC adopted the revised MARPOL Annex VI in the year 2008 which entered into force on 1st July 2010, along with the NOx (Nitrous Oxide) Technical Code 2008 (IMO, 2018).

The revised Annex VI made a progressive reduction of SOx, NOx and other particulate matter and also made a new introduction of Emission Control Areas (ECAs), where the emission shall be further restricted. The MARPOL Annex VI has restricted the emission on SOx and PM from 1.50% m/m to 1.0% m/m on and after 1 July 2010 and further down to 0.10%

m/m on and after 1 January 2015, in the designated ECAs. The current MARPOL Annex VI constitutes of 26 regulations segregated in 5 different chapters (Čampara et al., 2018).

This MARPOL Annex VI not only limits the emission of SOx, NOx and other particulate matters in the designated ECAs but has taken necessary measures to reduce the emission globally. As shown in Table 1, the limit for sulphur in bunker oil for ships worldwide will be reduced from 3.50% m/m to 0.50% m/m effective from 1 January 2020. Since the feasibility study concerning the availability of the required fuel oil was conducted in 2018, the MEPC 70 (October 2016) decided that the global sulphur cap regulation shall come into effect on 1 January 2020 (IMO, 2019h).

*Table 1: The limit of SOx and PM inside and outside the ECAs. Source (IMO, 2019h)*

| Outside an ECA established to limit SOx and particulate matter emissions | Inside an ECA established to limit SOx and particulate matter emissions |
|---|---|
| 4.50% m/m* prior to 1 January 2012 | 1.50% m/m prior to 1 July 2010 |
| 3.50% m/m on and after 1 January 2012 | 1.00% m/m on and after 1 July 2010 |
| 0.50% m/m on and after 1 January 2020 | 0.10% m/m on and after 1 January 2015 |

** Mass by Mass. The mass percentage represents the concentration of an element in a compound.*

### 2.1.3 *Emission Control Areas (ECAs)*

ECA or the Emission Control Areas is a set of a specific area of the sea, including port areas, that has been defined by the International Maritime Organization and where the emission regulations are more intense. Due to regulation 13 (NOx) and 14 (SOx) emission standards, there are currently four designated Emission Control Areas, to meet the requirements, as shown with a dark green highlight in Figure 1. Baltic Sea area, North Sea area, North American Sea area (covering designated areas of the US and Canada) and the US Caribbean Sea area (around Puerto Rico and the United States Virgin Islands), currently fall under the ECA zones (Čampara et al., 2018).

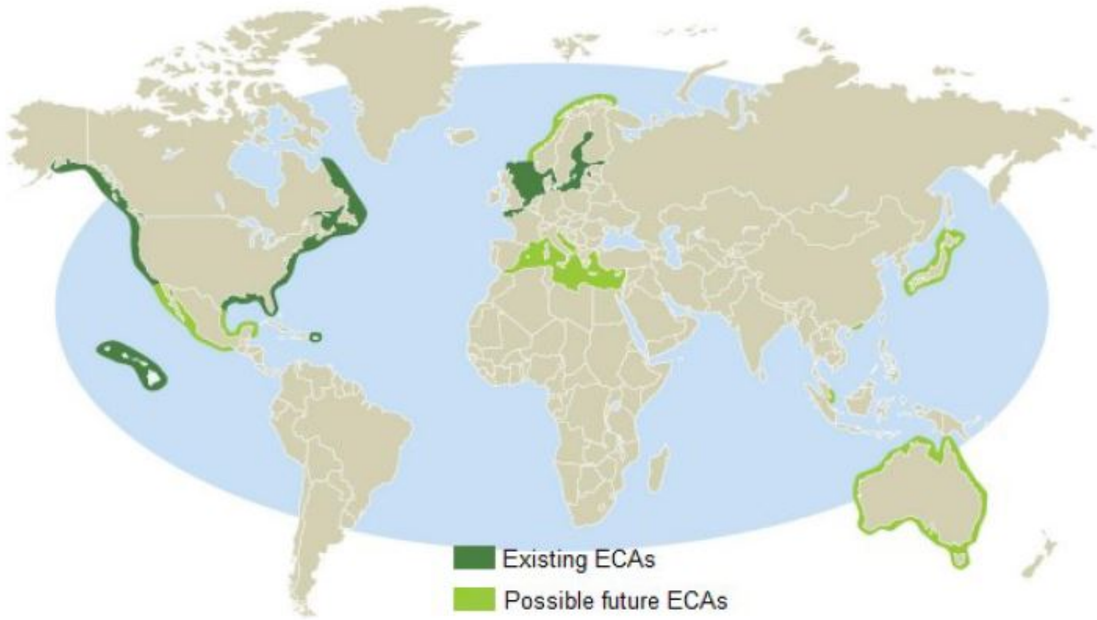


*Figure 1: Existing and Possible ECA regions (Čampara et al., 2018)*

Measures to reduce SOx and Particulate Matter emission from ships have already been implemented by IMO in these designated ECA regions. Effective from 1 January 2015, the emission limit for SOx and PM has been brought down from 1.00% m/m to 0.10% m/m, and shall remain the unchanged even after the Global Sulphur cap regulation comes into effect from 1 January 2020 (IMO, 2019b). The Nitrogen Oxides regulation (regulation 13 Tier III) does not apply to the North Sea and Baltic Sea region. However, amendments to MARPOL Annex VI has included the two regions as emission control areas for Nitrogen Oxides which entered into force on 1st January 2019 and shall be effective from 1st January 2021. This means that any ship built on and after 21st January 2021 and shall operate under the designated ECA waters, are or will be obligated to comply with the NOx Tier III standards hereafter (Čampara et al., 2018; IMO, 2019f). The four ECA regions were adopted by the IMO on different dates, along with compounds (SOx, NOx, and PM) adopted and applicable on different dates as well. Table 2 represents the four ECAs along with their adoption, enforcement and effective dates of different compounds.

*Table 2: MARPOL Annex VI ECAs dates of adoption, enforcement and effective. Source (IMO, 2019f)*

| ECAs | Adoption date | Enforcement date | Effective date |
|---|---|---|---|
| *Baltic sea area*: SOx | 26 September 1997 | 19 May 2005 | 19 May 2006 |
| *Baltic sea area*: NOx | 7 July 2017 | 1 January 2019 | 1 January 2021 |
| *North Sea area*: SOx | 22 July 2005 | 22 November 2006 | 22 November 2007 |
| *North Sea area*: NOx | 7 July 2017 | 1 January 2019 | 1 January 2021 |
| *North American area*: SOx | 26 March 2010 | 1 August 2011 | 1 August 2012 |
| *North American area*: NOx | 26 March 2010 | 1 August 2011 | 1 January 2016 |
| *US Caribbean Sea area*: SOx | 26 July 2011 | 1 January 2013 | 1 January 2014 |
| *US Caribbean Sea area*: NOx | 26 July 2011 | 1 January 2013 | 1 January 2016 |

### 2.1.4 *Sulphur Oxides (SOx) and Particulate Matter (PM):*

Particulate Matter (PM) are mixtures of small particles of solid substances and liquid droplets that can be found in the exhaust fumes from the ships. These little solid particles, known as PM which is usually a mixture of soot (dust) and fine particles of ash and $SO_x$ gases are formed from the combustion of fuels. The formation of PM and $SO_x$ gases depends upon the sulphur content in the fuel and forms more if the fuel contains higher sulphur (Čampara et al., 2018).

The international shipping industry is the most efficient and cost-effective mode of transportation which transports more than 80 percent of the world's trade to and from different nations worldwide. Being one of the most preferred modes for transporting good in bulk, the ships also make a huge contribution to marine environment pollution. Lindstad & Eskeland (2016) states that the global shipping industry accounts for 10% – 15% of Sulphur Oxides and Nitrous Oxides emission along with approximately 3% of global Carbon Dioxide ($CO_2$). According to (Corbett et al., 2007), ships engaged in transportation around the world are responsible for emitting about 1.2 – 1.6 million metric tons of particulate matter.

Most of the vessel worldwide are diesel powered engines, as diesel engines use comparatively less amount of fuel than other engine systems. Furthermore, the type of fuel used in operating a ship is residual in nature, which is the left-over residue from the contraction of the finest distillates from crude oil (Corbett & Fischbeck, 1997). These residual fuels are then mixed with the distillate diluent fuels, which are much cleaner in nature, to form the commonly used bunker fuel for ships known as Heavy Fuel Oil or HFO (Fritt-Rasmussen et al., 2018).

According to Corbett & Fischbeck (1997), on average, vessels that are equipped with medium-speed engines releases about 57 kgs of NOx per ton and about 87 kgs per ton if the vessels are operated by slow-speed engines. Since the bunker fuels (Heavy Fuel Oil) contains approximately 2.1 – 5% sulphur content, it is also estimated that maritime transport emits about 8.48 tera-grams (Tg) of SOx annually (4.24 Tg SOx per year using the European sulphur level of 3.3% and 2% for Marine Diesel Oil). A study conducted by (Cullinane & Cullinane, 2013) states that the bunker fuels used in ships contain about 27,000 parts per million (ppm) of sulphur whereas the fuels (diesel) used by vehicles contains just about 10-15 ppm.

The heavy fuels used by ships contain asphalt, carbon residues, metallic compounds, sulphur (up to 5 wt.%), compounds of high viscosity and much more. When the fuels that contain heavy sulphur is burned, the sulphur is converted into sulphur dioxide, to which when exposed, causes eyes, nose, throat irritation and sometimes also lead to asthmas. The SOx emission also contributes to acid rain which affects the vegetation. These fuels are also know for producing high amount of Black smoke, Carbon Monoxide (CO), Carbon dioxide ($CO_2$), Nitrogen Oxides ($NO_x$), Unburnt Hydrocarbons (UHC), Particulate Matters (PM) etc. (Lin & Lin, 2006), which are known as Greenhouse Gases (GHG) and contributes significantly to the depletion of the ozone layer. Due to such high emission of SOx, NOx, and PM, researches have been conducted to find the negative effects caused by such emissions. A large portion of particulate matter emission causes various diseases and exposure to such, is responsible for approximately 5% bronchus, trachea, and lung cancer mortality, 3% of adult cardio-pulmonary diseases and also causes acute respiratory infection in children globally (Cohen et al., 2005). Moreover, the study also shows that such pollution amounts up to 800,000 premature deaths.

#### **2.1.4.1** *Effects of SOx on Environment*

Sulphur oxides are compounds of sulphur and oxygen molecules which is colorless in nature. It can be detected through taste and smell when the Sulphur is concentrated at the range of 1,000 to 3,000 micrograms per cubic meters (μg/m3) and has a foul smell at the concentration of 10,000 μg/m3 (IFC, 1998). The major sources for Sulphur dioxide come from burning Sulphur content fuels, the roasting of metal sulfide ores, volcanoes, etc.

Sulphur Oxides emission not only effects the human life but also causes a significant impact on the overall environment. Vegetation, including agricultural crops, plantation, and forestry are adversely affected due to the exposure to the sulphur oxide emission. In recent years, studies have been conducted which shows that crops and plants lose their foliage and become less productive, sometimes even die prematurely when exposed to an environment with high sulphur concentration (IFC, 1998). These impacts vary greatly according to the plant/crop species, as some of them are more vulnerable and sensitive to exposure than the other. Crops like Alfalfa and Ryegrass are much more sensitive than other agricultural crops but nevertheless, causes damage to all. Trees and plants can also be affected by the SOx emission when the source of emission is quite close.

Sulphur Oxides is also responsible for causing acid rain, along with the other greenhouse gases, contributes significantly to form acid rain. These acid rain depositions can affect the soils yields and reduce productivity over a long period of time. The acid rain also impacts the water-bodies. Freshwater lakes, streams, rivers, etc., can be adversely affected by the acid rain, by lowering the pH of the water ecosystem (IFC, 1998). The reduction of pH in the water ecosystem, on the other hand, can disturb the fish and other species lifestyle. Very few species are capable of surviving in large shifts of pH, and the affected water-bodies can completely remove the marine species over a long period of time (IFC, 1998).

### 2.1.5 *Measures for Sulphur Reduction*

There are various alternatives in which ship-owners can opt to reduce the sulphur emission level and comply with the MARPOL Annex VI-legislation. The choice for adopting a particular emission reduction technology depends upon various factors like technology, market availability, the organization itself, etc. The three most common measures to meet the MARPOL Annex VI regulation are Installation of Scrubbers, Switching the bunker fuel from HFO to cleaner distillates and/or the use of LNG (ABS, 2018; DNV-GL, 2019; Jiang et al., 2014; Kim & Seo, 2019).

A conference paper presented by Nielsen & Schack (2012) gives us valuable insights about the three different abatement technologies, based on retrofitting a vessel with the emission reduction technologies, in order to reduce the ship emission as per the legislation.

#### **2.1.5.1** *Heavy Fuel Oil and Marine Gas Oil*

HFO or Heavy Fuel Oil is one of the major sources of bunker fuel for marine engines today. HFO is a residual fuel, which is rich in sulphur which is preferred by most of the shippers around the world as it is comparatively cheaper than the other distillates or cleaner fuels (Corbett & Fischbeck, 1997). Out of 350 million tons of fuel consumed by shipping in 2007, 250 million tons were residual fuel (Brynolf et al., 2014). With such a large consumption of residual fuel containing a high amount of sulphur, the emission caused when those fuels are burnt are significant. One out of many alternatives to reduce the SOx emission is to switch the bunker fuel.

Switching from HFO to cleaner fuels (distillates) is considered one of the most efficient ways to reduce the SOx emission as the capital investment incurred is low. The adjustment made to the vessels is simpler than other methods, and the wide availability of distillate fuels makes it easier for shippers to acquire them (Kim & Seo, 2019). Some refineries around the world are producing low sulphur heavy fuel oil containing about 1% sulphur content and marine gas oil with 0.10% sulphur. According to (Brynolf et al., 2014), it is possible to produce heavy fuel oil with even less sulphur content in European refineries.

#### 2.1.5.2 *Scrubbers*

Another option available for ship-owners to reduce the SOx emission is by installing *Scrubbers* onboard. Scrubbers are air pollution control devices that can be installed in industries and lately also on ships, in order to remove/reduce the harmful gases and particulars from the exhaust systems. They can either be retrofitted in an existing ship or pre-installed on a new-build ship, depending upon the buyer's preferences. Scrubbers are usually of two types, *Wet* and *Dry*, where the Wet scrubbers are further classified into Open-loop, Closed-loop, and Hybrid system, as shown in Figure 2. The wet scrubbers are more applicable in the shipping industry as they are much smaller in size and comparatively cheaper than the dry scrubbers. The open-loop scrubber system uses natural sea water to reduce the SOx and PM in the exhaust fumes, whereas the closed-loop scrubbers use fresh water mixed with caustic soda or sodium hydroxide solutions (alkaline). The Hybrid scrubbers, as the name implies, allows wider flexibility which uses the combination of both open and closed-loop scrubbers (Panasiuk & Turkina, 2015).

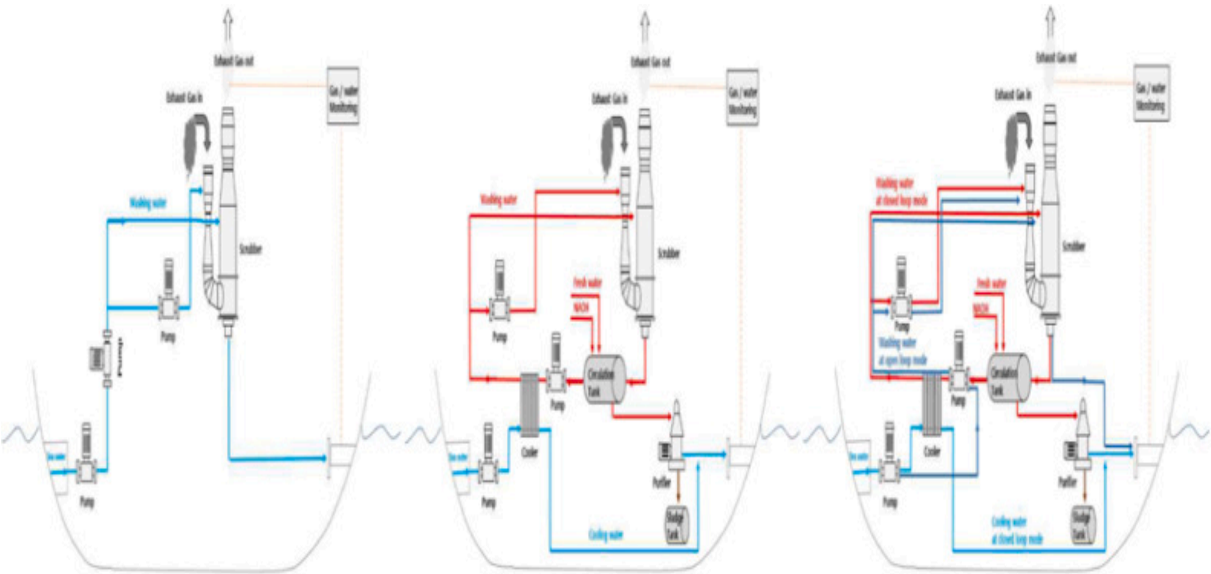

*Figure 2: Open-loop, Closed-loop and Hybrid Scrubbers. Source (Kim & Seo, 2019)*

The open-loop scrubber systems are much simpler and relatively cheaper than the closed-loop scrubbers however, it is highly restricted to use open-loop scrubbers in restricted water outlet like the Baltic Sea area. There are more restrictions relating to the usage of open-loop scrubbers as the water wash (containing sludge) is often discharged overboard (ABS, 2018; DNV-GL, 2019). On the other hand, there is no substantial difference between the closed-loop and hybrid scrubbers in terms of weight and dimensional features (Panasiuk & Turkina, 2015). Even though scrubbers help reduce the SOx and PM emission whilst using the heavy fuel oil, these are large equipment that needs frequent and specialist care which require high set-up cost (Kim & Seo, 2019).

#### 2.1.5.3 *Liquefied Natural Gas (LNG)*

Adoption of liquefied natural gas as bunker fuel for ships is an effective way to reduce the harmful exhaust gases. LNG is widely preferred as bunker fuel for ships as it is more widespread and most importantly, it is eco-friendly which reduces the emission of SOx, NOx, and PM significantly (Kim & Seo, 2019). LNG as a natural gas by its nature and has almost similar component as methane ($CH_4$) that is used for household purposes, which has the capability to reduce the Sulphur Oxides and Particulate Matter emission to almost 100%, Nitrous Oxides emission by 85% - 90% and Carbon Dioxide emission by 15% - 25% (Acciaro, 2014; DNV-GL, 2018, p. 69; Wang & Notteboom, 2014).

LNG is a natural gas by its nature and becomes liquid when it is cooled down to the temperature of - 162°C. In its gaseous state, LNG can occupy the volume corresponding to 1/600 of the product, which makes it efficient for storing a large amount of bunker fuel onboard (Wang & Notteboom, 2014). Ship's operating cost can also be reduced significantly as the calorific value in LNG is about 20% higher than the other existing fuels. This makes propulsion much efficient with significantly less fuel consumed. Due to such benefits, many argue that LNG is one of the best compliance options and helps to reduce air pollution significantly, and also the only marine fuel that contributes to the reduction of shipping's greenhouse gases like $CO_2$ (GHG) by at least 20%, abetting both human health and the environment (DNV, 2014; SEA/LNG, 2019)

However, it is crucial for ships to have an additional LNG fuel tank, LNG supply system (FGSS) and a Gas Valve Unit (GVU) in order to supply the fuel safely to the engines. Installation of such units adds up to the investment cost of up to 20% - 30% of the vessel price itself, that can also lead to the cargo carrying capacity of the vessel when installing the bunker (LNG) storage tanks (Kim & Seo, 2019; Wang & Notteboom, 2014). One of the major advantages of using LNG is that the shipowners do not need to invest in Scrubbers or use Distillates, but provides much cheaper alternatives to distillates without installing an Exhaust Gas Cleaning System (EGCS) onboard (Acciaro, 2014).

#### 2.1.5.4 *Other Emission Reduction Measures*

Apart from the most common solutions mentioned above, there are however other alternatives that are worth mentioning. Some of the other alternatives that are / or more likely to be of significance are by using various other types of fuels in order to reduce the emission like methanol, liquefied petroleum gas and other types of biofuels (DNV-GL, 2019). These methods are not very common in the market, but with the emerging nature of these fuels, we can consider them to have a significant impact in the upcoming future as compliance possibilities for ship emission. Methanol ($CH_3OH$) is produced by hydrogenation of carbon monoxide and has lowest carbon content and highest hydrogen content than any other liquid fuel (DNV-GL, 2018), and is capable of reducing the $CO_2$ emission by 10% as compared to oil. These types of fuel could be a very effective option to reduce the emission drastically, but the supply of such fuels in various countries can determine its global usage possibility.

Another rare, yet the emerging option is the battery-operated propulsion. The battery-operation can only be feasible if the ship is cruising for shorter distances like ferries. This is because the batteries onboard need to be charged on frequent intervals and is idle for small ships like ferries that take around 30-40 minutes to make the crossing. Ferries have already installed the battery-powered propulsion system in some of the countries like Norway, as it offers the zero-emission benefit from its operations (DNV-GL, 2019).

### 2.1.6 ***Sulphur Cap regulation influence on Freight Rates***

Installing a scrubber onboard ship to reduce the SOx emission as per the regulation comes with huge capital investment. Switching the bunker fuels from HFO to distillates has comparatively lower capital cost but however, can become a huge burden when the price for such distillates upsurges (Kim & Seo, 2019). With increased investment on the installation of Exhaust Gas Cleaning System (EGCS/scrubbers), the cost involved in modification for switching to distillates or the unpredictable price of the distillate fuels, can all contribute to increased transportation costs. It would be more sensible for the shipowners/operators to charge the customers to recover the added expense by increasing the freight rate (Notteboom, 2011).

The research based on the possible designation of the Mediterranean Sea as an emission control area shows that under ‘basic scenario,’ the transportation cost or the freight charges can go up to 6.95 €/ton (Panagakos, Stamatopoulou, & Psaraftis, 2014). Even though the study states that switching fuels from Heavy Fuel Oil to distillates (MGO) is the preferred compliance option for aged vessels, the availability of such fuels can have a huge impact on the fuel price itself, which later affects the freight rates. However, Panagakos, Stamatopoulou, & Psaraftis (2014) also states that installing a Scrubber onboard or using LNG as a fuel for propulsion is more preferred on newly-build ships or in case of new-buildings. The reason for not preferring such complex technical and expensive changes on old ships is because the old ships may not have enough time left to recuperate the expenses incurred on it before it is demolished.

Another study based on the competitiveness of RO-RO shipping in Northern Europe shows the implications of shifting from Heavy Fuel Oil to Marine Gas Oil. The study shows the possible increase in freight rate due to increased fuel price for traditional short sea shipping and fast short sea shipping (Notteboom, 2011). The estimated freight rate rise for short-sea shipping is from 8% to 13% (or up to 20% in extreme cases) and up to 40% (25% on an average) in the case of fast sea shipping. However, the author also adds that a substantial difference might occur in different forms of liner shipping.

Such an increase in freight rates can be a problem for the shipowners and recovering the cost incurred from customers is sagacious for them. Nonetheless, will the customers pay the added freight rates, and/or will they seek to recuperate from their customers?

# Chapter 3

## 3.1 Methodology

The third chapter of this paper will illustrate the method(s) used in this study, focusing on the collection and analysis of data. *"Methodology refers to the choices we make about appropriate models, cases to study, methods of data gathering, forms of data analysis, etc., in planning and executing a research study"* (Silverman, 2013, p. 446). In other words, the methodology chapter contains research design, various procedures, tools and techniques that have been used to collect and analyze the data required to answer the research question(s). The methodology is the base for conducting research and evaluating claims for knowledge.

The main purpose of the methodology is to help researchers communicate with each other, by providing a common ground, who have shared or willing to share a common experience. The methodology is not just about assisting the researchers in facilitating communication amongst themselves but also provides a framework for imitation and constructive criticism as they are easily accessible to all (Frankfort-Nachmias & Nachmias, 2008).

## 3.2 Research Design & Strategy

*"A research design is concerned with turning a research question, a hypothesis or even a hunch or idea into a manageable project"* (Hammond & Wellington, 2013, p. 131). A research design is basically a framework of methods and procedures that a researcher uses to address the research problem. It starts from formulating the research question, the types and modes of data collection, collecting (ethically), analyzing and interpreting the data and finally provide a logical discussion and conclusion. In other words, a research design is a theoretical framework that helps a researcher to address the research problem effectively in a logical manner. Any research design must have a well-defined research question and the research hypothesis for it to become more palpable and readily introduced in the overall planning of the research (Toledo-Pereyra, 2012).

The two main approaches or methods for data collection in research design are *Qualitative* research and *Quantitative* research. Qualitative research focuses on collecting data that describes the phenomena rather than measuring it. The data collected in qualitative approach are not presented in countable form but focuses on descriptive data and enables an inductive approach between the theory and the research. Whereas on the other hand, Quantitative data is a method that collects data in numerical form and involves counting and quantifying them. Quantitative data are normally associated with experiments, surveys, questionnaires and the data collected are countable, for example, test scores, number of reactions, etc. The data in qualitative research are collected through focus groups, in-depth interviews, reviews whereas qualitative research uses experiments, surveys, structured interviews, etc. as data collection techniques (Hammond & Wellington, 2013). Some of the major differences between the two approaches are listed below in Table 3.

*Table 3: Difference between Qualitative and Quantitative Research. Source (Bryman, 2016; Hammond & Wellington, 2013)*

| | **Qualitative Research** | **Quantitative Research** |
|---|---|---|
| *Data collection tools* | **Focus groups, in-depth interviews, document reviews, etc.** | **Surveys, structured interviews, experiments, etc.** |
| *Data form* | **Descriptive data** | **Numerical/Quantifiable Data** |
| *Data collection* | **Semi-Structured methods** | **Highly structured methods** |
| *Approach* | **More subjective** | **More objective** |
| *Hypothesis* | **Hypothesis are usually generated** | **Hypothesis is tested** |
| *Theory Vs. Research* | **Inductive** | **Deductive** |

The data collection for this thesis will be a qualitative approach based on Literature Study. *"A research literature review is a systematic, explicit, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners"* (Fink, 2010, p. 3). It is a study done on existing and published research works which are based on secondary data collection and does not include new experimental data. According to Flink (2010), there are seven steps/tasks to be followed while doing a literature review: (1) Selecting research question, (2) Selecting bibliography or article database, (3) Choosing search items, (4) Applying practical screening criteria, (5) Applying methodological screening criteria, (6) Doing the review, and (7) Synthesizing the results.

The reason for selecting this particular research strategy is because it gives a complete and comprehensive understanding of the research topic/problem. As the ship-owners operating in the ECA (Emission Control Areas) regions have already implemented the MARPOL Annex VI (Sulphur cap regulation), doing a literature study will give a proper understanding of the phenomena and also various measures adopted by them to comply with the standards.

## 3.3 Data Collection

The main purpose of collecting data is to address the research objective by answering the research questions in the most efficient manner. Data can be of various forms and can come from various sources. *Primary data* are data that are collected by the researcher himself using procedures such as questionnaires, interviews, analyzing databases or by observing individuals or groups. Every time a new data is collected, it will be added to the existing store of social knowledge, which is then made available for reuse, known as *Secondary data* (Hox & Boeije). Similarly, secondary data will be collected to support this thesis.

The major source for data for this thesis study will be from studying various published articles, journals, shipping company profiles, etc. In order to know the various technologies adopted by the ship-owners operating in the ECA regions, which ones are cost-effective and the most preferred ones, I prefer to do a literature study. The reason for selecting this approach rather than interviews is because by doing so, I can gather relevant and specific data in terms of size and quality. Collection of such data through interviews can consume time, and most importantly, it can be challenging to get an interview from most of the companies or get the desired responses from the interviewees. Furthermore, since the ship-owners are located in different regions and countries within the ECAs, it would be challenging to reach out to most of them. Therefore, collecting secondary data through literature study will give me the required information for my thesis research.

Sources for obtaining the required articles, journals, periodicals, etc. will mostly be online databases. Newspapers, magazines, various company's websites, press releases, annual reports, etc., will also be used to know the company's current trend in the shipping market.

## 3.4 Research Ethics

Research ethics are moral values that influence the researcher and the way they conduct their research. It is the researcher's moral responsibility to find and collect data for the research honestly, legally and accurately (Ghauri & Grønhaug, 2002). Some of the reasons why ethical norms are vital in research has been identified by Resnik (2015), which are:

- Ethical norms promote the aims of the research, for example, knowledge, actuality and to avoid errors.
- Since research involves participants, ethics helps to protect the interest of the participants and promote values that ensure collaboration, trust, fairness, etc.
- Ethical code of conduct also helps to ensure researchers can be held accountable for misconduct and misbehavior.
- Ethical norms also promote social values, such as human rights, compliance with the law, public safety, human and animal welfare, etc.

In my case of research, it is highly important to keep in mind the research ethics and follow the guidelines of authorship, patent and copyright policies. Since most of the data are publicly available for further studies, it is important to give proper credit and citations to the researchers for their contributions (Resnik, 2015). Therefore, all the works that have been used in this thesis have been given proper credit and references, protecting the researcher's original contributions.

# Chapter 4

## 4.1 Result and Main Findings

With stricter regulations emerging in recent years to control the ship emission, shipowners and/or ship operators are the ones who are directly affected due to increased operational or initial investment costs. The ship owners/operators must comply with the sulphur cap regulations in order to operate in the regulated areas without any interference of the regulatory bodies in their daily operations. Compliance with the sulphur cap regulations means that they must not cause sulphur emission of more than the percentage allowed. The IMO has already set the limit of 0.10% m/m (mass by mass) on sulphur (SOx) emissions in the Emission Control Areas (ECAs) of Europe and American waters, which came into force since 1$^{st}$ January 2015.

Due to the sulphur emission limit, shipowners had options to ensure compliance with the MARPOL Annex VI in the ECA regions. The four major options for compliance with the sulphur cap regulation according to (Brynolf et al., 2014; DNV-GL, 2019; Jiang et al., 2014) are:

- Switching fuel from high-sulphur fuel oil to marine gas oil
- Retrofitting vessels to use LNG or other sulphur-free fuels
- Using very-low-sulphur fuel oil or compliant fuels
- Installing Exhaust Gas Cleaning System (EGCS or Scrubbers) onboard.

Some researchers have conducted researches that the speed of the vessel is also responsible for air pollution as the ship tends to burn more fuel in order to gain more speed, hence causing more air pollution. Doudnikoff & Lacoste (2014), states that container vessels that primarily operates within fixed routes and on a timely schedule are one of the most fuel consumers and hence more air polluters. The study states that in the year 2007, container ships represented about 4% of the total fleet while producing almost 22% $CO_2$ emissions.

Apart from the air pollution reduction measures mentioned above, there are other measures that may influence the global market in the forthcoming future. Global Sulphur Cap 2020 report by DNV-GL (2019), identifies different types of biofuels, Liquefied Petroleum Gas (LPG) and Methanol as compliant fuels for the global sulphur cap regulation. Battery-powered ferries and hydrogen-powered ferries are also some viable options as those ships offer zero-emission operations.

This section of this thesis focuses on answering the research questions with the help of secondary data collected through a literature study. Various data have been collected by referring to various scientific studies, reports, press releases, journal articles, etc. The data collected shall give a brief understanding as to how the sulphur cap regulation has influenced the ship owners/operators in the ECA regions and what are the various measures adopted by them for compliance, in such a way that the research question/s can be addressed in a clear and precise manner.

### 4.1.1 Heavy Fuel Oil Vs. Marine Gas Oil

Studies and reports suggest that the easiest MARPOL Annex VI compliance method is said to be the usage or switching the bunker fuel to distillates from heavy fuel oil. From both technical and financial standpoint, using distillate fuels as the main bunker fuel due to the drop in oil price in 2015 (Index, 2016) is said to be the easiest compliance method. In one of the studies conducted by Stranden (2016), supports the above statement that distillate fuels such as MGO/MDO were the ideal compliance option. His study was conducted by interviewing six different shipowners operating in ECA regions. Stranden (2016), states that during the interview process, five out of his six respondents declared that the majority of their fleet was operating on distillates or had switched to distillates from HFO, *i.e.*, Marine Gas Oil or Marine Diesel Oil.

The Vessel Emission Study which was presented in the 9$^{th}$ Annual Green Ship Technology Conference presents a comparison study of various technologies in order to comply with the emission regulations in the ECA's. In this paper, one of the studies was conducted by switching the bunker fuel from HFO to MGO (distillates) to comply with the prevailing emission standards in the ECA regions and global from 2020. The fuel used in this study fall under the sulphur cap regulations, which is not more than 0.10% sulphur in ECA and 0.50% globally, under the expectation that there will be little price difference between 0.10% and 0.50% sulphur fuels (Nielsen & Schack, 2012).

There are a few important things that need to be taken into consideration when switching the fuel from HFO to distillates. One of the most important of all the factors, significant attention must be given to the cleaning of fuel tanks. It is crucial to have the fuel tanks properly cleaned before switching from heavy sulphur fuel oil to MGO/MDO so as to avoid contamination, which can lead to non-compliance (DNV-GL, 2019). Since distillate fuels have lower viscosity as compared to the heavy sulphur fuels, the study conducted by Nielsen & Schack (2012) shows that in order to increase the viscosity of the low sulphur fuels (distillates), it is crucial to install a fuel cooling system onboard, if the vessel operates for an elongated period of time. The study based on retrofitting a 38,500 dwt tanker ship recommends that the fuel cooler must at least have the capacity of 25 to 50 kW, which can be positioned parallel to the fuel preheating system of the main engine. The cost of such cooler lies between 30,000 to 50,000 USD, which can be assumed as a reasonable price. Fuel switching to distillate fuels such as MGO may also have an impact on the main engine, combustion, vessel speed, etc., which is why it is also necessary to pay significant importance to the lubrication oil (Jiang et al., 2014; Nielsen & Schack, 2012).

Although the initial investment for switching the bunker fuel for ships to much low sulphur fuels seems low, the daily operating expense for such vessels comes with an increased burden. The limited availability and the constant price fluctuation of such bunker fuels (distillates) can influence the fuel-switching option adversely.

Intermediate Fuel Oil (IFO) 380 is one of the cheapest bunker fuels available in the market. IFO 380 is a type of a high sulphur-content residual fuel which is a composition of about 98% of residual oil and 2% of distillate oil which makes about 80% of the bunker market due to its cheap price and higher viscosity of about 380 cSt (Marine Fuels and Emissions, 2013, pp. 9-10; Notteboom, 2011). Since this type of fuel contains about 98% of residual oil, the price per metric ton is considerably low. Figure 3. representing a graph shows the highest and lowest

($ per metric ton) price of IFO 380 on a monthly basis since January 2017 in Rotterdam.

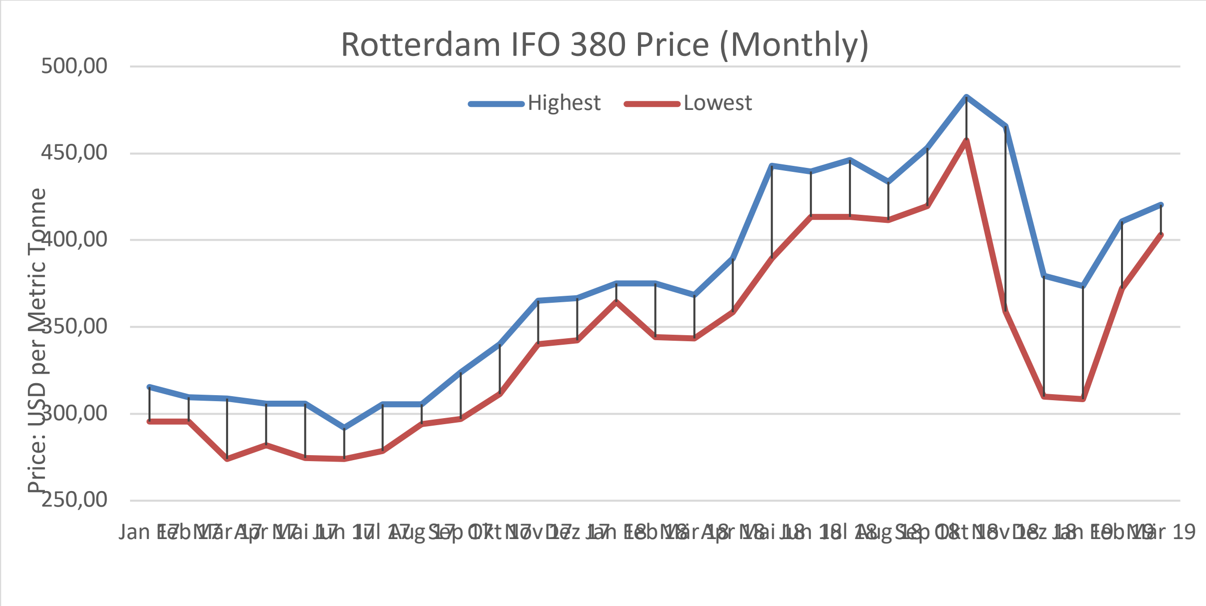


*Figure 3.* IFO 380 Price in Rotterdam. Source: own compilation based on the data driven from (Bunker, 2019).

The other type of high sulphur residual fuel oil available is the IFO 180, which is comparatively expensive than the IFO 380. IFO 180 is considered slightly cleaner fuel than the IFO 380 since it contains only 88% of the residual oil as compared to the 98% in IFO 380. While 88% of the IFO 180 is residual oil, the composition of the other 12% of the distillate oil makes it slightly cleaner, and has a viscosity of about 180 cSt (Marine Fuels and Emissions, 2013, pp. 9-10; Notteboom, 2011). Figure 4 shows the monthly price variation of IFO 180 for the last two years in Rotterdam, which is expressed in USD ($) per metric ton.

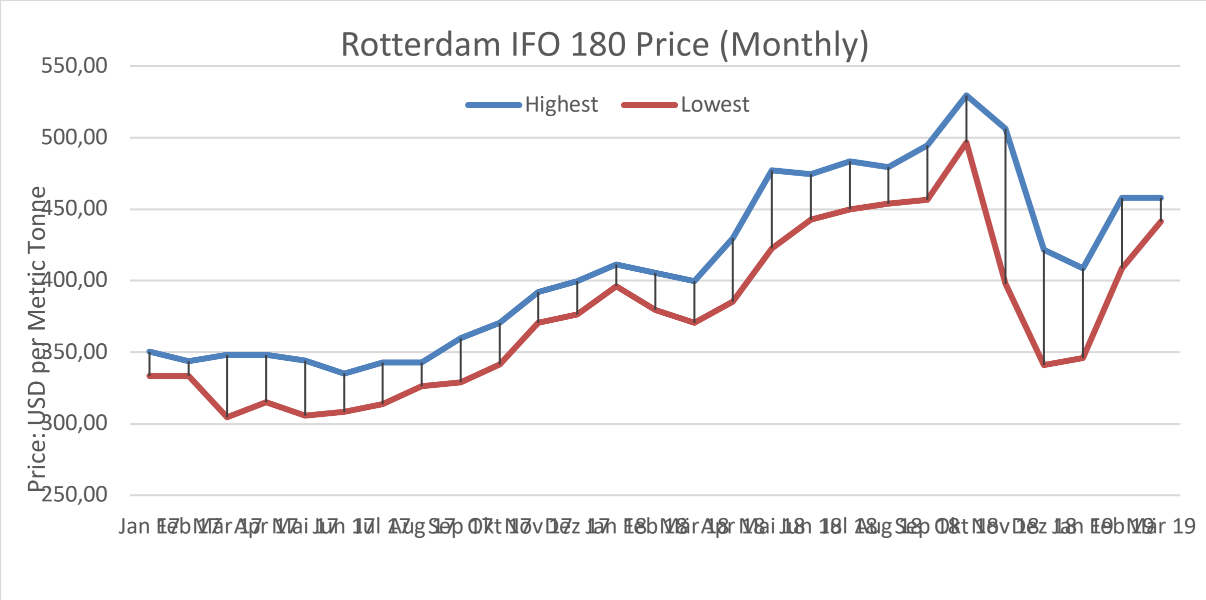


*Figure 4: IFO 180 Price in Rotterdam. Source: own compilation based on the data driven from (Bunker, 2019)*

HFO which is almost a pure residual oil and IFOs such as the ones mentioned above that contains residual oil at a large amount, combined with a minor amount of distillate, and is known for releasing significant amount of harmful exhaust fumes. However, there are cleaner fuels such as Marine Gas Oil (MGO), which is a pure distillate oil, known for its lowest sulphur content reduces the harmful exhaust gases significantly (Notteboom, 2011). The cost of MGO fuels is almost twice of what residual fuels cost because of the desulphurization process involved. Figure 5 represents the monthly price variation of MGO for the last two years in Rotterdam expressed in USD per metric ton. Similarly, Figure 6 represents the price difference between IFO 380, IFO 180 and MGO.

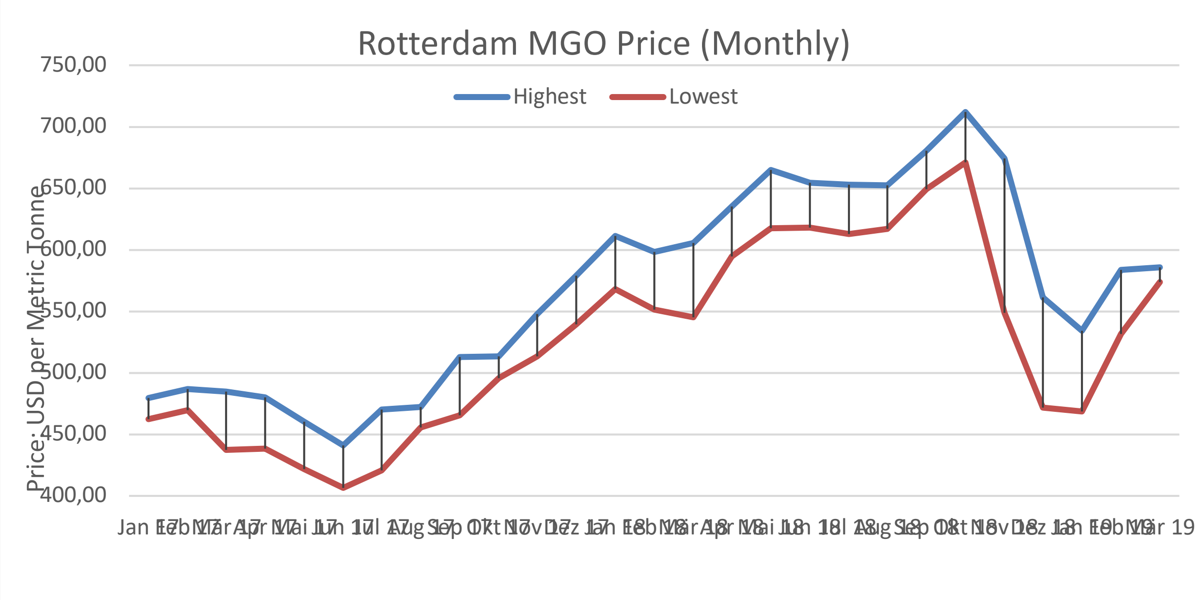


*Figure 5: MGO Price in Rotterdam. Source: own compilation based on the data driven from (Bunker, 2019)*

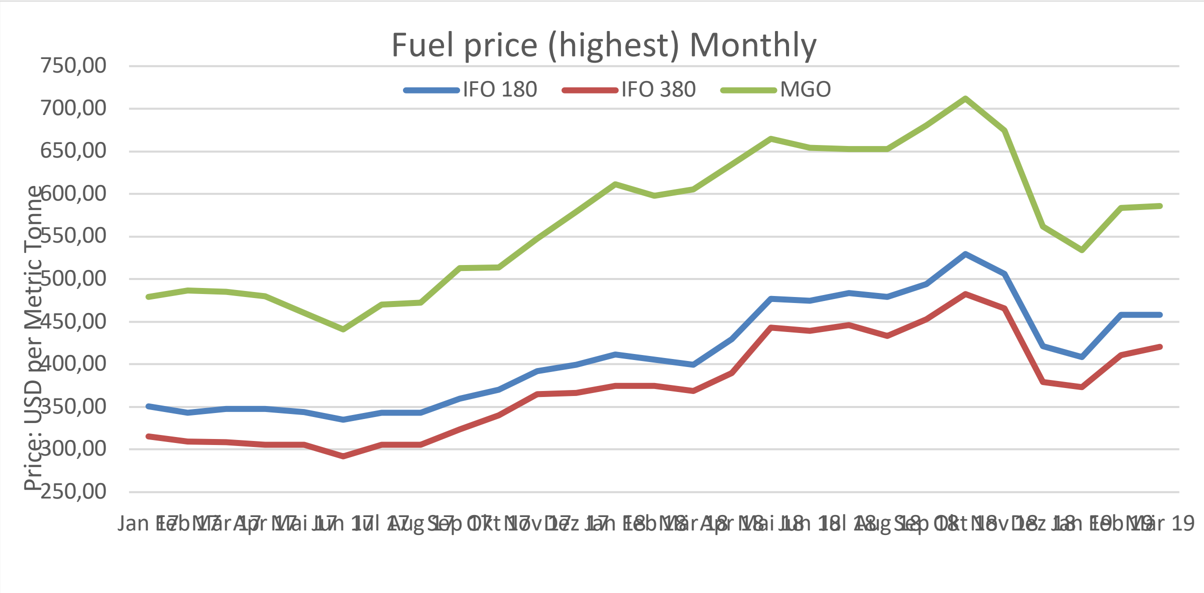


*Figure 6: Difference in the bunker fuel price for the last two years in Rotterdam. Source: own compilation based on the data driven from (Bunker, 2019)*

Here we can see that within two years the increase in price for all three types of fuel. The bunker cost increasing pattern is almost similar, reaching its peak in October 2018 where the costs of IFO 380, IFO 180 and MGO had escalated to \$482.50/mt, \$529.50/mt and \$712.00/mt respectively, with a price difference of \$229.5/mt between the IFO 380 and MGO. Fuel switching option from HFO to distillates can be significantly influenced by such a substantial increase in the price. Even though the initial investment cost is considerably low, the increasing cost of bunker fuel (especially for distillates) might result in much expensive compliance option in the long run. Theo Notteboom (2011) states that it is quite difficult to predict the future fuel price due to which the future gaps between different bunker fuels cannot be forecasted.

For any compliance options (e.g., fuel switch, LNG, Scrubbers, etc.), the payback time plays an important role in the decision making the process for the shipowners. Some researchers have studied that in order to determine as to which compliance option could be most suitable and feasible. The study presented by (Nielsen & Schack, 2012) suggests that other compliance methods such as LNG or Scrubber technology seems to be "*financially more attractive*" rather than switching the fuel to distillates, considering that the study calculated the Net Present Value (NPV) and payback time by assuming 9% discount rate and 10 years of savings period (2015-2024).

Another study conducted by (Cullinane & Bergqvist, 2014) using the data from the Danish Maritime Authority suggests that MGO is the least expensive option in terms of cost of investment. Apart from the cost of investment, MGO can reduce the sulphur emissions by 90%, carbon emission by 3% and up to 38% of Particulate Matter (Jiang et al., 2014). Jiang et al., also states that the NPV for MGO depends upon the price difference between the heavy fuel oil and distillates (MGO), where the NPV could fall severely if the price difference between the heavy fuel and MGO increases.

### 4.1.2 Exhaust Gas Cleaning System (Scrubbers)

The introduction of global sulphur cap regulation 2020 does not mean that Heavy sulphur fuel oil (HSFO/HFO) will become obsolete. The option for using such heavy sulphur fuel will still be available for the shipowners/operators around the world. However, the global sulphur emission limit of 0.50% m/m from ships standing strong, the shipowners must install an *Exhaust Gas Cleaning System* (EHCS or commonly known as ***Scrubbers***), in order to minimize the emission to the accepted level, whilst using HFO. Installing a scrubber system onboard allows the shipowners to operate on HFO, which is one of the cheapest bunker fuels allows a much cheaper operational cost for the charters rather than using other cleaner fuels or distillates.

A Scrubber or EGCS is an air pollution control technology that was commonly used in land-based industries to minimize the emission of harmful gases and other airborne particles from the exhaust systems, which can also be found in a number of ships since the introduction of $SO_x$ Emission Control Areas in 2015. There are three types of scrubbers that absorb harmful ship gases through chemical decomposition. ***Open-loop*** scrubbers use alkaline liquids (natural seawater), ***Closed-loop*** uses fresh water (mixed with caustic soda), or ***Hybrid*** scrubber system that offers operational flexibility by using both seawater and/or freshwater (Brynolf et al., 2014; DNV-GL, 2019; Kim & Seo, 2019; Panasiuk & Turkina, 2015).

A Scrubber system onboard must be able to meet the emission regulation and thus be approved by the IMO. Marine Environment Protection Committee MEPC.259(68) offers two Schemes possibilities for the approval of the scrubber system (DNV-GL, 2019; IMO, 2015):

- Scheme A offers approval of a single system or series of similar product range and to show compliance via continuous monitoring of operational parameters and emission spot checks.
- Scheme B must be fulfilled by continuous emission measurements and parameter checks.

When retrofitting a scrubber on a vessel, the scrubber system comes with necessary manuals approved by the authorities which contains instructions about the proper usage of the ECGS technology. The manuals will also include the proper way of reporting the performance of the scrubber system to the authorities, if and when demanded (IMO, 2015; Nielsen & Schack, 2012). These manuals that provide technical information about the installed system which ensures proper operation and reporting must be kept on board the ship in case of any surveys or inspections.

There are usually two types of Scrubbers: ***Wet Scrubbers*** and ***Dry Scrubbers***. Dry scrubbers usually have larger dimension and much more expensive than the wet scrubbers, which is why wet scrubbers are much preferred and accepted for the maritime industry. The wet scrubbers are moreover categorized into 3 different sub-types known as ***Open-loop*** scrubbers, ***Closed-loop*** scrubbers, and ***Hybrid*** Scrubbers, depending upon their operations. All of the wet scrubbers are operated using a similar basic chemical process. The main purpose of any wet scrubber is to dissolve the water-soluble gases in the exhaust fumes by mixing the exhaust gas with the specific scrubbing liquid used by different models (ABS, 2018). Natural seawater and freshwater along with some additives (like alkaline, sodium hydroxide and/or lime or calcium minerals) are the main types of scrubbing liquids used in the process.

## Open-Loop Scrubber system.

Open-Loop scrubber technology is a type of wet scrubber that uses natural seawater as the main liquid for absorbing or scrubbing the exhaust gases from ships. The open-loops are the simplest form of scrubbing system as they use natural seawater which is able to comply both globally (0.50%) and ECAs (0.10%) sulphur requirements, provided that the ship has access to natural seawater. Furthermore, some inland rivers around the world are “hard” water with high alkaline content, which makes it possible for ships with open-loop scrubbers to enter these inland rivers and operate efficiently. However, a proper study must be conducted in order to find the alkalinity content of the river before entering those rivers. If the water does not contain sufficient alkaline, the scrubber will not meet the required criteria and will not operate efficiently (will not be able to reduce the SOx from the exhaust gases). In such cases, the ship operators must prepare themselves to use cleaner fuels, such as distillates, to control the emission (ABS, 2018; DNV-GL, 2019).

Different Scrubber manufacturers have their own unique techniques regarding the scrubbing process and how the liquid used mixes with the exhaust fumes that lessens the SOx and PM emissions. These techniques are however approved by the regulating bodies (ABS, 2018).

Figure 7 represents an open-loop scrubber with its various features. Retrofitting a scrubber system onboard a ship usually comes with a major dimensional challenge. As scrubbers are usually significantly large in size, retrofitting a scrubber can modify the structural dimension of a ship.

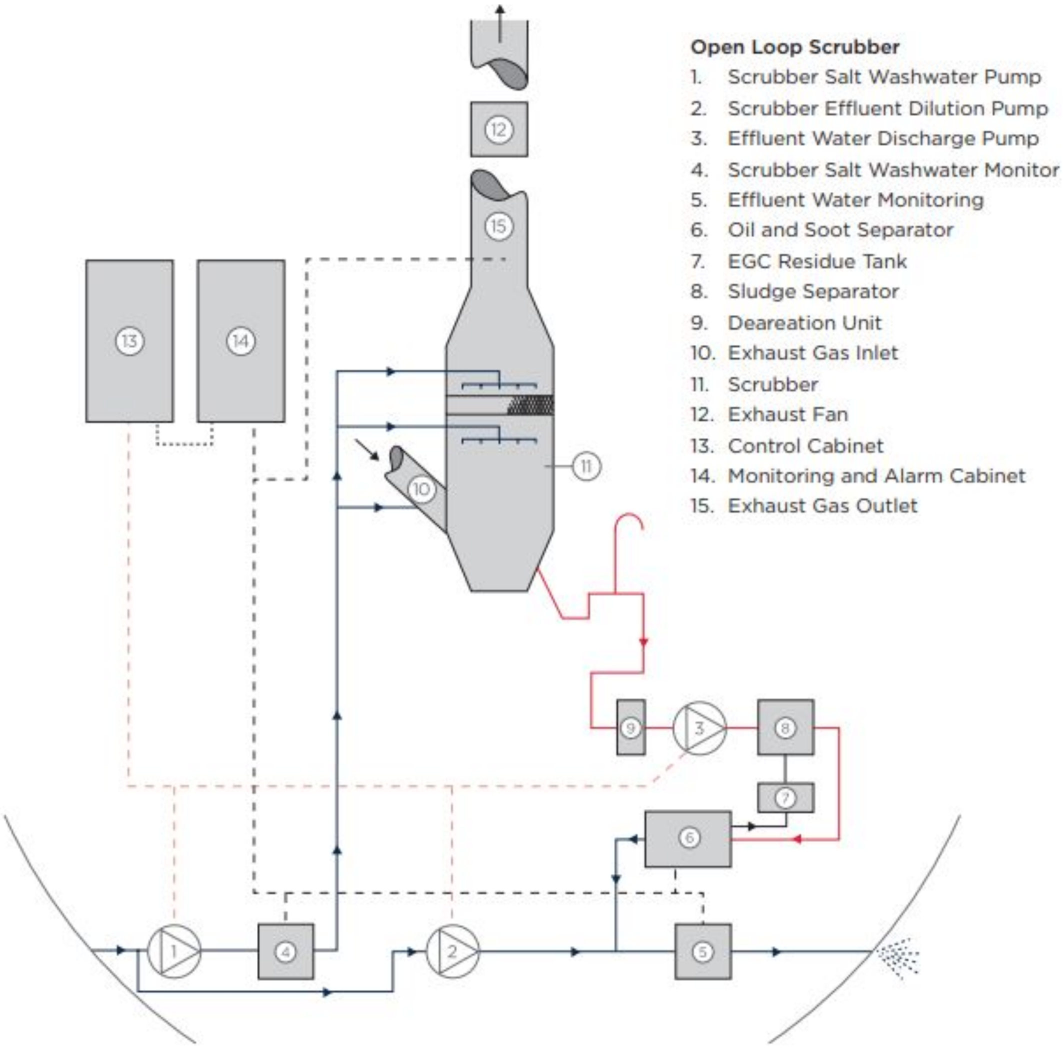


*Figure 7: Open-loop Scrubber Technology. Source: (ABS, 2018)*

Open-loop scrubbers have larger water flow rates than the closed-loop scrubbers, and with more scrubbing liquids used, the scrubbers tend to operate more effectively. Some of the scrubber technologies come with equipment for treating the water wash, while in most cases, the water wash is drained from the wet sump at the bottom of the scrubber tower and discharged from the ship through the outlets. However, discharging of water wash might not be feasible everywhere as there are some additional national and international restrictions, such as MARPOL Annex VI Regulation 16 paragraph 2.6, that restrict them to do so. In such cases, it is mandatory to install additional separators and storage to remove and store the harmful residues that are mixed with the water wash such as PM, heavy metals, ashes, insoluble calcium sulfate. The harmful residues must be contained onboard in a separate tank can be discharged in a dedicated facility when the ship docks (ABS, 2018).

## Closed-Loop Scrubber system

A closed-loop scrubber is another type of scrubber system which mainly uses fresh water with additives (such as caustic soda, sodium hydroxide solutions, etc.) to reduce the SOx and PM emissions from the ship's exhaust. The additives are added in order to maintain the alkalinity level of the water.

Compared to the open-loop, the closed-loop scrubbers come with extra equipment, and the major difference between the two is that the water wash will go through a proper segregation process and the water can be reused again as the scrubbing medium. Once the water wash has gone through the process, the water goes through the sludge separator from where the sludge will be stored in a separate designated tank for later discharge, and the water can be reused as a scrubbing liquid as shown the Figure 8. The water is added with alkaline chemicals before the water is sent back to scrubber in order to maintain the alkalinity (ABS, 2018).

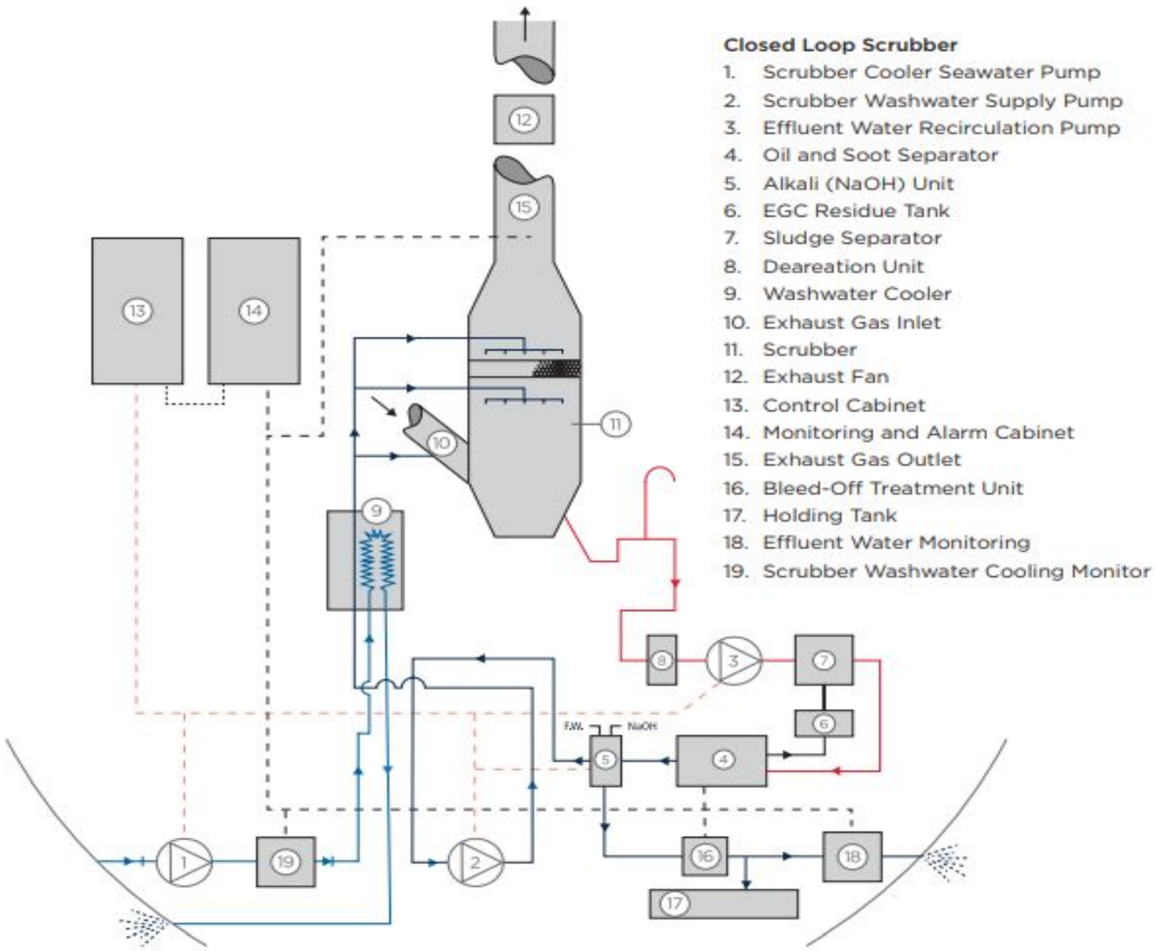


*Figure 8:* Closed-loop Scrubber Technology. Source: (ABS, 2018)

Since the water used in the closed-loop scrubbers are often dosed with alkaline (like sodium hydroxide solutions) using the alkaline chemical injection process prior to returning to the scrubbing process, closed-loop scrubbers are claimed to be more efficient than the open-loops. Closed-loop scrubbers also utilize almost half or even lesser water-wash than open-loop to achieve a similar level of emission reduction efficiency (ABS, 2018).

Table 4 compares the pros and cons of the different types of wet scrubbers available for ships.

| **Open-Loop Scrubber** | | **Closed-Loop/Hybrid Scrubber** | |
|---|---|---|---|
| Advantages | Disadvantages | Advantages | Disadvantages |
| The number of components is less | Restricted in some ports and coastal regions | More Flexible | Increased cost |
| Uses natural sea-water which is abundantly available | Not suitable where freshwater or brackish water is the natural availability | Can operate in all areas regardless of the level of alkaline in the water | Special handling and frequent supply of alkaline solutions which is hazardous in nature |

*Table 4: Advantages and Disadvantages between Open-loop, Closed-loop and Hybrid Scrubbers*

## Hybrid Scrubber System

It is always better to have a system that can be compatible with various environments, based on the availability of the scrubbing liquids, when required. The third type of wet scrubber known as the Hybrid Scrubber provides the shipowners/operators with the advantage of increased flexibility. A hybrid scrubber system can exploit the advantages from both open and closed loop scrubbers mentioned above (Kim & Seo, 2019). They can use an open-loop scrubbing technology in an open ocean and switch back to the closed-loop scrubbing system in the coastal or inland (rivers) navigation, where clean water is available. A hybrid scrubber will come in handy within those regions where the seawater does not meet the level of alkaline required.

The switching process from open-loop to closed-loop or vice versa, by changing over the circulating pump suction from seawater to the installed circulation tank, and by changing the water wash discharge from the ship to the circulation tank (see Figure 9) (ABS, 2018; Tran, 2017).

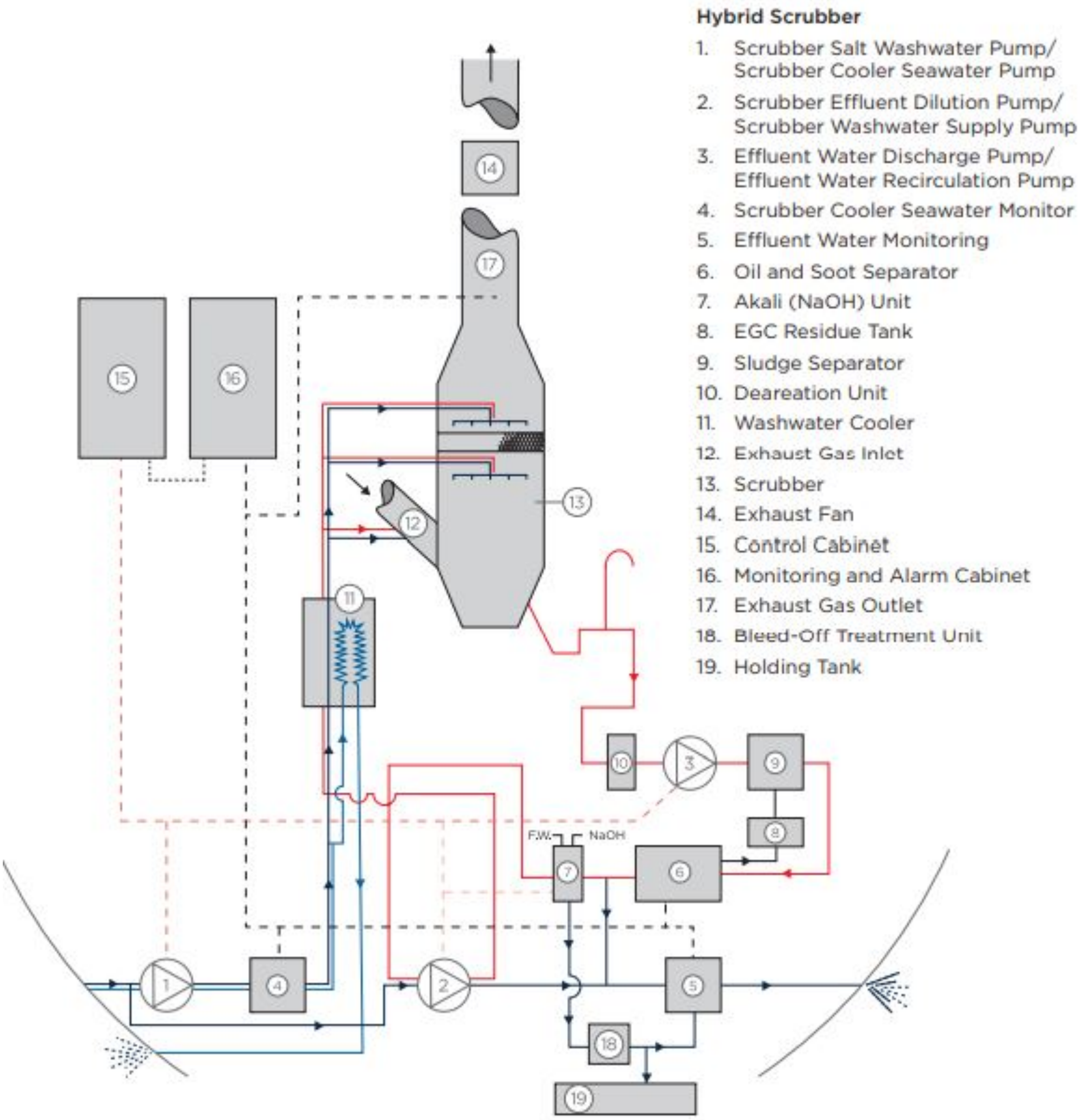


*Figure 9: Hybrid Scrubber Technology. Source (ABS, 2018)*

A paper presented by Nielsen & Schack (2012) on the 9th annual Green Ship Technology Conference, provides a real-time example by retrofitting of a scrubber (Hybrid) onboard a ship.

The ship used for the study was NORD BUTTERFLY, a chemical/oil products tanker built in 2008. In order to retrofit a scrubber system, onboard a ship, the following equipment had to be removed and installed.

| **Removals** | **New Installations** |
|---|---|
| Funnel Structure | Deck extension, pillars, ladders & platforms |
| Deck platforms and ladder | Sludge tank (Internal) |
| Exhaust gas pipes | FW circulation tank |
| Free-fall lifeboats | Alkaline compartment and tank |
| | Scrubber |
| | Free-fall lifeboats |
| | Exhaust gas pipes, scrubber water pipes |
| | Funnel top structure |
| | Scrubber auxiliary machinery and pipe connections |

The hybrid scrubber that was retrofitted on this ship was designed for completely automatic (can be switched to semi-automatic mode) operation with a minimal manning from the crews, and the exhaust system would pass through the by-pass chimney if the scrubber broke down. The secondary passage of the exhaust gases can be used until the scrubber is fixed and ready for operation (Nielsen & Schack, 2012).

When the scrubber operates in an automatic mode, the ship's GPS determines the scrubbing function (open-loop or closed-loop) depending upon the nature of water available, in a predefined manner. The emission from the scrubbers must be carefully monitored and logged to comply with the emission regulations, and the log must be presented during the time of inspections. The crews onboard must also be given proper training with regards to operation, maintenance and handling of the scrubber technology. Sodium hydroxide (alkaline) require proper handling as they have decomposition effects on proteins, and can cause a rapid effect on eye tissue which can lead to loss of vision if eyes are exposed to an alkali (Nielsen & Schack, 2012).

There are some operational and technical risks involved in installing a scrubber system onboard, regardless of the type of scrubber installed. DNV-GL (2019) has identified some significant risks, causes and the consequences involved in installing and operating a scrubber system from more than 170 completed projects. Some of them are listed below for both open-loop and closed-loop/hybrid scrubbers.

Risks involved in an Open-Loop system:

Type: **Scrubber Tower**:

| Risk | Cause | Consequences |
|---|---|---|
| Flooding of scrubber tower | ➢ Clogged piping<br>➢ Failure of high-level alarm<br>➢ Error in valve operation | ➢ Flooding of the engine room |
| Scrubber water and soot on deck | ➢ Soot accumulation during operation | |
| Cracks on Scrubber tower | ➢ Corrosion<br>➢ Improper installation<br>➢ Improper welding<br>➢ Stress between the scrubber parts | ➢ Flooding of the engine room |

Type: **Seawater Intake and supply**:

| Risk | Cause | Consequences |
|---|---|---|
| Loss of seawater supply | ➢ Marine growth in the sea chest<br>➢ Mechanical/electrical failure<br>➢ Clogged sea chest from debris/sand | ➢ Shutdown of scrubber |
| Leakage before scrubber tower | ➢ Clogged valves<br>➢ Corrosion<br>➢ Excess pressure | ➢ Flooding of the engine room |

| | | |
|---|---|---|
| | ➢ Cracks in the piping system | |
| Reduced performance of the water pump due to poor flow at the inlet | ➢ Pipe bends in front of the pump inlet | ➢ Reduced pump reliability |

Type: **Water wash discharge**:

| Risk | Cause | Consequences |
|---|---|---|
| Corrosion of overboard discharge pipe | Poor coating quality<br>Poor installation | Repair of discharge pipe in-service<br>Scrubber shutdown |
| ➢ **Corrosion of valves in the water wash discharge line** | ➢ Improper handling<br>➢ Improper installation<br>➢ Improper material properties | ➢ Scrubber Downtime |
| ➢ **Leakage after scrubber tower** | ➢ Corrosion<br>➢ Cracks in the water wash pipes<br>➢ Excessive pressure<br>➢ Clogged valves | ➢ Flooding of the engine room |
| ➢ **Turbulence creating gas in water wash** | ➢ Lack of de-gassing function | ➢ Possibility of non-compliance<br>➢ Visible gas bubbles and sheening possibility. |

Risks involved in a Closed-Loop and/or Hybrid system in addition to open-loop scrubbers:

Type: **Scrubber Tower**:

| Risk | Cause | Consequences |
|---|---|---|
| Clogging of Scrubber tower demister | ➢ Insufficient cleaning<br>➢ Spray nozzles don't cover the entire area | ➢ Soot on deck<br>➢ Increased back-pressure |
| Corrosion of spray nozzles | ➢ Corrosion | ➢ The decrease in spraying efficiency |

| | | |
|---|---|---|
| | | ➢ Increased pressure may lead to damage in piping or pump<br>➢ Downstream valves blockage |
| Insufficient scrubbing | ➢ Insufficient water volume<br>➢ Insufficient tower size for exhaust flow and retention time | ➢ High possibility of non-compliance |

Type: **<u>Exhaust Piping</u>**:

| Risk | Cause | Consequences |
|---|---|---|
| Corrosion of Exhaust pipe | ➢ Acidic environment<br>➢ Material degradation caused by erosion | ➢ Wet exhaust line leakage<br>➢ Scrubber downtime<br>➢ Flow disturbance |
| Internal leakage in exhaust gas bypass valves | ➢ Failure to fully close<br>➢ Failure of air seal fan | ➢ Internal leakage in bypass lines<br>➢ Possible non-compliance<br>➢ Exhaust may flow through both bypass and scrubber |
| Burst explosion of the exhaust line | ➢ Main and bypass valve both in the closed position during start-up of the engine | ➢ Damage to the exhaust pipe<br>➢ Structural damage<br>➢ Scrubber off-hire |

Type: **<u>Hull and Structure</u>**:

| Risk | Cause | Consequences |
|---|---|---|
| Corrosion at hull in wash water discharge area | ➢ Low pH water discharge | ➢ Structural degradation |

Type: **Automation & Control**:

| Risk | Cause | Consequences |
|---|---|---|
| Unreliability | ➢ Undetected internal failures<br>➢ Controller input failure | ➢ Inappropriate operation<br>➢ Unintentional system shutdown<br>➢ Delayed emergency response |

All of the above risks, causes and consequences have been collected from (DNV-GL, 2019) based on their experience from their completed projects. The risks can, however, be mitigated and/or prevented by selecting the best-possible materials and proper system design.

*Scrubber Market Trends*:

Since the global 0.50% sulphur cap regulation has been set and shall be applicable from and after 1st January 2020, the orders for installing a scrubber system onboard (retrofitting and/or installation on new-building) is on rapid growth. More than 2,700 ships have already installed or have ordered to install a scrubber system prior to 2020, as of February 2019. The figure was below 1,000 ships as of August 2018, which shows an increase for more than 1,500 ships within the time period of 6 months (DNV-GL, 2019).

Stena Bulk, one of the world leaders in tanker shipping recently announced that they would be installing scrubber system on 16 of its vessels prior to January 2020. The tanker giants have ordered scrubbers for 1 standard medium-range (MR) tanker, 10 for IMOIIMAXes and 5 for Suezmax vessels, which amounts to approx. $55 million (Index, 2019). Similarly, there are a large number of companies around the world that manufactures and offers such scrubbers to meet global demand. Companies such as Clean Marine, Wärtsilä Hamworthy Krystallon, Marine Exhaust Solutions, MAN Diesel and Turbo, Couple Systems, DuPont BELCO Clean Air Technologies, Green Tech Marine, Alfa Laval Aalborg, etc., offer their equipment to the global shipowners (Panasiuk & Turkina, 2015).

A Norwegian feeder owner, Songa Container has decided to install a scrubber system on all of its fleets, which is due to take place within 2019 and the first quarter of 2020 (News, 2019c). Maersk, on the other hand, plans to install just four scrubbers on selected long range 2 (LR2) vessels before January 2020 (News, 2019a).

As the IMO's global sulphur cap regulation approaches, more shipowners are joining the Clean Shipping Alliance 2020 (CSA 2020) supporting the installation of the scrubber system to comply with the standard. Wallenius Wilhelmsen, a Norwegian/Swedish shipping company is the latest shipowner to join the alliance, who plans to install a scrubber system on 23 vessels (out of approx 130) by the end of the year 2021. The CSA 2020 has also identified 242 more shipowning/operating companies with investments in scrubber technology (News, 2019b).

Figure 10 below represents a pie chart that shows various ship types opting or have opted for scrubber technology, whereas Figure 11 represents the number of retrofits and new-buildings and the types of scrubber systems.

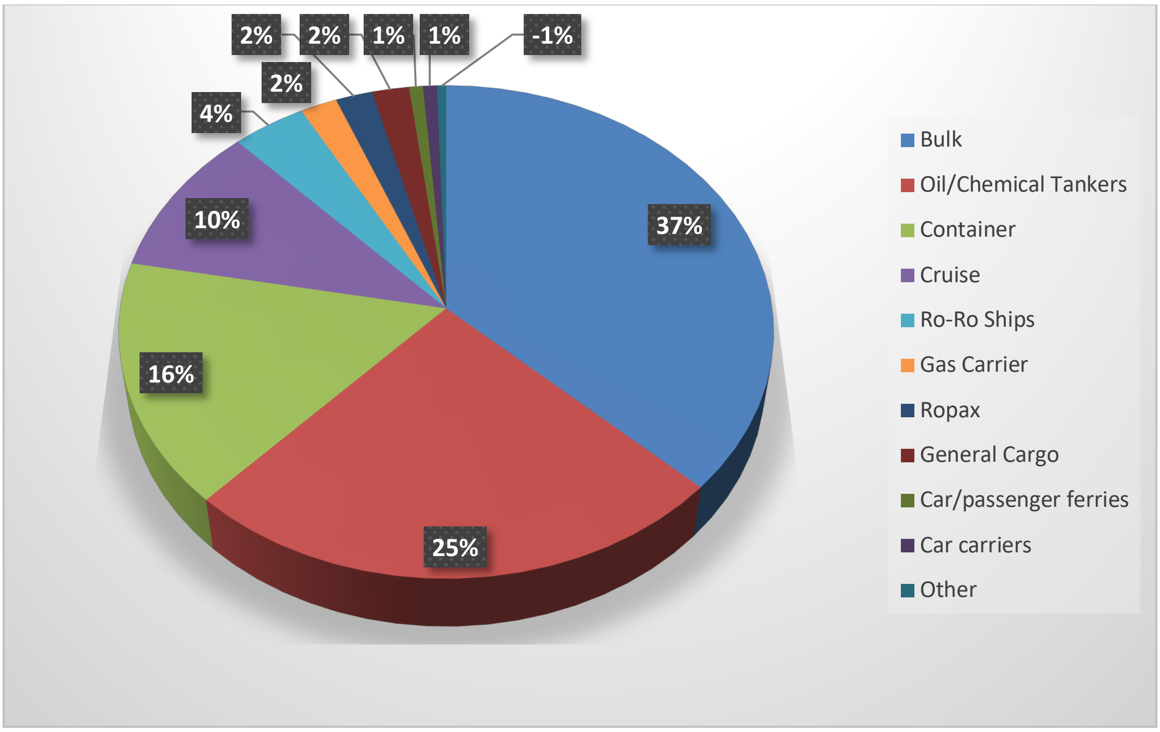


*Figure 10: Scrubber Installation on Vessel Types. Source: (DNV-GL, 2019)*


*Figure 11: Number of retrofits and new-buildings and number of scrubber types. Source: own compilation based on the data derived from (DNV-GL, 2019).*

### 4.1.3 Liquefied Natural Gas (LNG)

Liquefied Natural Gas, as the name implies, is a natural gas by nature which can transform into a liquid state when it is exposed to the temperature of approximately -162 °C. LNG mostly contains methane and a small amount of ethane, propane, and nitrogen (Andersson, Brynolf, Lindgren, & Wilewska-Bien, 2016, pp. 326-327). Due to the fact that LNG is capable of reducing the $SO_x$ and PM by almost 100%, and also reducing a significant amount of $NO_x$ and $CO_2$ emission at the same time, LNG is expected to gain a substantial position as an alternative marine fuel in the near future. LNG as a marine bunker fuel has good environmental performance and reduce the emission from ships at its most, which thus can meet the strictest emission regulation and the NOx Tier III requirements. Gas engines include a wide range of power outputs such as pure gas engines, dual-fuel two-stroke, and dual-fuel four-stroke engines as well, which makes LNG suitable for all types of ships (DNV-GL, 2019).

LNG as a marine fuel is more suitable for new-buildings but is also possible to convert the fueling system on an existing vessel as well. However, retrofitting an existing vessel involves removal and re-installation of various equipment and therefore, can incur a significant investment cost of up-to 20%-30% of the ship's price (Kim & Seo, 2019). Moreover, retrofitting or converting a vessel to LNG-powered ship can reduce a significant amount of the ship's cargo carrying capacity. A study conducted by Nielsen & Schack, (2012) shows the removal and installation of equipment and structures from a 38,500dwt tanker ship.

- Removal of deck pipes and electrical cable pipes in the area for LNG storage tank foundation and deck houses for LNG equipment
- Re-installation of the foundation for LNG-storage tanks, LNG tanks, Fuel gas supply system (FGSS), Gas Valve Unit (GVU), Gas piping system, main engine conversion, LNG piping, safety equipment, ventilation, inert gas system and so on.

It is also very important to take into consideration the safety standards for the handling of LNG. The crews onboard must have the proper competence for handling and operation of LNG, and proper training for such is essential for the crews who do not possess such experiences or knowledge. For safe bunkering/loading and unloading of LNG, it is also necessary for the onshore staffs to have similar knowledge and training.

Converting the ship's fueling system to LNG largely depends upon the availability of LNG in the global market. Some studies conclude that most of the LNG bunkering facilities are constructed and based in Europe, locally. With just about 18 exporting countries and about 25 importing countries trading LNG on a global scale by 2011, researchers had forecasted that the numbers could rise in the near future. However, the LNG trade for the year 2011 was about 5 times more as compared to 1990 (Wang & Notteboom, 2014). There are some bunkering facilities being developed in other countries as well, such as Singapore, in order to make the LNG available for the operators, especially for the Asian operators.

The total number of LNG-powered ships has been gradually growing up in recent years. There were about 100 ships that were using LNG as their main fuel, and another 100 were ordered to be fueled by the same, at the beginning of 2017. Moreover, about 70 ships were on the verge of conversion from fuel oil to LNG-powered (Seas, 2017). On the other hand, as of February 2019, the number of vessels operating on LNG had increased to 144, with 63 new-buildings order and about 112 ships to be retrofitted. The graph below represents the forecast for LNG ships (operating, order books, and/or retrofits). The figure contains data gathered from forecast/assumptions made by DNV-GL (2019).

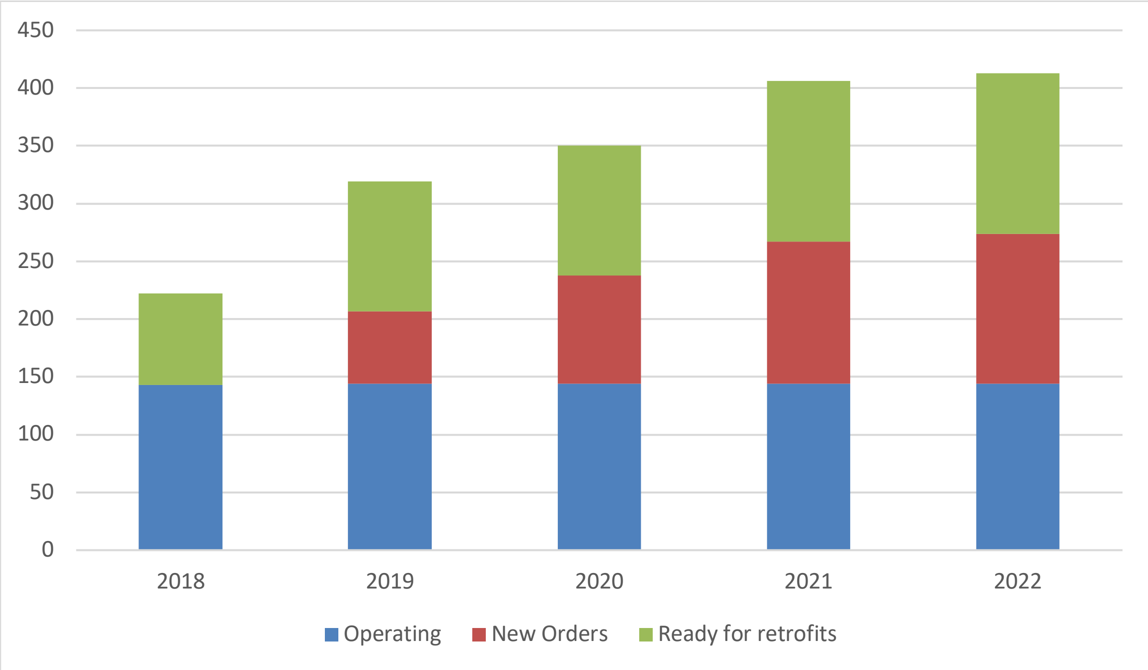


*Figure 12: LNG fueled ships, operating, ordered and retrofits.* *Source: (DNV-GL, 2019)*

### 4.1.4 Other compliance options

a) **Battery-operated Ships**:

From various emission reduction options available for shipowners or operators, ships that are powered by a battery-system is also one viable solution. The ship can also be a hybrid system, a combination of battery with other types of engine systems such as gas or diesel. This options can be primarily found in ferries that transport passengers and cars from one location to another. The time taken by ferries for such voyages from one port to another is generally 30 mins, which is suitable as the batteries need to be charged at certain intervals. There are however some challenges that affect the battery-operated ships such as huge investment cost, national and international rules and regulations, a lifetime of the battery, controlling/handling of the voltage peaks, efficiency, and availability of charging docks, etc. (Moe, 2016).

Norway is one of the leading countries operating battery-operated ferries between different locations and involves transporting about 19 million passengers annually. The selection of the battery technology or a battery-hybrid system depends upon the voyage time and also the weather conditions of the selected route. If the ferry is operating in an environment exposed to strong winds, it is not adequate for a full battery operation due to its low redundancy that affects the power stroke (Moe, 2016; Stensvold, 2015a). Tore Stensvold (2015b), has identified some connections in Norway that are suitable for full-battery operations and some for hybrid operation.

*Table 5: connections suitable for Battery and/or Hybrid operation. Source: (Stensvold, 2015b)*

| Battery operation* | Hybrid operation** |
|---|---|
| Larvik – Oppedal | Geiranger - Hellesylt |
| Molde – Vestnes | Finnøya - Sandøya |
| Moss – Horten | Bodø - Værøy |
| Måløy – Oldeide | Bodø – Moskenes |
| Sandvika – Edøya | Ørnes – Meløysund |
| Hella – Dragsvik | Frøyasambandet |
| Sand – Ropeid | Søvik – Herøy |
| Gjermundshavn - Varaldsøy | Dagsvik – Mosjøen |
| Buavåg - Langevåg | Øksfjord - Bergsfjord |
| Vennesund – Holm | Molde – Sekken |

*Suitable for battery-operation as the ferry crossing takes up to 35 minutes.

**Suitable for hybrid-operation (battery with gas or diesel engines) due to the time taken for crossing is more than 35 minutes.

b) **Methanol/Alcohol Fuels**:

Alcohol fuels such as Methanol and/or Ethanol, are also given much attention as a replacement of fuel for ships. Ethanol, which is produced from agricultural feedstock such as sugarcane, is already being used as a replacement for petrol in land-based vehicles. However, Methanol which is the simplest form of alcohol which may have a larger impact on the maritime sector as a compliant fuel in the upcoming future.

Methanol is a liquid chemical which is generally produced from natural gas but can also be produced from various energy sources like coal, biomass, agricultural and timber wastes, etc. The reason why methanol can be considered as a major fuel replacement for ships is that it has a similar emission profile as LNG. Methanol, like LNG, can reduce the emission of Sulphur oxide and Particulate Matter to almost zero, carbon dioxide ($CO_2$) by approximately 25%, and Nitrogen Oxide ($NO_x$) by almost 60%-70%. Due to such significant emission reduction capability, Methanol can comply with the strictest sulphur emission regulations and can also meet the $NO_x$ Tier III requirements (Andersson et al., 2016, pp. 329-330).

While converting the operation from regular fuels to methanol, conversion of the cylinder head, new fuel injectors, high-pressure fuel injection pipes, and new fuel pump solutions are necessary. It is assumed by some that methanol is a more realistic option rather than the LNG, in the short-term (Stensvold, April 20, 2016). There are already few ships that are operating in ECA with methanol as their fuel, and more ships are expected to be delivered. Lindanger, a ship owned by a Norwegian company, Westfal-Larsen, was one of the first ships in the world operating on methanol and was built by Hyundai, South Korea, in the year 2016. The ship is registered under the Norwegian International Ship Register (NIS) and Bergen as its home port (Larsen, 2016).

# Chapter 5

## 5.1 Discussion

Chapter 5 of this thesis paper reflects the discussion based on the research findings in chapter 4. The discussion shall be done by linking the research questions and the results from the previous chapter and discuss the economic viability and efficiency of various sulphur reduction methods.

### 5.1.1 Is the Exhaust Gas Cleaning System (Scrubbers) a suitable choice?

An EGCS or scrubbers are more robust and has been installed in many ships in the last couple of years, operating both in and out of the ECA regions. The scrubbers help reduce the SOx and PM emission significantly by using various scrubbing liquids depending upon the types of scrubbers installed onboard. The primary benefit of opting for such technological adaptation is that the operators do not have to concern about changing the fuel or significant engine modifications. Scrubber systems are capable of cutting down the emission from the ship's exhaust even if the vessel is operating on high sulphuric fuels.

The cost of installing a scrubber plays an essential role in selecting this compliance option, and the capital expenditure largely depends upon the type of modification (new-building or retrofit) and also on the types of scrubbers itself. The cost of installing a scrubber is around $2 – $3 million on a new-build vessel, whereas the price can go up to $4 - $4.5 million in case of retrofitting (News, 2018; Verma, 2018). The reason for the higher price for retrofitting is because it involves removal and re-installation of new equipment and parts and more importantly, must be well-matched with the dimension of the ship. In most of the cases for retrofitting smaller vessels, a significant amount of the ship's cargo carrying capacity will be lost and also increase the overall deadweight (dwt) of the ship, due to added components, equipment, tanks, etc. This will affect the earning capacity of the vessel. Some large vessels such as Capesizes, VLCCs, ULCCs, etc., are more eligible for installing scrubbers due to its ample space availability.

It is also imperative for the shipowners/operators to consider the payback time before investing in the technology. The Payback Time determines the approximate number of years for the ship to reimburse its investment in scrubbers. Verma (2018), mentions that according to Drewry's research, the price of the low sulphur fuel is expected to decline up to $87 per tonne by 2023, due to an increase in the supply after 2020. Such a decrease in bunker price would favor the ship operator immensely, and investment in scrubbers could be recovered within a few years. However, some researchers still argue that forecasting the future fuel price is very difficult.

Other important factors that the shipowners must consider are types of scrubber system to be installed onboard, the availability of the bunker fuel, operating expenses of the scrubber system, and the remaining lifetime of the ship itself (in case of retrofitting).

### 5.1.2 Fuel Switching as an option.

Switching the bunker fuel from Heavy Fuel Oil to marine distillates such as Marine Gasoil (MGO) is also one important and trending option in order to comply with the IMO's emission standards. The use of distillate fuels replacing the HFO has proved to reduce the harmful emissions from ships significantly and has been adopted by most of the shipowners in the ECAs. But will this option be as suitable for global adoption as it is in the ECAs? The global adoption can mostly be influenced by the price of cleaner fuels (distillates) and the, remaining operational years of the ship.

The important benefit of fuel switching option is that the ship does not require heavy modifications and unlike the scrubbers, the cargo capacity remains almost unaffected. However, it is important to increase the viscosity of the distillate fuel sufficiently as the viscosity is higher for heavy sulphuric fuels. Very few components need to be added or replaced to change the bunker fueling system, and the fuel tanks must be properly cleaned before replacing the fuel. Capital expenditure for this option is relatively less as compared to the EGCS technology which at the same time, can reduce the emission as per the prevailing standards.

Since distillate fuels are much cleaner fuels, the cost per tonne is almost as twice as the high sulphur fuels due to the desulphurization process involved. Even if the initial investment for fuel switch from HFO to distillates (MGO) seems to be reasonably low, the high bunker price increases the daily operational expenses immensely and can affect the income of the ship in the long run. Other important requirements that must be taken into consideration for fuel switching option are proper handling of cleaner fuel in order to avoid contamination, and proper lubricant and cylinder oils must be applied to the engine systems.

### 5.1.3 LNG as the Maritime Propulsion Fuel.

As discussed earlier, LNG as natural gas by nature can reduce the emission from ship immensely. Using LNG as ship's fuel for propulsion can reduce the emission of SOx and PM by almost 100%, NOx emission by 80% - 90%, and CO2 (Greenhouse Gas) by 15% - 20%, as compared to the heavy fuel oil. Due to such significant emission reduction capabilities, LNG can comply with the strictest emission standard in the world.

Using LNG as a fuel for ships can comprise of two options: Pure LNG propulsion or Dual fuel system. Since the new regulation limits the emission globally, it could be challenging to have a dual fuel system alongside LNG, in which case the secondary fuel must also comply with the emission regulation (i.e., 0.50% m/m). On the other hand, if the secondary fuel, on its own, can reduce the emission as per the regulation, there is very little need for having a dual fuel engine system (LNG) onboard, unless the ship is already equipped with one. Therefore, most of the new buildings may just need to be compatible with LNG.

As most of the bunkering facilities are concentrated mostly in Europe (primarily Baltic regions), it is difficult to obtain LNG as the propulsion fuel in some parts of the world. However, in recent years, there are some initiatives taken by some port authorities of various countries like Singapore, to develop bunkering facilities for supplying LNG to ships (Marine Fuels and Emissions, 2013, pp. 26 - 31). The development of such facilities might take some significant amount of time and might not be ready for operation by 2020.

The shipowners must also make sure that the crew has the ability to handle the LNG fuel safely and efficiently and is necessary to give them proper training if they are not qualified.

By comparing the three main options available for MARPOL Annex VI compliance, each option has its own traits. Firstly, the scrubber system can reduce the emission to the required level while still operating on the heavy fuels. The main advantage here is that such fuels are widely available, and some researchers predicts that the price of such heavy fuel might drop significantly. This factor will favor the shipowners a lot as the investment on the scrubber system can be recovered within a few years. However, installing open-loop scrubbers can lead to future challenges as some of the ports and coastal regions prohibit the use of such, as the water-wash from open-loop scrubbers are discharged into the open sea. Retrofitting a scrubber on older vessels could be risky as the question arises, *"Can the vessel reimburse the capital invested on scrubber before it is sent for demolishing?"*

Secondly, there is a high level of uncertainty in the price change for distillate fuels, which can influence the decision of fuel switch option. Even though the initial investment is low, the high bunker fuel cost can result in a substantial increase in operational expenses. Fuel

Switch option from HFO to Distillates seems to be the best fit for older ships which has a remaining lifetime of a few years.

Thirdly, LNG fuel has one of the best profiles in terms of emission reduction capabilities, and there are almost no alternate solutions that can match its performance. Although LNG may seem the best emission reduction option, access to bunker facilities around the world affects the adoption decision. It is also important to note that the initial investment and cost for retrofitting a ship with LNG is highly expensive and require significant space for the tanks. According to (SEA/LNG, 2019), concerns regarding the supply of LNG worldwide is being well addressed due to its growth and longevity. Nielsen & Schack (2012), also states that LNG and Scrubbers are *'financially more attractive.'* As the IMO aims to reduce the emission to 40% by 2030 and about 70% by 2050, using natural gases such as LNG could be a more attractive option to achieve that target. Apart from the expenses involved, the use of LNG as a bunker fuel can be one of the best environmentally friendly option.

Lastly, there are some other notable options that can be adopted by the shipowners globally in the long run such as Biogas, methanol/alcohol, battery-operated ships, autonomous ships, etc. These options are not new as some shipowners have already adopted such measures and the results for emission reductions are exceptional. It is possible that some of these options will be applicable for global adoption in upcoming years.

# Chapter 6

## 6.1 Conclusion

The international Maritime organization has set limits for emission from ships to 0.10% m/m in the European and the American regions (Emission Control Areas) since 2015. Similarly, they aim to reduce the ship's emission on a global scale from 3.5% m/m down to 0.50% m/m and shall be effective from January 2020. Since the shipowners operating in the ECA regions have complied to the 0.10% regulation since its implementation, this thesis paper aimed to identify the various measures adopted by them for compliance. Based on the literature study as the method used to collect the data for this paper, multiple options such as Exhaust Gas Cleaning Systems or Scrubbers, Liquefied Natural Gases, and Fuel Switch options were identified as some of the major adopted modes of compliance. However, the decision for choosing one option from another differ from owner to owner substantially due to the initial costs involved, overall dimension and the remaining life of the ship, availability and the price of bunker fuels, and technological possibilities in the future.

Based on the study, firstly, it can be concluded that the Scrubber system is financially more attractive for both new-buildings and retrofitting, and the possibility of a decrease in fuel price in the future certainly favors this option. Secondly, LNG as propulsion fuel is the environmentally friendly fuel due to its ability to reduce the ship's emission significantly. Thirdly, switching fuels from HFO to distillates is more suitable for old ships with less sailing time remaining. Lastly, there are other options available which have been adopted by the shipowners in the ECA and has a considerable possibility for global adoption.

## 6.2 Limitations & Further Studies

This thesis paper has some limitations and areas not covered which requires further studies. The paper consists of secondary data which is collected mostly from journal articles, conference papers, websites and news, and reports, so all the available emission reduction options were not identified. The concept of Autonomous ship can have a significant impact on the current emission regulation in the upcoming future, which itself could be a new area for future studies.

Some of the ideas for further studies that can be conducted in the near future are listed below.

Firstly, due to the rapid growth in technology nowadays, there are always possibilities for new technologies and methods to emerge and make a significant impact on shipping industry.

Secondly, since the emission reduction options mentioned in this paper are based on the options adopted by the ship-owners in the ECA regions, the same level of global adoptions might not be possible. Based on which, new and reliable research could be conducted to identify the measures adopted by the global ship-owners and identify the most efficient ones to reduce the emission from ships.

Thirdly, as mentioned earlier, the LNG bunkering facilities are more concentrated in the European regions. Therefore, a possible field of study is advised to investigate the different ways in which LNG can be made available globally.

We can but only hope that there will be more efficient and cost-effective technologies available in the future that can guide the shipping industry towards more emission-free, sustainable and green operation.

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