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The economic profitability of different alternatives to implement the sulphur directive on m/v Trica's example

Magistritöö

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LIST OF ABBREVIATIONS

BC – *Black Carbon*

BOTU – *Bleed–Off Treatment Unit*

CO – *Carbon Monoxide*

CO_2 – *Carbon Dioxide*

DM – *Dry Matter*

EC – *Elemental Carbon*

ECA – *Emission Control Area*

EPA – *Environmental Protection Agency*

EGC – *Exhaust Gas Cleaning*

EGCS – *Exhaust gas cleaning system*

EGSE – *Exhaust Gas Scrubber Effluent*

FNU – *Formazin Nephelometric Unit*

GRE – *Glass Reinforced Epoxy*

GRP – *Glass Reinforced Plastic*

HFO – *Heavy Fuel Oil*

IMO – *International Maritime Organisation*

LSHFO – *Low-Sulphur Heavy Fuel Oil*

LNG – *Liquified Natural Gas*

MARPOL – *Internatonal Convention for the Prevention of Pollution From Ships*

MCR – *Maximum Continuous Rating*

MDO – *Marine Diesel Oil*

MEPC – *Marine Environment Protection Committee*

MGO – *Marine Gas Oil*

m/t – *Motor Tanker*

m/v – *Motor Vessel*

NaOH – *Sodium Hydroxide (Caustic Soda)*

NECA – *Nitrogen Emission Control Area*

NO_x – *Nitrogen Oxides*

NTU – *Nephlometric Turbidity Units*

OC – *Organic carbon*

PAH – *Polycyclic aromatic hydrocarbons*

PAH_{phe} – *Polycyclic aromatic hydrocarbons phenantthrene equivalence*

PPB – *Parts Per Billion*

PPM – *Parts Per Million*

PM – *Particulate Matters*

PPE – *Personal Protective Equipment*

SO_x – *Sulfur Oxides*

SO_2 – *Sulfur Dioxide*

SO_3 – *Sulfur Trioxide*

SO_4 – *Sulfate*

SECA – *Sulfur Emission Control Area*

SDS – *Safety Data Sheet*

UTC – *Universal Coordinated Time*

INTRODUCTION

This document contains information about different scrubber systems, working principle and it's economic influence. The document also describes the basic technology of exhaust gas cleaning technology and chemical effect on the ocean and the whole environment.

Cargo transportation by water is the main transportation method in the world. Maritime transport covers around 90% of worldwide transportation of cargo, which includes raw materials and finished products. At the same time, emissions from marine transport are dominant in their effect on the marine ecosystem and with an increase of cargo traffic the amount of harmful substances released into the ecosystem also increased. Contamination of ecosystem including air and water is a significant health hazard to human civilization. Today, the MARPOL sulphur directive is enforced, which imposes strict rules on carriers regarding the environment, especially the type of fuel.

The research problem of the master's thesis which should be attempted to find out by the author is what options are available for the implementation of the MARPOL Directive and how they are justified from the point of view of the economy and the environment.

The nominated hypothesis by the author is:

"The use of exhaust gas scrubber is economically justified but may be undervalued from an environmental point of view."

The author will focus on data of a certain vessel cruising by a certain route in the Baltic and North Sea called "Trica" as a subject of this master thesis.

The aim of the present master's thesis "The economic profitability of different alternatives to implement the sulphur directive on m/v Trica's example" is to analyze and compare two investment options to fulfill requirements of sulphur directive, evaluate and show exhaust gas scrubber technology for ships from an economical and environmental point of view.

This master's thesis objectives are as follows:

1. Demonstrate the cost-effectiveness of the various alternatives of implementing the sulfur directive.
2. Overview of scrubber usage from an environmental point of view.
3. Find the optimal choice by looking at all factors.

The research questions that the author will try to give an answer to in the present master's thesis are as follows:

Question 1 - Is the installation of a scrubber justified from a financial point of view for the ship owner?

Question 2 - Is the installation and use of a scrubber safe for the environment?

Question 3 - What are the prospects for implementing the sulfur law in the future?

The research methods of the master's thesis are data collection, processing and generalization.

The study uses comparative analysis, in which the "Trica" vessel (there is combination of exhaust gas scrubber together with residual heavy fuel oil is used onboard) data for 2019 year will be reviewed by financial analysis in comparison with light fuel (MGO).

The master's thesis consists of three chapters.

The first chapter describes international legislation.

The second chapter describes how the scrubber works and consequences of using a scrubber.

In the third chapter data would be analyzed and compared.

In the end the author will make conclusions based on results of analysis.

- The basic data used are:
    - MARPOL Convention
    - Technical manuals

- Researches
- Guides
- Reports
- Ship's data (m/v Trica)

The material for master's thesis has been collected from various sources. If the material has been found in a other language, by author himself it has translated into English.

1. OVERVIEW OF LEGISLATION

1.1 Worldwide shipping transport

Transports represent today a very important part of a modern society both in terms of passenger transports and freight transports. Maritime transports are often both energy and cost effective.

The population in the world and the standard of living are increasing. This means an increased industrial activity globally and thus also increased transports. This also means increased global pressure on the environment, and increased material and energy resource use.

People's mobility and transport of goods play a decisive role in the development of the society both nationally and internationally. Trade and industrial activities are important components in our society and transports play a crucial role here. Shipping represents an important part of the world's transport and lots of goods are transported by ships over long distances.

For the shipping industry, the environmental legislation plays a crucial role. Environmental legislation also changes over time, and tightening requirements are imposed on shipping (Zhang Y., 2018).

1.2 International Maritime Organization

International Maritime Organization (IMO) is an agency of the United Nations, which has been formed to promote maritime safety including environmental issues (Zhang Y., 2018). It was formally established by an international conference in Geneva in 1948, and became active in 1958 when the IMO Convention entered into force (the original name was the Inter–Governmental Maritime Consultative Organization, or IMCO, but the name was changed in 1982 to IMO) (Hombravella A., 2011).

International Maritime Organization (IMO) is a the primary regulator of maritime transport (Psaraftis, 2019). Currently IMO has 174 member states and 3 associate members (IMO, 2020).

1.3 International Convention for the Prevention of Pollution from Ships

In 1973 the IMO formed the Marine Environmental Protection Committee (MEPC) to address matters concerned with marine pollution. In the same year, MEPC adopted the International Convention for the Prevention of Pollution from Ships, known as the MARPOL Convention. The MARPOL Convention has been amended by two Protocols in 1978 and 1997 (Psaraftis, 2019). The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. The MARPOL Convention was adopted on 2 November 1973 at IMO (IMO, 2020).

IMO has five main committees that consist of all member states. The marine environment protection committee (MEPC) is one of them (Vestergaard, 2013). The IMO's Marine Environment Protection Committee (MEPC), the main committee for addressing environmental issues falling under the IMO's mandate including vesselsource pollution, is responsible for the adoption and ongoing actualization of the MARPOL Convention's technical annexes, which address different categories of pollutants:

- oil and oily water (Annex I),
- noxious liquid substances in bulk (Annex II),
- harmful substances in packaged form (Annex III),
- sewage (Annex IV),
- garbage (Annex V),
- air pollution (Annex VI) (Kjølhol J., 2012).

Annex I, entitled Regulations for the Prevention of Pollution by Oil, entered into force on 2 October 1983. This mandatory annex regulates the prevention of pollution by oil or oily mixtures from ship operations and from accidental discharges.

Annex II, entitled Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk, entered into force on 2 October 1983. This mandatory annex specifies discharge criteria and measures for the control of marine pollution with noxious liquid substances transported in bulk.

Annex III, entitled Regulations for the Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form, entered into force on 1 July 1992. This optional annex establishes provisions regarding the packing, marking, labelling, documentation, stowage and quantity limitations for harmful substances.

Annex IV, entitled Regulations for the Prevention of Pollution by Sewage from Ships, entered into force on 27 September 2003. This optional annex contains requirements to control sewage pollution from ships.

Annex V, entitled Regulations for the Prevention of Pollution by Garbage from Ships, entered into force on 31 December 1988. This optional annex regulates the disposal of various types of garbage from ships.

Annex VI, entitled Regulations for the Prevention of Air Pollution from Ships, entered into force on 19 May 2005. This optional annex regulates emissions to the air from ships, including sulphur and nitrogen oxides. Under this annex, special so–called Emission Control Areas (ECAs) for sulphur oxides, nitrogen oxides and particulate matter can be designated.

In summary, MARPOL 73/78 is the primary legal instrument for the prevention of pollution originating from ships due to both operational and accidental activities (Andersson K., 2016).

In the IMO/MARPOL regulations, the emission of SO_x is regulated by regulating the content of sulphur in the fuel. In the regulation, a distinction is made between regulation for SECA/ECA regions and global regulations (Zhang Y., 2018).

The first ECA for SO_x emissions was the Baltic Sea which was designated in 1997. However, it was not until 2005 that the ECAs were enforced. The next ECA was the North Sea which was adopted in 2005 and enforced in 2006. In 2010 the North American ECA was designed and enforced in 2011. In 2011 the United States Caribbean Sea ECA was adopted and enforced at the beginning of 2013 (Psaraftis, 2019).

Year	Sulfur limit in fuel (wt.-%)	
	SECA/ECA	Global
2000	1.5 %	4.5 %
2010	1.0 %	
2012		3.5 %
2015	0.1 %	
2020		0.5 %

Figure 1. The development of IMO/MARPOL Annex VI sulfur limits for fuels.
Source: (Zhang Y., 2018).

Today (year 2020), the SECA/ECA limit is 0.1% sulphur in the fuel. The corresponding global limit is today 0.5% sulphur in the fuel. The highest sulphur limit (4.5%) corresponds to the maximum sulfur content for heavy fuel oils or residue oils (Zhang Y., 2018).

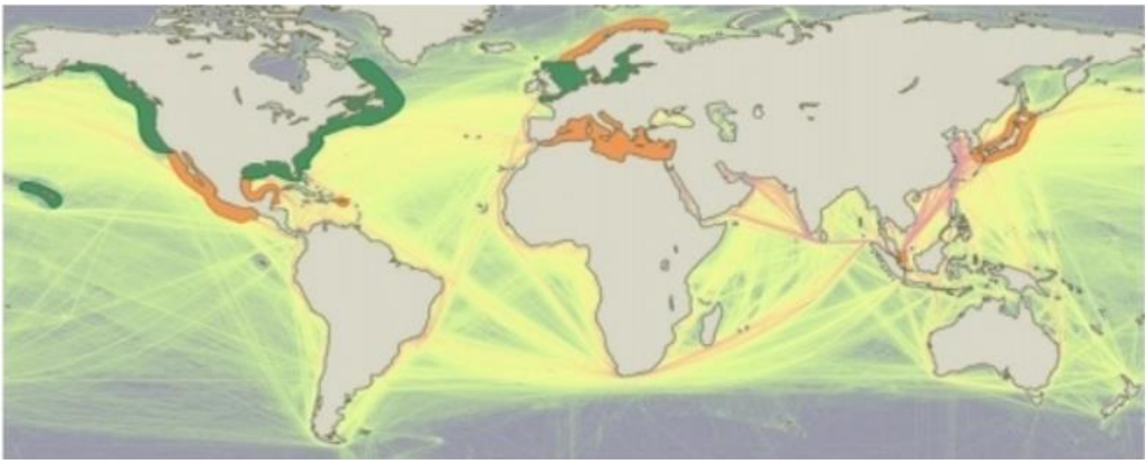


Figure 2. Global shipping activities (AIS data and locations of existing ECA's in green and possible ECA's in orange.)

Source: (Endres S., 2018).

1.4 Legal framework

To comply with the regulation within SECAs, ship operators can either use ultra–low–sulphur fuel (such as MGO) or rely in abatement technologies that result in the same SO_x emissions reduction (e.g. use of certified scrubber systems) (Psaraftis, 2019).
In resolution MEPC 259(68) the guidelines for implementation of MARPOL 73/78 Annex VI including the criteria for discharge of EGSE are stated. The values that must be monitored in the EGSE are pH, PAH, turbidity, temperature and total nitrates.

1) Criteria for pH:

a. The discharged EGSE should have a pH of no less than 6.5 at 4 m from the overboard discharge point with the ship stationary (Magnusson K., 2018).

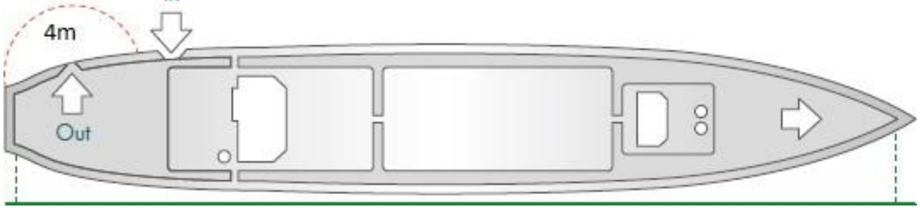


Figure 3. Measurement of pH.

Source: (EGCSA, 2012).

b. The pH of the washwater at the ship's overboard discharge should be no less than 6.5 except during manoeuvring and transit, when a maximum difference of 2 pH units is allowed between the ship's washwater inlet and overboard discharge (EGCSA, 2012).

2) Criteria for PAH concentration: The criterion for EGSE is that the maximum continuous PAH concentrations must not exceed 50 µg/L PAH_{phe} above the PAH concentration in the inlet water.

3) Criteria for turbidity: The maximum continuous turbidity in EGSE should not be greater than 25 FNU or 25 NTU or equivalent units, above the inlet water turbidity.

4) Criteria for nitrates: The scrubber water treatment system should prevent the discharge of nitrates beyond that associated with a 12% removal of NO_x from the exhaust, or beyond 60 mg/L normalized for EGSE discharge rate of 45 t/MWh, whichever is greater (Magnusson K., 2018).

To comply with legislation the ships emissions and effluents are measured and logged.

Monitoring conducted on discharge water from open–loop scrubbers show high concentrations of several contaminants, including metals such as copper and zinc. Even though IMO has developed washwater discharge criteria with respect to some parameters there are currently no criteria with respect to metals. Due to this lack of knowledge, several countries have decided to adopt stricter regulations than required by IMO. For example, Belgium has prohibited discharges of washwater in its coastal waters (3 nautical miles off the coast) and California does not permit the use of scrubbers as an alternative to use of low–sulphur fuel (Andersson K., 2016).

1.5 Technology investment options

There are mainly four alternatives for complying with the sulphur legislations:

1. Fuel switch. Fuel switching has a small investment cost and is a flexible solution, but leaves the operator with high operating cost in ECA and also risks with the fuel change procedure.

a. Change to MGO. Change to MGO is a convenient method, but gives high operating costs compared to running on HFO.
b. Change to LSHFO. As an alternative to using high–sulphur heavy fuel oil with exhaust gas scrubber cleaning, light low–sulphur heavy fuel oil can be used for the ship main engine. The latter alternative will include different processes in the refinery, which will also have some environmental and economic impacts (Zhang Y., 2018).
c. Convert to LNG. LNG is at the forefront when it comes to technology, but the infrastructure is still not fully developed in many areas. For many vessels, the conversion to LNG will be too complex (Paulsrud, 2015).

2. Scrubber technology. The big advantage with scrubber is that it will enable the ship operator to run on cheaper high sulphur fuel, and still be compliant with the sulphur limits. This means that the scrubber will in time pay for itself in form of fuel cost savings.

1.6 Consequences of scrubber

1.6.1 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are a large group of organic compounds with two or more fused aromatic rings. PAHs occur naturally in petroleum and are also produced as by–products of fuel combustion. PAHs are an important class of environmental contaminants, which are known to accumulate in ecosystems. The US EPA has identified 16 PAH compounds as priority pollutants. Some of these compounds are carcinogenic and/or mutagenic to mammals; in addition, they have both acute toxicity and sub–lethal effects on some aquatic organisms (EGCSA, 2020).

There are a very wide variety of sources for PAHs to enter the environment, both natural and man–made. These include industrial wastewater, road runoff, fossil fuel combustion, oil spills, forest and grass fires, volcanic particles, and natural oil seeps (EGCSA, 2020). A source of PAHs is the incomplete combustion of fuel oils and although engines and boilers are designed to optimize the combustion of fuel, exhaust gases will always contain a proportion of incompletely combusted material (EGCSA, 2020). A large fraction of the PAHs is found in the soils and sediments, which are the ultimate sinks, but they are also the most significant contaminants in marine environment (Cheruyiot N.K., 2015).

Partitioning of PAHs between the gaseous and particulate phases depends on the liquid vapor pressure, temperatures and particulate parameters such as size, surface area and chemical composition (Cheruyiot N.K., 2015).

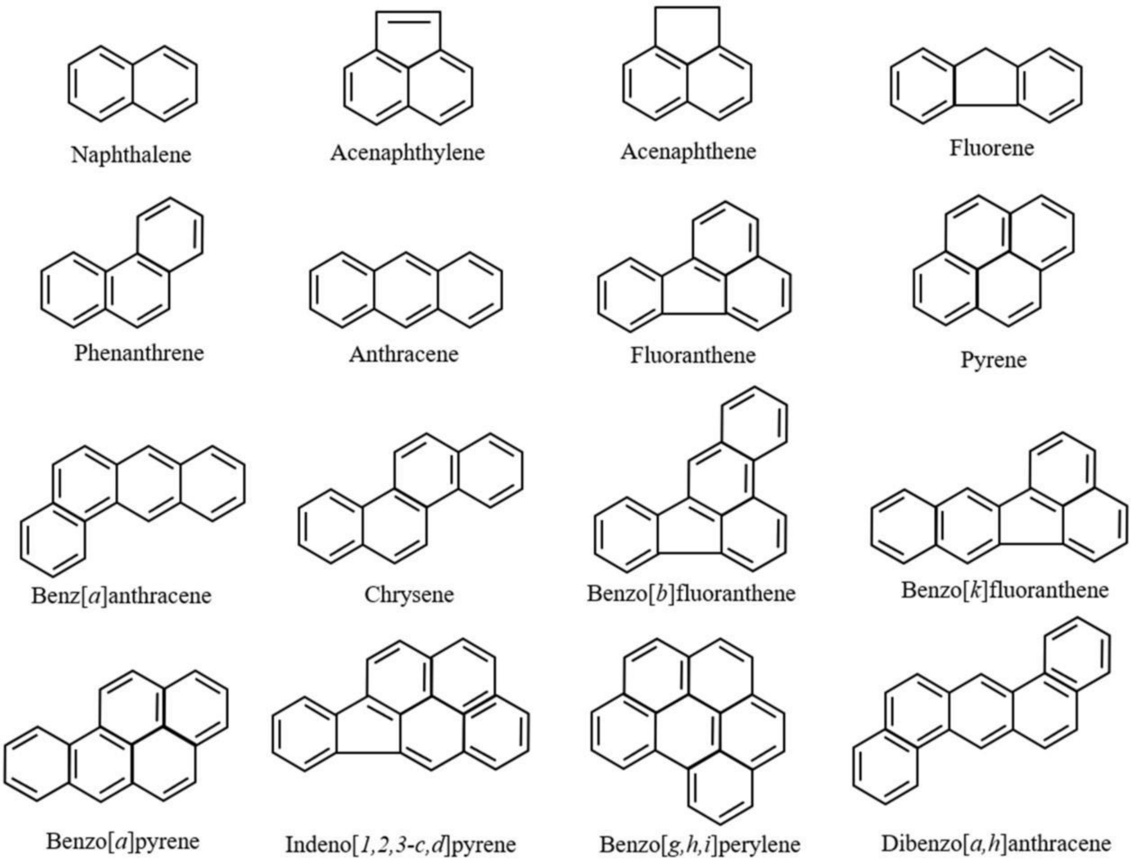


Figure 4. Most common PAHs.

Source: (Nogueira T., 2015).

There are also seasonal variations in concentration, for example increases can be seen in winter because of the heating of buildings in towns and cities. The highest PAH concentrations are found in sediments. Sediments can be disturbed during shallow water maneuvering of a ship and as a result may enter the wash water system. The IMO therefore requires the background concentration of PAH at the wash water inlet to be taken into account when measuring the PAH concentration at system discharge. It is also required that monitoring at discharge is before any dilution for correction of the wash water pH.

PAH must be continuously measured online and the data securely logged to confirm compliance with the IMO EGCS Guidelines (EGCSA, 2020).

The 50 µg/L PAH_{phe} limit is normalized for a washwater flow rate through the EGCS unit of 45 t/MWh. This limit should be adjusted for washwater flow rates, as shown below.

Flow Rate (t/MWh)	Discharge Concentration Limit (µg/L PAHphe equivalents)	Measurement Technology
0 - 1	2250	Ultraviolet Light
2.5	900	Ultraviolet Light
5	450	Fluorescence
11.25	200	Fluorescence
22.5	100	Fluorescence
45	50	Fluorescence
90	25	Fluorescence

Figure 5. PAH Discharge Concentration Limit by Flow Rate.
Source: (EPA, 2011).

1.6.2 Acidity

The pH scale, introduced by Sørensen (1909), is a measure of the concentration of H^+ or OH^- ions on a logarithmic scale. At atmospheric pressure and 25°C a solution is considered acidic if pH < 7, neutral if pH = 7 and alkaline if pH > 7. The point of neutrality is temperature–dependant and varies from pH = 7.47 at 0°C, pH = 7 at 25°C and pH = 6.92 at 30°C.

Low pH water can adversely impact marine organisms such as shellfish and, as many organisms are only able to survive when environmental conditions are stable, a decrease in pH may be a risk for those organisms (EPA, 2011).

In addition to decreasing pH in the marine environment, combustion and scrubber residues may also lead to increases in temperature and turbidity, as well as the introduction of further pollutants, such as heavy metals, black carbon, PAHs, and other organic compounds. As these compounds may have long lifetimes in seawater, their potential long–term accumulation needs to be considered (Endres S., 2018).

Studies have shown that the pH of wash water will readily return to that of the surrounding water. In an environmental impact assessment of a seawater scrubber conducted over 10 months, samples were taken directly in front of the washwater discharge from a stationary vessel in harbour at 1 to 5 m, 50 m, 350m and 700 m. Whilst samples taken from inside the ship were pH 6.2–6.5, in no sample taken after the discharge was the pH below that of the surrounding water (EGCSA, 2020).

1.6.3 Metals

Metals are a diverse group of pollutants, many of which are toxic to aquatic life and humans. While some metals, including copper, nickel and zinc, are known to be essential to organism function, many others, including thallium and arsenic, are non–essential and/or are known to have only adverse impacts. Even essential metals can do serious damage to organism function in sufficiently elevated concentrations.

The IMO Guidelines do not contain any limits for the concentrations of metals in washwater discharge, although the IMO requests ship owners to sample and analyze washwater for a suite of metals. Turbidity is monitored as a surrogate for suspended solids (Magnusson K., 2018). Turbidity is a measure of the cloudiness of water (Asplind). The underlying assumption is that by maintaining a low turbidity level, metals, which are usually bound to particles or were particulates themselves, are effectively removed by the washwater treatment plant (Magnusson K., 2018).

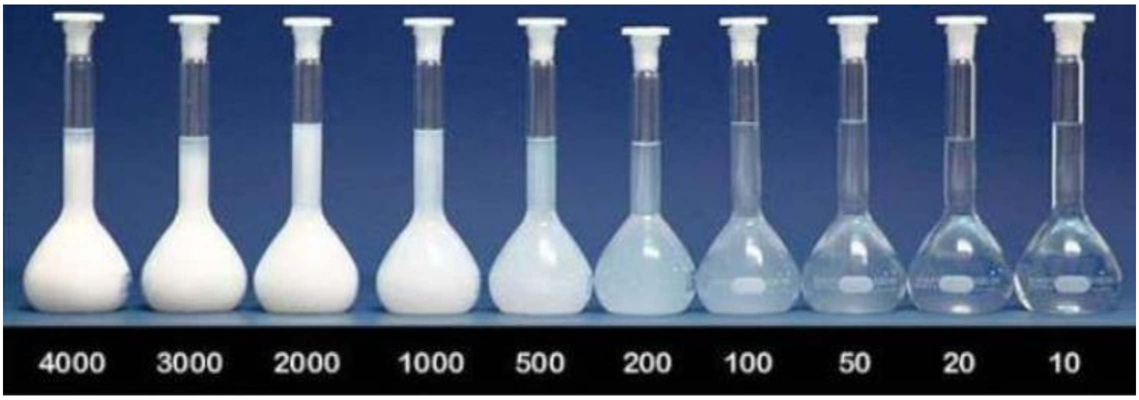


Figure 6. Explanation of turbidity. The higher the turbidity, the harder it is to see through the water. Source: (Asplind).

There are a number of sources for metals to enter the washwater in wet scrubber systems:

- System materials, typically iron, copper and zinc may be a source of metals. The reduced pH of washwater, which can be as low as pH 3 within the system, will increase the solubility of metal ions and therefore the choice of materials is very carefully considered by exhaust gas cleaning system designers.

- System inlet water may contain metals found in seawater or from electrochemical protection to prevent fouling of seawater pipes and from antifouling paints (typically copper). Electrochemical protection is often installed at the inlet to seawater pumping systems to prevent the parasitic growth of organisms that may foul pipework, filters and coolers of ship's machinery. An EGCS may take a washwater supply from a point with electrochemical protection, but will not have a direct influence on it.

- The combustion of fuel and lubricant is another source of metals, typically vanadium, nickel, calcium and zinc. Although it makes up a relatively small amount of the overall PM, ash represents the incombustible residue of burning fuel oil and lubricant. The majority of fuel oil ash content consists of metal compounds that occur naturally in petroleum; principally vanadium and nickel, which are oil soluble and so cannot be removed by onboard pre–treatment such as filtration and centrifugal purification. These metals can also enter ecosystems from unscrubbed exhaust emissions into the atmosphere (EPA, 2011).

The washwater treatment system should be designed to minimize suspended PM, including heavy metals and ash. The maximum continuous turbidity in washwater should not be greater than 25 FNU or 25 NTU or equivalent units, above the inlet water turbidity (EPA, 2011).

1.6.4 Nitrates

Nitrate is the most highly oxidized form of nitrogen, and excess nitrate concentrations in aquatic systems can result in a rapid increase or accumulation in the population of algae, possibly leading to algae blooms and eutrophication. This can disrupt functioning of an aquatic system, causing a variety of problems such as a lack of oxygen in the water needed for fish and shellfish to survive. In near–shore or harbour situations, where phosphorous is available (e.g. from river inputs, runoff from agriculture or direct input of domestic sewage), addition of nitrates may lead to enhanced biomass production (EPA, 2011).

1.7 Marine fuel oil

Crude oil is extracted from onshore and offshore locations. It can be transported either by pipeline or by a crude oil carrier from the extraction site to the refineries (Trafikanalys, 2016).

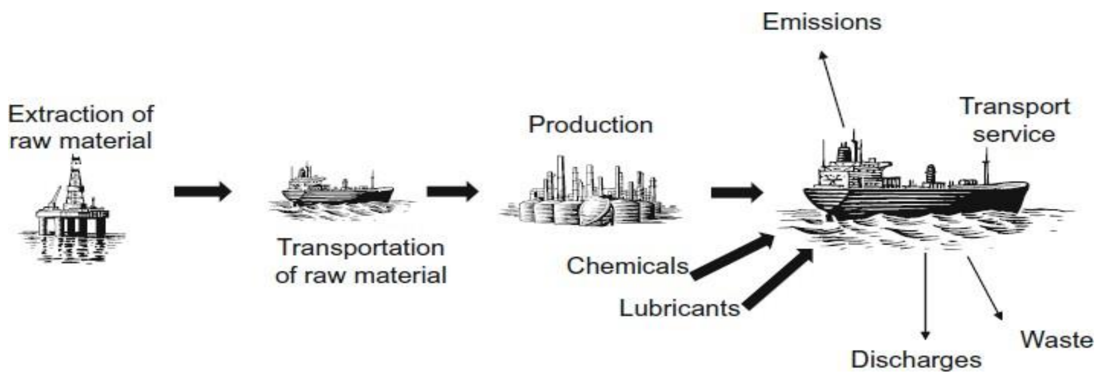


Figure 7. The life cycle of marine fuels.

Source: (Andersson K., 2016).

The fuel for the engines is based on crude oil and is available in different grades and pricing on the market. The availability of different grades may also vary depending on supply, demand and the current production situation at the fuel refineries. The crude oil used for the fuel oil production at the refinery can be of different quality mainly depending on the location of the oil well (Zhang Y., 2018).

An important quality aspect is the sulphur content. In crude oil classification one distinguishes between sour and sweet crude oil. The sweet crude oil contains less than 0.5% sulphur; other crude oils are classified as sour crude oil. Crude oil can usually contain up to 4% sulphur. The lighter crude oil products are the most sought after as one easily can produce light low–sulphur products as gasoline, diesel, kerosene etc. by fractional distillation (Hansen, 2012).

Crude oil naturally contains sulphur due to its origin from plant and animal material. (Andersson K., 2016).

Commercial shipping uses cheap, low–quality residual heavy fuels, that contribute significant emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x), metals, organic compounds and aerosols to the atmosphere during combustion (SOLAS, 2017).

The fuel quality and potential environmental impact due to, for example, sulphur and other components are dependent on the process of production of marine bunker fuels. Whereas MGO and MDO are the result of distillation processes in oil refineries, HFO is a residual product of the oil refinery process. For example, sulphur content is lower in distillate fuels than in residual fuels. In the latter, water and other sediments could also be components of the fuel (EEA, 2013).

Figure 8. Crude oil.
Source: (Abdullah, 2017).

1.7.1 Low–sulphur heavy fuel oil

Switching in SECA areas to a low–sulphur heavy fuel is relatively easy for shipping companies but can lead to increased costs. The environmental aspects of this technology can instead be found in the refineries where the low–sulphur fuel is produced.

Low-sulphur heavy fuel oil represents the fuel which meets the fuel standard requirement that can be used in SECA areas. LSHFO is a general name of a group of fuels that is produced by mixing different type of fuels to meet the SECA requirements. LSHFO is produced in a residue hydrocracker plant from HFO. Electricity and heat are used in the residue hydrocracker unit for cracking and desulfurization of the heavy fuel oil. In the refinery processing, the heavy residual oil from the fractional distillation is cracked into lighter molecules by catalytic or thermal cracking. To reduce the sulphur content in the heavy fuel oil products, they are treated in a hydrodesulfurization process (Zhang Y., 2018).

1.7.2 Heavy fuel oil

Heavy fuel oil is the fraction that remains after the lighter fractions have been distilled in the refinery; due to its lower price, heavy fuel oil is commonly used on ships. Heavy fuel oil consists of various mixtures of residual oils from the distilling and conversion processes in the refinery. This fraction has relatively high–sulphur content due to the sulphur content of crude oil. The sulphur contents are even higher in the heavy fuel oils than in the original crude oil because the sulphur is enriched in the heaviest fractions during the refining process. The global average sulphur content of HFO is 2.7% (Andersson K., 2016).

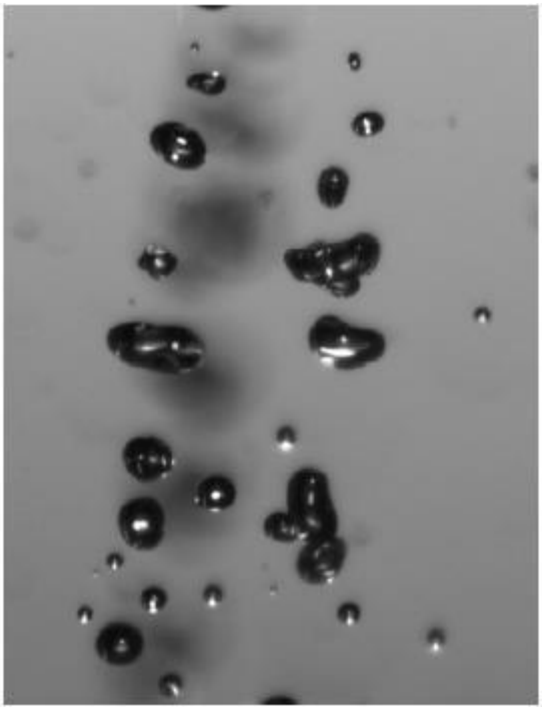


Figure 9. Heavy fuel oil drops.

Source: (Hombravella A., 2011).

To obtain the correct viscosity the residual fuel is mixed with lighter fuel distillates. HFO is characterized by its high specific mass and high viscosity. Due to the high viscosity the HFO needs to be heated to a maximum of 150°C in order to pump the fuel and since it is the residue after the distillation HFO has to be cleaned by using centrifuges (Vestergaard, 2013).

Heavy fuel oils contain organo–metallic compounds from their presence in the original crude oils. The most important of these trace metals is vanadium. Some crude sources, for example, from the Caribbean area and Mexico are particularly high in vanadium and this is reflected in high vanadium contents in heavy fuel oils produced from these crudes. Vanadium is of major significance for fuels burned in both diesel engines and boilers because when combined with sodium (perhaps from seawater contamination) and other metallic compounds in critical proportions it can form high melting point ashes which are corrosive to engine exhaust valves, valve seats and super heater elements. Other elements that occur in heavy fuel oils include nickel, iron, potassium, sodium, aluminum and silicon. Aluminum and silicon are mainly derived from refinery catalyst fines.

Heavy fuel oils are used in medium to large industrial plants, marine applications and power stations in combustion equipment such as boilers, furnaces and diesel engines (Hombravella A., 2011).

1.7.3 Marine gasoil

Low–sulphur MGO is pure distillate oil that contains less than 0.1% sulphur and can be used in conventional marine engines within ECAs and other sulphur–regulated areas (e.g. EU ports). This fuel can be used without major modifications, but one drawback is that it has to be stored at a different tank for vessels that use fuel switching. MGO in general has a lower viscosity than HFO, and as a result additional lubrication must be used to avoid damage in the engine's pumps (Psaraftis, 2019).

1.8 Exhaust Gases

The composition of the fuel directly affects the exhaust gas content. The main products in the combustion of fossil fuels in air are carbon oxides (CO_x) and water vapour (H_2O). The most common by–products are sulphur oxides (SO_x), nitrogen oxides (NO_x) and carbon based matter (soot, smoke). The by–products exist in small quantities but have a disproportionate effect on the environment (Ülpre H., 2014). The exhaust gas also contains vapours derived from the fuel and in the case of diesel engines also from the lubricant (EGCSA, 2012). All of these products and by–products are polluting and their release, therefore, has to be mitigated (Ülpre H., 2014).

The marine sector's environmental impact is significant as emissions from shipping occurring in European waters can contribute up to 10–20% of overall worldwide shipping emissions (EEA, 2013).

1.8.1 Sulphur oxides

Sulphur oxides (SO_x) refer to the family of chemical compounds formed from atoms of sulphur and oxygen. SO_x may refer to one of the following:

- SO (sulphur monoxide),
- SO_2 (sulphur dioxide),
- SO_3 (sulphur trioxide),
- S_2O (disulphur monoxide),
- S_2O_2 (disulphur dioxide) and
- Lower sulphur oxides.

Most of these SO_x are unstable and rarely encountered in nature. However, SO_x produced by fuel combustion in marine engines predominantly contain SO_2 emissions. Sulphur dioxide is a chemical compound that consists of two oxygen atoms and a sulphur atom. Its molar mass is equal to 64.066 g per mol. SO_2 is in gaseous form at standard temperature and pressure and exists in Earth's atmosphere in very small concentrations. SO_2 is considered a hazardous pollutant that can cause nerve stimulation in the lining of the nose and throat and affects people with asthma (Psaraftis, 2019).

SO_2 is heavier than air and has a suffocating odor at an atmospheric concentration of around 500 ppb, at which level it can be fatal (EGCSA, 2012).

When exposed to humidity, SO_2 and SO_3 will form sulphuric acid aqueous solutions. With condensation, they make up acid rain. The result of acid rain is the elevated acidity of both soil and bodies of water, the corrosion of stone– and metal constructions, as well as harmful effects on wildlife and human health. The typical ratio of SO_2/SO_3 in exhaust gasses is 0.95/0.05. Sea transport makes up for 3...5% of global SO_x atmosphere pollution (Punab, 2010).

Ships have continued to use low–grade, high–sulphur content heavy fuel oils, and are consequently responsible for a large proportion of man–made SO_2 emissions. It was estimated that in the year 2000 SO_2 emissions from shipping were around threefold greater than that from all road traffic and aviation combined (Endres S., 2018).

1.8.2 Carbon oxides

Figure 10. Estimated CO2 emission for transporting 1 tonne of goods 1 kilometre for different transportation modes. (Triple-E is a family of very large container ships of more than 18000 TEU).
Source: (Psaraftis, 2019).

The main contributor to greenhouse gas emissions from shipping is CO_2, which is formed from the combustion of the carbon in the fuel used for propulsion and from energy and heat production on ships. Therefore, CO_2 emissions are directly connected to a ship's fuel consumption. Reducing CO_2 emissions is foremost a matter of improving energy efficiency or changing to renewable fuels (Andersson K., 2016).

Carbon monoxide – CO: Carbon monoxide is a product due to an imperfect combustion where the amount of oxygen is too low and thereby, not turned into CO_2. It is merely happening close to the cylinder walls of the combustion chamber or if the air and fuel mixture is insufficient. It is a transparent and odorless gas, which is very toxic for both fauna and man (Vestergaard, 2013). CO to oxidizes into CO_2 in the atmosphere within a few hours. (Punab, 2010).

On a global scale, oceanic uptake of anthropogenic CO_2 emissions has already caused a pH decrease of 0.1 compared to the pre–industrial era. A further decrease of 0.3 is expected by the end of this century. CO concentration in exhaust gases of diesel engines is due to high burning parameters negligible (Endres S., 2018).

1.8.3 Nitrogen oxides

N_2O, NO and NO_2 make up for the largest part (roughly half) of all harmful additives. From all directly motor exhausted nitric oxides, about 95% is NO and 5% is NO_2. Their unanimous notation is NO_x. The portion and effect of N_2O (laughing gas) to the environment is minuscule. NO is a colourless non–toxic gas, which oxidizes in the atmosphere within a few hours to NO_2. The latter, NO_2 in its gas form, is a toxic reddish brown gas, which condenses into nitric oxide aqueous solution, causing so–called acid rain. This results in acidification and nitric compounds' saturation of freshwater areas and wetlands. The compounds work as fertilizer which promotes the lessening of oxygen in water and the areas growing shut.

Research shows, that with a temperature rise over 1700 K, the levels of NO_x in exhaust gases grow exponentially on the account of atmospheric nitrogen. For example, at temperatures 1700 K, 2000 K and 2500 K within 1 ms, the amount of formed NO_x are accordingly 0.1, 20 and 10 000 ppm. The NO_x emitted from ships make up 13% of all global NO_x emissions to the atmosphere (Punab, 2010).

When NO_x is released to the atmosphere, it contributes to a variety of different environmental impacts, such as eutrophication (increased nitrogen nutrients to biomass), acidification and also as a precursor to the formation of ground–level ozone and secondary particulate matter (Andersson K., 2016).

Coastal areas and semi–enclosed basins are already overloaded by emissions and human activities, leading to high levels of nutrients and pollutants. Additional nitrogen from exhaust deposition and scrubber effluents concentrates along shipping routes in the upper mixed layer and likely affects biological nitrogen cycling, especially during summer months when cruise ship operation peaks (Endres S., 2018).

Nitric oxide (NO) is formed in the cylinder during combustion by two main mechanisms.

- Thermal NO_x
- Fuel NO_x

Thermal NO_x is primarily formed in high temperature reactions between nitrogen and oxygen in the charge air. Formation is dependent on temperature, exposure time of the combustion gases to high temperature, and available oxygen. Above 1500°C the rate of formation rises exponentially.

Fuel NO_x is formed from the oxidation of the nitrogen compounds predominantly contained in residual fuel oils and biofuels. The process is dependent on the air fuel ratio (i.e., available oxygen) and the quantity of fuelbound nitrogen and, to a lesser extent, combustion temperature and the nature of the nitrogen compounds (Lloyd's Register, 2012).

Nitrous oxide (N_2O) (also known as "laughing gas") is a powerful greenhouse gas that has a long residence time in the atmosphere. N_2O is formed during the combustion of fuel under certain conditions (Andersson K., 2016).

1.8.4 Particulate Matter and Aerosols

Particles from combustion processes in engines are formed due to the incomplete combustion of hydrocarbons in the fuel particle emissions. In general, the emissions of particles are referred to as emissions of particulate matter. The abbreviation that is typically used for particulate matter is PM, and the known expressions are PM_{10} and $PM_{2.5}$, which refer to the masses of particles with diameters less than 10 and 2.5 µm, respectively.

Regarding particle emissions from combustion sources, the terms black carbon (BC), organic carbon (OC), elemental carbon (EC) and soot are frequently used.

Black carbon (BC) particles are light-absorbing particles that can absorb visible light with a wavelength exceeding 550 nm. These particles are refractory, and a temperature above 4000°K is needed to volatilise these particles.

Elemental carbon (EC) particles are also thermally stable, can be viewed as solid particles under atmospheric conditions and are insoluble in any solvent.

Organic carbon (OC) particles refer to particles composed of carbon that is chemically combined with hydrogen, oxygen, sulphur or nitrogen, as examples.

Soot particles are formed in the cylinder during the combustion of the fuel, are primarily composed of carbon and can be viewed as agglomerates of spherules composed of graphite–like micro–crystallites.

Primary particles are the result of the incomplete combustion of hydrocarbons in the fuel and lubrication oil. The formation of primary particles, also known as soot, begins immediately after the fuel is injected and occurs under high temperature. The available time for particle formation is several milliseconds. The soot particles are small residual carbon particles/spherules with diameters of 1–10 nm that are formed from the thermal decomposition of large hydrocarbon molecules in the fuel (Andersson K., 2016).

Ambient levels of small particulate matter $PM_{2.5}$ have been linked to a variety of health effects including asthma and heart attacks, and increases in $PM_{2.5}$ are closely associated with premature mortalities relating to heart disease and lung cancer.

Predictions from air–quality models suggest that ship–derived PM may contribute to tens of thousands of cases of premature mortality near coastlines every year (Endres S., 2018).

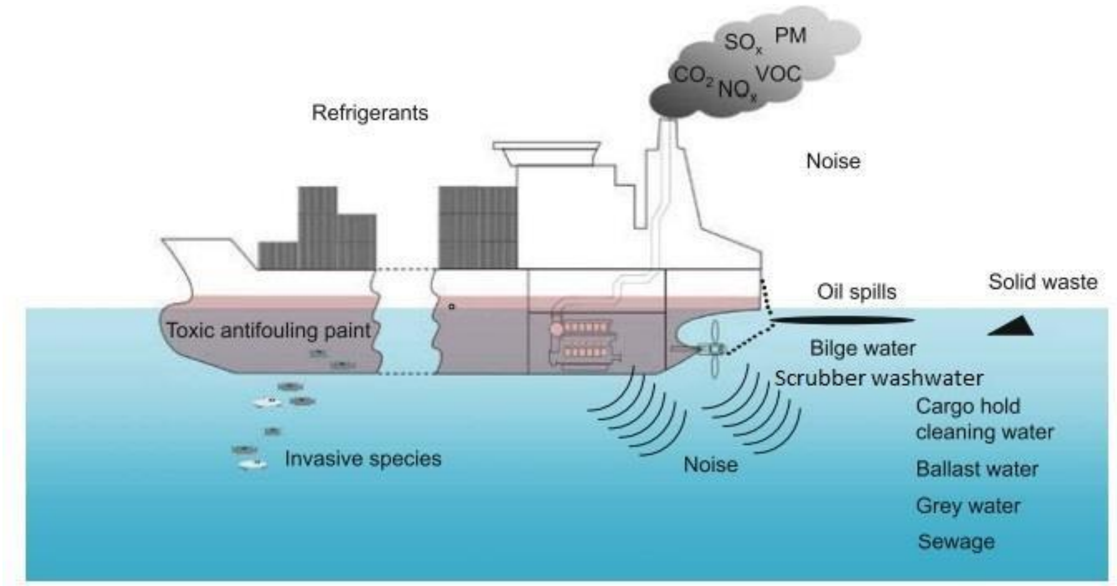


Figure 11. Environmental impacts of marine transportation during the use of a vessel.

Source: (Andersson K., 2016), corrected by author.

2. DESCRIPTION OF EXHAUST GAS SCRUBBER

2.1 History

In recent decades, global and regional efforts to reduce the environmental impact of ship emissions have been made.

The first prototype of seawater scrubber system for exhaust gas control onboard a vessel was installed in 1991. A comprehensive seawater scrubber field trial was conducted in May 1998 onboard the Canadian ice breaker Louis S. St.–Laurent (Sofiev J., 2018).

The m/t Suula scrubber was the first certified marine scrubber installation in the world. In the case of m/t Suula the installation was temporary, only for test purposes (Lahtinen, 2016).

In June 2010, it was announced the first commercial order for seawater scrubbers capable of meeting new European Union (EU) regulations on fuel emissions from ships, without requiring low–sulphur fuel oil. Seawater scrubbers were installed on four new 45,000–t ferries burning residual fuel oil to meet rules demanding sulphur emissions equivalent to 0.1% fuel–sulphur content (Sofiev J., 2018).

2.2 What is scrubber

Figure 12. Alfa-laval exhaust gas scrubber.

Source: (Alfa-Laval, 2017).

The use of scrubbers to clean the exhaust from marine engines using high–sulphur residual oil and diesel fuels is an option for reducing SO_x air emissions required by Annex VI of the MARPOL International Convention for the Prevention of Pollution from Ships (EPA, 2011). Scrubber technology primarily removes SO_x, from ships' exhaust, and NO_x and particles to some degree, but not CO_2 (Endres S., 2018).

Exhaust gas cleaning unit serves as a contact chamber that enables the exhaust stream from an engine or boiler to be intimately mixed with water, either seawater, freshwater, or both. Due to space and access limitations, the exhaust gas cleaning units tend to be high up in the ship, in or around the funnel area. Recalculation of ship stability in case of retrofitting existing ships may be needed (Sofiev J., 2018). Scrubbers add extra weight to ships – the weight of a typical 20 MW wet scrubber varies between 30 and 55 t, excluding the washwater and treatment system (Andersson K., 2016).

2.3 Producers of scrubber technology

- Alfa Laval Group (Sweden)
- Andritz AG (Austria)
- Bilfinger Enginering & Technologies GMBH (Germany)
- Clean Marine (Norway)
- CR Ocean Engineering (USA)
- Dupont Clean Technologies (USA)
- Ecospray Technologies (Italy)
- Fuji Electric (Japan)
- Ionada (Germany)
- Langh Tech (Finland)
- Pacific Green Marine Technologies Inc. (USA)
- Saacke Marine System (Germany)
- Valmet (Finland)
- VDL AEC Maritime (Netherlands)
- Wärtsilä (Finland)
- YARA Marine Technologies (Norway) (ABS, 2018).

The most of producers offers complete service packages for the market, including 3–D scanning, scrubber design and installation, along with the supervision of the scrubber's installation and use.

2.4 Exhaust gas cleaning technology

The main purpose of installing an exhaust gas scrubber on a ship is to reduce emission of sulphur dioxide to levels equivalent to emission levels from combustion of a fuel with 0.1% sulphur (Fridel E.l, 2018). A positive, additional effect is the trapping of particulate matter in the exhaust reducing airside emissions of heavy metals, soot, PAH's and also sulphur bonded to the particles (Kjølhol J., 2012).

Description of scrubber systems scrubber systems are generally composed of three parts;

1) the exhaust gas cleaning unit,

2) a washwater treatment unit, and

3) a sludge treatment unit (Winnes H., 2018).

The feed/circulation pumps supply the required water to the sprayers (Alfa-Laval, 2014). The water coming out of the scrubber is called washwater. In a scrubber, the exhaust gas is mixed with washwater and the water–soluble components of the exhaust gas are removed by dissolution into the washwater (EPA, 2011). The water can be either seawater, freshwater or both. In the cleaning unit SO_x is converted into sulfuric acid.

The effluent water is monitored in order to make sure it fulfils internationally agreed standards and the washwater may be treated on board in order to remove harmful substances before it is discharged (Winnes H., 2018).

Figure 13. New and used sprayers.

Source: Photo from author.

2.4.1 Wet scrubbers

A system is a unit that consists of different parts interacting with each other.

When the bypass damper closes, the exhaust gas is led through the jet(s) and absorber. The exhaust gas analysis system in the funnel monitors the quality of the cleaning process and informs and continuously saves data for the operator.

Depending on the operation mode, the jet(s) and the absorber are supplied with either seawater or freshwater. The exhaust gas is cooled in the jet(s) where an initial SO_x and particle absorption takes place. Further cleaning is done in the absorber.

The OL/CL switching valves (in case of hybrid scrubber) close off the water circulation circuit that includes the Water Cleaning Unit (WCU).

The system is usually equipped with water analysis and gas analysis units (Alfa-Laval, 2014).

Three types of wet scrubbers are commonly used – open–loop or closed–loop systems and hybrid systems. All types of scrubber systems can be installed on both new builds and older vessels (retrofitted) (Psaraftis, 2019).

2.4.2 Open loop scrubber system

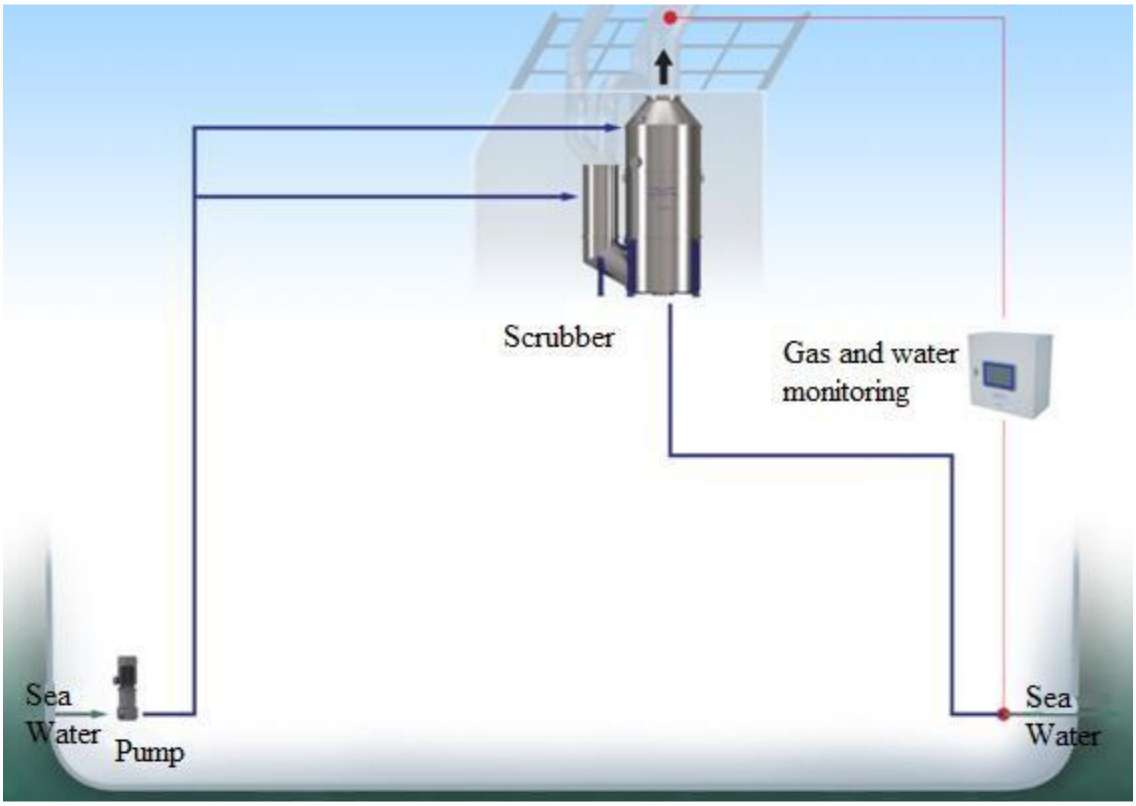


Figure 14. Open-loop scrubber.

Source: (Alfa-Laval, 2020), corrected by author.

In a open–loop scrubber, seawater is used as washwater for scrubbing, and the resulting wastewater is treated and discharged back to sea. The natural alkalinity of the seawater is used to neutralize the acidity that results from SO_x removal (EPA, 2011).

The flow rates of seawater in open loop scrubbers must be very high in order to accommodate the chemical processes in the exhaust gas cleaning unit.

For the open–loop scrubber system, the alkalinity of the seawater used for the scrubber is used to increase binding of SO_2 and SO_3. Scrubber technology also has a cleaning effect on several different substances. Scrubber techniques works well for particles and thus also for particulate substances such as metals, heavy hydrocarbons, PAH, soot, ash etc.

In addition to capturing SO_2, some of the NO_x may also be captured and released as nitrates with the EGSE (Magnusson K., 2018). The average flow rate of the washwater in open–loop scrubber is around 45 t/MWh. (Endres S., 2018). The energy consumption of a seawater scrubber is 2 to 3% of the engine power output (EPA, 2011).

2.4.3 Closed loop scrubber system

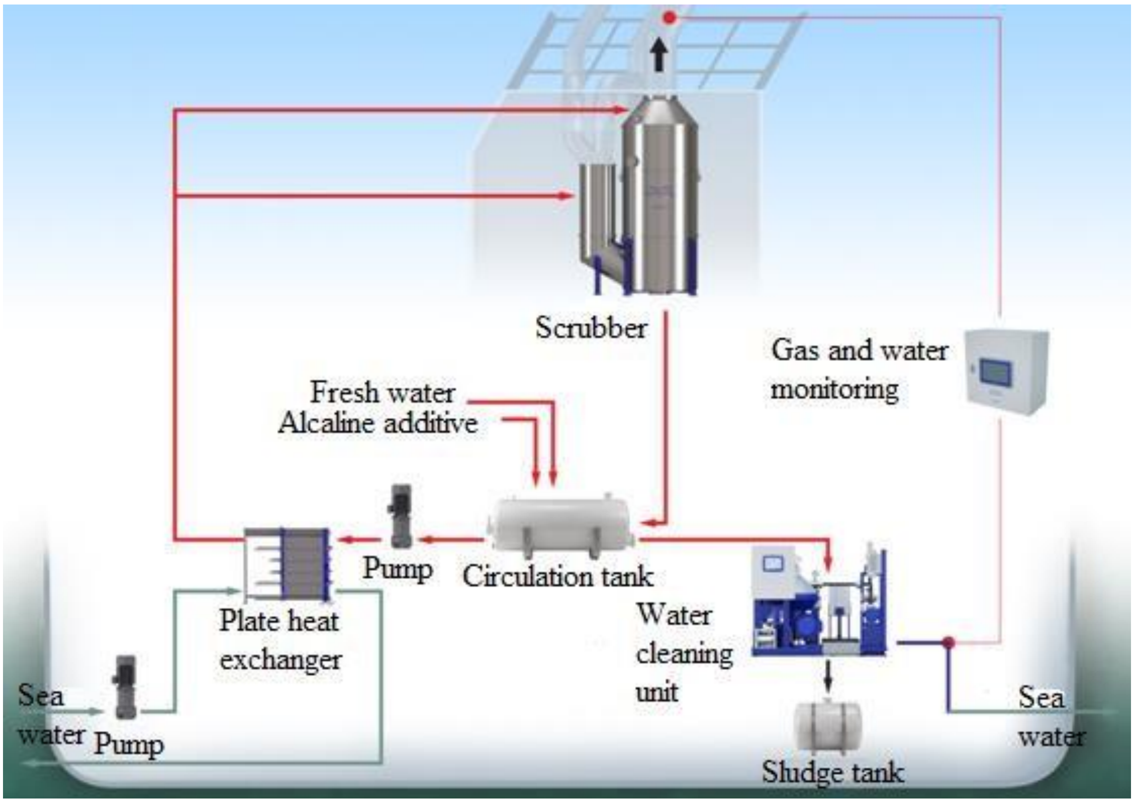


Figure 15. Closed-loop scrubber.

Source: (Alfa-Laval, 2020), corrected by author.

Closed–loop scrubbers are more complex technical systems than open–loop systems. A closed–loop system recirculates the scrubber fluid and applies sensors to operate process water bleed–off and addition of chemicals, and often includes water treatment before any discharge to the marine environment (Zhang Y., 2018).

Closed–loop scrubbers are not dependent on the alkalinity of the seawater for the cleaning process. Exhaust gasses are neutralized with caustic soda (NaOH), which is added to the process water in a recirculating system. The condition of the process water is continuously monitored. When the water reaches a defined limit value for density, a bleed-off is allowed from the system and exchanged with fresh seawater and sodium hydroxide (NaOH). The bleed–off is subsequently treated in a special unit to remove particulates and neutralize the pH (Magnusson K., 2018).

Sodium hydroxide has a pH of 14 and is hazardous. It can cause severe skin burns, respiratory damage and eye injury. Robust procedures are required for handling sodium hydroxide, including use of appropriate personal protective equipment (PPE) if there is risk of exposure. Reference should be made to material safety datasheets (SDS) (Lloyd's Register, 2012).

In such instances where the discharge of waste residues in the marine environment is not permitted, the port state is required to provide reception facilities to meet the needs of ships in disposing of them, without causing undue delay to ships. There should also be adequate storage capacity on board ships for scrubber residues generated during voyages in order to manage situations when port reception facilities are not available. (Endres S., 2018).

Closed–loop systems can periodically be operated in a "zero discharge mode" without discharging any washwater overboard (EPA, 2011).

The energy consumption of closed-loop scrubbers is reported to be about 0.5% of the engine power output (EPA, 2011). Closed–loop or freshwater scrubbers use fresh water in a circuit supplemented with sodium hydroxide on an average flow rate of 20 t/MWh. A minor fraction of the washwater (bleed–off) (~0.1 t/MWh) is discharged (Endres S., 2018).

Closed loop systems discharge small quantities of treated washwater to reduce the concentration of sodium sulphate. If uncontrolled, the formation of sodium sulphate crystals will lead to progressive degradation of the washwater system (Lloyd's Register, 2012).

Figure 16. Scrubber circulation pumps.

Source: Photo from author.

2.4.4 Hybrid scrubber

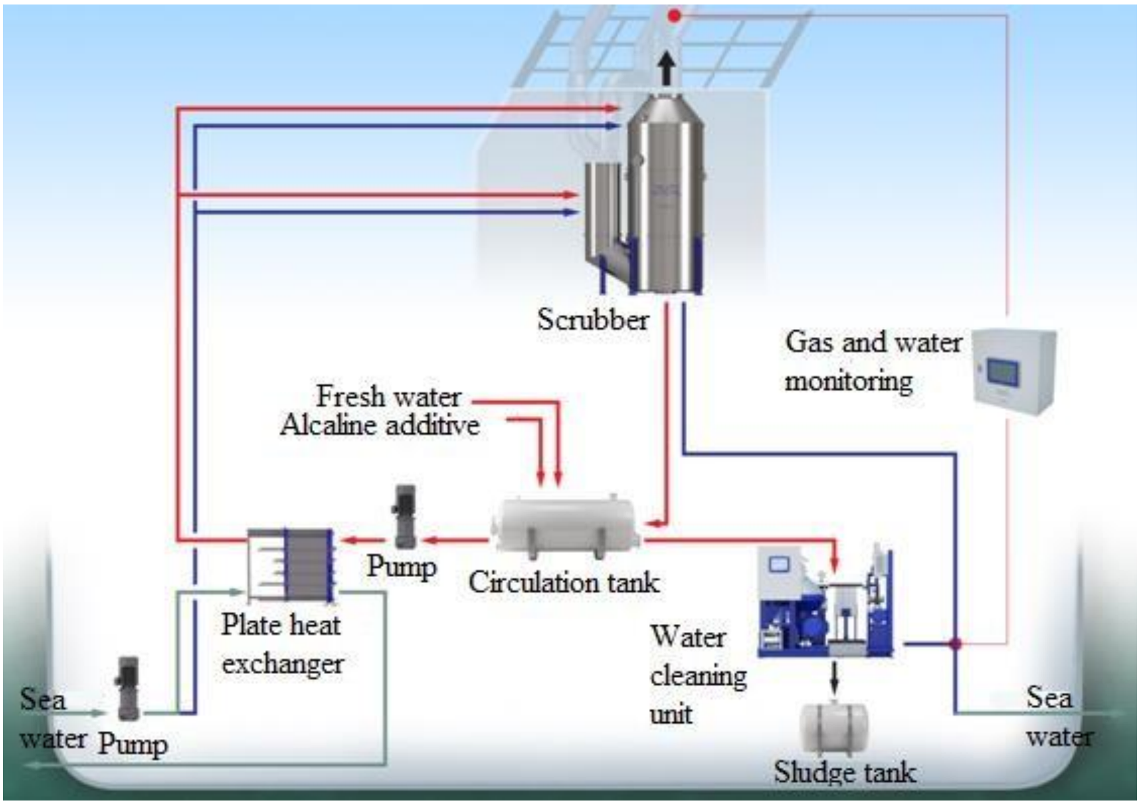


Figure 17. Hybrid scrubber.

Source: (Alfa-Laval, 2020), corrected by author.

Hybrid scrubber system is a combination of the open–loop and closed–loop, enabling flexibility for the customer by the possibility to switch between seawater and freshwater mode, depending on operational area (Paulsrud, 2015).

Hybrid systems have been the most popular solution when the ship owners have chosen to apply scrubber technology (E. Merta, 2016). Currently approximately 50% of ships equipped with scrubbers use hybrid systems and 40% use open–loop systems (Endres S., 2018).

The water cleaning unit can be operated as a stand–alone system, isolated from the rest of the EGCS. When switching over from closed–loop mode to open–loop mode, the water cleaning unit continues to clean the water in the water circulation circuit until the turbidity value is below a preset limit or the preset time is reached (Alfa-Laval, 2014).

The effectiveness of centrifugal separation and settling depends on the particle size distribution and particle density. Additional treatment processes can be added to improve the efficiency of solids removal, including various filtration methods and/or coagulation and flocculation. Coagulation and flocculation remove particles too small for gravitational settling by aggregating them into large, more readily separable particles. Such additional treatment has been used to treat the washwater bled from freshwater scrubbers (EPA, 2011).

Figure 18. The centrifuge is a high–speed separator.

Source: (Hansen, 2012).

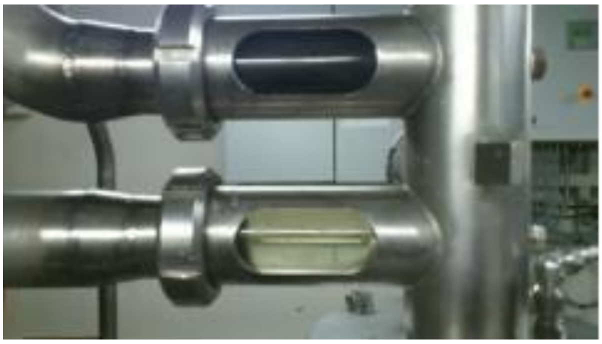


Figure 19. The dirty water is feed in through the top with a turbidity of approx. 250 FNU and the clean water leaves the separator 26 below the feed pipe with a turbidity of approx. 10 FNU. The separated sludge is shot from the separator into a collecting tank.

Source: (Hansen, 2012).

2.4.5 Dry scrubber

Dry scrubbers use solid media rather than washwater to capture sulphur oxides from the exhaust gas. Exhaust gas in a dry scrubber is passed through a bed of granular solid media, such as calcium carbonate ($CaCO_3$), burnt lime (CaO), or hydrated lime ($Ca(OH)_2$), to which the sulphur oxides absorb and react to form gypsum ($CaSO_4$).

The advantage of dry scrubbing technology is that pollutants are not transferred from air to water, as they are in wet scrubbers, but instead react with the solid media to form a byproduct. The byproduct can be reused for high–temperature desulfurization at power plants, as a raw material for cement and steel making, or as fertilizer.

Disadvantage of dry scrubbers that they are heavy and large–sized, which make them problematic to install onto ships. The filled dry SO_x scrubber unit for a 20 MW engine is heavier (around 200 t) than comparable exhaust capacity wet scrubbers (30–55 t) (Lloyd's Register, 2012). Usually dry scrubbers are used in power plants. There are over 500 dry scrubber installations for exhaust gas capture at power plants (EPA, 2011).

2.5 Installation

The ship's Loading Manual and Stability Manuals have had to be re–approved due to the impact of the scrubber and its associated systems on the ship's lightship weight and vertical centre of gravity (Lloyd's Register, 2012).
Choosing a scrubber system depends on many factors. By looking at the operating profile and layout of engine room, one need to assess which kind of scrubber installation will fit best. It is therefore recommended to involve technical experts from the supplier already in the early planning stage of installing scrubber, as the process is often quite lengthy (Paulsrud, 2015).

Installation time for an EGCS depends on the manufacturer and type of system being installed. The main considerations are size, complexity of the system and the components involved. Depending on manufacturer, the EGCS may or may not be in–line. An in–line unit should be installed directly in–line with the silencer and exhaust gas economizer.

Open–loop systems have fewer components and require less tank space than a closed–loop or hybrid system and installation can be expected to be less complicated and time consuming. Closed–loop, hybrid systems and dry systems take up more space, require several tanks for storage, dosing units, separators, multiple pumps and more complex control units. Depending on the complexity of the system and amount of preparatory work done beforehand, scrubber installation at wet berth can take several weeks. There are no technical limitations for scrubber installations regarding vessel size (OCIMF, 2016).

Installation of a scrubber on board involves integration of the scrubber system with the existing shipboard systems. This include the exhaust piping system, the electrical power supply, the control and monitoring system and in some ships, the sea water system.

The addition of a scrubber system on board will increase the operational power requirements of the ship and consequently, the ship's fuel consumption (MPA Singapore).

Retrofitting existing vessels with scrubbers is always more expensive than embedding scrubbers systems in new–builds (Yaramenka K., 2018). For retrofitting of scrubber on existing ship where the enclosed superstructure is enlarged, recalculation of the ship's GT is required. Due to change in the ship's GT, a new International Tonnage Certificate would need to be issued. Ancillary support machinery for the scrubber systems may also require structural modifications and strength enhancement, where necessary. Attention should be paid to penetration of watertight bulkheads for piping works and electrical cables (MPA Singapore).

In a wet EGCS, the biggest electrical load is the seawater feed pump and/or freshwater circulation pump. The capacity required for these pumps can be similar to the ship's seawater cooling pumps (OCIMF, 2016). The rotating speed of these centrifugal pumps is controllable by frequency converters (Lahtinen, 2016).

Many manufacturers create exhaust gas scrubber units with little or no moving parts (e.g. dry scrubbers) to reduce maintenance and prolong operational life. Most manufacturers design their units to reduce the sulphur content from 3.5% to the ECA's required 0.1% with a seawater alkalinity of about 2300 µmol $CaCO_3$/l. This covers the North Sea area, excluding the Baltic Sea where the seawater's low alkalinity may reduce efficiency (OCIMF, 2016).

Figure 20. Interior of a scrubber tower with nozzles and demister.

Source: (MPA Singapore).

2.6 Materials

Most wet exhaust gas scrubber units involve caustic reactions at high temperatures (typically where the exhaust gas temperature is over 250°C) which accelerate the corrosion process. The lower portion of exhaust gas scrubber units are often made of a high–grade nickel alloy or duplex stainless steel, chosen for their resistance to high temperatures and corrosion. The upper portion of the exhaust gas scrubber unit is typically made from a lower grade of stainless steel, because the increased condensation in the exhaust gas means it does not get as hot.

Hastelloy (special group of high corrosion–resistance alloyed steels) or AL6XN are examples of materials used in exhaust gas scrubber unit construction because of their increased oxidation, corrosion and high temperature resistance. However, such materials tend to cost more than lower grade materials of similar composition.

For ambient seawater supply systems, rubber–lined, galvanized, nickel–copper or Glass Reinforced Epoxy/Glass Reinforced Plastic (GRE/GRP) piping can be used (OCIMF, 2016). GRE piping is lightweight, which makes it easier to handle during retrofits, but its reduced rigidity means GRE piping requires more support and has a larger bend radius than its size equivalent in steel (MPA Singapore).

Figure 21. GRE pipes.

Source: (EGCSA, 2012).

Any piping, pumps and separators that will come in contact with washwater should use materials appropriate to the pH, temperature and content of the washwater. Tanks containing washwater, sludge or caustic dosing chemical can be constructed from approved plastics, GRP or stainless steel. Pumps should be equipped with seals of the proper material to withstand the corrosive environment of the washwater (OCIMF, 2016).

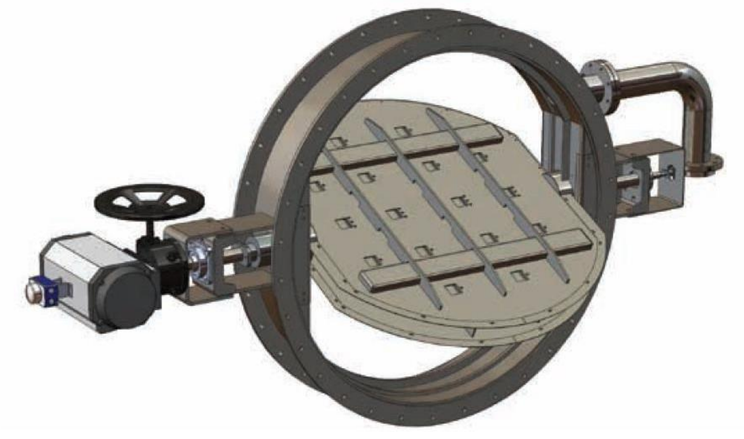


Figure 22. Exhaust gas isolation valve.

Source: (ABS, 2018).

2.7 Safety and crew training

The hazard and safety concern related to the installation of scrubber system may include the possible impact on the stability of the ship, flooding of the engines and boiler, operation and performance of the engines, chemical hazard and personnel safety (ABS, 2018).

IMO has identified the following as potential safety hazards associated with EGCS:

- Handling and proximity of exhaust gases.
- Storage and use of pressurized containers of pure and calibration gases.
- Position of permanent access platforms and sampling locations.
- Hazards associated with the handling of caustic materials.

Crews should be adequately trained to handle hazardous reactants or chemicals used (or chemicals that are created as a result of the process) and be trained to deal with possible medical emergencies. The required Personal Protective Equipment (PPE) is dictated in the associated Safety Data Sheet (SDS) of the hazardous chemicals that will be handled. Health, safety and environmental risk assessments associated with EGCS should be performed to identify hazards and to facilitate the reduction of uncertainties associated with costs, liabilities, or losses (OCIMF, 2016).

2.8 PURE SO_x

There is an Alfa-Laval PureSO_x hybrid scrubber installed onboard m/v Trica.

Figure 23. Scrubber installed onboard of Transfennica Ship.
Source: (Alfa-Laval, 2020).

PureSO$_x$ has been shown to reliably remove more than 98% of the SO$_x$ content in exhaust gas, as well as up to 80% of the PM. This exceeds both the global cap and ECA requirements set by IMO in MARPOL Annex VI. Even during periods of rapid change in engine load, SO$_x$ levels are kept well within emission limits, as has been demonstrated during thousands of hours at sea (OCIMF, 2016).

The scrubber is a hybrid, capable of operating in both open–loop and closed–loop modes. It includes an exhaust gas bypass to allow the ship to continue to operate at times when the scrubber is being maintained or repaired. A large number of sensors for various parameters including temperature and pressure have been fitted to the scrubber to gather data on its performance (Lloyd's Register, 2012).

2.9 Ocean processes

The chemical properties of seawater are usually characterized in terms of alkalinity and pH (Ülpre H., 2014). The average alkalinity level is 2200 µmol $CaCO_3$/l, but it can vary in areas with enclosed waters i.e. River Neva in St Petersburg can have alkalinity levels as low as 490 µmol $CaCO_3$/l. Lakes and rivers do normally have low alkalinity levels. In these low alkalinity areas a closed–loop scrubber or hybrid can be used, while one can operate in open–loop in high alkalinity areas (Paulsrud, 2015). The southern rivers of the Baltic Sea run through calcite bedrock resulting in high carbonate concentrations with consequently high alkalinity (approximately 1,650 -1,950 µmol $CaCO_3$/l), whereas the northern rivers run through granite bedrock resulting in low alkalinity (approximately 800-1,300 µmol $CaCO_3$/l). In general, the alkalinity in the Baltic Sea is lower than the open sea because of the minimal exchange of water through the Danish straits. Seawater scrubbers can operate at low alkalinity levels, but in some cases the SO_2 removal efficiency may be reduced (EPA, 2011).

Sulphate is a naturally occurring constituent of seawater. It is soluble and has a long "residence time", as it is unaffected by the natural pH, temperatures and pressures found in the oceans. It is therefore said to be "conservative" in that regardless of the total salinity it occurs mixed throughout the oceans in the same ratio to the other conservative constituents such as sodium. The large amount of sulphate in seawater is derived from volcanic activities and degassing at the seafloor. Further, sulphates reach the oceans via river flows, but the concentration in open seawater remains constant at around 20 kg of sulphur per t of seawater.

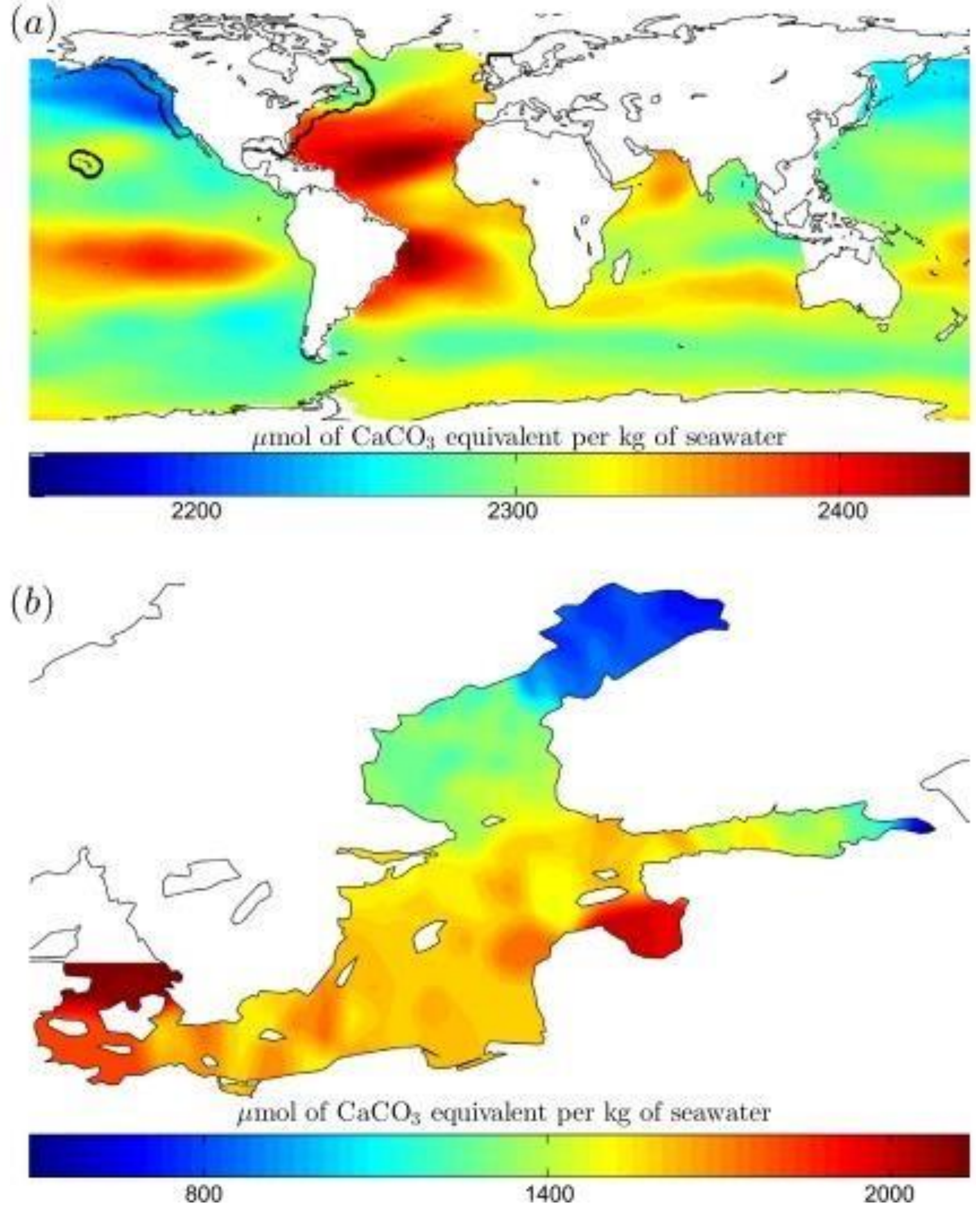


Figure 24. In (a), the global estimate of the total potential seawater alkalinity (μmol $CaCO_3$/l) based on seawater salinity. The Emissions Control Areas (ECA) are highlighted with thick black lines. In (b), the estimate of the average seawater alkalinity (μmol $CaCO_3$/l) between 2000 and 2012 in the Baltic Sea.

Source: (Ülpre H., 2014).

Studies and in field testing confirm that the sulphate increase from exhaust gas scrubbing will be insignificant when compared with the quantity already in the oceans. An analogy that has been used is if all the sulphur in the world's oceans were to be removed, it would form a layer around the earth about 1.7m thick. All the sulphur in all the known oil reserves would add only another 10 micron to this layer (EGCSA, 2020).

There are several mechanisms that lead to increased ocean acidity, but the main one is the oceans absorption of CO_2. Glacial ice melting in the summer introduces freshwater into seawater reducing the acid buffering capacity (Ülpre H., 2014). Unfortunately, it is not enough. Early calculations indicate that the global average pH of surface seawater (approximately 8.1) would be reduced by 0.3-0.4 by the end of the twenty-first century under the business-as-usual emission scenario.

2.10 Exhaust gas scrubber effluent

Before being discharged back to the sea, the washwater can be treated in a hydrocyclone, which separates suspended particles from water (Andersson K., 2016). The washwater obtained from the scrubbing process has a very low pH value and elevated temperatures (SOLAS, 2017). It can be diluted with ambient seawater to raise the pH (Andersson K., 2016).

Results from researches show that the emissions of sulphur dioxide to air are lower when using high–sulphur fuel together with a closed–loop scrubber than when a low–sulphur fuel oil is used. However, other important air emissions, apart from sulphur dioxide, are at higher levels than emissions from a low sulphur fuel. These emissions are mainly particles and particle components such as organic and elemental carbon. Combusting a low–sulfur fuel causes lower emissions of harmful particle to air than the use of a heavy fuel oil together with an exhaust gas scrubber (Winnes H., 2018).

The IMO guideline recommends pH, PAH concentration, turbidity and temperature should be continuously monitored and recorded when the EGCS is operated in ports, harbors, or estuaries. In other areas, these parameters should be continuously monitored and recorded whenever the EGCS is in operation, except for short periods of maintenance and cleaning of the equipment (EPA, 2011).

2.10.1 Measurement of effluent

The MEPC 2015 Guidelines state that the environmental criteria for scrubber residues need updating and that ship owners and scrubber manufacturers are requested to additionally monitor pH, PAH, oil, NO_x, and heavy metals such as cadmium, copper, nickel, lead, zinc, arsenic, chromium, and vanadium in the washwater.

Some of the commonly applied monitoring methods are scientifically questionable in terms of their significance: e.g., the fluorescence signal characteristic for one single compound, phenanthrene, is used as indicators of all PAHs emitted from combustion. PAHs are typically found as complex mixtures in the environment. Therefore, phenanthrene concentrations may differ from total PAH concentrations. Another example is the use of turbidity in order to determine PM concentrations. This method is problematic, as its measurements depend on the scattering of light, which is influenced also by the amount of organics in the seawater, and the type of light source used. Moreover, smaller particles have a very low influence on the turbidity (Endres S., 2018).

2.10.2 Sludge

The closed–loop scrubber effluent is more “concentrated” and caused effects at lower dilutions in the tests than the waters from the open–loop scrubber. Significant toxic effects are found in dilutions of 0.04-0.1% of closed loop EGSE and 1.0% of open–loop EGSE. However, the environmental risk depends on total amounts of harmful substances released to the environment and is thus a product of volume and concentrations. Open–loop discharges thus have higher risks than discharge from closed–loop systems (Magnusson K., 2018).

The soot (PM) collected in closed–loop mode (about 0.15 kg/MWh) mainly consists of unburned hydrocarbons but it also contains heavy metals – especially vanadium and nickel are detected. The heavy metals originate from the fuel oil and the carbon part is unburned fuel / lubrication oil (Hansen, 2012). Residue removed from SO_x scrubber washwater must be stored on board, landed ashore and disposed of appropriately; it is not permitted to incinerate it or discharge it to sea (Lloyd's Register, 2012).

The amount of generated sludge is approximately 0.1 to 0.4 kg/MWh. Samples of sludge produced when using 1.5% sulphur fuel have been extracted and analyzed. The results of the analyses show that scrubber sludge contains water (79%) and dry matter (dm; 21%). The composition of the sludge is mainly oil hydrocarbons (252 g/kg dm), ash (i.e. various inorganic constituents; 59% of dry matter) and metals (53 g/kg dm). The water emulsion contains hydrocarbons, metals and sulfate. Sludge quantity and quality depend on fuel oil quality. Due to the contents of nickel, vanadium and petroleum hydrocarbons it was assessed that the sludge should be classified as hazardous waste (Kjølhol J., 2012). All tests with LFSO show lower PAH concentrations than any of the other tests. Engine loads have little effect on the concentration of PAHs in the exhaust gas (Fridel E.l, 2018).

Scrubber sludge from ship is submitted for treatment on shore; after dehydration and removal of organic fraction it is burnt in cement kilns (Yaramenka K., 2018).

2.10.3 Scrubber washwater

Results from researches show that effluent waters from scrubber systems are an environmental risk. The combined effects of the substances in the discharged water, suggests that the marine environment in the vicinity of shipping lanes or busy areas such as ports and river mouths, may be altered due to discharged scrubber washwater in the lane.

Several samples on process and effluent waters were taken and analyzed. Below are presented results from the chemical analyses from the bleed off water before it enters the water treatment units (bleed–off treatment unit (BOTU) feed), effluent wash water that reaches the sea, and sea water.

Parameter	BOTU feed	Effluent washwater	Seawater	Reduction efficiency (%)
Turbidity (NTU)	**255**	**9.3**	**<2**	**96.4**
pH	**5.1**	**7.6**	**7.9**	
Alkalinity (mmol·L^{-1})	**0**	**6**	**2.5**	
NO_2^- *(mg N·L-1)	**<30**	**49**	**<30**	**>-64.6**
NO_3^- * (mg N·L-1)	**27**	**<1**	**<1**	**>96**
Microtox (EC50, 5 min) (%)	13	15.5	>45	16.1
Al (µg·L^{-1})	120 000	8 300	39	93.1
As (µg·L^{-1})	66	20	1.9	69.7
Cd (µg·L^{-1})	0.34	<0.2	0.11	>41.2
Cu (µg·L^{-1})	41	150	17	-265.9
Cr (µg·L^{-1})	90	9	<1.2	90
Ni (µg·L^{-1})	7 400	830	0.61	88.8
Pb (µg·L^{-1})	18	<6	0.098	66.7
V (µg·L^{-1})	27 000	9 800	3.7	63.7
Zn (µg·L^{-1})	1 200	<70	6.2	94.2
Hg (ng·L^{-1})	1.9	5.2	0.84	-173.7
S (mg·L^{-1})	22 000	19 000	1 100	13.6
Total hydrocarbon (µg·L-1)	**211 960**	**7 103_{max}/6 499_{min}**		**$96.9_{max}/96.7_{min}$ %**

Figure 25. Results from chemical analyses of the water entering the bleed–off treatment unit (BOTU) on m/v Stena Britannica (closed–loop scrubber system), the effluent water for discharge, the seawater and the calculated reduction efficiency of the treatment system on board.

Source: (Winnes H., 2018).

The BOTU efficiently removes most metals. Exceptions are copper (Cu) and mercury (Hg) that increase in concentration after the scrubber. Total hydrocarbons are also efficiently removed; many of the analyzed species to between 90% and 100%. The groups of the lightest hydrocarbon molecules tested are least efficiently removed.

The open–loop scrubbers are larger emitters with higher environmental risks than closed–loop scrubbers. Scrubber effluent from 1 ship with open–loop system exceeds the calculated threshold concentration by 6.3 times and closed–loop system effluents exceed the level by 1.9 – 3.8 times (Winnes H., 2018).

2.11 Impact on the marine ecosystem

Due to the increased levels of CO_2 in the atmosphere, a general acidification of the oceans is in progress. Negative effects of this have been observed especially for coral reefs and other limestone requiring organisms. This has also accelerated international legislation on acidifying emissions in other marine areas (Zhang Y., 2018).

Ecologic toxicity of effluent waters was tested, from both an open–loop system and a closed–loop system, on a selection of marine organisms. The effluents from open–loop scrubbers were concluded to cause larger risks for the marine environment than those from the closed–loop systems. Although the discharges from the open–loop systems are accompanied with significantly higher risks, the treated water from the closed–loop system was also found to compromise vital functions in marine organisms (Winnes H., 2018).

The EGSEs were tested for toxicity using experimental studies with field collected zooplankton of the species Calanus helgolandicus (zooplankton) and bottom-dwelling blue mussels, Mytilus edulis. Zooplankton species and therefore the group of marine animals that is likely to be most affected by the discharge of contaminated water from ships. Zooplankton is a crucial link between phytoplankton and higher trophic levels like fish and marine mammals. Toxic effects on zooplankton will therefore have serious consequences for the whole marine ecosystem. Zooplankton were found to be more sensitive than mussels. The discharged volumes from the open–loop scrubber were 35 times higher than those from the closed loop system. The closed–loop scrubber effluent was thus more "concentrated" and caused effects at lower dilutions in the tests than the waters from the open loop scrubber. Significant toxic effects were found in dilutions of 0.04-0.1% of closed loop EGSE and 1.0% of open loop EGSE. However, the environmental risk depends on total amounts of harmful substances released to the environment and is thus a product of volume and concentrations. Open–loop discharges thus have higher risks than discharge from closed–loop systems (Magnusson K., 2018).

The risks to the marine environment from the releases of effluent waters are concluded to be a concern that need further attention specially to protect sensitive and enclosed areas with heavy ship traffic. Additional scrubber water treatment methods, such as high efficiency filters, or keeping the water stored in a tank on board could reduce or eliminate the risks (Winnes H., 2018).

Figure 26. Marine ecosystem.

Source: (Alfa-Laval, 2020).

The impact of scrubber wash water discharge on marine microorganisms and biogeochemical processes has so far only been measured in one study. It reported increased adult zooplankton mortality and reduced feeding probably due to the synergistic effects of heavy metals and other constituents in the scrubber washwater. However, there are plenty of studies on the effects of some of the scrubber constituents (e.g., metals and PAH) on marine life and marine organisms.

Future research needs to increase our understanding of the ecological and biogeochemical effects of washwater discharge from shipping considering seasonally– and spatially–variable phytoplankton communities, cumulative effects as well as interactive effects with other environmental parameters (Endres S., 2018).

The effluent scrubber water as a whole was found to be more toxic to marine organisms than what could be predicted from available data on toxicity of the individual chemical substances it contained. The concentration of scrubber water in the mixing zone behind a ship is estimated to be at a level where there is a risk for harmful effects on planktonic organisms (Winnes H., 2018).

It cannot be excluded that even lower concentrations would have been harmful to the tested zooplankton species. Seawater concentrations of individual chemicals in the discharged EGSE were compared to Environmental Quality Standards (EQS) for priority pollutants in the Water Framework Directive 2000/60/EC (WFD). It was found that the toxicity of the estimated seawater concentrations of EGSE from both closed–loop and open–loop systems, when treating the discharged water as one unit, exceeded the threshold level derived from the toxicity tests on the zooplankton.

This means that there is a risk that discharge of EGSE will have a negative effect on the marine pelagic ecosystems in the area around shipping lanes (Magnusson K., 2018).

2.12 Human health

Pollutant emission from combustion sources, especially coal–based, and its effects on human health and ecosystems have been of concern to scientists and societies for many years. There is no doubt that these pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and heavy metals, e.g., mercury, negatively affect our health and deteriorate ecosystems. Year after year the world population and energy consumption systematically increases, increasing the amount of fuels combusted. Different energy technologies are being developed throughout the world, but forecasts indicate that coal and liquid fuels will remain a primary source of energy worldwide over at least the next three decades (Krzyzynska R., 2012).

95% of the SO_x emitted from the combustion of fossil fuel is sulphur dioxide. SO_2 is a toxic gas, which is directly harmful to human health. At lower levels than 500 ppb, chest pains, breathing problems, eye irritation and a lowered resistance to heart and lung diseases can be experienced. At 20 ppb or lower there should be no ill effects to a healthy person. The normal atmospheric background concentration of SO_2 is generally less than 10 ppb (EGCSA, 2020).

SO_x are harmful both to the environment and to human beings (respiratory problems such as asthma, COPD or lung cancer). SO_x dissolve in the water in air and form acid rain, destroying fresh water resources, land, buildings and crops (Snickars-Nykamb, 2017).

PAH are transported through the food web and exported to marine sediments. Sediment dwelling and filter–feeding organisms (e.g., bivalve), but also shellfish and fish may accumulate PAH and in that way entering human food. PAH are moderately persistent in the environment and moderate to high toxicity to aquatic life. The International Agency for Research on Cancer identified 17 PAHs as a threat to human health, some even as carcinogenic. PAH were found to be harmful to marine microbial food webs and human health (Endres S., 2018). PAHs may also bio–accumulate in edible shellfish, which gives them a pathway to humans (EGCSA, 2020).

People can become sick by eating shellfish (e.g., mussels, oysters, clams, and scallops) that filtered and fed on toxic microalgae. These microalgae can be found in resting forms within the sediment and hatch under appropriate environmental conditions. At the resting stages, they can be transferred with the sediments in ballast water tanks. Furthermore, microalgae can change state and become toxic under certain conditions. When humans consume shellfish containing microalgae toxins, the transfer of the toxins can result in poisoning, potentially leading to fatal consequences. Shellfish toxins are classified into different forms, including amnesic shellfish poisoning, diarrhetic shellfish poisoning, neurotoxic shellfish poisoning and paralytic shellfish poisoning. The paralytic shellfish poisoning form is known to be caused by toxic dinoflagellate species, which commonly occur in ship ballast waters as either viable forms or in resting cyst forms.

An increase in emissions of especially fine and ultrafine particles could cause an increase in the number of people seeking care due to asthma and bronchitis and an increase in deaths. The size of the particles is one of the most important properties in discussions of particle impacts on human health. Particles in the air reach the airways and lungs via inhalation. Larger particle become caught in the mucus layer in the upper regions of the airways and are moved up and swallowed. Smaller particles (i.e., diameter less than 2.5 μm) can reach the alveolus in the lungs, which lacks a protective mucus layer. Ultrafine particles, i.e., diameters less than 10 nm, can penetrate from the lungs to the blood and be transported to other parts of the body. The impact on the cardiovascular and respiratory systems due to ultrafine particle exposure has been observed in studies on both humans and animals. Thus, exposure to ultrafine particles from mobile sources, e.g., shipping, is difficult to assess and requires further monitoring system developments. These ultrafine particles work as carriers for toxic compounds, e.g., transition metals and organic substances that are condensed or adsorbed to the surface of the particles. Transition metals, such as vanadium and iron, have a negative impact on human health by catalysing the formation of reactive oxygen species, activating different biochemical processes and causing respiratory diseases (Andersson K., 2016).

2.13 Costs

The use of SO_x scrubbers in combination with high–sulphur residual oil fuels may be an economically attractive option in SECAs and worldwide (EPA, 2011). At the current fuel price rates, scrubber is more viable option from a ship owner perspective. However, estimates of future fuel prices are accompanied with high uncertainties.

Closed–loop scrubbers are more expensive than open–loop scrubbers due to high operation and management costs (consumption of NaOH, fresh water, flocculants and treatment of the generated sludge) (Yaramenka K., 2018).

The biggest operating cost associated with an EGCS is the additional power requirements of the system, which is highly dependent on the cost of fuel (OCIMF, 2016). There are examples of bunker fuel prices below.

Figure 27. Example of bunker fuel prices.

Source: (World bunker prices, 2020)

Other operating costs to consider include the EGCS and associated equipment maintenance; increased fuel costs due to:

increased back pressure and power consumption;

manning (additional to or additional percent of an operating engineer);

bulk reactant procurement, storage and consumption;

waste management and disposal;

and crew training (OCIMF, 2016).

The capital expenditure element of purchasing an EGCS is dependent on the size of the system, type of system, whether the system is single–inlet or multi–inlet, and the type of reactant used. Open–loop systems are typically less costly than closed–loop systems, which are similar in price to hybrid systems (OCIMF, 2016).

The alkali price (360 €/t) source was ICIS Services, Caustic Soda price report 10.01.2014. An extra 10% per t was added for alkali delivery to ship. The alkali concentration is 50% m/m (Lahtinen, 2016).

Scrubber sludge disposal price (200 €/t) was estimated and it includes transport from ship to disposal plant (Lahtinen, 2016).

The rationale behind the choice of scrubber instead of LSFO from a shipowners perspective when switching from HFO to one of the alternatives, since it is the least expensive approach to comply with current regulation. From the private perspective, open–loop scrubber has higher benefit–to–cost ratio than LSFO while closed–loop scrubber has lower ratio due to higher operation and management costs (Yaramenka K., 2018).

2.14 Conclusion

The use of emission reduction technologies, such as scrubbers, in the shipping industry has benefited the environment by significantly reducing the release of pollutants to the atmosphere. However, there is incomplete understanding of the impact of scrubber washwater discharge on marine chemistry, biodiversity, and biogeochemical processes. In particular, there is limited information on the amount and composition of washwater discharge and the associated marine biological impacts.

Standards and monitoring guidelines for application of scrubbers need to be improved. IMO member states recently recognized that it is necessary to improve and harmonize procedures in terms of washwater sampling and analysis to ensure comparability in different data sets.

Washwater measurements should include monitoring of pH, PAHs, oil, OC, BC, nitrogen, and heavy metals. Improved inspection protocols but also further technical developments of the scrubber systems, e.g., regarding reduction of biofouling and scrubber sensors failures, are needed to increase the compliance level national and international regulations as well as enforcement of emission reduction technologies.

Due to its complex nature, accurately forecasting scrubber operation and the related releases of pollutants requires further modeling efforts combining ship traffic data with ship emission factors and in–situ measurements of pollutants onboard. Using those global measurements and improving current maritime transport models, we may be able to better predict ship emissions, the use of scrubbers and their environmental impact in the future. In addition, there is a great need for interdisciplinary research comparing alternative emission reduction technologies in terms of their cleaning efficiency, economic costs, and environmental impact (Endres S., 2018).

Due the small number of previously conducted studies, there is a great need for further research on this topic. To date, there are only very few quantitative and qualitative measurements on the amount and composition of ship effluents and their biological impact in the marine environments. The consequences of ship emissions for marine chemistry, organic matter cycling and biodiversity are highly relevant to the development of shipping as sustainable transport medium. Profound scientific data will be valuable for subsequent policy recommendations and remove operational and investment uncertainty for shipping industry (SOLAS, 2017).

3 ANALYSIS

3.1 m/v Trica

Figure 28. m/v Trica.

Source: (Transfennica, 2020).

Name of ship – Trica

Nationality – Dutch

Port of registry – Amsterdam

Call Sign – PHLV

IMO Number – 9307384

Gross – 28289

Nett – 8486

L.o.a. – 205 m

L.p.p. – 190 m

Breadth – 25.5 m

Depth – 21.25 m

Main Engines – 2xWartsila 12V46 12600 kW each

Auxiliary Engines – 2xWartsila 8L20 1500 kW each

m/v Trica – one of the 6 "Transfennica" Con-Ro type ships. HFO is used for ME's and AE's. MGO is used for a boiler as a fuel.

Figure 29. m/v Trica has a certain travelling line between ports of Finland, Belgium, Germany, Great Britain and Russia. Some countries' legislation ask for a closed loop (marked as green) in certain cases (usually travelling within internal waters).

Source: (Transfennica, 2020), corrected by author.

3.2 Installation of scrubber

The total capital cost required to install a scrubber system depends on the type (open or closed loop) and size of the installation. Rough estimates include a cost range of between 100 and 200 € per kW of installed power on new builds and 200–400 € for retrofitting installations (Psaraftis, 2019).

Scrubber system	Vessel	Cruise ferry (~40 MW)	Cargo ship (~20 MW)
Seawater system	New build	3 M€	2.1 M€
	Retrofit	3.5 M€	2.4 M€
Freshwater system	New build	2.4 M€	1.9 M€
	Retrofit	3.4 M€	2.4 M€
Hybrid system	New build	3.8 M€	2.6 M€
	Retrofit	4.3 M€	3 M€

Figure 30. Total capital cost of different scrubber systems.

Source: (Psaraftis, 2019).

The Exhaust Gas Cleaning Systems Association calculated costs on real recent cases, such as a 24 megawatt (MW) scrubber retrofit costing $4.2 million (Abadie O., 2011).

The ship's operating life is supposed to be equal with the scrubber service life. The average lifetime of different ship types varies between 25 and 27 years. As an exception, the scrapping age of liquefied natural gas tankers is higher, typically 29 years (Lahtinen, 2016).

m/v Trica was built in 2007, the scrubber was installed in 2014. The author decided to set 20 years as the lifetime left for the ship, and also for the scrubber and $4.2 million as an investment, as mentioned above. In case 1 of analysis investment of scrubber, it is divided equally during 20 years without interest rate. In case 2 of analysis investment of scrubber, it is calculated as on–time investment. Below both calculations are compared with MGO analysis.

4’200’000 $ / 20 years = 210’000 $

3.3 Maintenance 2019

Table 1. Maintenance done in 2019

Action	Date	Price (€)
Replaced probe filter	07.04.2019	117.9
Replaced nozzles 24pcs	02.07.2019	6234
Replaced probe filter	04.07.2019	117.9
Filled up 1t of flocculent	01.08.2019	Negligible
Overhauled WCU discharge pump	10.08.2019	385
Replaced turbidity sensor	26.09.2019	3000
		Total € 9’854,8
		Total $ 11’057,28

Source: Made by author

Maintenance done in 2019 ($ x € approximate exchange rate in 2019 is 0.89125) (FCR, 2020). Routine jobs done by crew as calibration of sensors or cleaning the filters belongs to the system were not calculated in this analysis as maintenance costs.

3.4 Fuel oil 2019

Table 2. Fuel related expenses in 2019

Date	Amount [MT]	HFO Price (avg.)	Cost HFO [$]	MGO Price (avg.)	Cost MGO [$]
16.01.2019	800	393	314400	630	504000
28.01.2019	850	401	340850	634	538900
20.02.2019	900	438	394200	669	602100
04.03.2019	700	441	308700	674	471800
27.03.2019	800	436	348800	671	536800
08.04.2019	900	445	400500	675	607500
01.05.2019	800	450	360000	681	544800
13.05.2019	550	437	240350	686	377300
05.06.2019	800	396	316800	641	512800
17.06.2019	550	386	212300	624	343200
10.07.2019	900	440	396000	651	585900
31.07.2019	800	442	353600	657	525600
12.08.2019	550	371	204050	619	340450
06.09.2019	950	395	375250	639	607050
21.09.2019	100	489	48900	673	67300
25.09.2019	950	452	429400	662	628900
07.10.2019	850	401	340850	641	544850
30.10.2019	800	367	293600	648	518400
11.11.2019	560	357	199920	643	360080
04.12.2019	950	330	313500	648	615600
16.12.2019	700	349	244300	667	466900
Total	15760		6436270		10300230

Source: Made by author

3.5 Scrubber sludge 2019

Sludge was given ashore 14 times totally 94t in 2019.

Approximate price of discharge of wet scrubber residues is 200€/t (Lahtinen, 2016).

94 x 200 = 18’800 € = 21’094 $

3.6 Caustic soda 2019

According to table above NaOH was taken 5 times totally 92t in 2019.

Approximate price of NaOH is 360€/t + 10% transport (Lahtinen, 2016).

92 x 360 = 33’120 € + 10% (3’312 €) = 36’432 € = 40’877.42 $

3.7 Fresh water and flocculent 2019

As most of FW onboard of m/v Trica is self–produced and consumption of FW in closed–loop is small same like flocculent consumption during 2019 was less than 0.5m^3, so cost of fresh water and flocculent was putted as negligible by author.

3.8 Parasitic losses 2019

A very important extra cost stems from the increased fuel consumption to cover the energy requirements of the scrubbers. This varies per technology type and is estimated at approximately 1–3% for seawater systems and 0.5–1.5% for freshwater scrubbers (Psaraftis, 2019).

There are 1% of CL scrubber and 3% of OL scrubber numbers used as parasitic losses in this master’s thesis.
All closed–loop hours are available in log books and also in saved data loggers of the scrubber system.
Below is the table with the amount of closed–loop hours each month and the year 2019 total.

Table 3. Parasitic losses 2019

Month 2019	ME1 (12,6MW)	ME2 (12,6MW)	DG1 (1,5MW)	DG2 (1,5MW)	Total CL
January	71	71	181	86	182
February	59	59	152	76	161
March	61	61	105	73	127
April	81	81	154	129	178
May	63	63	143	80	139
June	92	92	204	126	209
July	66	66	134	66	134
August	52	52	157	59	157
September	41	41	94	59	101
October	59	59	171	60	171
November	67	67	175	67	175
December	62	62	94	89	121
Total hours	774	774	1764	970	1855
Total MW/h	9752.4	9752.4	2646	1462.5	Total 23613.3 MW/h

Source: Made by author

Table 4. Total OL/CL hours 2019

	ME1	ME2	DG1	DG2	MW/h
Total 2019	5945	5945	5086	4051	
OL	5171 (65155.6 MW/h)	5171 (65155.6 MW/h)	3322 (4983 MW/h)	3081 (4621.5 MW/h)	139915.7 (83.1%)
CL	774 (12.5%)	774 (12.5%)	1764 (34.7%)	970 (23.9%)	23613.3 (16.9%)

Source: Made by author

Parasitic losses OL 3%

6436270 x 0.831 = 5348540,4 x 0.03 = 160’456,2 $.

Parasitic losses CL 1%

6436270 x 0.169 = 1087729,6 x 0.01 = 10’877,3 $.

3.9 Total 2019

3.9.1 Case 1

HFO (2019) 6’436’270 +

Installation 210’000 +

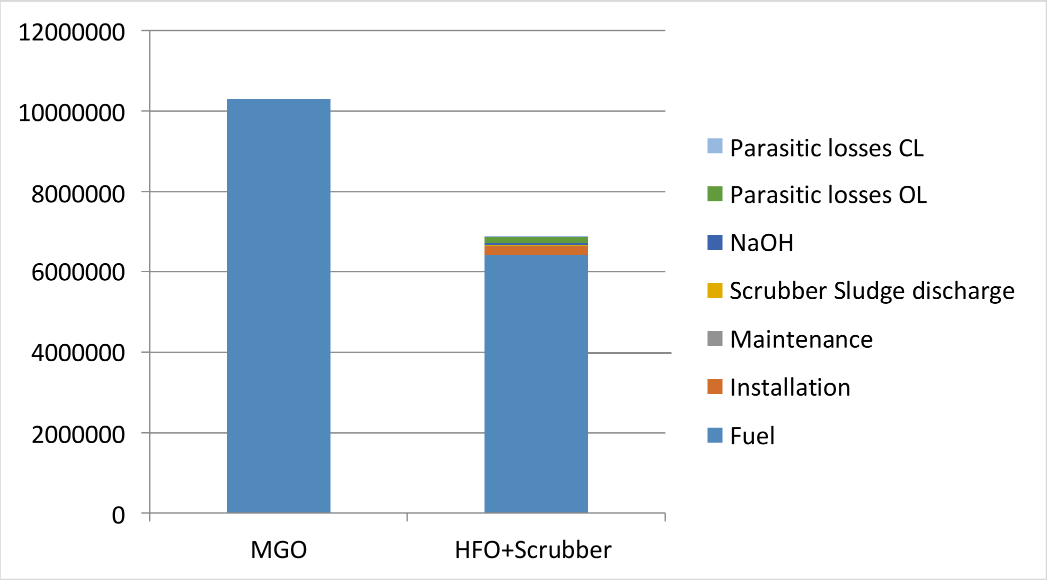
Maintenance (2019) 11’057.28 +

Scrubber Sludge discharge (2019) 21’094 +

NaOH (2019) 40’877.42 +

Parasitic losses OL (2019) 160’456.2 +

Parasitic losses CL (2019) 10’877.3 = 6’890’632.2 $



Difference shown between MGO and HFO + scrubber usage case 1

3.9.2 Case 2

HFO (2019) 6’436’270 +

Installation 4’200’000 +

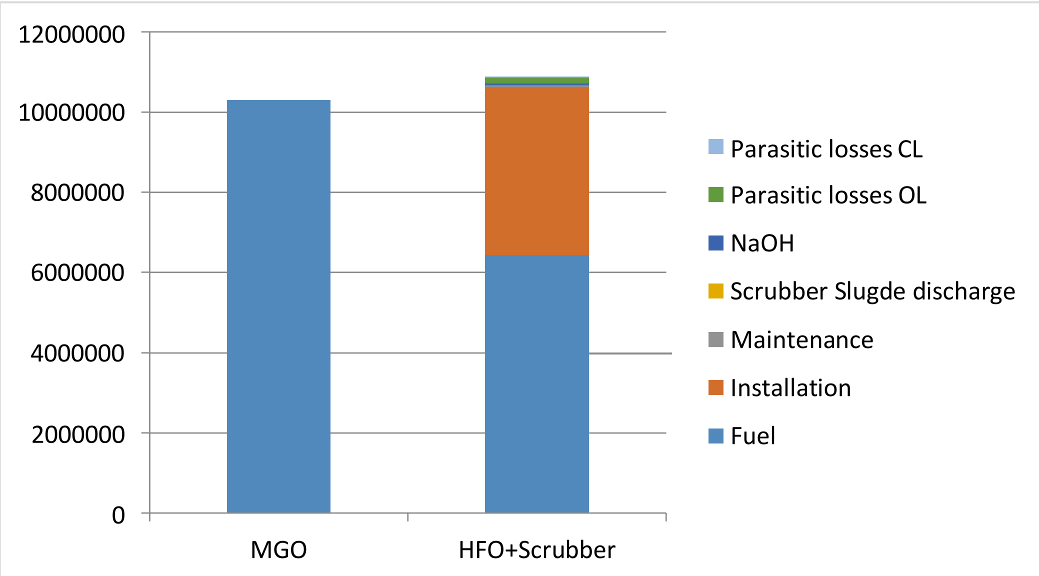
Maintenance (2019) 11’057.28 +

Scrubber Sludge discharge (2019) 21’094 +

NaOH (2019) 40’877.42 +

Parasitic losses OL (2019) 160’456.2 +

Parasitic losses CL (2019) 10’877.3 = 10’880’632.2 $



Difference shown between MGO and HFO + scrubber usage case 2

SUMMARY

The installation of scrubber (retrofit) is chosen as an optimal investment to fulfill the sulphur legislation according financial evaluation in comparsion with low–sulphur distillate oil (MGO). External costs of environmental and health damage associated with air and water emissions were not included in the analysis.

The purpose of the analysis has been to provide further information about the profitability of exhaust gas scrubber installation for ship owners. According to calculations, the total amount of investments in scrubber together with maintenance and installation is 6’890’632.2 \$ in case 1. In case 2 it is 10’880’632.2 \$

In comparison to the 2019 price of MGO and the same amount of fuel with total price 10’300’230 \$, it is concluded, that less than 1 year in case 1, or slightly over 1 year in case 2, of using scrubber together with price of installation is enough as payback time to cover the costs of all components of scrubber use with using HFO onboard of m/v Trica. This means that the vessel will already gain profit by next year using the combination of HFO and scrubber system in comparison to MGO.

The number of scrubbers installed on board of ships has increased considerably. Currently, the number of scrubbers on order is somewhere around 600 units and 3,500 scrubbers have already been installed. The reason for this is because the method of scrubbing sulphur oxides from the exhaust gases while continually using HFO has received attention as a less expensive option.

Conclusively, using scrubbers combined with heavy fuel oil burning is best considered for all medium and large sized cargo ships. For future development, zero–effluent technology should be researched and exploited. Effluent port reception facilities and large on board holding tanks could be arranged to meet this end.

Whether scrubbers are environmentally the most optimal technology is unclear. There is only little information about chemical composition of scrubber effluent wash water and its direct impact on the ecosystem as whole. More research and tests are required in the industry before the use of scrubbers becomes further widespread.

Currently pumping effluent into the sea is not optimal from an environmental standpoint. Ideally, non-polluting scrubbing solutions with zero effluent should be developed. The technologies that need improvement to enable this are effluent storage and treatment on board, port reception facilities and land based wash water treatment.

The scrubber technology should be considered as a whole with, for example, the following aspects:

Manufacturing of on board scrubber equipment.

The scrubber's electricity consumption and overall operation.

The scrubber and water purification chemicals used, along with disposing the residue.

Final disposal and/or recycling of the scrubber equipment. This will be topical when the scrubber plant and the ship are to be scrapped.

System thinking is required to completely and wholly analyze the former.

Once the monitoring specified in the IMO Guidelines are completed, it will decide the continued use of EGCS, along with long-term scientific studies to see if and how EGCS impacts the environment.

KOKKUVÕTE

Keskkonna seadusandlus kehtestab piiranguid meie planeedi kaitsmiseks pealekasvanud tarbimise ja sellega seotud tagajärgede eest. Samaaegselt, seadusandlus annab võimalust valida, kuidas saab seadust täita. Suurenenud tarbimise ja toodangu pärast kasvab kahjulike ainete arv aastate lõikes järjepidevalt. Kuna kõige suurem kaubavedu toimub läbi mereteede, suureneb ka koormus merekeskkonnale.

Tuleb märkida, et kuigi seadusandlus näeb ette piiranguid nii ookeanitele tervikuna, kehtivad ka erinevate tiheda liiklusega regioonidele rangemad piirangud. Merekeskkonna reostuse probleemi lahenduseks on olemas mitmeid erinevaid variante. Võimalik on vahetada sisepõlemisseadmete kütust või paigaldada väljalaskegaaside puhastusjaamu, midas nimetatakse skrubberiks.

Piirangute peamiseks põhjuseks on väävli olemasolu kütuses. Väävli põlemisprotsessis tekib kahjulikke aineid, mis on ohtlikud merekeskkonnale tervikuna. Väävlisisalduvaid aineid saab eraldada kütusest puhastusjaamades või ekspluatatsiooni käigus veevooluga väljapesemisel. Mõlematel meetmetel esinevad oma tagajärjed. Näiteks, madala väävlisisaldusega kütuse toodangu jaoks kasutatakse elektrit, mille toodang omab ka teatud keskkondlikke tagajärgi. Skrubber, selle toodang, ekspluatatsioon ja utiliseerimine samuti ei jää looduse jaoks märkamatuks. Skrubberi abil saab väljalaskegaasidest välja pesta enamus väävlit sisaldavaid kahjulikke lisandeid, mis annavad võimaluse kasutada sellega koos kõrge väävlisisaldusega odavat jääkkütust. Selline variant on väga kasumlik laevaomaniku jaoks. Aga, nagu viimased uuringud näitavad, ei ole skrubberi kasutuse tagajärgi piisavalt uuritud ja juba praegu võib öelda, et seadme ekspluatatsioon toob endaga kaasa oodatust tõsisemaid tagajärgi. Tõsi küll, skrubberi abil saab kõrvaldada enamus väävlisisaldavaid aineid, kuid põhiline probleem on selles, et skrubberi väljavoolavasse vette jäävad ohtlikud ained nagu metallid ja polütsüklilised aromaatsed süsivesikud (PAH). Need elemendid mõjutavad otseselt merekeskkonda, eriti planktonit, mis on merekeskkonna ökosüsteemis üks tähtsamaid elemente. Koos meretoodanguga, satuvad elemendid inimkehasse, soodustades erinevate haiguste tekkimist. Avatud kontuuriga skrubber on ohtlikum keskkonnale, kuna süsteemist väljuv pesuvesi läheb kõikide ainetega üle parda. Suletud kontuuriga skrubber on ohutum variant tulevikuks, kuna see annab võimalust hoida pesuvett pardal, et hiljem seda kaldale üle anda. Kuna skrubberi süsteemi paigaldus on kasumlik, hakatakse suure tõenäosusega seda paigaldama aktiivselt tulevikus laevade peale. See on ka üheks põhjuseks, miks tuleb väljalaske standardeid ümber vaadata, nagu soovitab ka IMO. Ümbervaadatud standardid peavad andma võimalust täpsemini analüüsida pesuvee koostist.

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