OLGA SHAKETANGE

Exhaust scrubber systems onboard vessels

DEGREE PROGRAMME IN MARINE ENGINEERING
2024

ABSTRACT

Shaketange Olga: Exhaust scrubber systems onboard vessels
Bachelor’s thesis
Degree programme in Marine engineering
January 2024
Number of pages: 37

The implementation of exhaust cleaning scrubber systems onboard ships represents a critical strategy for reducing air pollution and complying with increasingly emissions regulations. This thesis explored exhaust cleaning scrubber technology, focusing on its different types of designs, operation, and impact within the maritime industry. Using books, websites and online publications, the process itself proved to be eye-opening.

Concerning the environment, exhaust scrubber systems offer benefits and drawbacks. Sulphur emissions have decreased, which is a positive. However, waste wash water discharge contaminate seawater if not well monitored. Therefore, the purpose of this thesis was to educate interested parties such as shipowners, operators, regulators, and policymakers about the advantages and difficulties associated with implementing scrubber technology aboard ships, the various exhaust gas scrubber system designs, the impacts they have on the environment and all the laws that prohibit the discharge of wash water as well as the IMO regulations.

Keywords: International Maritime Organization, MARPOL, Exhaust scrubber, Open loop, Close loop, Water discharge, Sox reduction.

CONTENTS

1 INTRODUCTION 4
1.1 Overview 5
2 REGULATIONS AGAINST SHIP POLLUTION 6
2.1 Rules protecting the air from ships pollution 6
2.2 Local and regional laws 7
2.3 Verification of the Exhaust gas scrubber (EGS) certification 9
3 MARINE FUELS 10
3.1 Diverse characteristics and varying sulfur content of marine fuel ... 10
4 GENERAL KNOWLEDGE OF EXHAUST SCRUBBER 12
4.1 Varieties of exhaust scrubber system 12
4.2 Dry scrubber system 12
4.3 Wet scrubber system 13
5 SELECTING AND RETROFITTING SCRUBBER SYSTEM 15
5.1 Factors to consider 15
6 OPERATIONAL OF DIFFERENT WET SCRUBBER DESIGN 18
6.1 Open loop system 18
6.2 Close loop system 21
6.3 Hybrid loop system 24
7 ENVIRONMENTAL IMPACTS OF EXHAUST SCRUBBER SYSTEM .. 27
7.1 Exhaust gases 27
7.2 Air pollution reduction 28
7.3 Water pollution 29
8 MAINTENANCE OF SCRUBBER SYSTEM 31
8.1 Regularly upkeep 31
9 CONCLUSION AND RECOMMENDATION 32
9.1 Final thoughts and practical thoughts 32
10 REFERENCES 33

1 INTRODUCTION

The maritime sector is important for global trade as it connects economies and makes it effortless to travel between continents. However, the industry's reliance on fossil fuel for propulsion, environmental impact concerns were raised particularly regarding greenhouse gas emissions and air pollution. As the environmental awareness and regulatory demands escalates, ship operators and ship owners are forced to search for productive ways to improve sustainability and reduce emissions in maritime transportation industry.

Installation of exhaust cleaning scrubber system on board ships is a sole solution. Scrubber system reduce the pollutant emissions such as nitrogen oxides (NOx), Sulphur dioxide (SO2) and particulate matter (PM) which are part of the exhaust gas that the ship engine releases after combustion. Exhaust cleaning scrubber system offers effective ways to meet the emission regulations meanwhile reducing the environmental impact of maritime trading operations by cleaning the exhaust gases before they are released into the atmosphere.

This thesis explores various views of exhaust cleaning scrubber system onboard ships, aiming to provide in-depth understanding of their operation, local laws of certain ports regarding the use of scrubbers, installation, design, and consequences within the marine industry. This thesis aims to discuss crucial questions about scrubber technology and its adaptation into shipboard operations by using regulatory frameworks, real world case studies and existing literature.

The introduction of Maritime Organization's (IMO 2020), sulphur emission regulation has motivated shipowners to be interested in exhaust cleaning scrubber system enabling them to comply with the regulations, even though the system comes with operational limitations, environmental effects, and complex technology that this thesis will discuss in further detail.

Shipowners must adjust and be attentive to challenges and opportunities that this system presents and that will contribute to more sustainable manner and a future cleaner maritime transportation operation. This thesis aims to provide useful information into the role of the scrubber system by analysing the facts from industry reports and academic research done in the past.

1.1 Overview

Scrubber system is viewed as a necessary equipment for vessel operation, it is critical that the operators and engineers involved become fully familiar with the installed system. Although scrubbers are quite new installation in maritime applications, the technology has been widely acknowledged on land. It is proven that the system has extremely lowered the emissions of sulphur oxides and thus it has been used for decades on land-based fuel oil burning or coal facilities. (Luostarinen, 2019, p.5)

The air quality is improved by the exhaust gas filtration, as the scrubber system cools down the exhaust gases by removing solid particles, and gases mist. However, shipping sector pollutes air and water affecting the environment and marine life. Ships with open loop system contaminate the sea by discharging wash water overboard. Wash water has high acid and warmth comparatively to the surrounding sea water due to the exhaust gases that are being cooled by seawater circulation and that change affects the aquatic life. Metals such as nickel, lead, and copper are as well present in the wash water. Due to air pollution, some international, local, and regional regulations are presented in this thesis because they have an influence on scrubber performance monitoring and operation. We will also investigate the recommended guidelines that the IMO has provided for the certification and operation of scrubber units. (Teuchies et al., 2020.)

2 REGULATIONS AGAINST SHIP POLLUTION

2.1 Rules protecting the air from ships pollution

The International Maritime Organisation (IMO) mandates that the sulphur content of fuels carried by vessels be restricted to 0.50% worldwide and 0.10 % m/m in ECAs (Emission Control Areas; the United States, Canada, the Baltic Sea Area, and the North Sea area). The 1997 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL), which included MARPOL Annex VI, was the first step in the IMO's decision to regulate sulphur oxides (SOx) from ships. Ships are required to be equipped with exhaust gas scrubbers in compliance with global regulations. Using an exhaust gas cleaning system or alternative technological techniques, ships' main propulsion engine and auxiliary engines' combined sulphur emissions should be reduced to less than or equal to 6.0g SOx/kwh. (Sargun, 2021.)

According to the IMO, the use of the exhaust gas scrubbers is the rightful way to ensure that ships comply MARPOL Annex VI and reduce their sulphur emissions. Resolution MEPC.259(68), is a different guideline that summarizes the requirements for scrubber system testing, certification, verification as well as criteria of discharging wash water into the sea. (Fernandez & Sarkar,2021.)

According to the regulation, exhaust gas cleaning systems (EGCS) that lower SO2 concentrations in exhaust to levels that are comparable to regulated fuel sulphur limits are used. Reducing particle emissions is the goal of the same regulation that sets a limit on the sulphur content of marine fuel. (MARPOL ANNEX VI, 2013.)

The allowed particle emission levels are not quantified but they depend on the reduction of particle emissions with fuel sulphur content, which is a key difference from the sulphur limit. As a result, there is no set measurement standard or common limit on the number of particles released after exhaust gas scrubbing. When compared to using refined fuel, such as MGO, exhaust gas scrubber installation and operation on ships is generally a more interesting alternative. (Winnes et al., 2020, p.1.)

2.2 Local and regional laws

In spite the effort of installing scrubber system, the discharge of wash water from open loop scrubber is banned or restricted from several coastal states and ports that established their own requirements. As of this moment, those ports, states, and areas are recognized to have local laws controlling the release of exhaust gas scrubber wash water. Below lays some several areas though it shouldn't be assumed that the list is complete.

The Belgium federal law states that the discharge of wash water should only be done from a distance of at least three nautical miles away offshore, both in coastal waters and open waters. The EU Water Framework Directive goals that were set in 2016 cannot be compromised by discharges. Ports and inland waters are off limits to discharges states the Flemish regional law 26/3/176. From the date of 1 January 2019, the discharge of wash water from scrubbers has been forbidden in China’s inland emission control areas (ECAs), Bohai Bay waters and port water areas of coastal domestic ECAs in compliance with the Ministry of Transport's (MOT) "Notice on Regulating the Implementation of Supervision and Management of Ship Air Pollutant Emission Control Areas." (Tachera, 2013.)

Germany inlands waterways such as canals, Rhine and ports within inland waterways are prohibited from discharge in agreement with Articles 1 and 3 of the CDNI Convention. (Carlos, 2019.)

In 2018, the Ireland Port of Dublin had published the Notice to Mariners No.37, stating the prohibition on the discharge of exhaust gas scrubber wash water and further explaining how the banning of wash water discharge in waters under Dublin port jurisdiction. Dublin port jurisdiction extends to the waters east of the Matt Talbot Memorial Bridge, extending through the North and

South Burford buoys, Sorrento Point, and a line from the Baily Lighthouse. (Carlos, 2019.)

The USA has several states that have local strict laws too, discharge limits for scrubber wash water are covered by section 2.2.26 of the 2013 Vessel General Permit (VGP), which is somehow different from the IMO MEPC 259(68) guidelines. One of the differences is that the wash water discharged must have a pH of at least 6.0 and this is measured when the ship discharges overboard. (Tachera, 2013.)

California the USA state in order to complying with air emissions regulations, California Air Resource Board (CARB) has forbidden the use of scrubbers within 24 nautical miles of the California coast. In January 2020, CARB MN 2020-1 was published as a requirement reminder. Hawaii, referring to Section 6.7 of the 2013 VGP, wash water discharge in Hawaii is permitted under the conditional section 401 WQC (Water Quality Certification), providing that specific requirements indicated in the similar section of the 2013 VGP are fulfilled. (Damgaard, 2020.)

In areas where the discharge of wash water is prohibited, the vessel crew have to make sure that the sulphur limits are met. As an alternative to the use of open scrubber, compliant fuel is suggested to be used or conversion of an open loop to a close loop system or a hybrid system is recommended or otherwise operators can choose to operate in close loop mode system only.

Any switchover needs to be completed well before the vessel enters any areas where there are limitations on wash water discharges or restrictions. This will make it easier to spot any operational problems that may arise after the switchover and give you enough time to fix them before the vessel arrives.

2.3 Verification of the Exhaust gas scrubber (EGS) certification

For EGCS technology there are guidelines allow for two certification schemes (A and B). There are three methods of approval under scheme A which are unit approval, production range approval, and approval for specially manufactured units. The fundamental of all these three technics is the initial certification of emissions reduction performance, daily exhaust gas emission inspections, and in conjunctive with the ongoing operational parameter monitoring. The exhaust gas cleaning scrubber must be verified first that it fulfils the emissions limit value (also known as the "Certified Value") when performing continuously on fuel oils with the maximum sulphur content allowed by the manufacturer for a range of specific operating parameters in order for it to be approved. The unit's minimum exhaust gas mass flow rate must also be specified, and any deviation from these parameters or any combination of variations from them should ensure that the unit will not surpass the Certified Value. (Fernandez & Sarkar,2021.)

Initial certification is not necessary for the EGC unit to be approved under Scheme B. However, the system must be able to monitor exhaust gas emissions continuously and confirming operating parameters on a daily basis proving that it complies with Annex VI regulation 14 and then the unit will be approved under Scheme B. A Sox Emission Compliance Plan (SECP) that has been approved should be carried on every on-board vessel that has an EGC unit. If the unit is approved under Scheme A, the affirmative Administration should also provide a SOx Emissions Compliance Certificate (SECC) to it. The EGCS Technical Manual, Scheme A (ETM-A) or Scheme B (ETM-B), the Onboard Monitoring Manual (OMM), and an EGC Record Book should also be contained with every permitted EGC unit. (Fernandez & Sarkar,2021.)

3 MARINE FUELS

3.1 Diverse characteristics and varying sulfur content of marine fuel

When it comes to maritime operations, the selection of marine fuel contains a significant influence on environmental impact, vessel performance, and regulatory compliance. The choosing of a suitable marine fuel is becoming more important as the shipping industry deals with heightening evolving of environmental concerns and more demanding emissions regulations. The difference of sulphur content in each fuel type is necessary to this analysis because sulphur emissions currently contribute to serious risks to the environment and human health, including the development of acid rain and respiratory conditions. The marine fuels category is made up of a diverse variety of options, each with its individual qualities and implications. Marine fuel comes in the following main types: Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Liquefied Natural Gas (LNG), Low-Sulfur Fuel Oil (LSFO), and Very Low-Sulfur Fuel Oil (VLSFO). (Vedachalam et al., 2022.)

When crude oil is distilled it produces a residual fuel called heavy fuel oil (HFO), which has been commonly used widely in maritime industry operations. HFO is generally known for its high sulphur content, usually between 2.0% and 3.5%, being sticky, high viscosity, and having a high density. It has a long history of being a cost-effective choice for ship propulsion. Marine Gas Oil (MGO) is recognized for having a greater combustion characteristic as a result of its lowered viscosity and density as well as for consisting of a sulphur content that is normally less than 0.10%. Marine Diesel Oil (MDO) is similar to marine gas oil based on specific characteristics. In comparison to heavy fuel oil, marine diesel oil has better combustion characteristics and a lower sulphur content (0.10%). MDO is used in several different maritime applications, from main engine propulsion to auxiliary power generation. Emission control regulations are met by MGO and MDO because they are refined to meet strict marine fuel specifications. (Bilgili, 2021.)

The implementation of the International Maritime Organization's (IMO) sulphur emission regulations made low-sulfur fuel oil towards becoming a popular adaptation choice for vessel operators to comply with the regulations. In comparison to heavy fuel oil, LSFO has a substantially lower sulphur content, ranging between 0.50 to 1.0%. Ultra Low-Sulfur Fuel Oil (ULSFO) and Very Low-Sulfur Fuel Oil (VLSFO) both met IMO sulfur emission regulations, with ULSFO containing a sulphur content of 0.10% or less and VLSFO typically containing less than 0.50%. (Sulphur in marine fuels, 2012.)

Liquefied Natural Gas (LNG) is a natural gas mainly composed of methane which burns cleanly. In pure form, LNG is odourless, clear, non-corrosive and non-toxic. It consists of lesser emissions of sulphur, particulate matter, and greenhouse gases. LNG is defined by its methane content and needs some special technical handling and storage infrastructure. Liquefied natural gas is a practical replacement for traditional marine fuels as it has several positive environmental effects. LNG is approximately totally free of sulphur because of its extremely low sulphur content, which is usually less than 0.004%. (Wankhede, 2020.)

LNG is becoming more and more popular because it emits fewer emissions than ordinary marine fuels like diesel and heavy fuel oil. LNG contributes to better air quality and compliance with environmental regulations, especially the IMO 2020 sulphur regulations, by producing less pollutants like sulphur oxides and particulate matter. Furthermore, as contractions for LNG production, storage, and distribution develops further, it’s likely that its availability will arise. Although LNG is viewed as the "future fuel" for the shipping industry, the sector has not yet adapted to this development, so marine gas oil continues to be the most popular clean fuel used on ships. (Vermeire, 2021.)

Ships with huge loads require regular fuel burns from their large marine engines. It is well known that these engines use low grade fuel to reduce ship operating expenses, as it is less expensive fuel compared to low-sulphur high-quality distillate fuels thus exhaust gas scrubbers are primarily installed on ships using heavy fuel oil (HFO). (Wankhede, 2020.)

4 GENERAL KNOWLEDGE OF EXHAUST SCRUBBER

4.1 Varieties of exhaust scrubber system

There are two types of industrial scrubbers, dry and wet. Knowing the difference between wet and dry scrubbers is important. Although dry scrubbers generally cannot remove pollutants to the same extent as wet scrubbers, they are an excellent choice for applications in facilities without the need of infrastructure to handle produced wastewater.

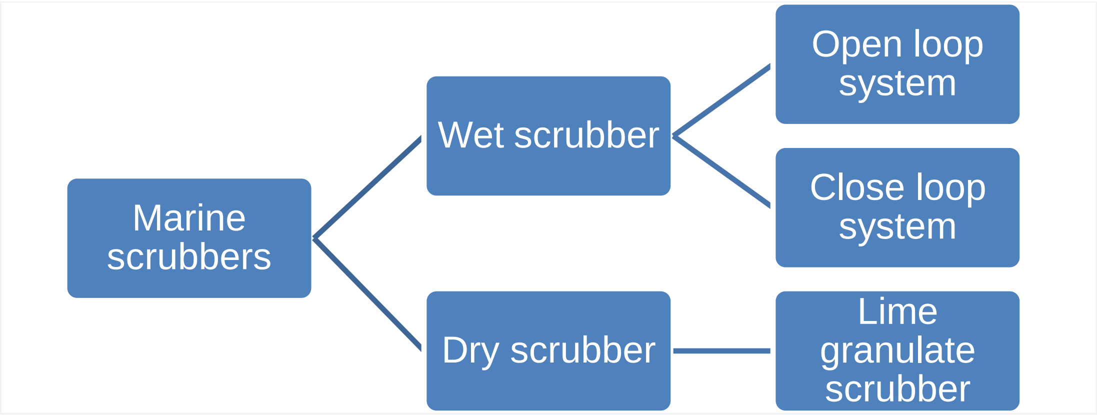

Fig 1: Classification of exhaust scrubbers (Shaketange, 2023)

4.2 Dry scrubber system

Dry scrubber system is an air pollution control device used to extract pollutants from industrial exhaust gases, this system is also called a dry sorbent system. As an alternative to liquid, sodium bicarbonate or lime are examples of dry sorbents that are injected into the gas stream in a dry scrubber. The removal of pollutants from exhaust gases is not done by liquid. However, by passing the gas through the sorbent dust to maximise binding, acid is removed from gas. They do this by using a dry reaction material known as sorbent, such as alkaline slurry. They are used in many industries to comply with environmental regulations and are especially useful for reducing acid gases (What is a dry scrubber, and how does it work, 2019.)

The sorbent particles are finely grinded in order to increase the surface area as well as the removal efficiency. When the sorbent particles are finely grinded, they make it easier to spread uniformly through the gas stream. The dry sorbent meets the contaminants in the gas stream. Pollutants are absorbed into the sorbent particles or adsorbed onto the surface of the sorbent, depending on the type of sorbent and pollutants in use. The combination of the sorbent and pollutants creates fewer toxic compounds during the chemical reaction. For example, when sulphur dioxide and lime react, they produce calcium sulphate. The cleaned gas is released into the atmosphere with lower pollutants. (What is a dry scrubber, and how does it work, 2019.)

There are two types of particulate control devices that are used to capture dirty sorbent particles, the baghouse and the electrostatic precipitation. The baghouse filter has filter sleeves or fabric bags that traps the particulate matter as the gas flows through the bags while the electrostatic precipitator collects the dirty sorbent particles from the gas stream by using electrostatic forces. Particles are charged as they pass through the ionization zone and then the charged particles are attracted to the oppositely charged collection electrode where they can be removed from. Relying on the system design, the sorbent might be recycled after capturing pollutants or disposed of as waste. Sorbent recycling can reduce operating costs. Constant monitoring of the dry scrubber's performance is important to ensure effectiveness, parameters like sorbent injection rates and gas flow rates are monitored and adjusted as necessary. (Sethi, 2021.)

4.3 Wet scrubber system

A wet scrubber system is another kind of air pollution control device designed to remove pollutants from exhaust gases. It operates by introducing liquid either sea water or fresh water with chemical additives into the exhaust stream to trap and neutralize pollutants. (Hesketh & Schifftner, 2017.)

The pollutants are either neutralized by sea water or chemicals known as sorbents or reagents resulting in cleaner emissions. Wet scrubbers are commonly used to control particulate matter, sulfur dioxide, and other harmful substances, contributing to environmental protection and compliance with air quality regulations. (Yildrimi, 2021.)

The exhaust gas is introduced into the wet scrubber system, where it meets the liquid scrubbing solution that might contain chemicals that improves the absorption or neutralisation of pollutant or seawater. This contact occurs through spray nozzles as the pollutants in the gas stream make contact with the added liquid, pollutants stick to the liquid droplets whereupon pollutants dissolve into the scrubbing liquid. (Babicz , 2015, p.161.)

Less toxic compounds are produced as a result of the reaction that occurs between the chemicals that are in the cleaning liquid with the pollutants. Sulphates are created when sulphur dioxide reacts with an alkaline solution. After the scrubbing, the liquid and gas are separated. After the gas has been purified it is then released into the atmosphere, the liquid that contains the pollutants is captured and it’s either disposed or recycled back into the scrubber. To ensure the system’s efficiency, the continuously observation of the scrubber’s performance is required. For excellent performance, parameters like liquid flow rates, temperature, and pressure must be regularly checked and adjusted. (Hee & Fisher,2023.)

The power input into a wet scrubber is often directly proportional to the amount of particulate matter the scrubber can collect. In addition, increasing the removal efficiencies the mist eliminator must be well-designed and well-functioning. Wet scrubbers are typically the only air pollution reduction system that removes both gases and particulate matter from a gas stream. Wet scrubbers are adjustable and has various design that are widely used in maritime industry to comply with environmental regulations and reduce the impact of toxic gasses emissions. (O’Donnell, 2021.)

5 SELECTING AND RETROFITTING SCRUBBER SYSTEM

5.1 Factors to consider

A cost- benefit analysis is a good starting point before installing the scrubber system. Ship owners have to analyse this to determine if the installation will save money or whether using low sulphur fuel will be much safer as it will never result in fines for breaking emissions regulations. Considering factors such as initial investment, fuel consumption and ongoing maintenance is important during the evaluation process of buying, running, and installing the scrubber system. (Considerations for scrubber retrofitting, 2019.)

Exhaust gases are cleaned by the scrubber system prior to their release into the atmosphere for this reason Sox emission is reduced. The chosen scrubber has to meet the emissions standards that are applicable to the ships trading or operating region, such standards are different on the basis of international, national, or local laws. Fuel’s sulphur content and administration demands on emission restrictions should be taken into account. Adhering to all applicable laws and regulations namely emissions control regulation, flag states, and classification society standards it is essential when retrofitting or installing scrubbers. (Bhonsle, 2023.)

Factors such as voyage routes, fuel availability are beneficial to be considered in the ship's operational profile. The scrubber system should be competent to effectively reduce emissions under a diversity of operating conditions, such as varying engine loads and fuel types. Explore the different scrubber technologies that are available, such as hybrid, closed-loop, and open-loop systems and their space requirements, operational complexity, and environmental impact, because each type has benefit and limitations. Select the design that mostly fit the special needs and limitations of the ship. Foreseeing future changes to emissions regulation or technological breakthroughs that could impact the scrubber system's validity or compliance is a good strategy. Select or install a design which is flexible to accommodate upgrades or modifications as necessary in the future. (Retrofitting SOx scrubbers with confidence, 2023.)

Existing ships have crowded engine rooms or tight compartments, limiting availability space for retrofitting scrubber systems. Finding suitable locations for scrubber units and associated equipment might be challenging. It is beneficial to ensure that all necessary safety precautions and clearing of the area where the scrubber will be installed is taken care of. When evaluating the space that can be used to install the scrubber system on the ship, the scrubber unit itself as well as related equipment like pumps, tanks, and piping should be taken into consideration. Elements to consider consists of the unit’s arrangement, unit’s dimensions, maintenance accessibility, and any possible challenges with other onboard systems or infrastructure. The selected scrubber must fit within the available space without obstructing other crucial systems or operations. (Retrofitting a scrubber shipowner’ s experience, 2014.)

The type of engine used on the ship will influence the design and operation of the scrubber. Different exhaust gas compositions and temperatures produced by different types of engines will influence the selection of scrubber technology. When retrofitting the unit, verify that the materials used in construction, engine type, exhaust gas temperature, and scrubber system are all corresponding with the ship's current exhaust system. Determine the power requirements for the scrubber's operation, in consideration of electrical connections and any additional onboard power generation capacity. Select the suitable type and size of scrubber according to the ship's engine type, emissions regulations, and operational requirements. (Exhaust gas emissions from ships, n.d.)

Retrofitting scrubbers involves the combining of the new equipment with existing systems, including engines, exhaust gas boilers, and auxiliary machinery. Retrofitting scrubbers generally requires structural modifications to the ship's existing exhaust system, including the modifications of piping, support structures, and ducting. It could be challenging to ensure compatibility and structural perfection when making these developments. The scrubber unit is expected to be mounted on to the acknowledged position, which is normally close to the ship's exhaust funnel or stack. This process involves welding or tightening the unit firmly in place with bolts. All the required electrical connections for control systems should be done and connect the scrubber to the ship's exhaust system, including the inlet and outlet piping. Scrubber retrofitting can result in difficulties with other equipment or systems on board, including deck machinery, fuel tanks, and cargo holds. Ensuring excellent coordination and compatibility between old and new components requires a careful planning and arrangement. Maintaining the ease of access and functionality of other systems requires the reducing of interference and better ensuring layout. (Karatuğ et al., 2022.)

Select a reputable manufacturer or supplier for the scrubber system, considering factors such as technical support, reliability, availability of spare parts, and warranty coverage. The installation should be conducted by qualified personnel with experience in exhaust gas cleaning systems and marine engineering or any relevant specialised field. It is necessary to hire a specialised installation company or working closely with the technical team of the scrubber manufacturer for quality assurance, safety consideration, trouble shooting and problem-solving expertise. Make sure that everyone on the crew who will be participating in the installation or operation of the scrubber is well trained, and that all the equipment is handled safely, and that safety procedures are followed throughout the installation process. (SAFETY4SEA, 2020.)

Provide training to ship crew members on scrubber operation and maintenance after the scrubber has been successfully tested and put into operation mode. Ensure that the scrubber system is operating correctly and adhering to emissions regulations by carefully testing it.

6 OPERATIONAL OF DIFFERENT WET SCRUBBER DESIGN

6.1 Open loop system

An open-loop scrubber system is a type of exhaust gas cleaning system used on ships to reduce air pollution by removing pollutants from the ship's engine exhaust. Sea water performs as the scrubbing medium since this design doesn’t need any chemical addition to neutralize sulfur from exhaust gases. The seawater alkalinity is used in the scrubber to treat the exhaust stream from the engine or boiler. This seawater's volume is determined by the power output and engine's size. (Saraogi, 2020.)

In an open-loop scrubber, seawater is used as the scrubbing medium. The system draws seawater from the sea and directs it into the scrubber. The seawater is introduced at the top of the scrubber through spraying nozzles, this results in an equally distributed spray pattern all over the scrubber or circulated through the exhaust gas flow in the scrubber tower. (Scrubbers at glance, 2018.)

Exhaust gases enter from the bottom side of the scrubber tower and the seawater is sprayed through the system’s nozzles. Chemical reaction occurs as the exhaust gases come into contact with the seawater. Sulphur particles in the exhaust gas dissolves into the water droplets under the right temperature and process conditions, initially neutralizing sulfur dioxide (SO2) in the exhaust. Sulfuric acid (H2SO4) is then formed as a chemical reaction product between sea water and sulfur dioxide. Sulfuric acid is less toxic compared to SO2 and soluble in water. During this dissolution process, water is acidified. (Comer, 2020.)

However, the acid is naturally neutralized by the alkaline properties of seawater, reducing its overall effect on the marine environment. The byproducts, which include sulfates, are then discharged back into the sea including with the treated seawater.

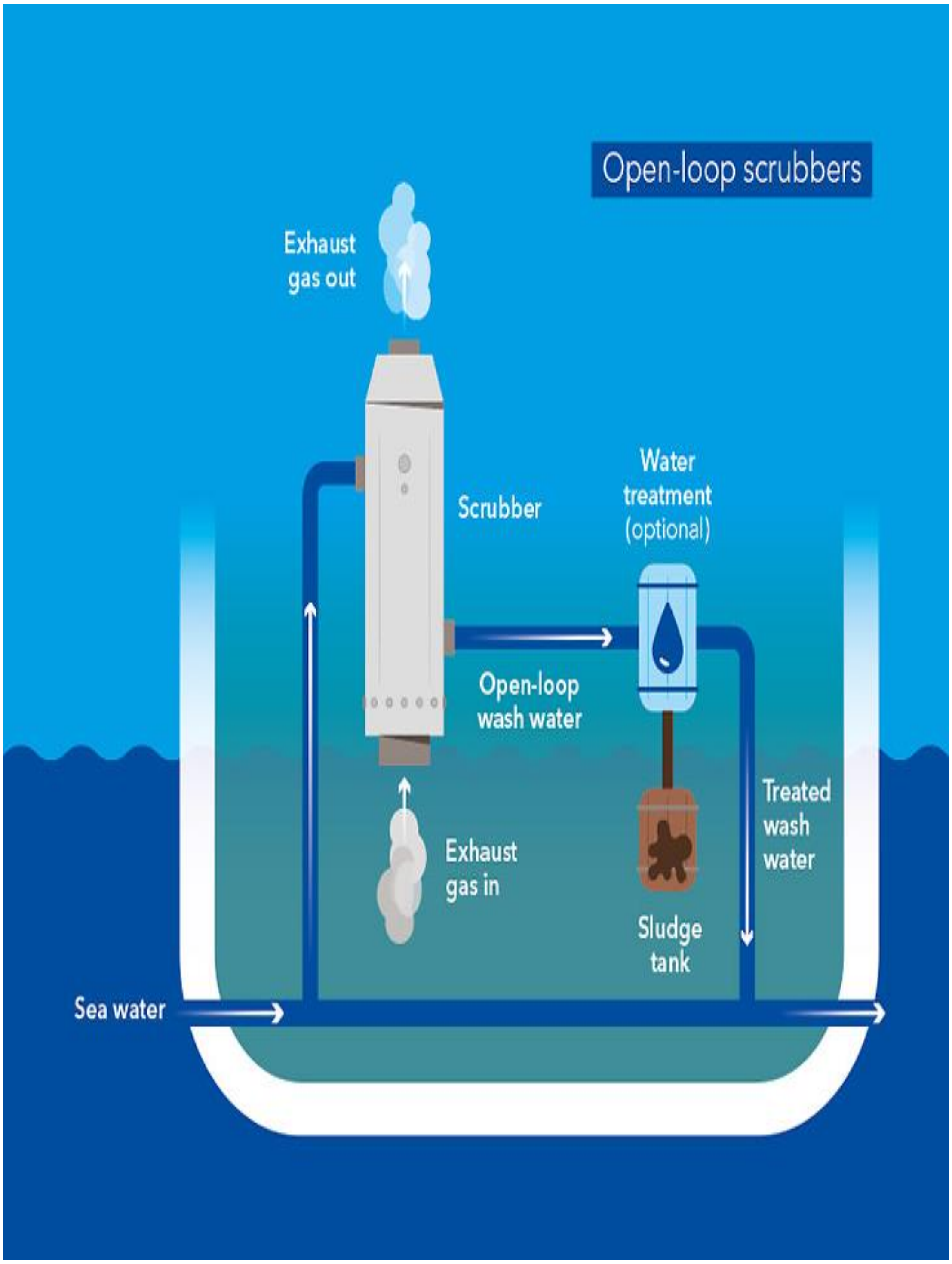

Figure 2: Open loop scrubber system (Scrubbers at glance, 2018)

The sulfur dioxide, particulate matter and other pollutants are removed or highly reduced in the scrubbing process. The cleaned exhaust gases are then released into the atmosphere, acknowledging the emission regulations. The system is equipped with monitoring devices to ensure compliance with environmental regulations. Factors such as scrubber efficiency, seawater pH, and discharge water quality those are the parameters that are continuously monitored. (Raunek,2013.)

There are a few benefits to this design, including its low number of moving parts and ease of installation on board. Low number of moving parts and soothe installation on board are some of the few advantages of this type of design. This design does not need chemical handling or storage and it is cost effective. Minimal maintenance is needed for the system, aside from de-fouling and operational checks. Waste materials do not need to be collected with this system. (Evans, 2015.)

The inability to use open loop wet scrubber systems in all situations as it depends on the alkalinity of the sea water available for effective operation, which causes challenges with exhaust gas cooling. Brackish or fresh water has deficiency of natural alkalinity, and thus the open loop scrubbers do not function well with them. Open loop scrubbers perform sufficiently with the natural alkalinity of seawater because of this, zones with lower salinity levels like the Baltic Sea, and areas near the land are not viewed to be appropriate locations for open loop scrubber’s operations. The effective cleaning requires a very large volume of sea water, thus the system uses a lot of power. (Moe,2020.)

Concerns have been raised about the environmental impact of discharging wastewater containing sulphate into the sea. As a result, some regions have enforced restrictions on the use of open-loop scrubbers, suggesting the maritime industry to explore alternative solutions resulting in low sulfur fuel to be used in ports and ECA zones. (Andersson, et al., 2021, p.150.)

6.2 Close loop system

The operating principles of close loop system is similar to those of the open loop system, besides that the scrubbing media in this design is fresh water treated with a chemical generally sodium hydroxide (NaOH) rather than seawater. The scrubbing liquid is introduced or sprayed into the exhaust gas flow in the scrubber tower via spray nozzles. As the exhaust gases come into contact with the liquid, pollutants like sulfur dioxide (SO2) are absorbed and neutralized during the process. The exhaust gas stream's SOx are then converted into sodium sulphate, which is harmless. (Dey, 2021.)

As the scrubbing liquid and exhaust gas mix, pollutants are captured, this mixture is then collected and directed to a closed-loop system. Wastewater is then settled in the process tank to separate heavier particles and reducing turbidity. Removal of particulate matter and other suspended solids or contaminants is done through several filtration processes. In the closed-loop design system, scrubbing liquid is recycled. A process tank is used to clean the waste wash water from a closed loop scrubber system before it is recirculated for use. The collected scrubbing liquid is then treated to neutralize and remove the trapped pollutants. This frequently involves chemical techniques to convert pollutants into least dangerous substances. (Babicz, 2015, p.163.)

After pumping water into a process tank, alkalis like sodium hydroxide (NaOH), commonly known as caustic soda or magnesium hydroxide (MgOH), is added to increase the pH (alkalinity) of the water and the dosage can be in line prior to the scrubber. The alkaline chemical in the water absorbs the acidic components from the exhaust gases reducing sulfur emission. During this process, the contaminated dissolved pollutants called scrubber slurry is collected at the bottom of scrubber chamber and goes to the process tank for further treatment. No additional chemicals are necessary to neutralise the scrubber wash water beside this alkaline solution. (Babicz, 2015, p.163.)

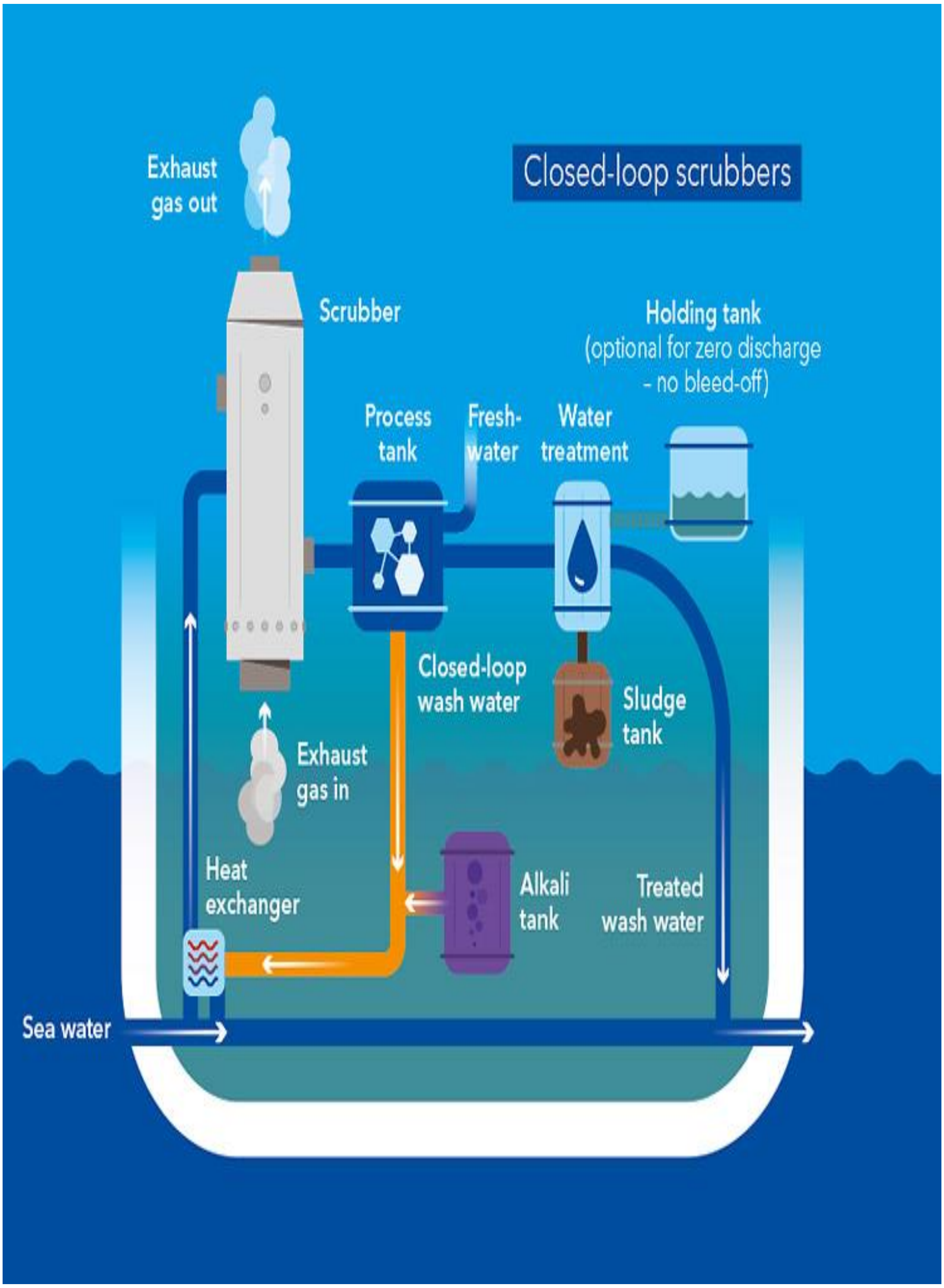

Figure 3: Close loop scrubber system (Scrubbers at glance, 2018)

The slurry is then treated by adjusting the pH levels as well removing impurities. After treatment, the cleaned treated slurry is recirculated back into the scrubber system, concluding the closed-loop cycle. This closed-loop design reduces the need for constant refilling of the scrubbing medium. To ensure that the system compliance with emission regulations, continuous monitoring is required. Small amounts of wash water are regularly removed and transferred to holding tanks where fresh water is added, this prevents the building up of sodium sulphate in the system. Parameters such as scrubber efficiency, liquid quality, and system performance are carefully monitored. (Dey, 2021.)

The closed-loop scrubber is more energy efficient as it uses nearly half as much wash water as an open-loop system. The recirculating of slurry reduces water consumption. It requires very little upkeep, and its operation doesn't depend on the vessel's operating conditions. This design is flexible, and the unit can operate sufficiently with various fuels without breaking any regulations. No switching of fuel is done when operating in ECA’s. No discharge of wash water to sea or introducing pollutants to sea such as metals as the system is a closed loop. (Jee, 2022.)

However, challenges include space requirement, there is a need for storage and treatment of the collected pollutants within the closed-loop system. Large storage spaces are needed for filters, pumps, and process or buffer tank as well as all the equipment that are connected with the treating and recirculation of slurry. A storage tank is used regulate the temperature of sodium hydroxide between 20 ºC and 50 ºC, which is generally used as a 50% liquid solution. Due to the alkaline chemicals presents in the system, piping and tanks have high potential to scaling or corrosion. Furthermore, this system requires often maintenance replacing of filters as well as the monitoring of chemical dosing, system performance and cleaning liquid quality. (Sargun, 2021.)

Scrubber sludge contains soot and contaminants that are extracted from the exhaust gas as well as oil compound from the combustion unit. This sludge is then collected is then secured for onshore disposal. As a result, a ship should have enough facilities for handling and storing sludge while waiting for removal. The sludge has to be drained using a filter press thus reducing weight, as well as helping with the separation of liquid from solid, reducing handling costs during the solid disposal. The wash water is then recirculated back into the system for further treatment. (Gerwick, 2007.)

Closed loop scrubber is regarded as a preferred design, especially in ECAs where the discharge of wastewater is prohibited. This system offers more manageable and controlled operating method compared to open loop systems.

6.3 Hybrid loop system

A hybrid scrubber system design, is a combination of both open loop scrubber and close loop scrubber, enabling it to be adjustable and easily adapting to changeable environmental regulations and operating requirements. Ship operators are required to changeover between these two modes. This flexibility makes it easier to transit from open loop mode to closed loop mode in regions where the use of open loop scrubber is prohibited. No need to burn or spend money on low sulfur fuel as high sulfur content fuel can generally be used without any issue as the system offers both modes. (Jee, 2022.)

Open-loop mode: Seawater is used as a scrubbing medium due to its natural alkalinity, sulfur in the exhaust gas is neutralized. Seawater is obtained from the ship’s sea chest and pumped into the system using sea water pumps as well as the booster pumps. Harmful contaminants are eliminated during the scrubbing process. The byproducts such as sulphates are then dumped into the sea. During the open loop mode, the system operates like an ordinary open-loop scrubber system. (Comer, 2020.)

Closed-loop mode: An alkaline chemical solution is used as a scrubbing medium. Sulfur is then neutralized from the gas stream. Pollutants are removed from the system as the scrubbing liquid circulate within the system. The solution with pollutants is then collected and treated and recirculated. No sea discharges are done in this mode. During the closed loop mode, the system operates like an ordinary closed-loop scrubber system. (Jee, 2022.)

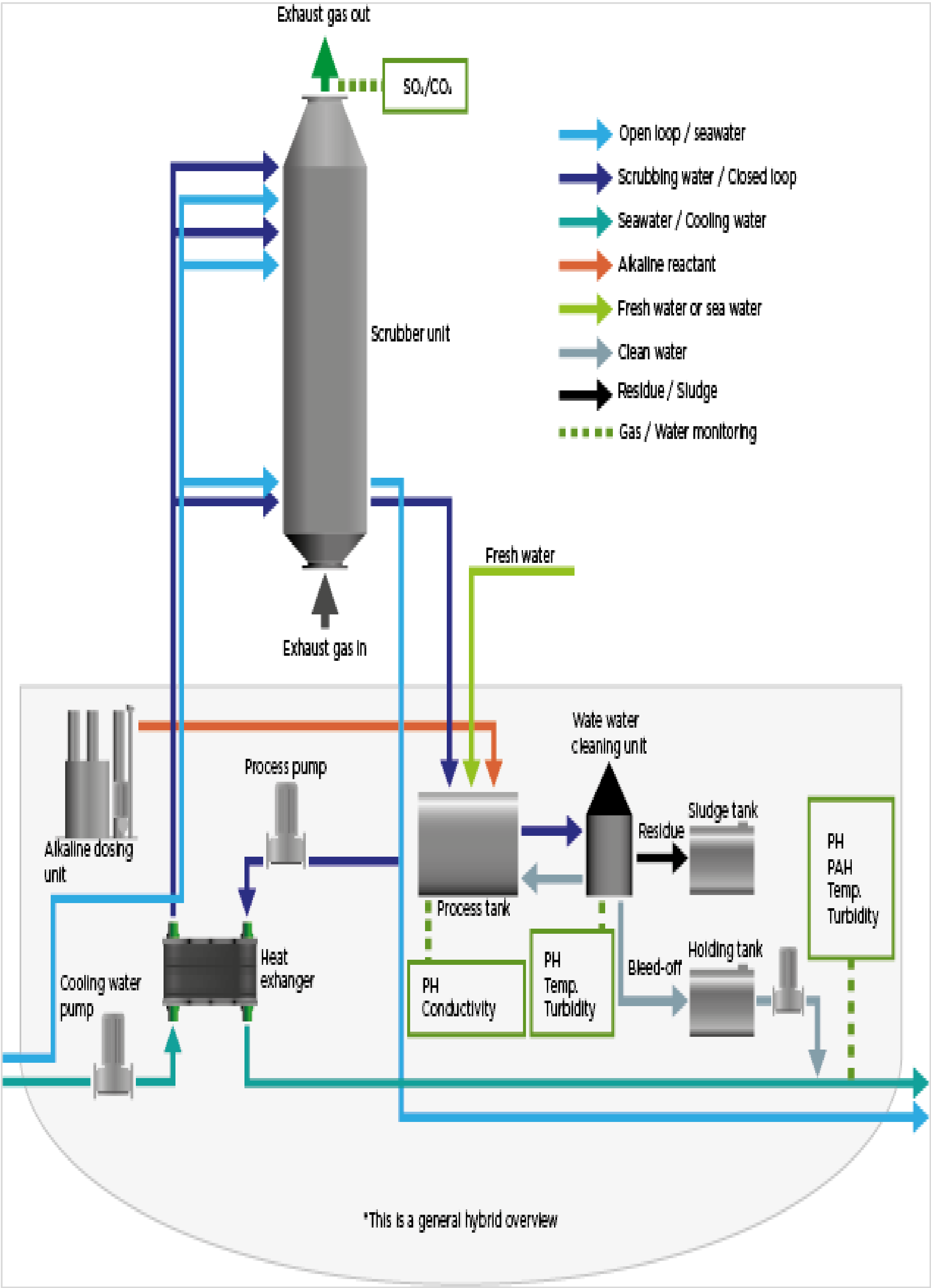

Figure 4: Hybrid loop system (ME production, n.d.)

After scrubbing, the treated gas is separated from the scrubbing solution. The contaminated scrubbing solution is treated to remove or neutralize the captured contaminants. The process involves filtration, chemical treatment, and settling to separate the pollutants from the solution. The contaminated scrubbing solution, now containing captured pollutants, is collected at the bottom of the scrubber unit. The scrubbing solution with pollutants go through settling process to remove any remaining suspended solids and the sludge collected on the bottom of the tank goes to the sludge tank which part of the system, where it is then collected and kept in plastics for offshore disposal. Adjustments of the pH are done by balancing the acidity or alkalinity of the solution by dosing in alkaline solution into the process tank. The alkaline dosing in this system is automatically controlled with relation to the results the system gets from measuring the pH process water before the scrubber water inlet. The treated scrubbing solution is then pumped through a heat exchanger, whereby sea water is used as a cooling agent and back to the scrubber tower. The treated scrubbing solution is then recirculated back into the scrubber system for reuse. (Hybrid scrubbers, n.d.)

Transition between the two modes: The switching of modes basically between open and closed loop are manually or automatically done by responsible crew ship members. This change is done prior entering locations with strict environmental regulations especially the banning of waste wash discharge.
This system made it easier to comply with all emission regulations. During port stay or operating in ECAs zones, closed loop mode is used and open loop mode is used at sea. Although the installation of the hybrid system is expensive, the system can operate on cheap fuel or low-grade fuels for longer period without breaking any regulation. However, due to more structural modifications, the system requires large amounts of storage space for chemicals and additives as well as tanks and pumps. (Hutchinson & Ravel, 2020.)

The hybrid system requires constant or carefully monitoring of liquid quality, system efficiency and, system performance to ensure compliance with emission regulations regardless of the mode of operation. The system has high risk of fouling and corrosive pipes.

7 ENVIRONMENTAL IMPACTS OF EXHAUST SCRUBBER SYSTEM

7.1 Exhaust gases

The burning of fuel in marine engines and boilers produces exhaust gas from ships, sometimes referred to as ship emissions. In addition to greenhouse gases and other pollutants, these emissions also contribute to air pollution and climate change. Ship exhaust gas usually consists of the following components water vapor (H2O), nitrogen oxides (NOx), sulfur dioxide (Sox), volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO2), and particulate matter (PM). (Bhonsle, 2023.)

Water vapour is created when hydrogen in fuel and oxygen burns. It is regarded as the good component because it plays a role in the water cycle particularly the formation of clouds. Nitrogen oxides (NOx) and Nitrogen monoxide are produced when oxygen and nitrogen in fuel react or burn during combustion at high temperature. The presence of these products (Nitrogen oxides (NOx) and Nitrogen monoxide), are associated with air pollution, acid rain, smog formation as well as respiratory health issues. Marine fuel consists of sulfur, and the burning of these fuels results in the production of sulphur dioxide which is the main source of acid rain, air pollution, climate change and breathing problems to living organisms. (Agarwal, 2022.)

Volatile organic compounds (VOCs) are formed from the products released from fuel combustion and other pollutants particles that had evaporated in the atmosphere. Concerns have been raised on health-related issues associated with VOCs, as it degrades the air quality. Particulate matter (PM) is made up of small particles such as soot, ash, and unburned hydrocarbons that are eliminated from ships as part of exhaust gas. VOCs is harmful as it also devalues air quality, worsening respiratory system as well as causing conditions affecting the blood vessels and heart related diseases in human. (Zhao et al., 2021.)

The incomplete burning of fuels containing carbon resulting in the production of carbon monoxide (CO). CO is a poisonous or hazardous gas, and it is a contributing factor to air pollution and health related issues of which high presents of CO can cause death. In addition, fuels containing carbon also produce carbon dioxide (CO2). CO2 is a greenhouse gas that contributes to global warming as well as climate change because it traps heat in the atmosphere. (Agarwal, 2022.)

All the above-mentioned elements of exhaust gas, has the ability to change based on the ship’s operating environment, emissions control protocols and fuel type. Sulphur, nitrogen, and particulate matter emissions can actually be controlled through using high grade fuel, fuel switching, and exhaust gas cleaning systems.

7.2 Air pollution reduction

Fuel sulphur content is reduced from 3.5% to 0.1% with a SOx reduction efficiency of 97.15% by using the exhaust cleaning scrubber system. The effectiveness of scrubber in reduction of Sox emissions is directly related to factors such as type of fuel being used and the ship’s operating conditions to say the least. Ships that use HFO with 2.6% sulphur content with scrubbers, they typically emit 31% less SO2 than ships using 0.07% sulphur MGO. Particulate matter emissions are almost 70% higher when using HFO with a scrubber rather than MGO. The emission of black carbon is increased by 81% when using HFO with a scrubber in medium speed engines instead of MGO. (Moldanová et al., 2020.)

Therefore, when it comes to lowering overall air pollution emissions, scrubbers are not as effective as using MGO or ULSF, however scrubbers have successfully been effective in reduction emissions of sulfur, nitrogen, and particulate matter. In addition, the use of HFO with a scrubber result in 1.1% higher life-cycle CO2 emissions than MGO, despite HFO having lower severe emissions. Comparing the emissions of carbon dioxide (CO2) between HFO with a scrubber and MGO, emissions are 4% higher in HFO. (Osipova et al., 2020.)

7.3 Water pollution

Scrubber discharge water from open loop design affects the sea living organisms. Generally marine organisms are harmed by too high or too low intensive changes of water pH level for example shellfish are harmed when the pH is too acidic or more alkaline, this negatively interrupt the balance of marine ecosystems. Metals like nickel, lead, and copper are deposited into the sea being part of the discharge. The scrubbing sea water gain energy from the hot exhaust gases resulting in raising temperature, this warm water is then discharged overboard causing thermal shock to the organisms as well as affecting the thermal balance of the sea. Long run of scrubber water discharge into sea in due time may cause DNA mutation in sea organisms as well as their behaviours. These extended exposures will leave sensitive various species stressed or harmed. (Moldanová et al., 2020.)

Monitoring the temperature and PH of wash water discharge is essential to reduce the negative impact that it will or has on the marine ecosystem. Therefore, IMO Guidelines set a pH limit of 6.5 for wash water and must not exceed a temperature of 60°C. (Moldanová et al., 2020.)

Turbidity is referred to as how optical or clear the water is. Turbidity in exhaust scrubber wash water is very high due to washing down of exhaust gas ashes and suspended sediments or particles. High turbidity at sea interrupts the ability of marine plants to photosynthesize as it reduces or blocks the amount of light that reaches the sea water as well as affecting the sight of some species. The presence of exhaust gas sediments in water has the ability to clog the fish’s gills, affecting their breathing. Turbidity levels should be monitored and controlled to avoid its negative effects on marine organisms. Reduce the number of suspended particles that are released into the wash water by using appropriate filtration or settling procedures in scrubber systems, according to the IMO, the discharge water's turbidity shouldn't be more than 25 FNUs higher than the inlet water's turbidity. (Comer, 2020.)

Polycyclic aromatic hydrocarbons (PAHs) in the wash water from exhaust scrubbers are harmful to marine life, contaminants are known to have dangerous or hazardous potential. PAHs accumulates in sediments after being discharged into the ocean, which has a number of negative consequences. The exposure to higher concentrations of PAHs, marine organisms will suffer negative consequences resulting in DNA damage, reproductive issues, and developmental abnormalities. Furthermore, PAHs have the ability to bioaccumulate in the food chain, endangering fish and marine mammals as well as other trophic. (Osipova et al., 2021.)

To reduce the release of PAHs and their effect on marine ecosystems, strict adherence to environmental regulations, efficient monitoring, and appropriate treatment of scrubber wash water are essential. (Osipova et al., 2021.)

By monitoring the pH, temperature, PAH, turbidity, and other parameters, the water monitoring unit installed in scrubbers guarantees compliance and consistent quality of the treated water. Vessels that violate the scrubber wash water discharge limitations may be subject to fines or denied access to ports.

8 MAINTENANCE OF SCRUBBER SYSTEM

8.1 Regularly upkeep

For a scrubber system to last a long time and function properly, maintenance is required. Regularly checks, cleaning of the filters and scrubbing media in an exhaust scrubber system is mandatory to keep it in good working order. Keeping eyes on the manufacturer's recommendations regarding the maintenance intervals and carrying out any suggested testing or calibration should always be done. To guarantee peak performance, look for leaks, keep an eye on fluid levels, and take quick action when necessary. Periodic maintenance helps in preventing malfunctions that could possibly directly endanger crew members. (Smith, 2020.)

Make routine visual inspections to spot any damage, corrosion, or wear. For effective pollutant removal, clean or replace the scrubbing media and filters in accordance with the manufacturer's recommendations. Inspect the spray nozzles, clean the scrubber's internal components, and regularly check the amount of scrubbing fluid and refill as necessary, ensure the appropriate addition concentration. (SOX SCRUBBER SYSTEMS, n.d.)

System updates are made when necessary to accommodate evolving needs. To confirm the system's functionality, calibrate it according to the manufacturer's instructions and conduct routine testing. Check the entire system for leaks and fix any problems right away to avoid contaminating the environment. Maintain thorough maintenance records that include the dates of all cleanings, repairs, and replacements. Crew members should be trained or should be familiar with the system as well as how to carry out routine maintenance and to report any irregularities right away. Crew members responsible for the system's operation should assure that the system complies with all applicable environmental laws. (Smith, 2020.)

9 CONCLUSION AND RECOMMENDATION

9.1 Final thoughts and practical advice

Considerably reducing the number of pollutants released into the atmosphere, the shipping industry's adoption of new emission reduction machinery, like scrubbers, has improved the environment. The effects of scrubber wash water discharge on marine chemistry, biodiversity, and biogeochemical processes, however, are not fully understood. Specifically, there is insufficient data regarding the volume and makeup of wash water discharge and the corresponding effects on marine life.

There are three different types of sulphur scrubbers designs mentioned in this thesis, that shipowners can choose one system to be installed on ships in order to reduce sulphur emissions. Open-loop scrubbers, which discharge both the washing water and the harmful substances it contains into the sea, closed-loop scrubbers, which wash exhaust gases and collect harmful substances in a tank that is emptied in port for appropriate further treatment, and hybrid scrubbers, which can operate in either an open or closed loop.

Although open-loop scrubbers reduce shipping emissions into the atmosphere and meet Sulphur directive requirements, their use leads to heavy metals and other pollutants, including sulphur, ending up in the sea with washing water. All these issues are heavily regulated by the IMO (IMO resolution MEPC.184 (59)), however pollution can still enter the sea despite the current controls. If hybrid scrubbers are used in an open-loop mode, they can also cause issues.

When taken as a whole, the closed-loop scrubber is the only one of these types that is truly environmentally friendly because it produces no emissions into the air or water as long as the waste is treated in ports after it is collected. The other alternative is the use of high-grade fuel which is drastically expensive.

10 REFERENCES

Sargun, S. (2021, March 22). A guide to scrubber system on ship. Retrieved from https://www.marineinsight.com/tech/scrubber-system-on-ship/

Winnes, H., Fridell, E., & Moldanova, J. (2020). Effects of marine exhaust gas scrubbers on gas and particle emissions. Marine science and engineering. Retrievedfromhttps://pdfs.semanticscholar.org/528b/ba49b130e681bdea7a44fe43b64b1e4f4dc5.pdf

Tachera, E.J. (2013). Marine environmental governance: International law to local practice. Taylor & Francis Ltd.

Carlos, C. (2019, February 25). Beware of local restrictions before discharging wash water from scrubbers. Euroshore. Retrieved from https://euroshore.com/blog/news/2019-02-25/beware-of-local-restrictions-discharging-wash

Damgaard, J. (2020, January 27). Britannia P&I. List of jurisdictions restricting or banning scrubber wash water discharges. Retrieved from https://britanniapandi.com/2020/01/list-of-jurisdictions-restricting-or-banning-scrubber-wash-water-discharges/

Babicz, J. (2015). Ship systems and machinery. Baobab Naval Consultancy.

Sethi, S. (2021, March 22). A guide to scrubber system on ship. Available https://www.marineinsight.com/tech/scrubber-system-on-ship/#:~:text=Dry%20scrubbers%20employ%20solid%20lime%20as%20the%20alkaline,into%20the%20exhaust%20gas%20for%20the%20same%20purpose.

Yildirim, O. (2021). Scrubber on marine vessels. Retrieved from https://www.adv-polymer.com/blog/scrubbers-on-marine-vessels

Hee, D. & Fisher, K. (2023, June 8). What is a wet scrubber. CECO environmental. Retrieved from https://www.cecoenviro.com/what-is-a-wet-scrubber/

Hesketh, D.H., & Schifftner, C.K. (2017). Wet scrubbers (2nd ed.). CRC Press.

Fernandez, A.E., & Sarkar, P.J. (2021). Marine environment protection systems. Shroff publishers & Distributor Pvt Ltd.

O'Donnell, D. (2021, November 22). Wet scrubber and industrial application. Senorex. Retrieved from https://sensorex.com/wet-scrubbers/

What is a dry scrubber, and how does it work. (2019, December 7). Retrieved from https://teral-aerotech.com/what-is-a-dry-scrubber-and-how-does-it-work/

Saraogi, V. (2020, January 8). The problem of ships using open-loop scrubbers. Ship technology. Retrieved from https://www.ship-technology.com/features/open-loop-scubbers/?cf-view&cf-closed

Scrubbers at glance. Maritime impacts. (2018, October 18). Retrieved from https://www.dnv.com/expert-story/maritime-impact/Scrubbers-at-a-glance.html

Evans, P. (2015). Density of metals: Density of common metals.

Osipova, L., Georgeff. E, & Comer. B. (2021, 29 April). Global scrubber washwater discharges under IMO's 2020 fuel sulfur limit. Retrieved from https://theicct.org/publication/global-scrubber-washwater-discharges-under-imos-2020-fuel-sulfur-limit/

Shaketange, O. (2023). Classification of exhaust scrubbers.

Moe, G. (2020, March 24) Onboard with marine scrubbers: Resilient solutions for lower emissions. Retrieved from https://nickelinstitute.org/en/blog/2020/march/onboard-with-marine-scrubbers/

Andersson, K., Jang, H., & Jeong, B. (2021). Life cycle and cost assessment of a marine scrubber installation. Journal of international maritime safety, environmental affairs, and shipping, 4(4), 162-176. https://doi.org/10.1080/25725084.2020.1861823

Comer., B. (2020, 18 June). Scrubber on ships: Time to close the open loop (hole). Retrieved from https://theicct.org/scrubbers-on-ships-time-to-close-the-open-loophole/

Raunek., K. (2013, 20 August). Video: Working of Wartsila open loop scrubber system. Retrieved from https://www.marineinsight.com/videos/video-working-of-wartsila-open-loop-scrubber-system/

Luostarinen, M. (2019). Exhaust Gas Cleaning Scrubbers [Bachelor's thesis, Satakunta University of Applied Sciences].

MEproduction: Scruber hybrid.Retrieved from https://meproduction.com/front-page/marine-exhaust-gas-scrubbers/hybrid-loop/

Dey, A., K. (2021). What are industrial scrubbers: Their working, types, and advantages. Retieved from https://whatispiping.com/industrial-scrubbers-types-dry-wet-scrubbers/?utm_content=cmp-true

Hutchinson, K., & Ravel, B. (2020). Meeting the material and coatings challenges posed by scrubbers. Retrieved from https://www.safinah-group.com/wp-content/uploads/2020/08/Meeting-Challenges-of-Scrubbers-%E2%80%93-Hutchinson-Ravel-%E2%80%93-Shiprepair-Maintenance-Q3-2020.pdf

Osipova, L., Georgeff. E, & Comer. B. (2020, 24 November). Air emissions and water pollution discharges from ships with scrubbers. Retrieved from https://theicct.org/publication/air-emissions-and-water-pollution-discharges-from-ships-with-scrubbers/

Smith, B., R. (2020). Monitoring wet scrubber performance. United States.

Moldanová, J., Fridell, E.& Winnes, H. (2020). Effects of marine exhaust gas scrubbers on gas and particle emissions. 8(4), 299. https://doi.org/10.3390/jmse8040299

Jee, J. (2022, 30 October). Hybrid multi-criteria decision-making for marine SOx scrubber systems. 10(11), https://doi.org/10.3390/jmse10111599

Gerwick, B.C. (2007). Construction of marine and offshore structures (Third edition). Tylor & Francis group.

IMARPOL ANNEX VI and NTC 2008 with Guidelines for implementation. (2013). IMO

SOX SCRUBBER SYSTEMS. (n.d.). Wartsila.com. Retrieved from https://www.wartsila.com/encyclopedia/term/sox-scrubber-systems

Wankhede, A. (2020, December 8). A Guide To Marine Gas Oil and LSFO Used On Ships. Retrieved from https://www.marineinsight.com/guidelines/a-guide-to-marine-gas-oil-and-lsfo-used-on-ships/

Vermeire, M., B. (2021, August). Marine products: Everything you need to know about marine fuels. Retrieved from https://www.chevronmarineproducts.com/content/dam/chevron-marine/fuelsbrochure/Chevron_Everything%20You%20Need%20To%20Know%20About%20Marine%20Fuels_v8-21_DESKTOP.pdf

Sulphur in marine fuels. (2012, 25 January). Transport and Environment. Retrieved from https://www.transportenvironment.org/discover/sulphur-marine-fuels/

Hybrid scrubbers. (n.d.). VDL AEC Maritime. https://www.vdlaecmaritime.com/sox-scrubbing/hybrid-scrubbers

Vedachalam, S., Baquerizo, N., & Dalai, A. K. (2022). Fuel: Review on impacts of low sulfur regulations on marine fuels and compliance options.310. https://doi.org/10.1016/j.fuel.2021.122243

Bilgili, L. (2021). Life cycle comparison of marine fuels for IMO 2020 Sulphur Cap. Science of the Total Environment, 774. https://doi.org/10.1016/j.scitotenv.2021.145719

SAFETY4SEA. (2020, April 7). Lessons learned from scrubber installation and operation. SAFETY4SEA. Retrieved from https://safety4sea.com/lessons-learned-from-scrubber-installation-and-operation/

Bhonsle, J. (2023, April 5). Marine Insight. Types of bunker/ scrubbers carriers can use to ensure compliance with international emission control regulations. Retrieved from https://www.marineinsight.com/environment/types-of-bunker-scrubbers-carriers-can-use-to-ensure-compliance-with-international-emission-control-regulations/

Considerations for scrubber retrofitting. (2019, January 29). Wilhelmsen. Retrieved from https://www.wilhelmsen.com/medianewsandevents/industryperspectives/2017/considerations-for-scrubber-retrofitting/

Retrofitting SOx scrubbers with confidence (2023, October 24). Seatrade Maritime. Retrieved from https://www.seatrade-maritime.com/regulation/retrofitting-sox-scrubbers-confidence

Karatuğ, Ç., Arslanoğlu, Y., & Soares, C. G. (2022). Feasibility analysis of the effects of scrubber installation on ships. Journal of Marine Science and Engineering, 10(12). https://doi.org/10.3390/jmse10121838

Retrofitting a scrubber shipowner’ s experience. (2014, April 29). SAFETY4SEA. Retrieved from https://safety4sea.com/retrofitting-a-scrubber-a-shipowner-s-experience/

EXHAUST GAS EMISSIONS FROM SHIPS. (n.d.). Wartsila.com. https://www.wartsila.com/encyclopedia/term/exhaust-gas-emissions-from-ships#:~:text=Exhaust%20emissions%20from%20marine%20diesel%20engines%20comprise%20nitrogen%2C,threats%20to%20vegetation%2C%20the%20environment%20and%20human%20health.

Agarwal, M. (2022, May 5). Understanding Various Components of Exhaust Gas Emissions from Ships. Marine Insight. https://www.marineinsight.com/guidelines/understanding-various-components-of-exhaust-gas-emissions-from-ships/

Zhao, J., Wei, Q., Wang, S., & Ren, X. (2021). Progress of ship exhaust gas control technology. Science of the Total Environment, 799, 149437. https://doi.org/10.1016/j.scitotenv.2021.149437

Teuchies, J., Cox, T. J. S., Van Itterbeeck, K., Meysman, F. J. R., & Blust, R. (2020). The impact of scrubber washwater on inland waters. Research Square (Research Square). https://doi.org/10.21203/rs.3.rs-23441/v1