Scrubbers – An economic and ecological assessment

Prepared for:
NABU

Report
Delft, March 2015

Author(s):
Eelco den Boer
Maarten 't Hoen

Publication Data

Bibliographical data:
Eelco den Boer, Maarten 't Hoen
Scrubbers - An economic and ecological assessment
Delft, CE Delft, March 2015

Ships / Fuels / Sulphur / Emissions / Reduction / Scrubbers / Environment / Economy / Factors / Analysis

Publication code: 15.4F41.20

CE publications are available from www.cedelft.eu

Commissioned by: NABU.
Further information on this study can be obtained from the contact person, Eelco den Boer.

CE Delft
Committed to the Environment

Through its independent research and consultancy work CE Delft is helping build a sustainable world. In the fields of energy, transport and resources our expertise is leading-edge. With our wealth of know-how on technologies, policies and economic issues we support government agencies, NGOs and industries in pursuit of structural change. For 35 years now, the skills and enthusiasm of CE Delft's staff have been devoted to achieving this mission.

Contents

Summary

Introduction
The recent tightening of the fuel sulphur limits for fuel used in Sulphur Emission Control Areas (SECAs) requires the use of fuels with a maximum sulphur content of 0.1% in these regions, or a technology that can reduce emissions to an equivalent level, from January, 1st 2015. Most low sulphur fuels are distillates (e.g. marine gasoil MGO, which are more expensive than the residual fuels that are traditionally used by ships (e.g. heavy fuel oil HFO)). Exhaust gas scrubbers, in combination with the use of HFO, have been accepted as an alternative means to lower sulphur emissions. Four different types of scrubbers are available today:

1. **Seawater scrubbers** (open loop) utilize untreated seawater, using the natural alkalinity of the seawater to neutralize the sulphur from exhaust gases.
2. **Freshwater scrubbers** (closed loop) are not dependent on the type of the water the vessel is operating in, because the exhaust gases are neutralized with caustic soda, which is added to freshwater in a closed system.
3. **Hybrid scrubbers** give the possibility to either use closed loop or open loop technology.
4. **Dry scrubbers** do not use any liquids in process but exhaust gases are cleaned with hydrated lime-treated granulates.

The scrubber market is highly dynamic at the moment, due to the recent tightening of the SECA fuel sulphur limits. The number of scrubbers installed on ships has increased significantly over the last years. About 80 scrubbers are installed at the moment, most of which are hybrid or open loop scrubbers. The number of orders amounts to approximately 300 at the time of writing. Available outlooks forecast a potentially more important role for scrubbers in the next decades as a means to reduce sulphur emissions, but at the moment the majority of ship owners have switched to MGO and investments have been postponed.

Objective
The study analyses environmental and economic aspects of the use of exhaust gas scrubbers in comparison to the use of MGO. Seawater scrubbers discharge different kinds of pollutants to the marine environment. Moreover, the study analyses the impacts of the pollutants on aquatic coastal ecosystems. The economic impacts are assessed for a 38,500 DWT product tanker.

Ecological impacts
Scrubbers reduce the emission of sulphur to the atmosphere by more than 90%. Also PM emissions, in terms of mass not number, are reduced significantly, by 60-90%. The emission of NO_x is reduced by 10% or less. Due to the additional power needed to drive pumps and caustic soda consumption, the estimated additional GHG emissions range between 1.5 and 3.5%, including caustic soda consumption for the latter figure. It should be noted, however, that also the use additional MGO in the SECA causes an increase of GHG refinery emissions by roughly 6.5%.

Concentrations of hazardous substances in the discharge of closed loop systems are higher than in open loop systems, but the mass flow rate of these substances determines the environmental impact. This is larger in case of seawater scrubbers, which are not always equipped with discharge water cleaning systems.

The current dominance of seawater and hybrid scrubbers indicate that a large share of the pollutants captured in the wash water may be released to the sea water.

Although the IMO wash water criteria for scrubbers are generally met, scrubbers may have a negative impact on marine environment due to acidification, eutrophication and the accumulation of hazardous hydrocarbons and heavy metals in case dilution is limited. This may lead to a deterioration of the water quality. The long term impacts of the use of open loop scrubbers, especially in vulnerable coastal areas with a reported moderate water quality, therefore needs to be investigated systematically by measuring and modelling of the water quality. On the basis of such results, it should be evaluated if scrubbers can be used in accordance with the European Water Framework Directive and Marine Strategy Framework Directive that set maximum concentrations for certain hazardous pollutants, prohibit deterioration of water quality, and aim to achieve 'good environmental status' respectively. Few EU countries decided to ban the use of open loop scrubbers in their waters to protect against potential contamination.

The use of MGO or LNG is inherently cleaner than the use of seawater scrubbers because no contaminated wash water is discharged. Additional impacts of increased MGO production on land, apart from increased energy use, are expected to be limited, due to the stringent environmental legislation and enforcement.

Scrubbers' business case

The installation of scrubbers requires significant investments. Typical installation costs range between 200 and 400 EUR/kW, which imply an investment of several millions, depending on a ship's engine power.

It is difficult to draw firm conclusions on the profitability of using scrubbers, as this depends on the operational profile of the ship, the difference between HFO and MGO prices, and the time ships sail in SECAs. The fuel price difference between MGO and HFO ranged between 240 and 300 $/ton between January 2014 and February 2015. When the difference is high, scrubbers are profitable in more cases than when the difference is low.

Under optimistic conditions, ship owners may be able to offer services at relatively low prices, but consequently there is a risk that scrubbers may lead to higher transport costs for operators instead of lower. The annual depreciation costs of scrubber installations are relatively high in comparison to a ship's annual hire costs, illustrating the significance and potential risk of the investment. Table 1 provides an overview of the impact of uncertain parameters on the annual benefits of scrubber installation.

Table 1 Impact of fuel price difference and number of days at sea (SECA) for a 38,500 DWT product tanker

	Annual benefits of seawater scrubber installation (euro)
Fuel price difference of 350 $/ton and 286 days at sea	+0.7 million
Fuel price difference of $240 $/ton and 154 days at sea	-0.5 million

Due to the additional costs of caustic soda consumption, it is likely that hybrid scrubbers will be used in open loop where possible and that the number of freshwater scrubbers installed will remain limited.

To assess the cost and benefits for the society as a whole, the benefits for ship owners would need to be weighed against the potentially harmful impacts of scrubbers on vulnerable coastal ecosystems. Such an analysis is conditional to the availability of monitoring and modelling of the impact of scrubbers on the water quality and marine ecosystems.

1 Introduction

1.1 Background

IMO and EU policies require ship operators to reduce the sulphur emissions of their ship operations. Ships operating in a Sulphur Emission Control Area (SECA) need to use of distillate fuels in these regions, or a technology that can reduce emissions to an equivalent level, of from January, 1st 2015. Several options are available to comply with the new limits, including:
- marine gas oil (MGO);
- LNG;
- HFO + scrubber (different types).

Since marine gas oil is more expensive than heavy fuel oil, scrubbers have received attention over the last years and the number of scrubbers installed onboard of ships has increased. However, the overall number of scrubbers installed is yet relatively limited and the recent drop in price differences between MGO and HFO resulted in postponing of investment decisions. This can be explained by various related factors like uncertainty about future global limits, large investment costs and limited experience with the technology and 'acceptance' of the technology within the maritime industry.

NABU asked CE Delft to review the available literature on scrubbers and to consult experts involved in different specialist areas in order to investigate the technology's ecological impact and to assess the installations' economic outcome compared to other of ways of being compliant with current legal requirements.

1.2 Objectives and report structure

The objective of the study is to analyse environmental and economic aspects of the use of exhaust gas scrubbers in comparison to the use of MGO.

This report highlights three distinct aspects of scrubbers:
- the current market of scrubbers and the outlooks (Chapter 2);
- regulations and environmental impacts, focussing on near shores (Chapter 3 and 4);
- the scrubber business case for ship operators (Chapter 5);
- conclusions and discussion (Chapter 6).

Various terminologies are used for naming scrubbers. In the report reference is made to seawater scrubber (SWS) which are also known as open loop scrubbers and freshwater scrubber (FWS), also referenced to as closed loop scrubbers.

2 The scrubber market

2.1 Introduction

In this chapter, an overview of the current scrubber market and future expectations are given. First, we provide relevant figures on the market (number, scrubber types, ship type). Figures refer to the number of scrubbers installed world wide. Second, we provide a future outlook on the expected distribution of the various technologies to meet the stricter upcoming legislation.

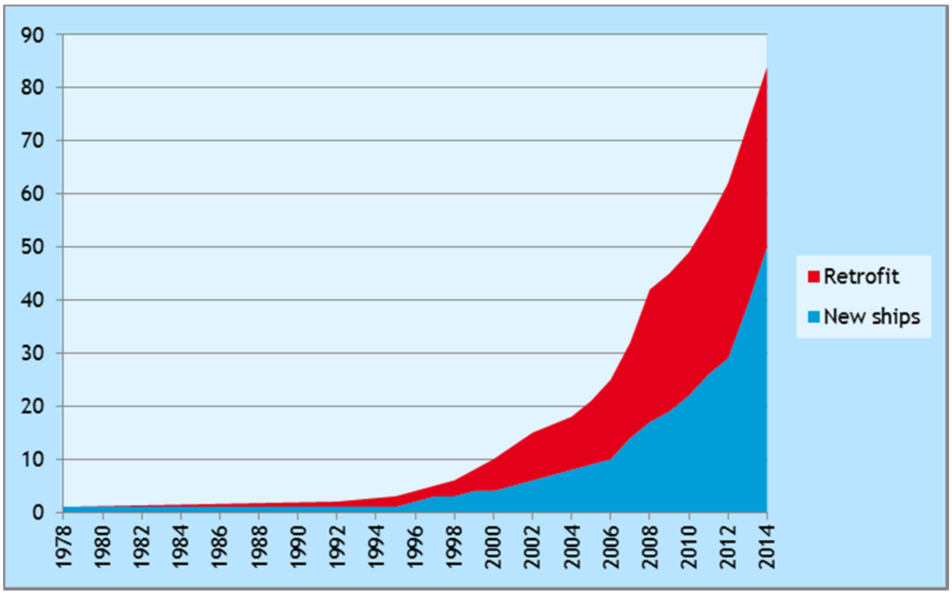
2.2 Scrubber types

Four different scrubber types are available today:
1. **Seawater scrubbers (open loop)** utilize untreated seawater, using the natural alkalinity of the seawater to neutralize the sulphur from exhaust gases. The negative characteristic of an open loop system is its greater energy consumption compared to a close loop system, but there is no need for chemical additives like caustic soda in a closed loop system.
2. **Freshwater scrubbers (closed loop)** are not dependent on the type of the water the vessel is operating in, because the exhaust gases are neutralized with caustic soda, which is added to freshwater in a closed system. Circulating water is processed after the scrubber and dosed with caustic soda in order to restore the alkalinity of wash water. The amount of the water which is needed in a closed loop process is about half of the flow in an open loop system.
3. **Hybrid scrubbers** give the possibility to either use closed loop or open loop technology. Hybrid scrubbers are generally used as an open loop system when the vessel is operating in the open sea and as a closed loop system when operating in harbour or estuaries, where water discharge is prohibited. Among the different types of scrubbers a hybrid scrubber is becoming increasingly common because of its flexibility and restrictions.
4. **Dry scrubbers** do not use any liquids in process but exhaust gases are cleaned with hydrated lime-treated granulates. There is not any discharge to the sea from the system. As a result of the process a gypsum, which is used to manufacture wallboard, is generated. An advantage of a dry scrubber is its lower energy consumption compared to a wet scrubber.

2.3 Description of the market

The interest in scrubbers has greatly increased over the last years, as a result of the gradual lowering of the sulphur content of ship fuels, resulting in the 0.1%S regulation that came into play in January 2015. Figure 1 provides an overview of the number of scrubbers installed on the world fleet over the last 27 years. The figure shows that scrubbers are installed both a new ships, as well as being retrofitted afterwards. For marine use, wet scrubbers are dominating the market. As of the beginning of 2011, only two dry scrubbers have been installed.

Figure 1 **Development of the world fleet with scrubbers installed**

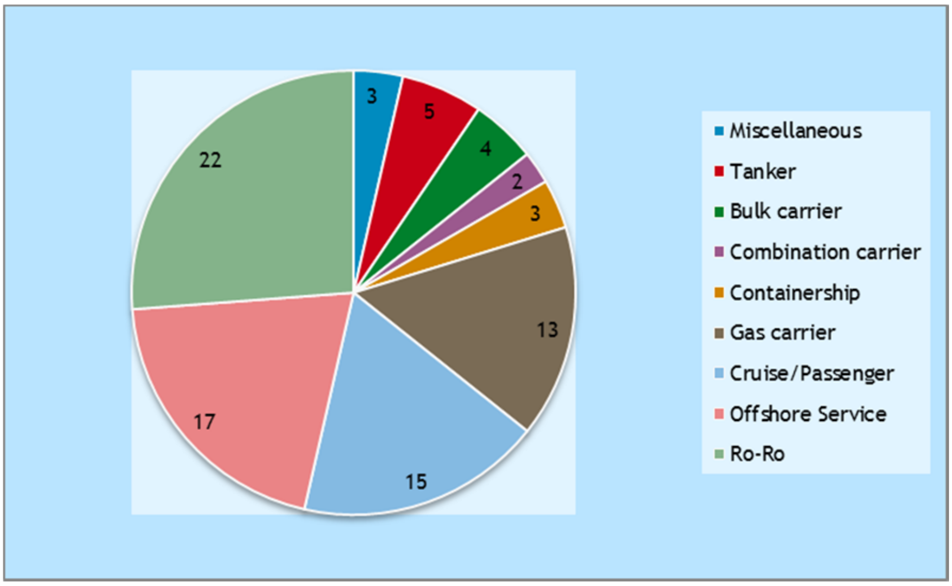


Source: (CE Delft, 2015).

The Exhaust Gas Cleaning Systems Association (EGCSA) estimates there are now some 300 (member and non-member) exhaust cleaning gas systems installed or on order, with Carnival Corporation announcing a very significant investment. Halfway 2014, the number of installations and orders was 122, showing the sharp increase of interest by the maritime industry for scrubbers prior to the coming into effect of the 0.1% sulphur cap in January 2015.

Scrubbers are most widely installed on Ro-Ro ships, offshore service ships, cruise/ passenger ships and gas carriers, see Figure 2. Especially Ro-Ro ships and offshore service ships typically operate in the SECA. The relatively large numbers of scrubbers fitted onto Ro-Ro ships can be explained by the fierce competition with truck transport.

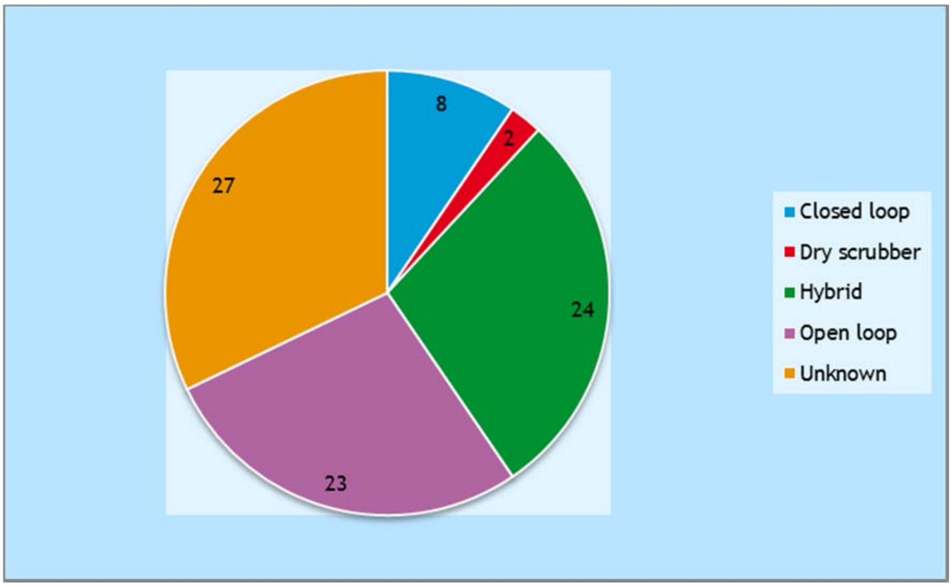
Figure 2 **Distribution of exhaust gas scrubbers over ship types**



Source: (CE Delft, 2015).

Hybrid scrubbers and open loop scrubbers are most widely installed on ships currently. In the year 2014, 14 hybrid and 11 open loop scrubbers were installed on ships, while the number of installed closed loop scrubber amounted only 2. See Figure 3 for an overview of the different scrubber types.

Figure 3 Different scrubber types in the fleet



Note: Unknown scrubbers are mainly installed on offshore service vessels.
Source: (CE Delft, 2015).

Most of the scrubbers are installed on smaller ships. 56 of the 84 scrubbers in use are installed on ships with a dead weight tonnage (DWT) of below 20,000 tonnes, illustrating the dominance of these ships in the world fleet and the SECAs. Larger ships (e.g. big container vessels) are not frequently equipped with scrubbers now, due to the limited share of their time sailing in a SECA. Open loop and hybrid scrubbers are distributed evenly over the different ship types, while closed loop scrubbers are only implemented on ships with a DWT under 40,000 tonnes.

2.4 Future options to meet SECA requirements

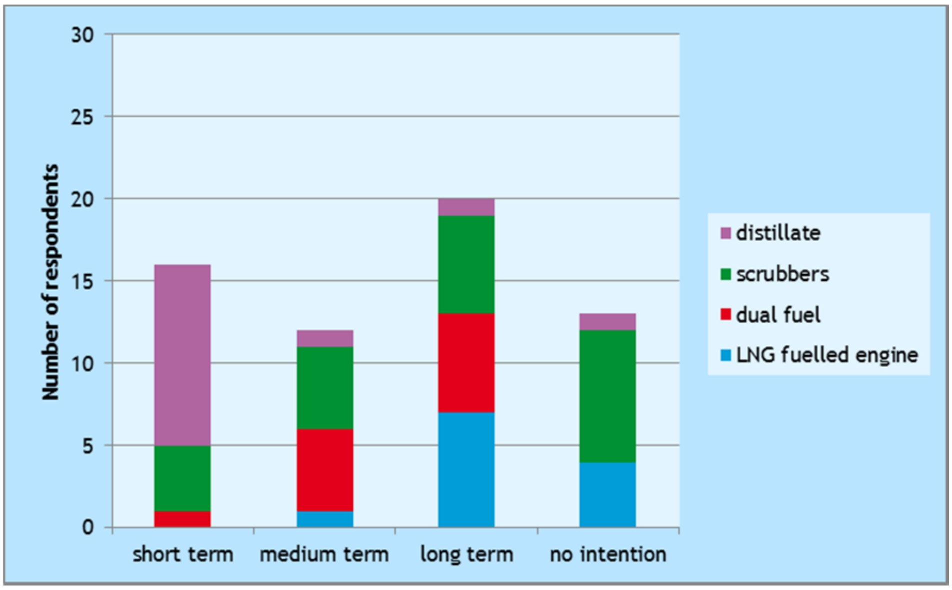
The number of scrubber orders illustrates the interest in this technology to meet SECA criteria and the same is true for LNG (80 ships in operation by 2016), which is also a technology to meet the fuel sulphur requirements. It is widely believed that these technologies and the use of distillate fuel will all play a role in meeting the fuel sulphur requirements. The number of scrubbers ordered or installed is roughly 2-3 times higher than the number of LNG installations or orders. This implies that the vast majority of ships is currently using MGO for meeting the 0,1% fuel sulphur requirement in the SECA.

From a ship owners' survey organised by Lloyds Register (Lloyds Register, 2012) amongst ship owners, the following became clear:

- low-sulphur fuel oil is seen as a short-term option for compliance with SO_x emission regulations;
- scrubbers are seen as a medium term option;
- gas engines (LNG) are a viable option in the medium and long term.

However, many ship-owners (30 respondents) indicated that they were doubting as to which compliance option would be best.

Figure 4 Results of a survey among ship owners on intentions to mitigate SO_x emissions



Source: (Lloyds Register, 2012)

In their Global Marine Fuel Trends 2030 study (Lloyds & UCL, 2014), Loyds Register and UCL estimate that HFO will hold at least half of the fuel share in any of the scenarios developed. In other words, in the decades to come, HFO combined with abatement technology (scrubbers most likely) is still considered the most cost-effective option for the majority of the fleet, but a considerable proportion of the fleet, mainly older tonnage, will rely on distillate fuel for SECA compliance. Obviously, the review of the 2020 global fuel sulphur content within IMO will strongly influence the business case for scrubbers and LNG.

2.5 The European SECA (Baltic + North Sea)

There are about 5,000 vessels in the SECA at any time, on average. About 14,000 vessels visit the area in a year. 2,300 ships spend all of their time in the area, 2,700 more than 50 % of their time and 9,000 less than 50% of their time. 71% of the ships belong to European operators. In the Baltic Sea and the area leading into it, the share of ships that stay 100% of their time in the SECA is highest (DMA, 2012).

The following ship types are most represented in the SECA (DMA, 2012)):
- tug;
- dredging;
- general cargo/containers (< 5,000 DWT);
- ferry (< 5,000 DWT).

The overall amount of bunker fuel used in SECA during 2010 can be summed up to 12 million tonnes, which can be allocated as follows:
- North Sea: 5.0 Million tonnes;
- Baltic Sea: 3.3 Million tonnes;
- English Channel (SECA-part): 2.3 Million tonnes;
- Skagerrak & Kattegat: 1.5 Million tonnes.

We estimate that about half of the fuel consumed in the SECA is consumed by ships that operate more than 50% of their time in the SECA, amounting at around 6 million tonnes. This estimate is based on:
- overall fuel consumption;
- the number of ships active for respectively 100%, 50-100% and less than 25% of their time in the SECA;
- double engine power for the ships being less than 50% of their time in the SECA, compared to ships being active in the SECA over 50% of their operating time.

3 Scrubber operation

3.1 Introduction

This chapter illustrates the operation of the scrubber, including the monitoring requirements issued by IMO.

3.2 Scrubber working principles

A scrubber generally consists of:

– The **exhaust gas cleaning** unit serves as a contact chamber that enables the exhaust gas stream from an engine or boiler to be intimately mixed with water, either seawater, freshwater, or both. In the contact chamber, SO_x is converted to sulphuric acid. 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.
– The **wash water treatment plant** differs by scrubber type and design. Generally, physical separation techniques are used to capture suspended solids, if captured. The treatment process typically includes a multicyclone, or a cyclonic separator similar to that used to separate water from residual fuel prior to delivery to the engine. Heavier particles may also be trapped in a settling or sludge tank for disposal.
– **Sludge handling** to retain sludge removed by the wash water treatment process for disposal shoreside.

Wet scrubbers are not supposed to be operated without wash water flowing. Therefore, a separate bypass is generally installed in case the scrubber is non-operational for any reason (ABS, 2013).

3.2.1 Seawater scrubber

The most important chemical reactions that take place during the desulphurisation process are the following:

SO_2 (gas) + H_2O + ½O_2 → SO_4^{2-} + $2H^+$
HCO_3^- + H^+ → CO_2 + H_2O

SO_2 absorbed in seawater reacts with oxygen to form sulphate ions and hydrogen ions. Increased concentration of hydrogen ions means increased acidity and decreased pH. Bicarbonate ions (HCO_3^-) from the seawater react with hydrogen ions and thereby neutralise the acidity and raise the pH again.

In addition to the capture of SO_2 some NO_x may be removed from the exhaust gas in the scrubber. It is mainly the NO_2 fraction that is captured, which will be emitted with the wash water as nitrates.

Open loop scrubbers have larger water flow rates than closed loop scrubbers because there is less control over water alkalinity[1] and more water is needed to make the scrubbing process effective when lower alkalinity water is used. The Baltic Sea is known as having a low alkalinity, especially the northern part.

The efficiency of the scrubber process increases with higher alkalinity. Lower alkalinity implies a higher need for wash water and results in higher energy consumption.

In a marine seawater scrubber the flue gas either passes through a spray of seawater or is bubbled through seawater. System manufacturers have their own techniques for how the scrubber mixes the exhaust gas and the water. Wash water residues can be collected for deposit on land, but not necessarily.

3.2.2 Freshwater scrubber

In freshwater scrubbers, SO_2 combines with a salt and consequently does not react with the natural bicarbonate of seawater. The following reactions occur:

$2NaOH + SO_2 \rightarrow Na_2SO_3 + H_2O$ (Sodium Sulfite);
$Na_2SO_3 + SO_2 + H_2O \rightarrow 2NaHSO_3$ (Sodium Hydrogen Sulfite);
SO_2 (gas) $+ H_2O + \frac{1}{2}O_2 \rightarrow SO_4^{2-} + 2H^+$;
$NaOH + H_2SO_4 \rightarrow NaHSO_4 + H_2O$ (Sodium Hydrogen Sulfate);
$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$ (Sodium Sulfate).

A freshwater scrubber discharges typically 250 times less water than a seawater scrubber. For fresh water systems, the bleed off is considerably smaller (0.1-0.3 m^3/MWh) and as a consequence, the pollutant concentration is higher, easing the wash water cleaning.

In a closed loop-type system, the scrubber's wash water is always collected in a process or circulating tank. A limited quantity of wash water from the bottom of the process tank, where the residuals have collected, is extracted using a low suction, and it goes to a hydrocyclone or separator, where the residuals are removed.

3.2.3 Dry scrubber

Dry scrubbers use granulates with caustic lime ($Ca(OH)_2$) which reacts with sulfur dioxide (SO_2) to form calcium sulfite: $SO_2 + Ca(OH)_2 \rightarrow CaSO_3 + H_2O$.

Calcium sulfite is then air-oxidized to form calcium sulfate dehydrate or gypsum: $CaSO_3 + \frac{1}{2}O_2 \rightarrow CaSO_4$.

Reaction with sulphur trioxide (SO_3) is: $SO_3 + Ca(OH)_2 \rightarrow CaSO_4 + H_2O$.

Which with water forms: $CaSO_4 \bullet 2H_2O$ (Gypsum).

A dry scrubber works by feeding dry pellets of hydrated lime treated granulates through a packed bed absorber. The hydrated lime reacts with the hot exhaust gas and absorbs the SO_x components to form pellets of gypsum. Dry SO_x scrubbers claim there is a modest market for the used granules in building materials. Testing has been carried out so far only with two vessels with a medium-speed main propulsion engine.

[1] The capacity of an aqueous solution to neutralize an acid (HCO^{3}- in case of seawater).

3.3 Monitoring of appropriate operation

The 2009 IMO guidelines[2] for exhaust gas cleaning systems (IMO, 2009) contains a set of guidelines for monitoring the appropriate functioning of exhaust gas cleaning systems. The two EGC system schemes apply the following concepts:

- **Scheme A** is based on initial emission performance unit certification together with a continuous parameter check of operating parameters and daily exhaust emission monitoring;
- **Scheme B** is based on continuous exhaust emission monitoring together with a daily parameter check of operating parameters.

EU Directive 2005/33 only accepts continuous monitoring (Scheme B) as an appropriate option. This implies that ships sailing in the European SECAs have to install continuous monitoring equipment.

In both cases the condition of any water used in the scrubbing process is to be monitored and recorded. IMO has set several criteria for the wash water:

- turbidity;
- pH;
- polycyclic Aromatic Hydrocarbons (PAH) concentration;
- nitrate concentration.

Residues (sludge) generated by the scrubbers need to be delivered ashore to adequate reception facilities. Such residues should not be discharged to the sea nor incinerated on board. The IMO Guidelines do not contain limits for the concentrations of metals in the wash water discharge.

Turbidity

Turbidity is a measure of the amount of particles in the water, or rather the cloudiness caused by suspended solids. Turbidity in open water can be caused by several different reasons, e.g. phytoplankton or high levels of sediment in the water. In lakes and shallow areas the turbidity can decrease the amount of light reaching the lower depths and thereby affect submerged plants and in the end also species that are dependent on the amount of plants. Turbidity is measured in FTU (Formazin Turbidity Unit) or FNU (Formazin Nephelometric Units). The IMO wash water criteria regarding turbidity:

- The maximum continuous turbidity in wash-water should not be greater than 25 FNU or 25 NTU above the inlet water turbidity.

PAH

Polycyclic aromatic hydrocarbons (PAH) are the largest known group of carcinogenic substances and include many individual chemical substances containing two or more condensed aromatic rings. A group of 16 PAHs are usually measured and analysed, but in the IMO wash water criteria, PAHphe or phenanthrene equivalence is used. Phenanthrene is a member of the PAH group and is insoluble in water. PAH is sometimes used as an indicator of the total emissions of hydrocarbons.

---

[2] The International Maritime Organization's Pollution Prevention and Response (PPR) subcommittee recently drafted an amendment to the scrubber guidelines, which would allow the use of calculation-based methodologies alongside measurements, since the guidelines require measurements need to be taken at full scrubber load based on maximum fuel-sulphur content, as well as while the vessel is ‘at rest in harbour’, which excludes ships that are directly shaft-driven.

The IMO wash water criteria regarding PAH:

- The maximum PAH concentration in the wash water should not be greater than 50 µg/l PAHphe above the inlet water PAH concentration (normalized at a flow rate of 45 m^3/h). The PAH concentration should be measured downstream of the water treatment equipment.

pH

pH is a measure of the acidic or basic (alkaline) nature of a solution.
The concentration of the hydrogen ion [H+] in a solution determines the pH. Ocean water usually has an excellent buffering system, with interaction of carbon dioxide and water, and pH generally varies between 7.5 and 8.5. Neutral water has a pH of 7 while acidic substances are less than 7 (down to 1, which is highly acidic) and alkaline substances are more than 7 (up to 14, which is highly alkaline). Anything either highly acid or alkaline would severely affect marine life but the oceans are usually very stable with regards to pH.

The IMO wash water criteria regarding pH:

- The discharge wash water should have a pH of no less than 6.5 measured at the ship's overboard discharge. During manoeuvring and transit, a difference between inlet and outlet of 2 pH units is allowed.
- The discharged wash water plume should be measured externally from the ship (at rest in harbour) and the discharge pH will be recorded when the plume at 4 metres from the discharge point equals or is above pH 6.5. This will become the overboard discharge limit.

Nitrates

Nitrogen oxides, i.e. the sum of NO and NO_2, are produced during combustion at high temperatures. Nitrate (NO_3^-) is the most highly oxidised form of nitrogen and excess nitrate concentrations in aquatic systems can lead to algae blooms and eutrophication. The nutrient concentration in seawater usually decreases during springtime and all processes in the nitrogen cycle are seasonally dependent. When oxygen is present, ammonia can be oxidised to nitrate (via nitrite) in a process called nitrification.

The IMO Wash water criteria regarding nitrates:

- Nitrates should be monitored. The wash 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 wash-water discharge rate of 45 tonnes/MWh, whichever is greater.

4 Environmental impact assessment

4.1 Introduction

The use of a scrubber in the SECA is one of the legally allowed options to reduce sulphur emissions to the atmosphere. Alternatively, ship operators can switch to low sulphur fuels like MGO or LNG. When combined with particulate filters and SCR catalysts using MGO will reduce air pollutant emissions significantly.

In contrast to HFO, MGO is a pure distillate that must not contain any residual components, which are allowed in HFO (e.g. Nickel and Vanadium).
The emission of metals, particles (ranging from 30 to 80% less in mass (Litehauz, 2012) and around 80% less in numbers (Lappi, et al., 2012)) and sulphur will therefore be less for ships running on MGO compared to ships using HFO.

When the impact of scrubbers are compared with a situation with MGO, one thus has to keep in mind that a large part of the substances emitted in the case of the use of scrubbers will not be released to the marine environment when using MGO. Due to the strict environmental legislation on land, it is most likely that air pollution emissions on land due to further refining will be limited.

In this chapter, we examine the environmental impacts of the use of scrubbers on the marine environment. Therefore, the main focus lies on the composition of the discharged wash water and its impact on the marine environment, coastal areas in particular.

4.2 Reduction of pollutants from exhaust gases

The main objective of scrubber operation is washing out sulphur, but also significant amounts of particle mass is trapped. Table 2 provides an overview of scrubber's cleaning performance referenced in available studies. Scrubbers mainly remove SO_X and PM emissions from the exhaust gases. The relative impact on particle number is less than on particle mass. A scrubber captures particles relatively large in size ((Køcks, et al., 2012). The scrubber technology does not remove nitrogen oxides or only to a very small degree and no CO_2.

Table 2 Scrubber exhaust gas cleaning performance

Pollutant	Reduction
SO_x	>90%
PM	60-90%
NO_x	<10%

Source: summarised from (COWI, 2012).

4.3 Analysis of wash water

Various scrubber trials have been performed over the last years and several ships have been subject to in-depth monitoring, see Table 3. The available monitoring reports have been used to analyse the scrubber discharge water and have been the basis of the presented environmental impact analysis.

Table 3 Characteristics of monitoring projects

	MV Ficaria Seaways	MS Zaandam	MT Suula	Pride of Kent
Monitoring report	(COWI, 2012)	(EPA, 2011)	(Wärtisilä, 2010)	(Hufnagl, et al., 2005)
Main/auxiliary engine	2-stroke main engine	Auxiliary	Auxiliary	Auxiliary
Scrubber type	Hybrid scrubber	Seawater scrubber	Freshwater scrubber	Seawater scrubber

Specific hazardous substances such as heavy metals polycyclic aromatic hydrocarbons (PAH), are released together with the scrubber wash water. All available monitoring reports show that the IMO guidelines generally can be met, with a few single measurements as exception.
However, this does not imply that the wash water discharge can not have an impact on local ecosystems, if scrubbers will be used at a larger scale.

In the below, we detail the results of the different measurement campaigns.

4.3.1 Heavy metals

Heavy metals are not biologically degradable. Several metals (Hg, Cd, Cr, Cu, Ni, Zn) found in scrubber wash water are toxic to plants and human life. Cancer and neurological disease have been connected with exposure to heavy metals. The metals found in wash water are reported to be of different origin:

- System materials, typically iron, copper and zinc may be a source of metals. The reduced pH of the washing water will increase the solubility of the metal ions. Therefore, the choice of materials is very important.
- System inlet water may contain metals found in seawater or from electrochemical protection to prevent fouling of seawater pipes.
- Combustion of fuel and lubricants, typically result in the emission of vanadium, nickel, calcium and zinc. The majority of heavy fuel oil consists of metals that naturally occur in oil, principally vanadium and nickel, which are oil soluble.

In many cases, when metals were detected in the discharge samples, the metals were also present in the intake samples, with several exemptions. However, in several measurement campaigns metals were found in the washing water that were not traced in either the fuel or the inlet water (Hufnagl, et al., 2005); (Buhaug, et al., 2006).

(COWI, 2012) reports the ability of the scrubbers to trap nickel and vanadium from exhaust gases as limited, resulting from a measuring campaign with the Ro-Ro ship Ficaria seaways. The capture rate of the scrubber for these substances was between less then 1 and 39%, depending on the sulphur content of the fuel, that is related to the amount of nickel and vanadium in the fuel, and the engine load.

Copper and zinc were found in relatively high concentrations, higher than what could be explained from the content of these metals in the fuel and inlet water. Contamination during sampling was mentioned as an explanation, but could not be proven. Experts indicate that those metals could origin from the engine components and lube oil.

The IMO guidelines do not contain any limits for the concentration of metals in wash water, but turbidity is monitored as a surrogate for suspended solids.

4.3.2 pH

The discharge of wash water to the sea contributes to acidification of seawater, since the air pollutants are converted into the strong sulphuric and nitric acids.

It has been found that wash water from ships quickly dilutes and buffers to delta pH of below 0.2, which is considered to be safe margin, in case a ship is sailing (Buhaug, et al., 2006). In a report by (COWI, 2012), it was shown that for a larger sea area with significant ship traffic (e.g. the Kattegat) the impact of such discharges on the alkalinity of seawater would be small, also just behind the wake of a ship. (COWI, 2012) shows that also for busy shipping lanes, the increase of pH and the reduction of alkalinity are small (less than 0.01 pH units), also in waters with typically low alkalinity such as the gulf of Bothnia.

In their advice on the IMO exhaust gas cleaning system guidelines (GESAMP, 2009), GESAMP stated:

IMO should consider the potential contribution to ocean acidification of the large scale application of SO_2 capture from ships and the discharge of sulphurous/sulphuric acid containing effluents.

Recent research (Hassellöv, et al., 2013) concludes that scrubber wash water can contribute especially to acidification in coastal waters, with a contribution that matches CO_2 driven acidification. The work justifies the prudence of GESAMP on the impact of scrubbers on pH reduction. The study states that increased acidity poses a threat to marine ecosystems, harming species such as coral and algae, as well as commercial aquaculture species, such as shellfish.

4.3.3 Nitrates

Nitrate emission contributes to eutrophication of seawater, which may result in an explosive growth of algae leading to reduced water clarity. Eutrophication is a relevant environmental problem for the North Sea and especially for the Baltic sea.

The amount of nitrogen washed by scrubber water is limited and well below the IMO Guidelines (Wärtisilä, 2010), since only NO_2 is soluble in water, while NO is insoluble. Engine out NO_x emissions typically consist of over 90-95% of NO. It should be noted that part of the exhaust NO_x emissions finally end up in the sea water, independent of the use of a scrubber.

4.3.4 PAH

The biological effect of polycyclic aromatic hydrocarbons (PAH) is linked to the planar structure of the molecule and its ability to affect DNA in the cell nucleus. PAH are formed if hydrocarbons are heated under anoxic conditions, i.e. with insufficient oxygen, and are the products of incomplete combustion. PAH are not usually present as individual compounds but occur in mixtures with other exhaust gas pollutants. PAH are fat soluble and bio-accumulative (in fatty tissues). In the aquatic environments, PAH are usually bound to particles which transport to sediment, which may pose a risk.
Many PAH compounds accumulate in invertebrate organisms. Fish eggs and fry

exposed to PAH have been found to suffer mutation, bleeding, heart conditions, reduced growth and increased mortality.

Although within the IMO limits, measurements performed show a significant difference in concentration of PAHs in the wash water (UBA, 2014).

4.4 Comparison of seawater and freshwater scrubbers

The impact of seawater scrubbers on the water quality is significantly higher than the impact of freshwater scrubber. This can be explained by the higher flux of hazardous substances. This difference in discharge of hazardous substances is illustrated (UBA, 2014) on the basis of the available monitoring reports (COWI, 2012). The discharge of heavy metals and organic substances from seawater scrubbers are significantly higher.

Table 4 Hazardous substances discharged via wash water (in g)

	Scubber type	Kiel-Gothenburg (230 nm)
Vanadium	SWS	685
	FWS	0.03
Lead	SWS	55
	FWS	0.03
Arsene	SWS	0.8
	FWS	0.08
PAH	SWS	3.4
	FWS	0.0
Nickel	SWS	173
Mercury	SWS	0.4
Copper	SWS	486
Zinc	SWS	840
Oil (kg)	SWS	1.68
Nitrate	SWS	546

Source: (UBA, 2014).

4.5 Interaction with EU Water and Marine Strategy Framework Directive

To cover both long-term and short-term effects resulting from exposure to chemicals in aquatic environments, Environmental Quality Standards (EQS) values have been defined in the Water Framework Directive (EC, 2013)The WFD takes into account direct ecotoxicological effects in different habitats (water, sediment) and indirect ecotoxicological effects occurring after bioaccumulation in biota (secondary poisoning of top predators) and also effects on human health by oral uptake of water and food. To following Environmental Quality Standards (EQS) are defined:

a Annual average (AA) concentration.
b Short-term maximum acceptable concentration (MAC) peaks.

The annual average standard refers to long term exposure, while the maximum acceptable concentration refers to protection against acute toxic effects exerted by exposure to short-term peak concentrations. The MAC-EQS is a figure not to be exceeded at any time. In conjunction, the AA-EQS and the MAC-EQS are intended to protect the structure and function of aquatic ecosystems from any significant alterations by chemical substances.

The marine strategy framework Directive (EC, 2008) aims to achieve ‘good environmental status’ of the EU’s marine waters by the year 2020 and to protect the resource. The MSFD provides amongst others the following descriptors for ‘good environmental status’:

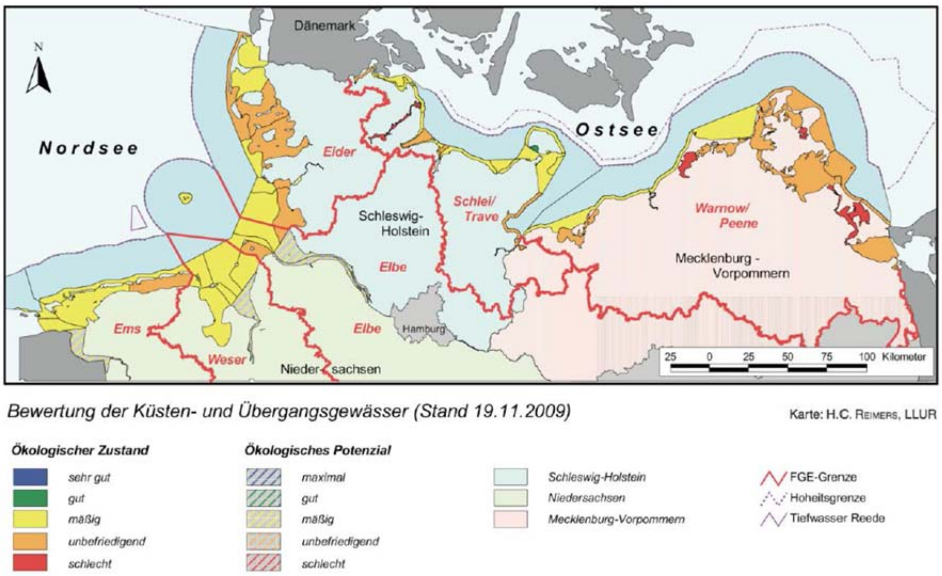
- properties and quantities of marine litter do not cause harm to the coastal and marine environment;
- populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock;
- contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards.

Member states are required to develop strategies to achieve a good environmental status by 2020. It needs therefore to be assessed if this good environmental status can be achieved with the allowance of (open loop) scrubbers.

Both the WFD and MSFD refer to the precautionary principle in their preambles, illustrating the importance of environmental protection through preventative decision-taking in the case of risk. The currently available research does not irrefutably exclude the deterioration of the environmental status of the vulnerable (near shore) ecosystems e.g. as a result of the accumulation of hazardous substances. It is also not yet illustrated if and how the ‘good environmental status’ can be met by the year 2020, taking into account a growth of the number of scrubbers in use.

The limited available information on the water quality like mentioned by UBA, 2014 shows that for example the water quality in German coastal waters is moderate or worse (UBA, 2014). UBA questions if the precautionary principle and the objective of improvement leave room for the application of scrubber, open loop scrubbers in particular (UBA, 2014).

Figure 5 Environmental status of German coastal areas



Source: (UBA, 2014).

4.5.1 Impact of scrubber wash water to water quality

The concentration of various substances found in the wash water of scrubbers is higher than the Environment Quality Standards (EQS) listed in EU Directive 2013/39, the table illustrates. It should be noted that the concentration of substances and variations in parameters in the discharge water depends on the specific wash water rate.

Table 5 Comparison of SWS discharge water and water quality standards (EQS)

	AA-EQS(ųg/l)	MAC-EQS(ųg/l)	SWS wash water (ųg/l)
Lead	1.3	14	13-21
Mercury		0.07	0.08-0.12
Nickel	8.6	34	41-43

Source: (UBA, 2014) referencing, (COWI, 2012).

For several metals, there is no EU EQS, but the scrubber discharge water does not meet the Danish EQS, Table 6 shows. To reduce the concentrations of hazardous substances towards levels below the EQS, a certain mixing zone is required. Ship-owners and ports have asked for clarity over the issue of whether scrubber wash water can be discharged overboard[3].

Table 6 Comparison of SWS discharge water with Danish EQS

	Danish MAC-EQS (ųg/l)	SWS wash water (ųg/l)
Lead	2.8	21
Copper	2	260
Vanadium	57.8	180
Zinc	8.4	450

COWI (2012) shows that the concentration of hazardous substances in the Kattegat area remain typically an 2 to 3 orders or magnitude below the EQS for most hazardous substances, assuming an ‘all ships fitted with scrubber’ scenario.

Taking into account several uncertainty factors, like an increase in ship traffic, the reliability of the measurements, a higher level of contaminants, leading to an increase of emissions by factor 10, would also lead to factor 10 increase in the predicted long term concentration of hazardous substances. None of the resulting concentrations will exceed the corresponding EQS value.

The study assumes rise of the concentration of the hazardous substances towards an equilibrium due to dilution with ‘fresh seawater’. Long term impacts have, however, not been studied.

Although available analyses (COWI, 2012); (Buhaug, et al., 2006) show that the contribution of scrubber discharge water are limited in comparison to the EQS, no quantitative analysis is, however, available on the impact of scrubber wash water discharges in vulnerable or ecologically degraded estuaries coastal areas.

3 http://www.ecsa.eu/9-latest-news/163-scrubbers-shipowners-urge-for-clarity-and-legal-certainty-at-the-eleventh-hour

UBA, 2014 states that the knowledge in relation to the environmental impact of scrubber discharge water is still insufficient, especially in case of sensitive coastal areas.

4.5.2 The use of scrubbers in coastal area's and ports

While being in port most ships use auxiliary engines to provide electricity and power for e.g. heating of crew and passenger areas, lightning, cooling of sensitive cargo or pumping of water, etc. The overall power consumption is less than at open sea and consequently the discharge of scrubber wash water, but also the mixing of water in port areas is significantly less than on open sea levels.

Furthermore, as a result of industrial pollution alongside rivers upstream of ports, the concentrations of pollutants in ports can be high. An example is the German river Elbe, alongside which the port of Hamburg is situated. This river contains concentrations of heavy metals (Hg, Cd, Pb, Cu, Zn, Cr, Ni, As) and hazardous organic substances (a.o. PAKs) in concentrations that exceed the EQS values from the WFD (UBA, 2014).

Several global analysis were performed, but an in-depth analysis of the impact of scrubber discharges in ports areas has not been performed, while problems due to improper mixing in port areas are much likely to occur in ports than at open sea. (AEA, 2009) states that if all ships in the port of Hamburg were to use an seawater scrubber, 21 tonnes/s of water would be needed for scrubbing and buffering. For comparison, the flow in the Elbe is around 720 tonnes/s. (COWI, 2012) has calculated a total volume of scrubber discharge water of 12,000 m^3/day for the port of Aarhus, compared to a total volume of water in the port of 20 million m^3, corresponding with a dilution factor of 1,200.

Wash water discharging in coastal waters is still under consideration within the EU. Few countries have set their own policies. National governments and ports can set limits lower than the WFD limits for concentrations of hazardous substances, or can prohibit the discharge of scrubber wash water. Several countries restricted the discharge of scrubber wash water:

- Germany prohibited the discharge of wash waters in inland waters rivers (certain ports, including the Kiel Canal);
- Belgium prohibited the discharging within 3 nm off coast.

Also Californian regulations do not permit the use of scrubbers as an alternative to low sulphur fuel use.

Further work and analyses in the area of ports and coastal waters may be needed, since the state of knowledge regarding the environmental impact of scrubber waste water is insufficient. In order to estimate the cumulative impact of scrubber waste water disposal for the marine ecosystem, the critical non degradable substances released with scrubber waste water should be included in the regular monitoring programme for the North and Baltic Sea and further studied, especially in the near of ports, dense shipping routes and estuaries.

UBA states that the German coastal waters suffer from a strong pressure due to pollution by different economic entities. In some sections of the German coast, the environmental status is moderate to poor (UBA, 2014). The polluted scrubber waste water would mean an additional stress factor for the marine organisms in the North and Baltic Seas and the adjacent from seagoing ships busy river basins.

4.6 Additional energy consumption and GHG emissions

The use of a scrubbers increases the energy consumption which is calculated to raise fuel consumption by 3 % in case of seawater scrubber and by 1% in case of freshwater scrubber. According to Wärtisilä the additional energy needed was estimated at around 0.3% for a freshwater scrubber, not taking into account the energy needed for the production of chemicals (Wärtisilä, 2010).
In context of the CARB rule on low sulphur fuel use, Corbett calculates an increase of 1-2% of CO_2 emissions, based on the additional energy consumption needed to produce distillate fuel (Corbett & Winebrake, 2008). Concawe studied the impact of increased MGO production for the SECA by European refineries, in combination with a global cap of 0,5% and estimates a 10% increase of refinery GHG emissions (CONCAWE, 2009).

It should be noted however that the carbon intensity of distillate fuel is 4% lower than that of HFO, due to a higher share of C-H bounds in the fuel. This should be taken into account when evaluating the well-to-wake (WtW) GHG emission impacts.

Ma (Ma, et al., 2012) studied the well-to-wake GHG emissions of SO_x abatement options for the marine industry, taking the life cycle energy consumption of the different fuels and chemicals into account, see Table 7.

Table 7 WtW GHG emissions increase for different scenario's (%)

Scenario	WtW GHG emissions
HFO	Baseline
Seawater scrubber	4.0-4.9
Freshwater scrubber	2.5-2.9
Dry scrubber	4.9-5.5
50% conversion to MGO	6.5
100% conversion to MGO	15.8

Source: Ma et. al, 2012.

From the table, it can be seen that the additional GHG emissions are lowest for freshwater scrubbers, followed by seawater scrubbers. During the measurements at the MV Ficaria Seaways, additional energy consumption were estimated at 1.4% (1% additional power consumption and 0,4% additional back pressure) (COWI, 2012). The energy associated with NAOH consumption was estimated at 2.1% of the energy in the HFO. Overall, the additional energy for fresh water scrubbers equals 3.5%.

The value of 6.5% additional GHG emissions in case of additional MGO production is likely for the European SECA, assuming that the European refineries have to upgrade 50% of their HFO production.

Regarding LNG methane slip as well as the diverse extracting methods have to be taken into account in order to assess the climate warming potential correctly.

4.7 Waste production and disposal

Sludge is produced in parallel with the water discharge. The amount of generated sludge by scrubbers is approximately of 0.1 to 0.4 kg/MWh, depending on the amount of water mixed with the particulates.
This represents less than 10% of the 'normal' sludge production, which stems for purification of the fuel by centrifugation. Centrifugation is used to eliminate water and abrasive particles of heavy metals, (vanadium, nickel) sediments and others. Sludge is typically collected in a standard 1m^3 plastic container. A typical reported dry weight of sludge is between 11-21%, depending on the effectiveness of centrifugation. 10% of the dry weight consists of the hydrocarbons.

The sludge generated in FW-mode contained (COWI, 2012):
- high levels of sulphur (max. 79 g/kg dw);
- THC (max. 111 g/kg dw);
- PAH was significant (230 mg/kg dw);
- dioxins/furans (26 ng/kg dw);
- PCBs were below the detection limit (1 µg/kg dw);
- vanadium (max. 12 g/kg dw);
- nickel (max. 5.4 g/kg dw);
- copper (max. 1.1 g/kg dw).

Due to the contents of nickel, vanadium and hydrocarbons, the sludge is classified as hazardous waste and must be treated and disposed of accordingly when transported to land. Facilities suitable for reception, handling, transport, treatment and disposal of scrubber sludge generally exist or can be made easily available in ports and downstream installations/facilities.

Tests and analyses carried out on freshwater scrubbers indicate that the properties and treatment of the sludge from scrubbers are very similar to other engine room sludge. This has also been confirmed by operators of waste reception facilities in Finland and Sweden (EMSA, 2010). However, interviewed experts point at the low calorific value of scrubber sludge and propose not to mix scrubber slurry with engine room sludge that can be processed into a secondary fuel.

Several mechanisms contribute to correct disposal of sludge in EU ports as the indirect financing mechanism for waste disposal in EU port and the requirement to document waste disposal in the oil record book. Scrubber sludge could, however, be processed illegally, due to the lack of systematic control and the financial incentive.

5 Scrubber business case

5.1 Introduction

In this section, we provide an overview of the costs of scrubbers, from a SECA perspective. Both investment and operational cost data is provided. This data is subsequently used for the development of a case study for a product tanker, taking due account of uncertainty factors like the fuel price difference, the number of days at sea and other ranges in available data.

The costs/benefit calculation in this chapter has been based on available data for a 38,500 DWT product tanker. It should be noted that the results can be different for other ship types, as a result of different operational profiles. Since Ro-Ro ships generally have a higher service speed, the attractiveness for scrubbers may be highest in this market, but this also depends on the annual number of hours at sea.

5.2 Analysis of scrubber costs

5.2.1 Investment costs

There is high uncertainty regarding scrubber costs due to the limited number of scrubbers currently in operation and the application of available cost data (in terms of € per installed kW) to different engine sizes. The reports concur that scrubber costs will be considerably higher for retrofit systems than for new systems and that closed systems are more costly than open ones.
AMEC estimates -based on discussions with industry- that the off service period for a ship for installing a scrubber is up to 28 days (AMEC, 2013). Furthermore, the report states those costs appear to not have been taken into account.

Table 8 Available investment cost figures

Study	Scrubber type	Newbuild Capex (€/kW)	Retrofit Capex (€/kW)	Installation* costs (€/kW)	Operation & Maintenance costs**
Entec (2009)	Open loop	122	156		1-3% of investment costs
AEA (2009)	Open loop - closed loop	100-200	200-400		€ 28,000 per year (12 MW vessel)
SKEMA (2010)	Open loop	118-168			0.3-0.8 €/MWh
DMA (2012)	Unknown	150	150	180-225	2.5 €/MWh
Greenship (2012)	Closed loop		363		
DFDS	Hybrid		~250		

Note: * The lower margin refers to newbuild costs, the upper margin to retrofit costs.
** The upper values represent small ships, lower values represent large ships.

Greenship estimates the off hire costs of a 38,500 DWT product tanker at 340,000 USD for a period of 20 days. Compared to the investment costs, this cost category seems to be relatively limited and not of significant influence (Greenship, 2012).

Both DMA and Greenship refer to contacts with various engine manufacturers and ship yards for data gathering (DMA, 2012); (Greenship, 2012). Because of the use of recent industry data and given that in recent years commercial application of scrubbers has increased, DMA and Greenship are deemed to be the most reliable and used for calculations (DMA, 2012); (Greenship, 2012).

5.2.2 Operational costs

Operational costs are influenced by the parameters as illustrated in Table 9.

Table 9 Operational cost data

Cost category	Assumptions
Caustic soda consumption (S-content 2.2%)	0.048 kg/kg HFO, € 200 per tonne 50%
Additional fuel consumption	1,5% for a seawater scrubber, 1% for a freshwater scrubber
Difference in fuel consumption	The energy content of MGO is higher, measured per ton (5%)
Slurry disposal	0,25 kg/MWh
Maintenance	0,25 €/MWh

In comparison with investment costs and the additional fuel costs, all of these cost categories are relatively limited. This is illustrated by the calculations in the following section.

5.3 Illustrative case study for ship installation (newbuild)

On the basis of available data from the literature, a case study for the product tanker MS Nord Buttarly has been constructed, calculating the costs and benefits of scrubber installation compared to the use of MGO. The data has been extracted from Greenship (Greenship, 2012) and from the tables above.

Table 10 Case study data for product tanker MS Nord Buttarly

Ship activity and installed power			
Days at sea	220		
Harbour, idling	115		
Harbour, unloading	30		
Power main engine	9,480	kW	
Power all 3 aux. engines	2,880	kW	
Ship fuel consumption			
At sea fuel consumption ME	HFO mode	28.7	t/d
	MGO mode	27	t/d
At sea AE	HFO model	3.7	t/d
	MGO mode	3.5	t/d
Harbour idling	HFO mode	4.3	t/d
	MGO mode	4.1	t/d
Harbour unloading	HFO mode	12.7	t/d
	MGO mode	11.9	t/d

Total fuel consumption	HFO mode	8,003	t/a
	MGO mode	7,538	t/a
Costs data			
HFO cost	575		$/ton
MGO cost	875		$/ton
Caustic soda	200		€/ton
Exchange rate	1.2		$/€
	SWS	**FWS**	
Investment+installation	300	375	€/kW
Caustic soda		0.096	kg/kg HFO
Additional fuel consumption	0.015	0.01	kg/kg HFO
Slurry disposal	2.825	2.825	kg/ton HFO
Maintenance	2.825	2.825	Euro/ton HFO

On the basis of the data on ship fuel consumption, activity data and cost figures, the calculations were made, with results as shown in Table 11.

Table 11 Results case study product tanker MS Nord Buttarly (x 1000 Euro)

	Seawater scrubber	Freshwater scrubber
Additional costs MGO fuel use	**1,662**	**1,662**
Scrubber costs		
Annual investment costs	1,482	1,854
Caustic soda consumption		153
Additional fuel costs	69	46
Slurry disposal costs	11	11
Maintenance	22	22
Total scrubber costs	**1,586**	**2,087**

The analysis above shows that MGO is more attractive in case of a freshwater scrubber. However, it should be noted that several factors influence the outcome of the analysis. The yearly costs for a FWS are € 425,000 in addition to the cost for MGO.

The use of a freshwater scrubber is € 500,000 more expensive than a seawater scrubber on annual basis, because of higher investment costs and caustic soda consumption. This explains the limited number of freshwater scrubbers installed on board of ships.

Retrofitting a scrubber is generally more expensive than installing a scrubber on a new ship, due to the space and weight requirements, machinery system's rearrangement and integration of the systems in the existing ship. The annual costs for a scrubber scenario would be € 250,000 higher in the central case, compared to the new build reference, assuming an additional investment cost of € 50/kW.

5.4 Impact analysis of variables

Various factors have influence on the return of investment time. Analysis showed that the following parameters have the greatest impact on the economics of scrubber installation:

- cost differential between HFO and MGO;
- number of days in ECA/at sea[4];
- depreciation period;
- Investment costs.

Other factors, like caustic soda consumption, additional fuel costs due to increased back pressure and increased power consumption, slurry disposal and scrubber maintenance play a relatively limited role in comparison to the fuel cost differential and annual investment costs.

The impact of the parameters has been analysed by use of the bandwidths illustrated in Table 12. Representative values have been used as central cases. The low case for fuel prices represent the fuel prices in early February 2015. The high case represents the case of August 2008. The high case fuel price difference is in line with values referenced in (AMEC, 2013).

The central case for the number of days at sea has been taken over from (Greenship, 2012). The high estimate represents a case where the number of days at sea (active days) is higher (e.g. under contract) and the lower end represents a case where the number of days in the SECA is significantly lower. The estimate for the depreciation period has been based on the statement from (CE Delft, ICCT, JS&A Environmental Services and Navigistic Consulting, 2011) that a depreciation period of 4 years is evaluated in the industry as a not sufficient incentive. For that reason, a 3.5 years payback time has been used as high case, 2.5 years as central value and 1.5 years as low value.

Investment costs may differ, depending on market conditions, the size of scale advantage and the ease of scrubber installation at a ship. The cases have been selected from the range available investment data. The labels optimistic, central and pessimistic have been used from the viewpoint of a positive business case for scrubbers.

Table 12 Optimistic, central and pessimistic cases for influencing parameters

Fuel price($/tonne)	HFO	MGO
Optimistic	850	1,200 (situation Aug. 2008)
Central	575	875 (situation Jan. 2014)
Pessimistic	280	520 (situation Feb. 2015)
Days at sea/in SECA		
Optimistic	286	Days at sea
	40	Harbour, idling
	39	Harbour, unloading
Central	220	Days at sea
	115	Harbour, idling
	30	Harbour, unloading

4 The number of days is used as an indicator net number of days in the SECA. This can be influenced by a higher number of ‘idling’ days, or operation outside the SECA.

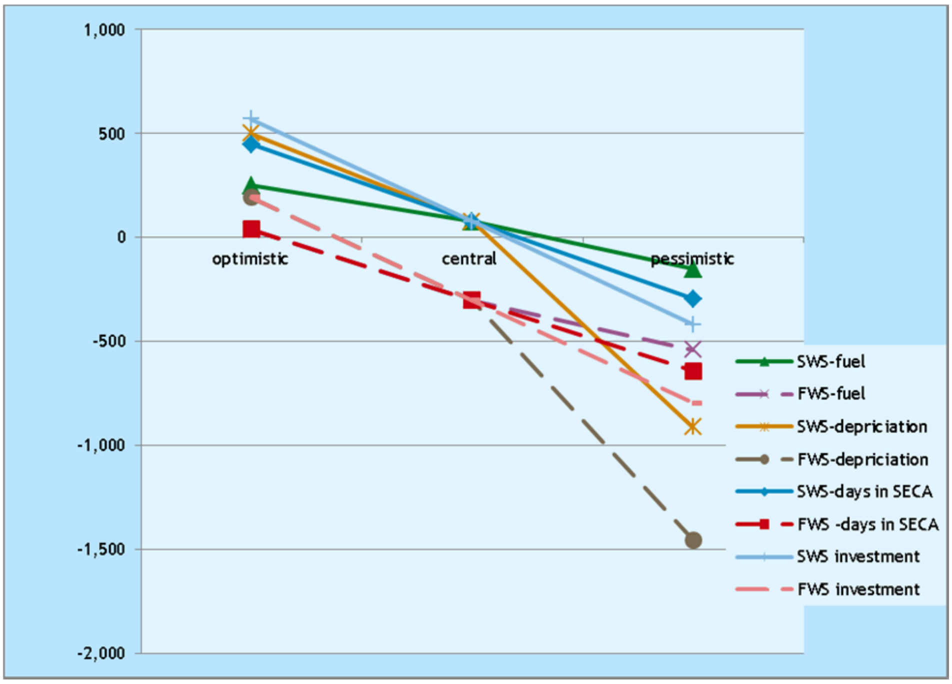
Pessimistic	154	Days at sea
	190	Harbour, idling
	21	Harbour, unloading
Depriciation period		
Optimistic	3.5	Years
Central	2.5	Years
Pessimistic	1.5	Years
Investment costs (SWS/FWS)		
Optimistic	200	€/kW
Central	300	€/kW
Pessimistic	400	€/kW

Figure 6 and Figure 7 provide the outcome of the analysis. Figure 6 illustrates the influence of high and low values for depreciation and investments, fuel price differences and the number of days in the SECA. A positive balance implies a positive business case for scrubbers, a negative balance implies a negative case for scrubbers. The graphs show that the impact of the period of depreciation is greatest. In case ship owners require a return on investment of 1.5 year, the annual scrubber cost will be 2 million euro per year higher than in case a return on vestment period of 3.5 years is acceptable. With the other parameters as 'central value' the business case is positive in case of 3.5 years of depreciation, but negative in case of 1.5 years of depreciation.

The impact of the other 'optimistic' and 'pessimistic' parameters from Table 12 on the business case has been estimated, and comparable conclusions can be drawn. The business case does not always lead to a winning situation for ship-owners: the 2008 fuel price difference may lead to a positive business case, while the fuel prices of early 2015 may not. The estimated future fuel price difference and the number of days at sea in the SECA seriously influence the business case. In contrast to the period of depreciation, which is a figure that can be controlled by the ship-owner, the future fuel price difference and the number of days at sea are variables that cannot be easily estimated in advance of investment decisions.

With the current limited difference in price between MGO and HFO, it is not easy to make a positive business case for scrubbers. Several ship-owners therefore have announced to postpone their investment decisions.

Figure 6 **Annual benefits of scrubber installation as function of various parameters (in euro x 1,000; relative to MGO use)**

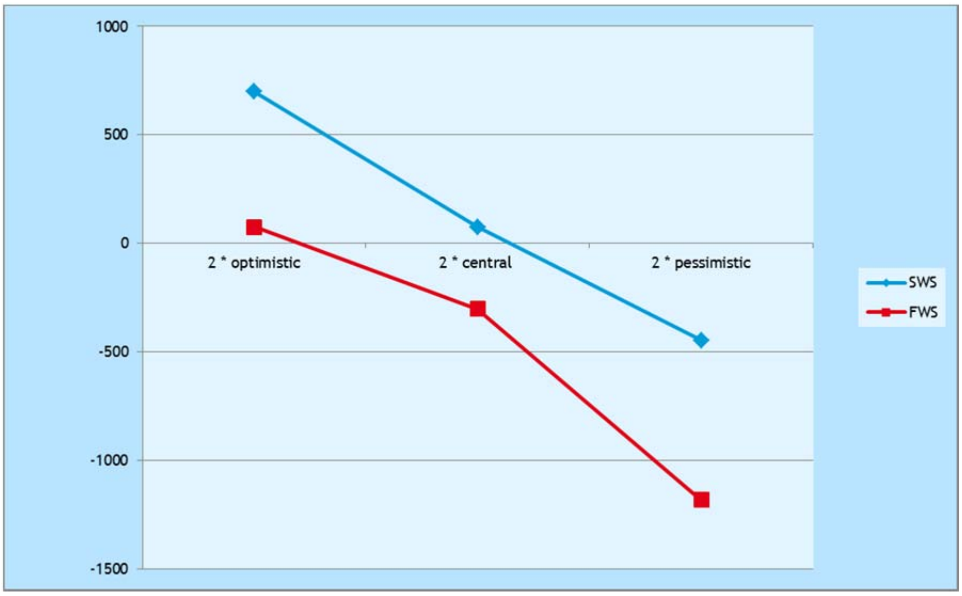


Note: Optimistic, central and pessimistic refer to the definitions from Table 12.

The investment costs and period of depreciation will be known prior to the investment decisions by ship-owners, however, the fuel price difference and the number of days in the SECA are more difficult to predict. Taking these variables into account, the difference between an 'optimistic' situation and a 'pessimistic' situation is around 1.1 million euros, see Figure 7. The most optimistic case for a seawater scrubber is a benefit of 0.7 million euro per year, in case of a situation with a high fuel price difference (in the year 2008) and a high number of days at sea. The most negative case is close to costs of 0.5 million euro per year, reflecting the February 2015 fuel price difference and a relatively low number of days at sea.

For a freshwater scrubber, the most optimistic case results in a benefit of 0.1 million euro, but for the other scenarios the ship-owner will have additional cost of between 0.6 million euro and 1.2 million euro per year.

Figure 7 **Annual benefits of scrubber installation as function of fuel price difference and days at sea (in euro x 1,000; relative to MGO use)**



Note: Optimistic, central and pessimistic refer to the definitions from Table 12.

The figures should be compared with the annual turnover of the ships. Based on a daily hire cost of 17,000 USD for this ship, the annual turnover of the ship is around 6 million euro, not taking fuel costs into account. This implies that scrubber costs can significantly influence the ship's business case.

The ship studied is representative for the fleet equipped with a scrubber in these days. For larger ships, with a higher fuel consumption and more hours at sea, the business case for scrubber installation can be more positive. However, these ships sail a larger share of time outside the SECA. In the period after 2020, the number of scrubber on larger ships may increase if the 0.5% fuel sulphur regime will be implemented outside ECAs.

5.5 Liquified natural gas

LNG is another option for reducing pollutant emissions. However, also for LNG applies that the future fuel price is uncertain, which makes it difficult to develop a business case. In the case of LNG, not only the reference MGO price is uncertain, but also the LNG price. The future LNG price is linked to the oil price to some extent, but will also be subject to demand from other sectors (power generation) and supply and demand (e.g. availability of shale gas).

The investment costs are estimated to be around € 625-675/kW for low and high pressure dual fuel engines (DMA, 2012). Again, the fuel price difference, the depreciation period and the number of days at sea or in the SECA strongly influence the business case's results. The parameters used for the optimistic, central and pessimistic situation are shown in Table 13. The corresponding results are depicted in Figure 8.

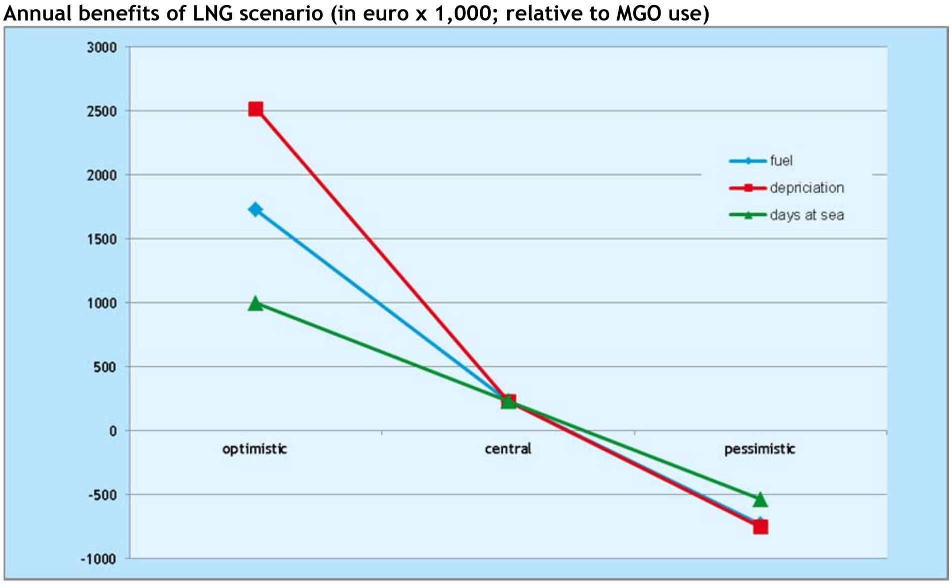
Table 13 **Optimistic, central and pessimistic cases for influencing parameters**

Fuel price	**LNG ($/mmBTU)**	**MGO ($/tonne)**
Optimistic	15	1,200
Central	11	875 (Jan. 2014)
Pessimistic	6.8	520 (Feb. 2015)
Days at sea/in SECA		
Optimistic	286	Days at sea
	40	Harbour, idling
	39	Harbour, unloading
Central	220	Days at sea
	115	Harbour, idling
	30	Harbour, unloading
Pessimistic	154	Days at sea
	190	Harbour, idling
	21	Harbour, unloading
Depriciation period		
Optimistic	3.5	Years
Central	2.5	Years
Pessimistic	1.5	Years

Under ‘central’ conditions, the business case for LNG is slightly positive, Figure 8 shows. A high fuel price difference, a high number of days at sea and a long depreciation period results in strongly positive business case (+5,5 million).

Based on the ‘pessimistic’ fuel price conditions of this moment, the business case is negative, due to the low fuel price difference. The same is true in case of a limited number of days at sea.

Figure 8 **Annual benefits of LNG scenario (in euro x 1,000; relative to MGO use)**



Note: Optimistic, central and pessimistic refer to the definitions from Table 13.

It should also be noted, however, that the value of an LNG ship may reduce in case the developed of the required bunkering network will not evolve.
This may impact the second hand value of a ship.

6 Conclusions and discussion

6.1 Introduction

In this chapter, the main conclusions are drawn and the study's results are discussed.

6.2 Market and outlook

The scrubber market is highly dynamic at the moment, due to the recent tightening of the SECA fuel sulphur limits. The number of scrubbers installed on ships has increased significantly over the last years. About 80 scrubbers are installed at the world fleet at the moment, with greatest interest for hybrid and open-loop scrubbers. The number of orders amounts 300 at the time of writing. Available outlooks forecast a potentially more important role for scrubbers in the next decades as a means to reduce sulphur emissions, but at the moment the majority of ship owners switched to MGO and investments have been postponed.

6.3 Environmental impacts

Scrubbers reduce the emissions of sulphur to the atmosphere by more than 90%. Also PM emissions are reduced significantly in terms of their mass (not in number), by 60-90%. The emissions of NO_x are reduced by 10% or less. Due to the additional power needed to drive pumps and caustic soda consumption, the estimated additional GHG emissions range between 1.5 and 3.5%, including caustic soda consumption. It should be noted, however, that also the use MGO in the SECA causes an increase of GHG refinery emissions of roughly 6.5%.

Concentrations of hazardous substances in the discharge of closed loop systems are higher than in open loop systems, but the mass flow rate of these substances determines the environmental burden. This is larger in case of open loop scrubbers, which are not always equipped with discharge water cleaning systems. The current dominance of seawater and hybrid scrubbers indicate that a large share of the pollutants captured in the wash water may be released to the seawater.

Due to the release of wash water, the use of distillate fuels or LNG is inherently cleaner compared to the use of open loop scrubbers. Especially in case of vulnerable ecosystems in e.g. estuaries. In addition, the risk of pollution and contamination in case of accidents is also highest for HFO. Additional impacts of increased MGO production on land, apart from increased energy use, are expected to be limited, due to the stringent environmental legislation.

IMO has issued criteria for the scrubber wash water that needs to be met on pH, nitrates, and hazardous hydrocarbons. All measured wash water concentrations are well below the thresholds from IMO wash water guideline, but the available measurements show variation in pollutant concentrations.

Although the IMO criteria are met, scrubbers may have an impact on acidification and accumulation of hazardous substances like heavy metals and PAHs, especially in vulnerable coastal areas where dilution is limited and the water quality is reported to be moderate. Increased use of scrubbers may lead to a deterioration of the water quality.

The long term impacts of the use of open loop scrubbers should be further investigated systematically by measuring and modelling in order to prevent negative cumulative environmental impacts of scrubber waste water discharge. It should be evaluated if scrubbers can be used in accordance with the European Water Framework Directive that sets maximum concentrations for certain hazardous pollutants, especially in the near of dense shipping routes and vulnerable estuaries.

Since the currently available research does not irrefutably exclude the deterioration of the environmental status of the vulnerable (near shore) ecosystems, it is not clear if objectives set by the Marine Strategy Framework for achieving 'good environmental status' can be met by the year 2020 and later on, taking into account a growth in the number of scrubbers installed. As to protect against potential contamination, few countries prohibited the discharge of scrubber wash water in their waters.

It should be noted that some of the metals discharged are not related to the composition of the fuel, but related to engine wear and tear and the composition of lube oil.

6.4 Scrubbers' business case

The installation of scrubbers requires significant investment costs. Typical installation costs range between 200 and 400 EUR/kW, which imply an investment of several millions, depending on a ship's engine power.

It is difficult to draw firm conclusions on the profitability of using scrubbers, as this depends on the operational profile of the ship, the difference between HFO and MGO prices, and the time ships sail in SECAs. The fuel price difference between MGO and HFO ranged between 240 and 300 $/ton between January 2014 and February 2015. When the difference is high, scrubbers are profitable in more cases than when the difference is low. The prediction of a ships' future utilization is an important parameter that varies between markets.

Under optimistic conditions, ship owners may be able to offer services at relatively low prices, but consequently there is a risk that scrubbers may lead to higher transport costs for operators instead of lower. The annual depreciation costs of scrubber installations are relatively high in comparison to a ship's annual hire costs, illustrating the significance and potential risk of the investment. Table 14 provides an overview of the impact of uncertain parameters on the annual benefits of scrubber installation.

Table 14 **Impact of fuel price difference and number of days at sea (SECA) for a 38,500 DWT product tanker**

	Annual benefits of seawater scrubber installation
Fuel price difference of 350 $/ton and 286 days at sea	+0.7 million
Fuel price difference of $240 $/ton and 154 days at sea	-0.5 million

Due to the additional costs of caustic soda consumption, it is likely that hybrid scrubbers will be used in open loop where possible and that the number of fresh water scrubbers installed will remain limited.

To assess the cost and benefits for the society as a whole, the benefits for ship owners would need to be weighed against the potentially harmful impacts of scrubbers on vulnerable coastal ecosystems and the lower lifecycle GHG emissions of using HFO and scrubbers. Such an analysis is conditional to the availability of monitoring and modelling of the impact of scrubbers on the water quality and marine ecosystems.

7 Bibliography

ABS, 2013. *Exhaust Gas Scrubber Systems : Status and Guidance,* Houston: ABS.

AEA, 2009. *Cost Benefit Analysis to Support the Impact Assessment accompanying the revision of Directive 1999/32/EC on the Sulphur Content of certain Liquid Fuels,* Didcot (UK): AEA technology plc.

AMEC, 2013. *Impact on Jobs and the Economy of Meeting the Requirements of MARPOL Annex VI,* s.l.: AMEC Environment & Infrastructure UK Limited.

Buhaug, Ø., Fløgstad, H. & Bakke , T., 2006. *Washwater Discharge Criteria for Exhaust Gas-SOx Cleaning Systems, MEPC 56/INF.5, 6 April 2007, MEPC, 56th session, Agenda item 4, Submitted by the United States,* s.l.: Marine Environment Protection Committee (MEPC).

CE Delft, ICCT, JS&A Environmental Services and Navigistic Consulting, 2011. *Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures MEPC 62/INF.7,* sl: IMarEST.

CE Delft, 2015. *The Market for Scrubbers,* Delft: CE Delft.

CONCAWE, 2009. *Impact of marine fuels quality legislation on EU refineries at the 2020 horizon ,* Brussels: CONCAWE.

Corbett, J. J. & Winebrake, J. J., 2008. Emissions tradeoffs among alternative marine fuels: Total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil. *Journal of Air & Waste Management,* Volume 58, pp. 538-542.

COWI, 2012. *Exhaust Gas Scrubber Installed Onboard MV Ficaria Seaways : Public Test Report , Environmental Project No. 1429,* s.l.: COWI.

DMA, 2012. *North European LNG Infrastructure Project: A feasibility study for an LNG filling station infrastructure and test of recommendations, full report,* Copenhagen: Danish Maritime Authority (DMA).

EC, 2008. Directive 2008/56/EC of the European Parliament and of the Council of june 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework). *Official Journal of the European Union,* Issue L164, pp. 19-40.

EC, 2013. Directive 2013/39/EU of the European Parliament and of the Council of 12 august 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. *Official Journal of the European Union,* 24 8, Issue L226, pp. 1-17.

EMSA, 2010. *The 0.1% sulphur in fuel requirement as from 1 January 2015 in SECAs : An assessment of available impact studies and alternative means of compliance,* Lissabon: European Maritime Safety Agency (EMSA).

Entec, 2010. *Study To Review Assessments Undertaken Of The Revised Marpol Annex VI Regulations, Final report,* Londoin: Entec UK Limited.

EPA, 2011. *Exhaust Gas Scrubber : Washwater Effluent (EPA-800-11-006),* Washington: United States Environmental Protection Agency.

GESAMP, 2009. *Advice by GESAMP on the interim criteria for discharge of washwaterfrom Exhaust Gas Cleaning Systems for removal of sulphur-oxides,* London: GESAMP.

Greenship, 2012. *Greenship of the future – Vessel emission study: comparison of various abatement technologies to meet emission levels for ECA's "ECA retrofit technology".* [Online]
Available at:
http://www.greenship.org/fpublic/greenship/dokumenter/Downloads%20-%20maga/ECA%20study/GSF%20ECA%20paper.pdf
[Accessed 2015].

Hassellöv, I.-M., Turner, D. R., Lauer, A. & Corbett, J. J., 2013. Shipping contributes to ocean acidification. *Geophysical Research Letters,* Volume 40, pp. 2731-2736.

Hufnagl, M., Liebezeit, G. & Behrends, B., 2005. *Effects of SeaWater Scrubbing, Final report,* s.l.: BP Marine.

IMO, 2009. *2009 Guidelines for Exhaust Gas Cleaning Systems (IMO Annex 9, Resolution MEPC.184(59), adopted July 17, 2009),,* London: IMO.

Køcks, M. et al., 2012. *Shipboard characterization of a wet scrubber system:Influence on particle number concentration, particle size distribution and chemical composition.* Aarhus, et al., Danish Technological Institute, et al..

Lappi, M., Hänninen, S. & Murtonen, T., 2012. *Origin of particle emissions of a new IMO NOx Tier 2 category cruising ship compliant with European SOx emission control areas.* s.l., VTT Technical Research Centre of Finland.

Litehauz, 2012. *Investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping,* Copenhagen: Litehauz.

Lloyds & UCL, 2014. *Global Marine Fuel Trends 2030,* London: Lloyds & UCL.

Lloyds Register , 2012. *LNG-fuelled deep sea shipping: The outlook for LNG bunker and LNG-fuelled newbuild demand up to 2025,* London: Lloyds Register.

Ma, H., Steernberg, K., Riera-Palou, X. & Tait, N., 2012. Well-to-wake energy and greenhouse gas analysis of SOX abatement options for the marine industry. *Transportation Research,* 17(Part D), pp. 301-308.

SKEMA, 2010. *Impact Study of the future requirements of Annex VI of the MARPOL Convention on Short Sea Shipping'.* [Online]
Available at: http://www.eskema.eu/defaultinfo.aspx?topicid=189&index=1
[Accessed 2015].

UBA, 2014. *Auswirkungen von Abgasnachbehandlungsanlagen (Scrubbern) auf die Umweltsituation in Häfen und Küstengewässern, TEXTE 83/2014,,* Bremen: Umweltbundesamt (UBA).

Wärtisilä, 2010. *Exhaust gas scrubber installed onboard MT "SUULA" : public test report.* [Online]
Available at:
http://www.wartsila.com/file/Wartsila/1278517851584a1267106724867-Wartsila-Scrubber-Test-Report-_final_2.pdf.
[Accessed 2015].