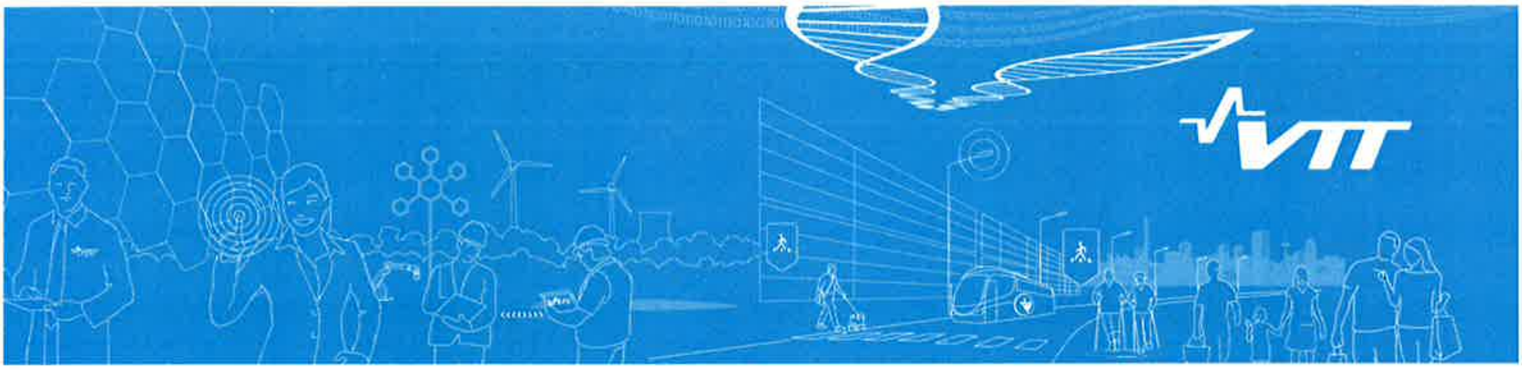

CUSTOMER REPORT

VTT-CR-02008-16 | 11.5.2016

Technical Study on Scrubber Waste Management

Authors: Elina Merta, Saara Hänninen & Jutta Laine-Ylijoki

Client: Helsingin Satama Oy

Confidentiality: Confidential

Co-financed by the European Union
Connecting Europe Facility

Report's title	
Technical Study on Scrubber Waste Management	
Customer, contact person, address Helsingin Satama Oy Aino Rantanen PL 197, 00141 HELSINKI aino.rantanen@portofhelsinki.fi +358 9 310 33521	**Order reference**
Project name Technical Study on Scrubber Waste Management	**Project number/Short name** 109121 ScruWa

Summary

The aim of this technical study on scrubber waste management, commissioned by the Port of Helsinki, was to gather relevant information on the current status of the application of SO_x (sulphur oxides) scrubber technologies in ships and explore possible management options for sludge and wash water produced by ships equipped with scrubbers.

Based on purification medium and mode of operation there are various types of scrubber systems. Wet scrubbers can be either open loop or closed loop scrubbers, or hybrids which can be operated in open or closed loop mode, and dry scrubbers. The waste fractions generated by wet scrubbers include sludge (closed loop and some open loop scrubbers) and effluent (treated wash water from closed loop scrubbers). The characteristics of scrubber wastes depend on the components of exhaust gas which in turn are influenced by the quality of the fuel used and completeness of combustion. The gaseous sulphur oxides are trapped in the scrubber water where they react to sulphuric and sulphurous acid (the latter being oxidised further to sulphuric acid). The particulate matter captured by the scrubber can contain metal oxides and sulphates, soot, and other organic compounds. The effluent can in some cases be delivered to the port but it can be expected that mostly the treated effluents are discharged to sea. The sludge cannot be discharged into sea and the ports have to provide reception facilities according to MARPOL Annex VI Regulation 17.

The overall trend is that scrubbers will become more common, especially in the cruise liners being a large customer segment using the facilities provided by the Port of Helsinki. There are multiple possible management options for both effluent and scrubber sludge. The choice of the most feasible option is dependent on the expected quantities and qualities of effluent and sludge, and therefore there is a need to gather more precise information on this matter. This report proposes a number of measures to support the port in taking needed actions.

Espoo 11.5.2016

Written by	Reviewed by	Accepted by
Elina Merta, Research Scientist	Saara Hänninen, Senior Scientist	Jutta Laine-Ylijoki, Senior Scientist

VTT's contact address
Biologinkuja 7, P.O. Box 1000, FI-02044 VTT, FINLAND

Distribution (customer and VTT)
Helsingin Satama Oy/Aino Rantanen
VTT project team, central archive

The use of the name of the VTT Technical Research Centre of Finland (VTT) in advertising or publication in part of this report is only permissible with written authorisation from VTT Technical Research Centre of Finland.

Contents

Abbreviations

BOTU	Bleed-off treatment unit
CEF	Connect Europe Facility
CLIA	Cruise Lines International Association
COD	Chemical Oxygen Demand, mg/l. Common test used to indirectly measure the amount of organic compounds in water.
DAF	Dissolved Air Flotation
DW	Dry weight, mass-%
EGCS	Exhaust Gas Cleaning Systems
ESSF	European Sustainable Shipping Forum
EU MS	European Union Member State
HFO	Heavy Fuel Oil
HSY	Helsinki Region Environmental Services Authority
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LOI	Loss on ignition, % of DW. Can be used as a measure of the organic content of a sample.
NABU	Nature and Biodiversity Conservation Union
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
PAH	Polyaromatic Hydrocarbons
pH	Acidity
PRF	Port Reception Facility
SECA	Sulphur Emission Control Area
SO_x	Sulphur oxides, e.g. sulphur dioxide, SO_2
SS	Suspended Solids, mg/l. Refers to small solid particles which remain in suspension in water as a colloid or due to the motion of the water.
Tot-N	Total nitrogen
Tot-S	Total sulphur
UBA	German Environmental Protection Agency
VOC	Volatile Organic Compounds. Organic chemicals that have a high vapor pressure at ordinary room temperature.
WFD	Water Framework Directive (2000/60/EC)

1. Preface

This technical study on scrubber waste management, commissioned by the Port of Helsinki, was conducted by reviewing existing studies, literature, interviews and available public data on SO_x scrubber wash waters and wastes. As a result of the study the possible management options at the Port of Helsinki are listed and evaluated both technical and economical wise, if possible. Based on the review results insights for best practices for scrubber residue (sludge) and wash water management in the Port of Helsinki are given.

The project manager at VTT was senior scientist Jutta Laine-Ylijoki and the project members included research scientist Elina Merta, senior scientist Saara Hänninen and senior scientist Ulla-Maija Mroueh. During the work three face-to-face meetings with the client were held.

The study was realised as a part of EU project "Black from Black - Study and deployment of the affordable scrubber retro fitting technology for SME shipowners" (2014-EU-TM-0379-M).

2. Introduction and objectives

Ship emissions are regulated internationally by the International Maritime Organization (IMO). As a result of the implementation of the revised Annex VI of MARPOL in January 2015, in Sulphur Emission Control Areas (SECAs) marine fuel with a maximum sulphur content of 0.1% only is allowed. As an alternative to low-sulphur fuels, exhaust gas after-treatment units called scrubbers can be utilised to reduce air pollutant emissions to a required level.

Use of scrubber produces wash water when the sulphur is washed out from the exhaust gas. Wet scrubbers can be either open loop or closed loop scrubbers, or hybrids which can be operated in open or closed loop mode. Open loop sea water scrubbers re-circulate the wash water back to sea. In the closed loop scrubbers, the bleed-off water is brought to a treatment unit to obtain cleaned effluent and sludge. Sludge is placed in a holding tank and delivered to port and furthermore to appropriate waste disposal plant. Cleaned wash water (effluent) can be discharged into sea when it fulfils the set criteria. The regulations on scrubber wash water quality can be found in the 2015 IMO Resolution MEPC.259(68) (IMO, 2015).

Discharging open loop scrubber wash water as well as closed loop scrubber effluent into the sea are both topical matters at the moment. Although the qualities and quantities fulfil the IMO criteria, local authorities are entitled to impose stricter restrictions on ship based discharges within their area.

Currently, the discharge of scrubber wash water is being prohibited in some EU Member states (MSs, such as Germany and Belgium) in certain limited waters/port areas based on national implementation of the Water Framework Directive (WFD) and potentially other local laws. Furthermore, other MSs (such as Estonia) are questioning the discharge of scrubber wash water in limited areas. New limitations pose trouble especially for the scrubbers used in open loop mode since the wash water amounts are very large. With the scrubbers that can be operated in closed loop mode, the wash water can be collected in the holding tank and discharged in areas where accepted or delivered at port.

The management and treatment of scrubber wastes and wash water at ports is becoming more topical also in the Baltic Sea. The objective of the commission is to explore from both technical and economic point of view the management options that the Port of Helsinki has for diverse scrubber wash waters and residue (hereafter also called as sludge).

3. Overview on the legislative framework

3.1 Regulations on ship emission control

Ship emissions are regulated internationally by the International Maritime Organization (IMO) and must comply with the limits prescribed in Annex VI of MARPOL in particular. In order to reduce sulphur emissions, worldwide limits on the sulphur content of marine fuel are established. As a result of the implementation of the revised Annex VI of MARPOL in January 2015, marine fuel with a maximum sulphur content of 0.1% only is allowed in Sulphur Emission Control Areas (SECAs). As of 2020, or alternatively as of 2025 depending on the availability of fuel, a 0.5% sulphur limit will apply worldwide. As an alternative to low-sulphur fuels, exhaust gas after-treatment units called scrubbers can be utilised to reduce air pollutant emissions to a required level. Similarly, European Union Directive 2012/33/EU (EU, 2012) requires all ships sailing in SECAs – one of which is the Baltic Sea – to use fuels with a maximum sulphur content of 0.1% or emission abatement methods, such as scrubbers.

Scrubbers can be applied both for new constructions and retrofit projects. The decision to install a system and partly also the choice between the different types depends e.g. on the cost of low sulphur fuels, capital and operating expenditure of the scrubber, or time spent in SECA. (Klopott, 2015)

3.2 Regulations on scrubber waste and water management

According to IMO resolution MEPC.259(68), the residues generated by the EGC unit may not be discharged to the sea or incinerated on board (IMO, 2015). Port reception facilities (PRF) are regulated in MARPOL Annex VI Regulation 17 (IMO, 2011). It states that reception facilities for exhaust gas cleaning residue (sludge) from ships must be ensured in ports.

The regulations on scrubber wash water quality can be found in the 2015 IMO Resolution MEPC.259(68). The scrubber wash water may cause environmental degradation through short-term and spatially limited pH value reduction, increase in temperature and turbidity as well as pollutant discharge of sometimes persistent materials. Furthermore, according to the proposed amendments to the 2015 Resolution MEPC.259(68), *"when the EGC system is operated in ports, harbours, or estuaries, the wash water monitoring and recording should be continuous. The values monitored and recorded should include pH, Polyaromatic Hydrocarbons (PAH), turbidity and temperature. In other areas the continuous monitoring and recording equipment should also be in operation, whenever the EGC system is in operation, except for short periods of maintenance and cleaning of the monitoring equipment."* (ESSF, 2016a)

If the set wash water discharge criteria are fulfilled, IMO regulations do not give additional restrictions, e.g. related to location of discharges of scrubber wash water (such as 3 or 12 nautical miles minimum distance from shore that is in force for discharging sewage). Consequently, the scrubbers can be in operation in either mode unless specifically prohibited by local authorities.

Currently, the discharge of scrubber wash water is being prohibited in some EU Member states (MSs, such as Germany and Belgium) in certain limited waters/port areas based on national implementation of the Water Framework Directive (WFD) and potentially other local laws. Furthermore, other MSs (such as Estonia) are questioning the discharge of scrubber wash water in limited areas. These area-specific restrictions concern all scrubber types. However, these restrictions do not pose any trouble for closed loop scrubbers since their wash water volumes are small enough to be temporarily stored on-board in a holding tank and discharged when at sea or delivered ashore. The matter is especially relevant to new diesel-electric cruise ships, equipped with open loop scrubber, where there are no separate main and auxiliary engines (auxiliary usually burning 0.1 S-% marine gas oil (MGO) in port) but possibility to operate always on heavy fuel oil (HFO) (with scrubber in the emission control areas, of course). The issue has been discussed also in the Sub-Group on EGCS in the European Sustainable Shipping Forum in 4 November 2015 (ESSF, 2015).

Studies regarding the environmental impact of using scrubbers in open loop mode have been done and are on-going. For example Nature And Biodiversity Conservation Union (NABU) has commissioned an economic and ecological assessment of scrubbers (den Boer and Hoen, 2015) and German Environmental Protection Agency (UBA) will launch a research project in 2016 which will investigate the cumulative impacts of scrubber wash water (Hamburg Port Authority, 2015).

4. Scrubber types and technologies for emission control in ships

4.1 Scrubber types

The cleaning effect in a scrubber results from the fact that the combustion exhaust gases from the engine are passed through a purification medium. This can be seawater, fresh water with a suitable additive (usually sodium hydroxide) or dry granules. The majority of the exhaust constituents is dissolved or reacts chemically with the ingredients of the water or the granules and is removed from the exhaust gas stream. (Lange et al., 2015) The primary target pollutants are the sulphur oxides but simultaneously also particulate matter is removed thus reducing the airborne emissions of heavy metals, soot, PAH's and also sulphur bound to the particles (Kjølholt et al., 2012).

Based on purification medium and mode of operation there are various types of scrubber systems. Wet scrubbers can be either open loop or closed loop scrubbers, or hybrids which can be operated in open or closed loop mode, and dry scrubbers. All these scrubber systems achieve the required emission reduction, but wastes and wash waters they produce differ in terms of qualities and quantities requiring therefore different practises at ports.

4.1.1 Wet scrubbers

In wet scrubber systems the sulphur dioxide from the exhaust gas dissolves in water to form sulphurous acid H_2SO_3 which dissociates in solution into bisulphate/sulphite which are further oxidised to sulphate and hydrogen ions. The resulting water has a pH level of ca. 3. In the scrubber the water is neutralised by the natural alkalinity of seawater or alkaline additives. (Lange et al., 2015)

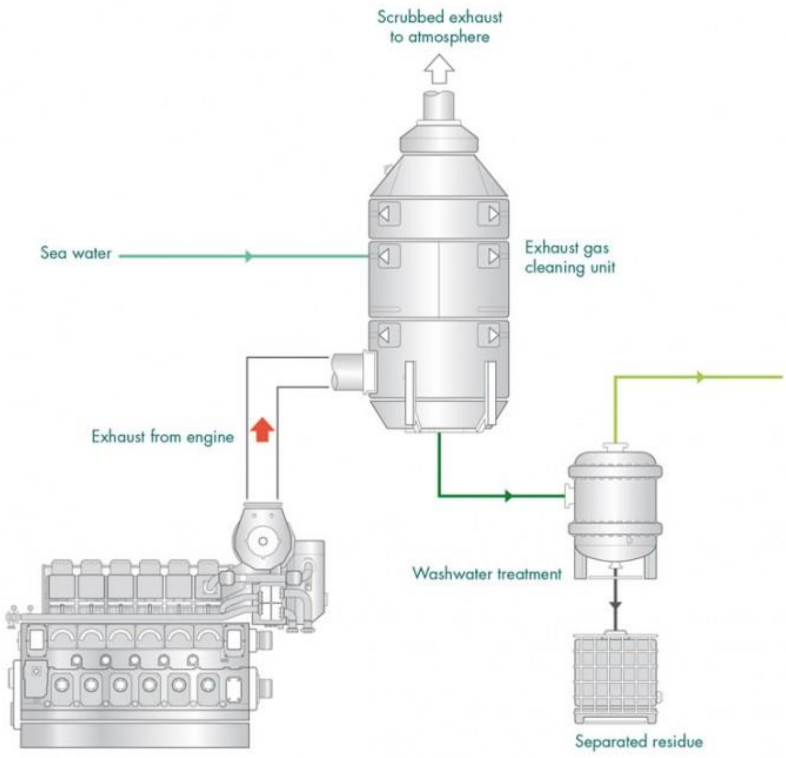

Figure 1. Exhaust gas cleaning system basic components (EGCSA, 2016)

In wet scrubbers (Figure 1) the mixing of exhaust gas and wash water is realised by letting the gas pass through a spray of wash water or bubbling it through water.

A schematic of an open loop scrubber is shown in Figure 2. In open loop system by Wärtsilä seawater is used directly as wash water in scrubber and used wash water is stored in a residence tank to allow gas separation from water and contribute to subsequent solids removal in hydrocyclone. Separated solid phase is stored in sludge tanks (typically standardized IBC containers) where it is let to settle. The separated water phase is pumped back to the residence tank and further again to hydrocyclones before discharge overboard. Additional sea water may be pumped to dilute the discharge to meet the pH requirements when operating near ports. Sludge is stored in the container and disposed of ashore. (Wärtsilä, 2014) There are also commercial open loop scrubbers on market that do not produce any sludge (e.g. Alfa Laval PureSOx system and Langh Tech). Thus, in these systems there will be no waste requiring management at port.

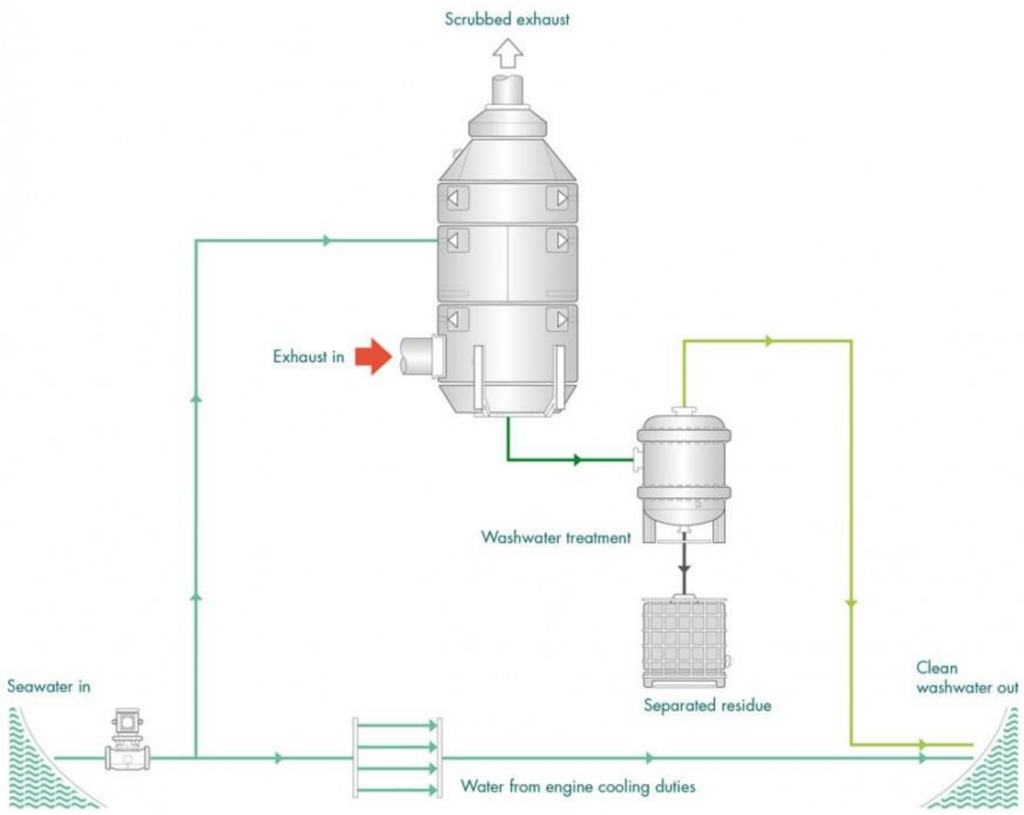

Figure 2. Open loop exhaust gas cleaning system (EGCSA, 2016)

In closed loop, or fresh water system (Figure 3), wash water is used multiple times and only a small flow of water is extracted from the circulation. Used wash water is collected in a process tank and mostly circulated back to scrubber. In order to maintain the purification results a small quantity of wash water, so-called “bleed-off”, is transferred from the bottom of the tank to bleed-off treatment unit (BOTU) where it is divided into sludge and effluent meeting the effluent quality requirements. (den Boer and Hoen, 2015)

In closed loop system by Wärtsilä, BOTU technologies include dissolved air flotation (DAF), which is chemical-mechanical process or centrifugal separator which is fully mechanical process. In DAF system the bleed-off is first aerated in a buffer tank to oxidize sulphites to sulphates. The main module houses an influent feed pump, a chemical dosing system, a flotation stage, sludge removal system, discharge holding tank and effluent discharge pump. The sludge from BOTU is stored in sludge tank in a similar manner as in open loop systems. Optionally, an additional dewatering unit may be used to further reduce the water content of sludge to form a nearly solid product (also applicable to sludge from open loop system). The effluent of BOTU can be discharged overboard or stored in a holding tank to enable a zero-discharge mode. The removed bleed-off is replaced with fresh seawater together with addition of alkaline chemical. (Wärtsilä 2014)

When discharged, the effluent carries the sulphur flows into the sea and is efficiently diluted into the sea water when the ship is moving. The dilution of 1:2 000 is estimated 50 meters after the stern (Niemi *et al.*, 2006). It has also been brought up that the closed loop scrubber effluent discharge is diluted to a lesser extent in ports, estuaries and rivers (Lahtinen, 2016a). The local authorities may set zero emission requirements, forcing the effluent to be pumped into a holding tank and further to municipal sewage system (if the quality fulfils the local acceptance criteria) or discharged to open sea.

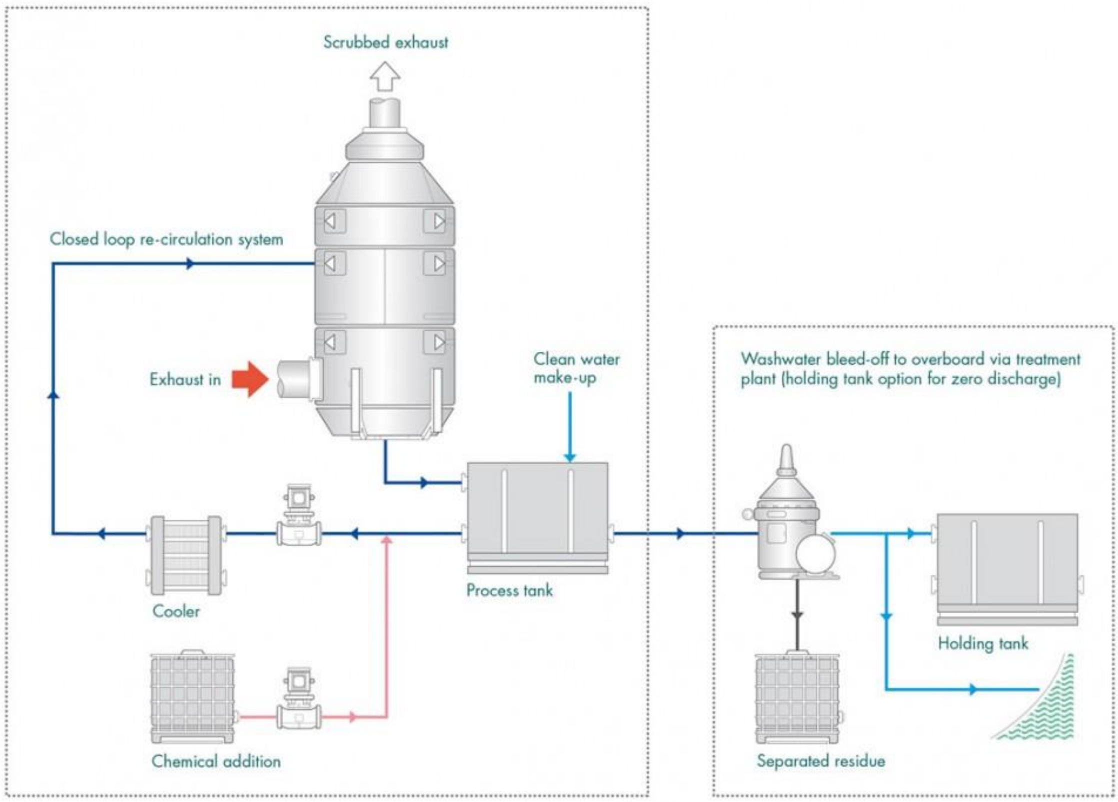

Figure 3. Closed loop exhaust gas cleaning system (EGCSA, 2016)

Hybrid scrubbers offer the possibility to operate in open or closed loop mode (Figure 4 and Figure 5).

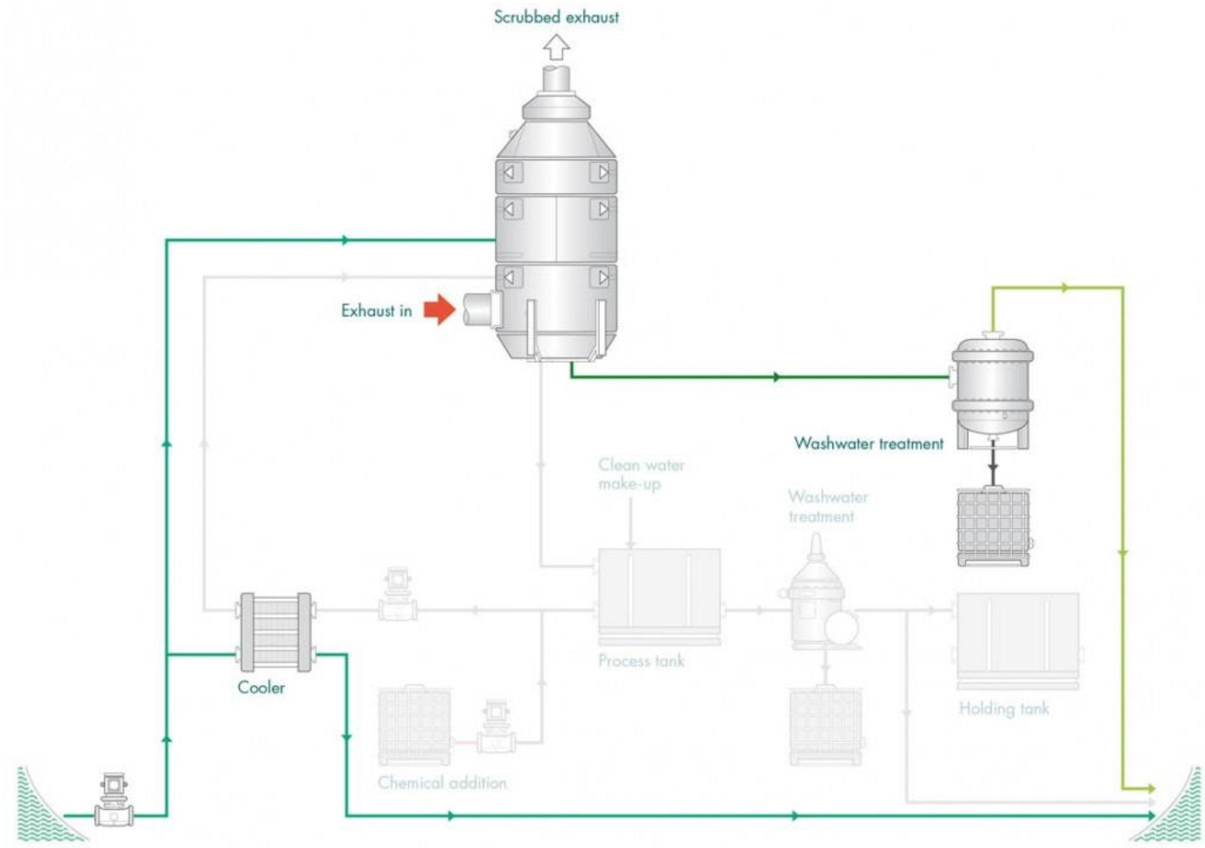

Figure 4. Hybrid exhaust gas cleaning system in open loop operation (EGCSA, 2016)

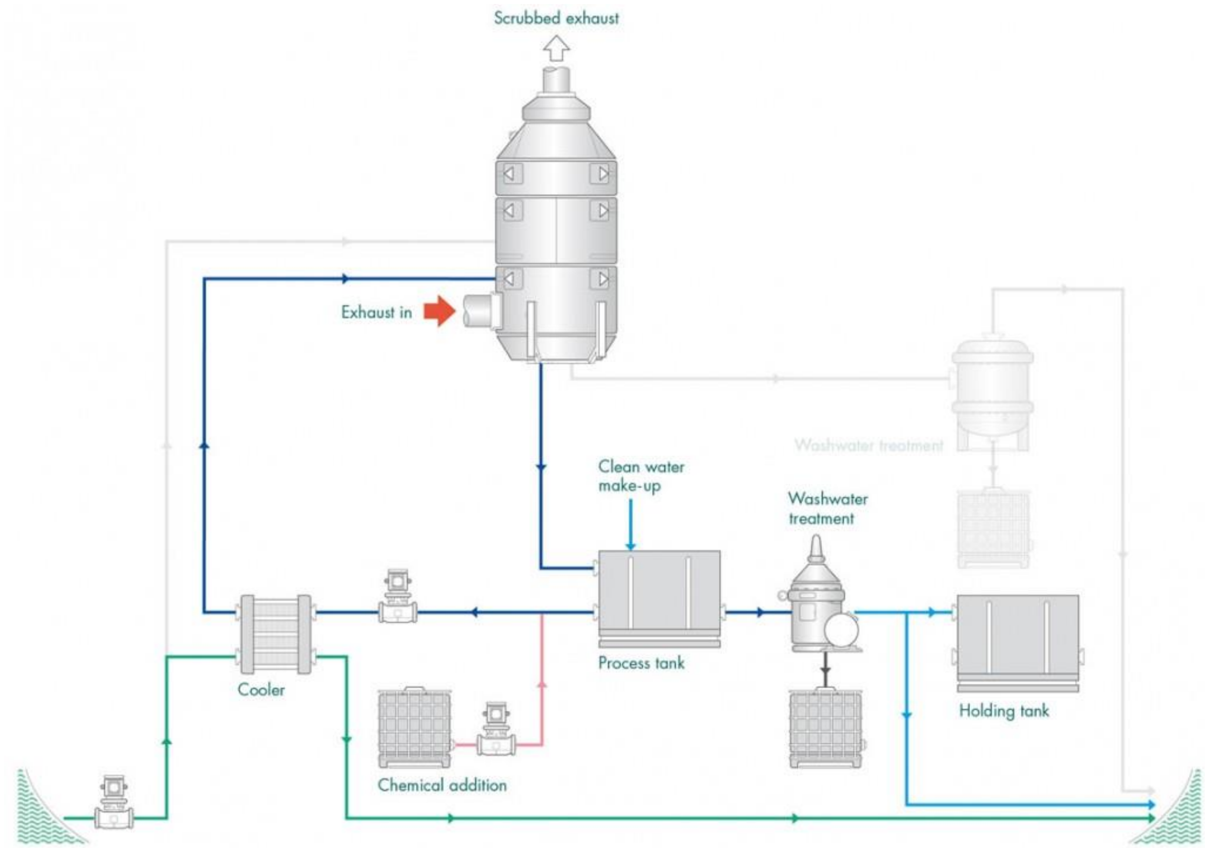

Figure 5. Hybrid exhaust gas cleaning system in closed loop operation (EGCSA, 2016)

From the environmental point of view, the main advantage of the closed loop scrubber systems compared to open loop systems is the good control of pollutants in the marine environment as there is a possibility to operate without wash water discharges if needed. Furthermore, the gas cleaning result in closed loop system is independent of the surrounding seawater quality. (Lange et al., 2015; den Boer and Hoen, 2015)

From an operational perspective, the energy consumption of open loop systems is typically larger compared to closed loop systems due to high water streams needed, especially in sea areas with low alkalinity. Manufacturers indicate that a closed loop scrubber requires about half or less of the wash water flow compared to an open loop scrubber to achieve the same scrubbing efficiency. The closed loop system also works with the same efficiency independently of the ambient seawater chemistry. On the other hand, in open loop systems there is no need for chemical additives and no need to store any hazardous substances on-board. (den Boer and Hoen, 2015; ABS, 2013)

4.1.2 Dry Scrubbers

Dry scrubbers have been long used as a desulphurisation method for exhaust gases from power plants but the system has not thus far been widely used in marine applications. The system uses granulates of $Ca(OH)_2$ which react with SO_x to form calcium sulphate, i.e. gypsum. The usage rate of lime is high and the system requires relatively large storage and material handling capacities for both input and output materials on-board. (ABS, 2013)

ConRo vessel Oceanex Connaigra, built in 2013 at FSG shipyard, features one of the few dry scrubbers on-board (Ship Technology, 2016). Oceanex's dry scrubber exhaust gas cleaning system is designed by Couple Systems that went bankruptcy in January 2014. Another German company, Hellmich GmbH, has agreed to deliver dry scrubber systems on-board two vessels, Timbus and Cellus of the shipping company Rörd Braren (Rettig, 2014). According to (Nordström, 2015) the Hellmich dry scrubber has also been tested on-board Bore's M/V Seagard.

4.2 Status of scrubber technologies in selected markets

Even though the oil price has fallen remarkably during the last years, and the fact that marine gas oil (MGO) is now cheaper than heavy fuel oil (HFO) was a few years back, it is still economical to fit a ship with a scrubber since the price difference between MGO and HFO has remained approximately the same. In his Doctoral Thesis, Lahtinen (2016a) concludes that the greatest benefit of scrubber installation is achieved by the big merchant vessels with high fuel consumption; large tankers, bulkers, general cargo ships and container vessels. Also special ships consuming large volumes of fuel, such as ocean-going tugs and ice-breakers, are good platforms for scrubbers. This explains the steadily growing demand of the scrubbers. State aid granted for scrubber installations may speed up the process. For example, European Union has started to support the projects improving environmental performance, including scrubber retrofitting, as a part of Connect Europe Facility (CEF) programme (Marine propulsion & auxiliary machinery, 2015).

According to the two largest scrubber manufacturers, Alfa Laval and Wärtsilä, their reference list now consist of exhaust gas scrubber orders for 80 and 64 ships, respectively. Alfa Laval's 80 vessels include 64 retrofit projects and 16 newbuildings, totally consisting of 87 units of PureSO_x systems. In addition AL had two pilot systems on-board two vessels. In addition to Wärtsilä's 3 test units in three vessels, the 64 vessels in their reference list include 28 retrofits and 36 newbuildings, totally consisting of 70 scrubber units. Wärtsilä's list is not quite up-to-date, since it is from June 2015. In addition to these two large manufacturers, for example Finnish Langh Tech has 6 hybrid scrubber systems in operation, 10 on order and an on-going project for 7 water treatment plants for cruise vessels.

The manufacturers' lists show that hybrid systems have been the most popular (Table 1).

Table 1. Scrubbers ordered from manufacturers Alfa Laval, Wärtsilä and Langh Tech.

	Closed loop	Open loop	Hybrid	Total
Alfa Laval*	8	24	57	89
Wärtsilä**	10	26	37	73
Langh Tech			16	**16**
Total	18	50	110	**178**

*Total number of units in 82 vessels is 89, including two pilot units in two ships
**Total number of units in 67 vessels is 73, including three test units in three ships.

Institute of Shipping Economics and Logistics (ISL, 2015) calculates that there are now some 300 exhaust cleaning gas systems installed or envisaged, representing less than one per cent of the world merchant fleet. The size of the world merchant fleet varies depending on the source but the number is somewhere between 50 000 (ICS, 2016) and 85 000 (Equasis, 2015).

4.3 Scrubber types in the Baltic Sea

The authorities do not have statistics about the scrubber installations on-board ships in the Baltic Sea traffic. IMO has a database, GISIS, where flag states are obliged to report the approved alternative systems for low sulphur fuel use. All of these systems are not scrubbers and most probably not all approved scrubbers have been reported. In addition, the vessel list does not include information about the sailing area. It can also be presumed that not all installed systems have approval yet. For example, only a few more than half of the installed scrubbers in Finnish ships have type approval. (Intovuori, 2016)

According to IMO GISIS database, in total 13 Finnish ships have received type approval for scrubber. Two of these are hybrid and 11 are open loop systems. In addition, the type approval process is on-going with 10 Finnish ships, five of which are hybrid and five open loop systems. Thus, for Finnish ships the open loop scrubbers have been the most popular solutions whereas in total (according to the manufacturers' reference lists, Table 1), the hybrid systems have been the most popular. Anyhow, for example Finnlines has chosen to install such open loop scrubbers that can be easily upgraded as hybrids (hybrid prepared open loop systems) giving more operational flexibility, if necessary (Finnlines, 2014).

4.4 Scrubber types in international cruise liners

Cruise shipping companies seem to be fairly interested in installing scrubbers. Cruise liners use great amounts of fuel and some of the main cruise business areas, like the Baltic Sea, are SECA areas where exhaust gas sulphur limit is 0.1% since January 2015. Also, the global sulphur limitation is getting closer and use of scrubbers is then even more economic as the vessels operate on different areas depending on the season. Even though the oil price is historically low, the price difference between HFO and MGO remains significant and that is what makes scrubbers an economic choice.

In the European Sustainable Shipping Forum's sub-group on Exhaust Gas Cleaning Systems (ESSF, 2016b) the Carnival Corporation has stated that they have installed 100 seawater (open loop) scrubbers. Anyhow, it is not profitable to install scrubbers on all existing cruise liners since:

- they are not all cruising in SECA areas;
- retrofitting is expensive;
- some ships are old enough not to face the global sulphur limit (coming into force 2020 or 2025).

It can be expected that in the SECA areas, like the Baltic Sea, scrubbers will be popular option to fulfil the sulphur criteria.

5. Scrubber sludge and wash water

The characteristics of scrubber wastes depend on the components of exhaust gas which in turn are influenced by the quality of the fuel used and completeness of combustion. The particulate matter captured by the scrubber can contain metal oxides and sulphates, soot (carbon), other organic compounds such as PAH, PAH derivatives, aldehydes, alkanes, alkenes and some unburned fuel or incombustible elements in fuel (Kjølholt et al., 2012). Furthermore, the constituents possibly entering the scrubber system within seawater and the cleaning efficiency of the scrubber have an effect on the quality of residuals. (Lange et al., 2015)

The use of closed loop scrubbers emphasizes the need for wastewater management at ports. Sludge from both closed and open loop wet scrubbers as well as solid waste from dry scrubbers require waste management at ports. Overview of scrubber types and technologies with their main specific features is presented in Table 2.

Table 2. Scrubber types and technologies (Lange et al., 2015; den Boer and Hoen, 2015; Marine Exhaust Technology, 2016)

Scrubber technology	Purification medium	Wastes generated and their management on-board	Examples of commercial brands
Wet open loop scrubber	Untreated seawater; use of natural alkalinity (bicarbonate, HCO_3^-) as neutralising agent	**Wash water**: diluted with sea water to meet a required pH level and discharged to sea. **Sludge** from the solids separation: stored in tanks. All systems do not produce sludge in the open loop mode.	Pure SOx by Alfa Laval Wärtsilä LMB-EGS by Saake DuPont™ BELCO® by DuPont™ Marine Scrubbing Systems MES EcoSilencer®
Wet closed loop scrubber	Freshwater with additives, typically NaOH to form Na_2SO_4 in scrubber. Also MgO has been used. Dosage depends on the sulphur content of the fuel.	**Wash water**: treated in mechanical / mechanical-chemical process and circulated back to scrubber. Effluent discharged or stored in a tank. **Sludge** from the solids separation: stored in tanks.	Pure SOx by Alfa Laval Wärtsilä DuPont™ BELCO® by DuPont™ Marine Scrubbing Systems MX Scrubber by Marine Exhaust Technology A/S
Wet hybrid scrubber, can be operated in open loop or closed loop mode	See above, depending on the mode of operation.	See above, depending on the mode of operation.	Pure SOx by Alfa Laval Langh Tech Hamworthy Krystallon by Wärsilä/Moss Clean Marine DuPont™ BELCO® by DuPont™ Marine Scrubbing Systems GTM R15 by Green Tech Marine
Dry scrubber	Hydrated limestone granules in special packed bed absorbers	**Solid waste** from the exhausted limestone granules: stored on-board and disposed of at port.	DryECGS by Couple Systems Hellmich

5.1 Scrubber sludge

The sludge generated in open loop scrubbers consists of hydrocarbons, soot and metals. The amount of sludge may increase due to the capture of estuarine sand and silt. In closed loop system the sludge contains impurities separated from the bleed-off in the treatment process. (Wärtsilä, 2014)

Table 3 summarises, based on available literature sources, the typical quantities and qualities of sludge from wet scrubbers.

Table 3. Quantities and quality ranges of sludge from wet scrubbers.

Waste	Ref	Quantity kg/MWh	DW %	LOI % of dw	pH	Metals mg/kg dw	Organics mg/kg dw	S mg/kg dw
Sludge from wet open loop scrubber	1)	0.1						
	3)	0.2						
Sludge from wet closed loop scrubber	1)	DAF: 3.5 Separator: 5.5						
	2) Fuel S 2.2 %		11	51	7.1	As 8.4 Pb 54 Cd 0.080 Cu 1100 Hg <0.050 Ni 5 400 V 12 000 Zn 260	PAH 230 (16 USEPA) Total hydrocarbons 111 000 PCDD/PCDF 26.3 ng/kg dw	79 000
	2) Fuel S 1.0 %		11	59	7.2	As 7.0 Pb 31 Cd 0.11 Cu 1400 Hg <0.050 Ni 4200 V 6000 Zn 210	PAH 220 (16 USEPA) Total hydrocarbons 77 000 PCDD/PCDF 16.2 ng/kg dw	52 000
	4) Fuel S 1.5 %	0.1 to 0.4	21		5.6	53 000	Hydrocarbons 252 000	
	5)	Average 1.5, maximum 3.5						
	6)	0.5						

1) Wärtsilä, 2014
2) Kjølholt et al., 2012. Sludge from closed loop operation of Alfa Laval scrubber at Ficaria Seaways, fuel S content 2.2 %.
3) Ritchie et al., 2005
4) Wärtsilä, 2010. Sludge produced in closed loop scrubber operation at MT Suula when using fuel with S content 1.5 %.
5) Brands, 2016
6) Langh, 2016

The high Loss of Ignition (LOI) value recorded by Kjølholt et al. (2012) indicates a very high organic content of sludge. The characteristics of scrubber sludge presented in Table 3 indicate that the sludge would be classified as hazardous waste.

Scrubber sludge is fairly similar in composition to engine room sludge, but the calorific value of scrubber sludge is considerably lower than that of engine room sludge (den Boer and Hoen, 2015). EGCS waste is classified by IMO as Annex VI waste and therefore it may not be mixed with Annex I waste (sludge etc.) (Kämäräinen, 2016).

5.2 Scrubber wash water

Both open and closed loop wet scrubbers generate wash waters but as mentioned above, in the open loop systems discharge is direct from flow-through salt water systems and usually without removal of the trapped particles. In closed loop systems the small amount of treated bleed-off (called effluent) can also be discharged but when operating in zero discharge mode the effluent is stored on-board for subsequent disposal at port. Therefore, considering the need for port reception facilities the main focus is on closed loop scrubbers' effluents.

Bleed-off from closed loop scrubber system contains small amounts of hydrocarbons and combustion products and its pH is typically close to neutral. As the sludge volume is relatively small compared to the total flowrate, the amount of effluent from the bleed-off treatment unit (BOTU) can be estimated being close to bleed-off flowrate. (Wärtsilä, 2014) The effluent quality is also influenced by the operation and effectiveness of the BOTU process on-board.

Table 4 summarises, based on available literature sources, the typical quantities and qualities of effluent from wet closed loop scrubbers.

Table 4. Typical quantities and quality ranges of final effluents from closed loop scrubbers (effluent of bleed-off treatment unit)

Waste	Ref	Quantity	SS mg/l	COD mg/l	pH	Metals mg/l	Organics mg/l	tot-S mg/l	tot-N mg/l
Effluent from wet closed loop scrubber (effluent of BOTU)	1)	50-110 litres/ MWh/% of fuel S							
	2)	0.1-0.3 m^3/MWh (with wash water circulation rate 20 m^3/MWh)							
	3) Fuel S 3.5 %	0.17 m^3/MWh							
	4) Fuel S 2.2 %		25	440		As 0.0098 Pb 0.0038 Cd < 10^{-4} Cu 0.860 Hg < 10^{-4} Ni 3.1 V 14 Zn 0.420	PAH 0.0038 (16 USEPA) Total hydrocarbons 11	9 000	120
	4) Fuel S 1.0 %		39	490		As 0.0088 Pb 0.0016 Cd < 10^{-4} Cu 0.390 Hg < 10^{-4} Ni 1.3 V 6.1 Zn 0.16	PAH 0.024 (16 USEPA) Total hydrocarbons 21	4 800	86
	5) Fuel S 3.4 %				7.7	As 0.005 Pb 0.002 Cd < 10^{-4} Cr < 10^{-4} Cu 0.27 Ni 0.66 V 4.4 Zn 0.19	PAH 0.0044 (16 USEPA) Oil hydrocarbons 0.12 Aliphatic		Nitrite 230 Nitrate 220

							hydrocarbons as sum C5-C35 < 0.2		
	6) Fuel S 2.83 %				6.7-7		PAH (phenanthrene) 0.00078 to 0.00174		

1) Wärtsilä, 2014
2) MEPC 58/23 Annex 16 (2008)
3) Henriksson, 2016
4) Kjølholt et al., 2012. Wash water from closed loop operation of Alfa Laval scrubber at Ficaria Seaways. Wash water treated by centrifugation after 120 min water circulation in scrubber.
5) Tikka and Lipponen, 2009. Marine exhaust gas scrubber tests at M/T “Suula”. Flotation as BOTU. Note: synthetic fuel made for experiments from 2.7 S-% fuel (Lahtinen, 2016b).
6) Lahtinen, 2016a. Effluent from closed loop Wärsilä scrubber at Containerships VII.

5.3 Dry scrubber waste

Dry scrubbing process generates gypsum containing pellets which are removed from the equipment and stored on-board for disposal ashore. Transport of the pellets to and from the scrubber can be done pneumatically. (ABS, 2013)

In case of dry scrubbers both the supply and disposal of limestone granules has to be carried out at port and appropriate material handling systems are thus required. The lime usage of dry scrubber has been indicated to be around 50 kg/MWh. For a vessel with 10 MW engine this means a usage rate of 500 kg/h (240 tonnes for a 20 day usage at full power). (ABS, 2013) It has been proposed that the gypsum formed in the scrubber could be reused at power plants, as a raw material for cement and steel making, or as fertilizers. (USEPA, 2011)

6. Management of scrubber residuals at Baltic ports

According to MARPOL Annex VI Regulation 17 the reception facilities for exhaust gas cleaning residues from ships must be ensured in ports “without causing undue delay to ships” (IMO, 2011). The reception system at port for scrubber sludge and effluent may be a permanent installation with pipelines for line traffic or it may be based on tank trucks. (Lahtinen, 2016a) The MARPOL requirement concerns residue (i.e. sludge). Residues generated by the EGC unit should be delivered ashore to adequate reception facilities. Such residues should not be discharged to the sea or incinerated on-board. (IMO, 2015)

The EU Landfill Directive (1999/31/EC) regulates that liquid, leaching and reactive waste types cannot be landfilled, but must be contained in storage facilities until such time that treatment operations are implemented. The waste streams from closed loop scrubbers are therefore not in any case acceptable to landfill as such.

When a closed loop scrubber is run in zero discharge mode, the effluent of bleed-off treatment unit is stored on-board. According to Lahtinen (2016a), there are in principle three management options for this effluent stream:

1. The stored effluent is pumped into the sea when the ship has reached a suitable location;
2. The effluent is discharged into municipal wastewater network at port, provided that the local criteria for sewage are met;
3. The effluent is dried to a sufficiently reduced volume to allow storage on-board and transported to wastewater treatment plant.

The last two alternatives incur extra costs and also cause logistic challenges but also allow sea water to remain free from pollutants. A possible scenario is the delivery of bleed-off into port reception facilities as such (Lahtinen, 2016a).

With regard to port, scrubber waste related issues requiring further improvement have been listed by ESSF (2014). The forum identified port reception facilities for effluent and sludge as being key issues. In addition, scrubber use in ports, if zero effluent mode is not possible, is a question requiring attention.

6.1 Port of Helsinki

The Port of Helsinki governs the South Harbour (and Katajanokka), the West Harbour and Vuosaari Harbour, a part of the Kantvik Harbour and Helsinki's coal quays.

The South and West Harbours are specialised in passenger transport but serve also cargo transported on wheels and carried by passenger ferries. In 2015, 2 552 vessels visited the South Harbour of which 84 were cruise liners. The West Harbour was visited by 3 694 vessels, of which 170 were cruise liners. (Port of Helsinki Ltd., 2016a and 2016b)

Vuosaari Harbour serves unitised cargo traffic carried by lolo, roro and ropax vessel and passengers carried by ropax vessels. In 2015, Vuosaari Harbour was visited by 2 159 vessels (62 % roro and 37 % container ships). The cargo is mainly transported on wheels. (Port of Helsinki Ltd., 2016c)

According to environmental protection act for shipping (1672/2009), chapter 9, the port keeper must prepare a waste plan for the management of ship wastes. In addition, port regulations as well as environmental and waste legislation (e.g. Waste Act 646/2011, Environmental protection Act 86/2000) and waste management instruction issued by Helsinki Region Environmental Service Authority (HSY) for the metropolitan area and Kirkkonummi give guidelines for waste management at the Port of Helsinki. The port keeper must ensure adequate port infrastructure and procedures for receiving shipping wastes listed in the environmental protection act for shipping. (Port of Helsinki Ltd., 2015a) These include:

- oil containing waste (MARPOL annex I)
- waste containing hazardous liquid substances (MARPOL annex II)
- lavatory wastewater (MARPOL annex IV)
- solid waste and cargo waste (MARPOL annex V)
- exhaust gas cleaning waste the discharge of which is prohibited (MARPOL annex VI)

Scrubber waste from shipping is thus included in the reception requirement of ports.

According to port regulations discharging grey or black water, oily bilge water or sludge to the sea at the port area is strictly prohibited. Furthermore, no solid waste must to be thrown overboard. (Port of Helsinki, 2015d)

The basic principle of ship originated wastes is the delivery ashore for further treatment. The vessels must prior to arrival at port (minimum 24 h beforehand) inform using a standard notification form on the intention of delivering ship originated and cargo wastes. The ship waste management will be invoiced independently whether the ship leaves waste at port or not. The Finnish Transport Safety Agency (Trafi) can, however, issue an exemption permit from the obligation of delivering ship waste if the ship is in regular traffic and it has a contract with competent waste management company or with port. (Port of Helsinki Ltd., 2015a)

The share of exempted vessels operating to the South, West and Vuosaari Harbours represented 96.5, 92.1 and 77.1 % of the ship visits, respectively, and the Port of Helsinki is mainly responsible for the waste management of international cruise liners and thus only a small proportion of all ship visits. In Vuosaari Harbour the Port of Helsinki is responsible for ship waste from occasional, irregular traffic. Nevertheless, also the exempted vessels are entitled, without extra fee, to discharge their ship wastewaters to the sewage network of the Port of Helsinki and further to the HSY network for treatment. (Port of Helsinki Ltd., 2016a, 2016b and 2016c)

The Port of Helsinki contracts waste management companies for the port waste management services. The contracted service providers are responsible for the transportation, pre-treatment, disposal and reporting of wastes as well as for the waste reception facilities and their maintenance. The port orders appropriate waste reception from the service provider based on information received through ship notification. Only recyclable wastes are stored at the harbour area for a certain time period; otherwise wastes are transferred directly from the ship to collection vehicles. (Port of Helsinki Ltd., 2015a)

Mixed waste (food and household waste) from ships is transported from the Port of Helsinki to Vantaa Energia's waste-to-energy plant. Paper and cardboard, glass, metal and biowaste are separately collected. Oily engine room wastes, such as fuel residue sludge and other hazardous waste types from ships are collected and transferred to treatment facility for hazardous waste. Ship wastewaters can be divided into black wastewater from lavatories and grey wastewaters generated in ship washing rooms and kitchens. Ship wastewaters can be directly pumped into the port's sewer system which is connected to sewerage network of HSY. (Port of Helsinki Ltd., 2015a)

The reported amounts of received ship wastes in different harbour units of the Port of Helsinki are summarised in Table 5.

Table 5. Amounts of wastes and wastewater received by harbours governed by the Port of Helsinki in 2015 (Port of Helsinki Ltd., 2016a, 2016b and 2016c)

Harbour	Total ship waste received, tonnes	Main waste types received, % of total	Wastewater received from ships, m^3
South Harbour	839	Oily water, 69 % Mixed waste, 23 % Food waste, 5.5 %	156 000
West Harbour	2 508	Oily water, 55 % Mixed waste, 26 % Food waste, 7.2 % Recyclables, 11 %	179 000
Vuosaari Harbour	118	Oily water, 91 %	28 800

The current waste management fee charged for each hundred (100) units of measurement of a vessel's net tonnage ranges from € 12.85 (vessels carrying mainly cargo) to € 16.10 (vessels carrying mainly passengers). Vessels carrying mainly passengers are granted a 20 % discount of the waste management fee if they discharge their sewage into the port's sewer network. The waste management fee covers the reception, treatment and disposal of all solid and recyclable ship originated waste types and oily engine room wastes. The fee does not depend on the amount of delivered waste but is dependent on the vessel's net tonnage. Discharging sewage into the port's sewer system is not subject to a separate fee. If the wastewater pumped from a ship is classified as industrial, the waste management charge will be determined separately. Also, fees for receiving and handling of other waste (such as waste generated by scrubbers) or exceptionally large waste quantities are based on actual costs incurred. (Port of Helsinki Ltd., 2016; Port of Helsinki Ltd., 2015)

The first vessel with scrubber installed and having traffic to Port of Helsinki Vuosaari harbour was Containership VII. The ship, equipped with a fresh water scrubber system, generated

40-50 m^3 effluents a day. Scrubber sludge was mixed with engine room sludge and delivered on land. (Vuorivirta, 2011) This procedure seems to be forbidden now, as EGCS residue (scrubber sludge) is already classified as Annex VI waste by IMO and therefore it may not be mixed with Annex I waste (engine room sludge etc.) (Kämäräinen, 2016).

6.2 Other Baltic ports

Currently there are few publicly available case studies on scrubber effluent management and treatment at ports.

The overall status of port reception facilities for scrubber wastes in the Baltic ports has been recently reviewed by Klopott (2015). It was concluded that some ports (e.g. Stockholm, Riga, Rostock, Tallinn, Szczecin) are ready to receive at least scrubber sludge from vessels. Many ports require a 24 hours to 5 working days' notice from vessels that wish to deposit scrubber waste before arrival at the port. Many of the Baltic ports are still preparing their facilities and the fees are being considered. Tallinn port has informed that scrubber wastes are covered by the no-special-fee scheme. Rostock indicates that scrubber residues are included in the waste disposal fee, however, the fee depends on the characteristics of the waste, to be analysed beforehand. (Klopott, 2015)

Kjølholt et al. in 2012 indicated that most Danish ports already then had facilities that could be utilised for the reception of effluents from closed loop scrubbers as well as scrubber sludge. Vacuum truck services that are used at ports for collecting engine room sludge and spill oil could be used also for scrubber sludge collection, due to its similar characteristics. For vacuum truck collection the sludge should be in pumpable form.

According to Kjølholt et al. (2012) the standard treatment for effluent from closed loop scrubber at port would be the addition of lime to precipitate heavy metals followed by solids separation e.g. in a filter press. The liquid could be sent to wastewater treatment plant and the sludge to final disposal at an appropriate landfill.

Recently, the shipping company Scandlines has contracted APATEQ to develop, build, and supply a harbour installation at the Port of Gedser in Denmark for treating scrubber effluent ashore. The plant is scheduled for commissioning in spring 2016. The treatment system will be a containerised MarinePaq plant which will treat wash water produced on-board Scandlines' new ferries Berlin and Copenhagen, equipped with closed-loop scrubbers. The ferries will sail on the Gedser-Rostock route once they have been completed. According to APATEQ, scrubber wash water will undergo primary treatment, followed by ultrafiltration and heavy metal extraction process, producing an effluent which can be safely discharged into port waters. Scrubber sludge will be compacted by an integrated filter press and disposed of in landfill. The MarinePaq will be built in two 40 feet containers stacked on top of each other ensuring a minimum footprint. (Baltic Transport Journal, 2016; APATEQ, 2015)

6.3 Estimate of scrubber sludge production on a cruise ship

The amount of scrubber sludge in kilograms can be estimated when the average sludge amount given by the scrubber manufacturer [kg/MWh] and the power generated on-board [MWh] are known. The actual engine power data is scarcely available but electrical power use in a cruise liner can be found. The following calculation has been made for the cruise ship Freedom of the Seas which has been equipped with a hybrid scrubber by Alfa Laval (Alfa Laval, 2015).

Freedom of the Seas has a capacity of 154 407 GT and can accommodate 3 634 passengers (double occupancy) and has a crew of 1 365. Freedom of the Seas has a diesel-electric machinery and its installed machine power totals 75 624 kW and installed propulsion power is 42 000 kW. Sea trial speed was 21.6 knots.

Ship data is obtained from Master's Thesis by Mika Heiskanen (Heiskanen, 2009), where the actual electrical power used and hours spent at sea and at port in a one week typical cruise in the Caribbean were measured during the time 9.-16.7.2006. The electrical energy consumption in MWh has been determined from the ship's electric control panels as the average power need every hour. The energy consumption in one week cruise was:

At sea: 30.88 MW * 126h = 3 890.88 MWh

At port: 12.5 MW * 42h = 514.5 MWh

In total: 4 405.38 MWh

6.3.1 Closed loop mode

The sludge production in closed loop mode given by Alfa Laval depends e.g. on the fuel quality. More sulphur in the fuel results in larger amount of sludge, average values being between 1.5 kg/MWh and 3.5 kg/MWh. Since the availability of 3.5 S-% fuel is limited at least in the Baltic Sea, one may assume the fuel with 2.5 S-% to be used, meaning the amount of sludge being about 2.5 kg/MWh. In addition, ship's steam boilers add the amount of sludge with about 10% depending on the ship and its use profile. In a long run it has been estimated that the average distribution of fuel is 90% for the main engines and 10% for the steam boilers (Heiskanen, 2009).

With the energy consumption figures given above, the closed loop mode sludge production during a one week cruise totals:

2.5 kg/MWh * 4 405.38 MWh / 0.9 = 12 237 kg = 12 tonnes (in one week)

Since the power measured and used in the calculation is "electrical energy consumption", the actual engine power is somewhat higher due to operating efficiency of the engines and generators. The loss factors have not been taken into account in the calculation (they are fairly small, generator efficiency being ~0.97, for example). Similarly, the efficiency of the steam boilers has been ignored. The meaning of the calculation is to show the magnitude of the sludge volumes in cruise liners, not the exact number. The effect of fuel quality and possible operation in open loop mode has much more significance to the sludge volume than the loss factors.

The amount of 12 tonnes can be stored during a one week cruise. Transportation of this amount from port requires one tank truck. This estimate has been calculated for a fairly large cruise ship in the Baltic Sea cruise business and the energy consumption in the Baltic cruise is not necessarily the same as in the Caribbean. For example the air conditioning and heating needs are different in the Baltic. One may assume that this could represent the upper scale amount of cumulating sludge during a one week cruise in the Baltic. The sludge amount may be lowered by using the following means:

- Operate the scrubber in open loop mode either partially or all the time.
- Use of land power when at port.
- Use of better quality fuel.
- Save energy with different energy saving methods, slow steaming etc.

6.3.2 Open loop mode

Due to the additional costs of caustic soda consumption and waste management, it is likely that hybrid scrubbers will be used in open loop when and where possible. Sludge production in open loop mode is only a fraction of that in closed loop mode; Alfa Laval states that no sludge is produced in open loop mode (Brands, 2016) and Wärtsilä gives a value of 0.1

kg/MWh (Wärtsilä, 2014). With the specification given in the previous chapter for Freedom of the Seas, the maximum open loop mode sludge production during a one week cruise totals:

0.1 kg/MWh * 4 405.38 MWh / 0.9 = 489 kg (in one week)

6.3.3 General cargo ships

The energy consumption in cruise ships and general cargo ships are very different and so are the cumulating amounts of scrubber sludge as well. For example, Langh Tech tells that as they are also able to effectively reduce the amount of water in the sludge, their ships are not required to leave it to port more than 1 m^3 in a month when operating 50% of time on closed loop mode. They give a number of 0.5 kg/MWh for sludge recovery on closed loop mode. (Langh, 2016) Langh Ship's M/S Laura is a 6500 DWT general cargo vessel equipped with a 6 MW main engine.

6.4 Estimate of scrubber effluent production on a cruise ship

In closed loop systems the treated wash water bleed-off called effluent can either be discharged into sea or if chosen to operate in zero discharge mode, the effluent will be stored on-board for subsequent disposal at port. Therefore, considering the need for port reception facilities, the closed loop scrubbers' effluent production should also be estimated. Wärtsilä gives a value of 0.17 m^3/MWh for effluent production for fuel with 3.5% sulphur, and proportionally lower for lower fuel sulphur content (Henriksson, 2016). With the specification given in the previous chapter for Freedom of the Seas, the closed loop mode effluent production during a one week cruise totals:

0.17 m^3/MWh * 4 405.38 MWh / 0.9 = 832 m^3 (in one week)

7. Future trends in ship emission control and reduction

7.1 Prevalence of scrubber types and current discussion on wash water discharges

The DNV GL conducted an Energy Management Study in 2015 (DNV GL, 2015) via a web-based questionnaire sent to about 700 professionals. The results are based on 80 respondents' views. According to the answers, the most shipping companies (91%) use low-sulphur fuel oil in ECAs in an apparent attempt to buy time for investment decisions. Only 6 % of the respondents said they have installed scrubbers; none have converted their vessels for alternative fuels such as liquefied natural gas (LNG). However, 25 % of the respondents said they plan to install scrubbers in the future, while 24 % are considering the use of alternative fuels such as LNG.

Cruise Lines International Association (CLIA) has expressed the shipping companies' worries about prohibiting the open loop scrubbers in some EU areas by submitting a paper "Operation of EGCS in open loop mode in EU waters" to the Maritime Group of the Baltic Marine Environment Protection Commission (HELCOM) for the meeting held in Klaipeda, Lithuania on 23-25 November, 2015. CLIA calls on *"governmental authorities to preserve the intent of the Sulphur Directive, ensuring consistent implementation across the EU and uniformed acceptance of EGCS in Open Loop mode as currently done by the overwhelming majority of Member States".*

The shipping companies that have chosen to install a hybrid scrubber are able to switch to using the scrubber in closed loop mode in the areas where wash water discharge is prohibited. The shipping companies that have installed open loop scrubbers would face more trouble if the prohibition of wash water discharges becomes a general rule in EU waters. For example, Carnival Corporation has ordered over 100 open loop scrubbers in their vessels (ESSF, 2016b) and they are concerned if the wash water is assumed to pose unwanted environmental effects and if the use of open loop scrubbers will be restricted.

The discussion on the wash water discharge goes on in European Sustainable Shipping Forum EGCS sub-group. There still seems to be lack of clear and consistent information on SECA Member States criteria for wash water discharges in territorial waters. The discussion on the legal aspects of WFD is going on at ESSF Implementation sub-group. There are also on-going parallel sampling and analysis campaigns by EGCSA and Carnival (with DNV GL) with promising preliminary results and subject of current sub-group discussions. According to Carnival their samples fulfil almost all known regulations but the nickel concentration exceeds the EC limit for surface water with 50%. (ESSF, 2016b) The campaigns and the reporting are still unfinished, thus the final results are not yet available and it is too early to jump to a conclusions.

The market leader scrubber manufacturers Wärtsilä (Henriksson, 2016) and Alfa Laval (Brands, 2016) admit that the uncertainty of the future legislation hinders the scrubber sales. The future compliance is important for ship owners. Especially the EC Water Framework Directive is tricky since it does not present any actual limits for discharges but obliges the member states to look after the water quality in their territorial waters. Possibilities to comply with the uncertainty are to install a hybrid scrubber in the first place or to upgrade the open loop scrubber to hybrid if legislation requires. Continuing the operation with low sulphur fuel is a popular option as long as the oil price is low. LNG is becoming common slowly and will not generally substitute other options to comply with the global 0.5% sulphur limit 2020/2025 (Henriksson, 2016).

In his Doctoral Thesis, Lahtinen (2016a) presents a concept of zero-discharge mode use of closed loop scrubber, meaning the ship would not discharge any effluent into sea but dispose all the bleed-off (effluent and sludge) on shore to port reception facilities. Zero-discharge use of closed loop scrubber may catch on especially with the cruise industry where the passengers have become more and more environmentally conscious. The bleed-off could be pumped to PRF either after the on-board treatment as separated effluent and sludge or as such to be treated on land. The latter offers the possibility of removing effluent treatment apparatus from the ship but leaves the port to handle larger amount of more dirty waste.

Lahtinen (2016a) has estimated that the theoretical bleed-off volume on board during zero-effluent operation may grow to equal volumes with the fuel bunker but would not exceed it. He suggests considering the possibility of using empty fuel tanks as dirty effluent buffer tanks during the voyage. In such an arrangement, fuel would be replaced tank by tank with dirty effluent during the voyage. In this “double-acting fuel tank concept”, “effluent-in-oil” and “oil-in effluent” contamination after the liquid swap should be solved. Another option would be to dry the effluent into a powder. Sodium sulphate – the main component in dry effluent – is typically used in the pulp, glass and textile industries. To enable this scrubbing mode, effluent storage on board, treatment on board, port reception facilities and land based wash water treatment technologies, including the dry waste recycling option, should be improved.

7.2 The Port Reception Facilities (PRF) Directive

The Commission has recently started an Impact Assessment for a future legislative revision of Directive 2000/59/EC on port reception facilities for ship generated waste and cargo residues ("the PRF Directive"). (EC, 2016)

The roadmap for the revision of the PRF Directive mentions as a possible measure the inclusion of the waste arising from the implementation of MARPOL Annex VI in the scope of the Directive.

In order to develop a better understanding of the operation of scrubbers, and the waste and wash water resulting from such operation, input has also been requested from the ESSF Scrubber (EGCS) Sub-Group. General information is needed in order to identify how and to what extent this waste needs to be handled by PRF. The following data has been excerpted from the consolidated replies table updated on March 23, 2016 and received from Trafi (Kämäräinen, 2016):

- *"It is very likely that scrubber sludge will form only a very small addition to the current oily waste streams landed ashore." (EGCSA)*
- *"At present ship owners are reluctant to invest in EGCS technology due to a number of uncertainties. These include fuel price, date of global implementation of the 0.5%S limit and uncertainty surrounding the Marine Fuels Directive and its implementation as applicable to wet EGCS." (EGCSA)*
- *"The majority of ships using scrubbers are on intra EU trades. The preference for scrubbers is based upon the economic benefit versus the alternative." (EGCSA)*
- *"I believe that some ports are conducting a program in which they installed a wash water treatment plant at port to treat the wash water from ships at berth." (CR OCEAN ENGINEERING)*
- "*As the wash water regardless open or closed mode operation will contain too many salts for ordinary municipal treatment plants to cope with it, the ports might need to invest in some kind of settling treatment. The pollutants will settle as sediment and float on the surface and when removed, the remaining is clean salty water, which can be discharged to harbour/sea. If it is found that, there are too high levels of certain kinds of metals, those can most likely be precipitated by the aid of some kind of coagulant."* (Alfa Laval)
- *"It is not likely that the closed loop scrubbers would avoid treating the wash water on-board as the loss of freshwater would be too big. Freshwater on-board is a limited resource."* (Alfa Laval)

8. Management options for scrubber wastes at the Port of Helsinki

Management of scrubber sludge and effluent at ports is still a developing area with very few practical examples currently in place.

8.1 Benchmarks from the energy sector

When considering future options for handling scrubber wastes from ships, one can review management requirements for wastes from exhaust gas cleaning units at land based power plants as corresponding technologies are used in both sectors and therefore the generated waste can be considered as having at least partly similar properties.

The Finnish Government Decree 750/2013 on the environmental protection requirements of energy production units with a rated thermal input below 50 megawatts applies to energy production units that use solid, liquid or gaseous fuels. According to Section 9 of the decree:

"The operator must determine the quantity and quality of wastewater produced by the energy production plant. If operations result in or make use of substances that contain substances specified in Annex 1 of the Government Decree on Substances Dangerous and Harmful to the Aquatic Environment (1022/2006), precautions must be taken so that they are not conducted into ground waters, water environments or a sewer. (------) Wastewater formed in a waste gas scrubber and as a result of waste gas condensation (condensation water) that is conducted into a sewer must be neutralised, clarified and filtered before conduction."

Thus, there is no categorical limitations for the conduction scrubber wash water from land based power plants into a municipal sewer, but the adequate quality must be ensure by pretreatment.

According to a review conducted by Ramboll for Energiateollisuus ry (2008) the first unit operation in a typical treatment process of wastewaters from small heat production facilities is the neutralisation of acidic waters using NaOH. This brings the water pH to optimal level (8-9) for hydroxide precipitation of heavy metals. After this the solids are separated in clarification basins and the clarified water is lead to sewer. Depending on the wastewater quality and requirements for water to sewerage network the treatment can be improved by using aluminium or iron salt and polymer. The efficiency of solids separation can be improved by filtration.

For large combustion plants (> 50 MW) the Finnish Environment Institute has published an expert report on best available techniques (2011). The application of wet scrubbing technology for exhaust gas desulphurisation requires a wastewater treatment plant in order to remove heavy metals and to decrease solids concentration. The treatment plant typically includes adjustment of pH, precipitation of heavy metals and removal of solid matter and the precipitate from the wastewater. In some plants the water is delivered to municipal wastewater treatment plant for further treatment while in some cases it is led directly to waterbody.

8.2 Conditions of draining scrubber wash water into municipal sewer

Discharging industrial wastewater or other untypical wastewater to municipal sewerage network may only be done under a valid permit and the decision on the reception is taken by the wastewater treatment plant. When applying such permit the applicant must provide information e.g. on the activity, formation and quality of wastewater, usage of raw materials and chemicals, process scheme of any wastewater pretreatment processes and the valid environmental permit of the site. The resulting contract on industrial wastewaters defines conditions for discharging wastewater into municipal sewer and obligations for monitoring wastewater quality. Wastewater quality may influence also the collected fee. The Viikinmäki treatment plant receives and treats also liquid wastes that are not harmful for the treatment process. The applicability of any waste is evaluated case by case and the fee is set according to the quantity and quality of waste. (Helsinki Region Environmental Services Authority HSY, 2015a)

Table 6 shows the general limit values for wastewater delivered to treatment plants of Helsinki Region Environmental Services Authority HSY. In addition to the general limits, case based limit values may be established to ensure proper functioning of the sewerage network or treatment processes. These might apply e.g. to pH, solids, metals, grease or fat, biological oxygen demand (BOD_7) or substances disturbing nitrogen removal. It is to be noted that if the wastewater does not as such comply with the presented requirements it may not be diluted to reach the limit value. The limit values apply also to occasional wastewater batches. The point of compliance of the requirements is defined in contracts.

Table 6. HSY limit values for wastewater delivered to treatment plants (Helsinki Region Environmental Services Authority HSY, 2015b)

Constituent	**Maximum value**
Arsenic (As)	0.1 mg/l
Mercury (Hg)	0.01 mg/l
Silver (Ag)	0.2 mg/l
Cadmium (Cd)	0.01 mg/l
Total chromium (Cr)	1.0 mg/l
Chromium IV (Cr^{6+})	0.1 mg/l
Copper (Cu)	2.0 mg/l
Lead (Pb)	0.5 mg/l
Nickel (Ni)	0.5 mg/l
Zinc (Zn)	3.0 mg/l
Tin (Sn)	2.0 mg/l
Sulphate	400 mg/l
Total cyanide (CN)	0.5 mg/l
Temperature	40 °C
pH	allowed range 6.0 -11.0
Very easily flammable, easily flammable and water insoluble VOC compounds	not allowed
Chlorinated VOC compounds	not allowed
Non-chlorinated VOC compounds	total 3 mg/l
Total hydrocarbons (C10-C40)	100 mg/l

Based on a literature review (Table 4) on the quality of closed loop scrubber effluents, the sulphate concentrations probably exceed the HSY limit value of 400 mg/l for wastewater delivered to treatment plants. Nickel is the only metal exceeding the limit value.

8.3 Insights into scrubber sludge and effluent management

8.3.1 Options for scrubber sludge management

Using the available data (Chapter 6.3) it is estimated that a relatively large cruise liner using only closed loop mode could generate around 12 tonnes of scrubber sludge a week. In open loop mode the sludge amount in the same ship would vary between 0 and 500 kg. Due to the additional costs of caustic soda consumption and waste management, it is likely that hybrid scrubbers will be used in open loop where possible. However, the use of closed loop mode would become more common if the strict interpretation of WFD would in the future be applied more widely. Considering the number of cruise liners visiting the Port of Helsinki yearly (in 2015 South Harbour: 84 cruise liner visits and West Harbour: 170 cruise liner visits) and the currently received waste amounts this possible new waste stream, if even partly delivered to Helsinki, can be considered as an issue requiring plans for preparation.

According to data on scrubber sludge this waste is most likely classified as hazardous due to its high metal contents. The management options for sludge can be summarised as follows:

Option a: Delivery to metal recovery.

Option b: Delivery to hazardous waste treatment plant, e.g. Ekokem.

Option c: Treatment for landfilling by e.g. filtration, sedimentation, precipitation, and stabilization with subsequent evaluation of acceptability on respective landfill.

According to the literature review the scrubber sludge contains high levels of metals, especially nickel and vanadium (Table 3). The possibility of using this waste material as a secondary metal resource (option a) could therefore be evaluated (e.g. availability of refineries in the vicinity, specifications of feed materials, economics of delivery).

Option b has already been applied by the Port of Helsinki for the management of scrubber sludge delivered by the vessels. The costs of this option are solely dependent on the mass based fees set by the service provider, and thus the total costs are probably lower if any excess water is removed prior to the delivery. The pro of the option is the flexibility in operation. However, the option may be costly and dependent on few service providers capable of handling hazardous wastes.

In option c the port would operate directly with the respective landfill. This option would require treatment at the port or by an external service provider prior to delivery to landfill. The costs of the option will depend on the quality of waste, required treatment and the gate fee of respective landfill.

For options b and c the service contracts could be planned not to be dependent on one-at-a-time logistics and operation. Competitive bidding could be applied in order to lower unit costs.

When considering the different options for scrubber sludge management, the possibilities for co-operation as well as procedures adopted by other ports (e.g. possible inclusion of scrubber sludge in the no special fee system) situated in the Baltic Sea area could be screened and evaluated.

8.3.2 Options for scrubber effluent management

Using the available data (Chapter 6.4) it is estimated that a relatively large cruise liner using only closed loop mode could generate around 800 m^3 effluent during a one week cruise. Considering the typical characteristics of closed loop scrubber effluents presented in Table 4 the possible management options for this water stream at port can be summarised as follows:

Option 1: Discharge into the municipal wastewater network at a port based on mutual agreements.

Option 2: Treatment facilities installed at port to allow direct discharge to sea.

Option 3: Short-term intermediate storage and subsequent transportation of effluent to specialised treatment off-site.

Taking a benchmark from the energy sector (Chapter 8.1), option 1, possibly complemented with simple pre-treatment such as clarification, could be the most feasible option for scrubber effluent management. Based on available literature, the sulphur content of the effluent can be seen as moderately critical and nickel somewhat exceeding the HSY limit values. Intermediate storage at port could be applied to allow mixing of several effluent batches and to regulate discharge flow to wastewater network. However, the amount of existing data is very limited and based on few vessels only. Therefore, there is a clear need to gather more reliable and relevant data on the scrubber effluent quality as received at the port through well-prepared measurement campaign. Based on adequate data this option should be discussed further with HSY. The cost of delivering industrial waste water to municipal treatment plant is defined based on the effluent quality.

Solution according to option 2 will be applied by the Port of Gedser in Denmark; the treatment plant is to be commissioned in spring 2016. There is no publicly available information on the investment and operational costs of the plant or the actual effluent streams (volumes) the plant receives.

Option 3 has already been applied by the Port of Helsinki for the management of sporadic effluent batches delivered by the vessels. The viability of this option depends highly on the availability of treatment service providers as well as logistics and treatment costs. This option could be feasible for occasional deliveries of small effluent volumes.

The three options could be evaluated not only based on current gate/service-fees, but also for their overall environmental effects and sustainability, e.g. concerning the logistics to the waste treatment. When considering the options for scrubber effluent management, the environmental authorities of Helsinki City are also to be consulted for their view on the overall environmental impact of the proposed solution. Based on current knowledge there remains an uncertainty on the actual effluent amounts that will in the future be delivered to the PRF of the Port of Helsinki. The choice of the most feasible management option is dependent on the expected volumes and qualities, and therefore there is a clear need to gather more precise information on these.

9. Conclusions

The aim of this technical study on scrubber waste management, commissioned by the Port of Helsinki, was to gather relevant information on the current status of the application of scrubber technologies in ships and explore possible management options for sludge and effluents produced by ships equipped with scrubbers.

Based on purification medium and mode of operation there are various types of scrubber systems. Wet scrubbers can be either open loop or closed loop scrubbers, or hybrids which can be operated in open or closed loop mode, and dry scrubbers. The waste fractions generated by scrubbers include sludge (closed loop and some open loop scrubbers) and effluent (closed loop scrubbers). The effluent can in some cases be delivered to the port but in can be expected that mostly the treated effluents are discharged to sea. The sludge cannot be discharged into sea and the ports have to provide reception facilities according to MARPOL Annex VI Regulation 17 (IMO, 2011). The characteristics of scrubber wastes depend on the components of exhaust gas which in turn are influenced by the quality of the fuel used and completeness of combustion. The particulate matter captured by the scrubber can contain metal oxides and sulphates, soot, and other organic compounds.

Hybrid systems have been the most popular solution when the ship owners have chosen to apply scrubber technology. However, it seems that the international cruise liner companies (e.g. the Carnival Corporation) have preferred open loop scrubbers.

The overall trend is that scrubbers will become more common, especially in the cruise liners being a large customer segment using the facilities provided by the Port of Helsinki. Despite the fact that the oil price is historically low, the price difference between heavy fuel oil (HFO) and marine gas oil (MGO) remains significant and that is what makes scrubbers an economic choice for the cruise ships that use a lot of fuel.

Ship emissions, and on the other hand scrubber wash water quality, are regulated internationally by regulations given by the International Maritime Organization (IMO). Currently, some of the EU Member states have prohibited or are questioning the discharge of scrubber wash waters in certain limited waters/port areas based on national implementation of the Water Framework Directive (WFD) and potentially local laws. Studies regarding the environmental impact of the use of scrubbers have been done and are on-going.

The amount of scrubber sludge generated on a one week typical cruise by a relatively large cruise ship (3600 passengers) has been estimated using the average sludge generation value and the power used on-board. Using the available data it is estimated that using the closed loop mode, the vessel could generate around 12 tonnes of scrubber sludge a week. In open loop mode the sludge amount in the same ship would vary between 0 and 500 kg. Due to the additional costs of caustic soda consumption and waste management, it is likely that hybrid scrubbers will be used in open loop where possible. However, the use of closed loop mode would become more common if the strict interpretation of WFD would in the future be applied more widely. Considering the number of cruise liners visiting the Port of Helsinki yearly (in 2015 South Harbour: 84 cruise liner visits and West Harbour: 170 cruise liner visits) and the currently received waste amounts this possible new waste stream, if even partly delivered to Helsinki, can be considered as an issue requiring plans for preparation. However, some Baltic ports have already informed that scrubber wastes are covered by the no-special-fee scheme and obviously these would be the preferred options for delivering such waste.

For sludge management at port, the basic option is the delivery to hazardous waste treatment plant, e.g. Ekokem. However, the possibilities for delivering sludge to metal recovery could be screened and evaluated as the contents of metals can reach considerable levels. Another option would be to treat the sludge on-site to directly meet the acceptability criteria of respective landfill.

The possible management options for scrubber effluent include the discharge into the municipal wastewater network at a port based on mutual agreements with the waste water treatment plant; on-site treatment facilities installed at port to allow direct discharge to sea; or short-term intermediate storage and subsequent transportation of effluent to specialised treatment off-site. There remains an uncertainty on the actual effluent quantities and qualities that will in the future be delivered to the Port of Helsinki and at least in the shorter term the issue of sludge is more topical.

Proposals for future work

The choice of the most feasible management option is dependent on the expected quantities and qualities of effluent and sludge, and therefore there is a need to gather more precise information on this matter. The following approaches are proposed:

- A questionnaire for the cruise ships visiting Helsinki the coming summer about their need and possible plans to use the PRF for scrubber wastes would help the port in preparing for further actions.
- There is also a clear need to gather more reliable and relevant data on the scrubber effluent composition and quality as received at the port through well-prepared measurement campaign. This could be realised already in summer 2016 on the cruise ships visiting Helsinki.
- The measurement campaign may also be extended to sludge, at least if the waste treatment services are subjected to competitive bidding.

When the quantity estimates and quality data have been collected and analysed the possible management options can be more precisely evaluated. Better data enables discussions and negotiations with different stakeholders (such as city authorities and Helsinki Region Environmental Services Authority HSY) as well as organisation of competitive bidding in order to rationalise the management of scrubber wastes. This also enables economically and environmentally best practises for storage, logistics, and treatment.

References

ABS, 2013. Exhaust Gas Scrubber Systems. Status and Guidance. American Bureau of Shipping. Available: http://ww2.eagle.org/content/dam/eagle/publications/2013/Scrubber_Advisory.pdf

Alfa Laval guide (publication date not known). Deciding your route to SOx compliance. A guide to SOx abatement alternatives, scrubbers and suppliers. Available: http://www.alfalaval.com/microsites/puresox/documents/MDD00105EN_LOWRES.pdf

Alfa Laval, 2015. Press release on May 8, 2015. Alfa Laval and RCL close deals for four PureSOx scrubbers, including an inline. Available online at: http://www.alfalaval.com/media/news/2015/alfa-laval-and-rcl-close-deals-for-four-puresox-scrubbers-including-an-inline/?id=66918 [cited 23.4.2016].

APATEQ, 2015. APATEQ provides scrubber water treatment technology for Scandlines ferries. News release of 21 December, 2015. Available: http://www.apateq.com/about-us/news.html

Baltic Transport Journal, 2016. Gedser port to have a scrubber treatment plant. Publication date 5 January, 2016. Available: http://baltictransportjournal.com/gedser-port-to-have-a-scrubber-treatment-plant,2460

den Boer, E. and Hoen, M., 2015. Scrubbers – An economic and ecological assessment, Report prepared for NABU, Delft, March 2015. Publication code: 15.4F41.20. Available: https://www.nabu.de/downloads/150312-Scrubbers.pdf

Brands, Philippe. 2016. Personal e-mail from Philippe Brands / Alfa Laval to Saara Hänninen 26.2.2016.

DNV GL, 2015. Energy Management Study 2015. Energy efficient operation – what really matters. ©DNV GL 08/2015. ID: 846623.

EC, 2015. European Commission website. Information on waste/The European List of Waste. Available: http://ec.europa.eu/environment/waste/framework/list.htm

EC, 2016. Inception Impact Assessment: REFIT Revision of EU Directive 2000/59/EC on port reception facilities for ship-generated waste and cargo residues. Available online at (cited 11.4.2016): http://ec.europa.eu/smart-regulation/roadmaps/docs/2017_move_001_refit_directive2000-59_port_reception_facilities_for_waste_en.pdf

EGCSA, 2016. Exhaust gas cleaning systems association. Available online at (cited 14.3.2016): http://www.egcsa.com/resources/reference-documents/.

Energiateollisuus ry, 2008. Alle 50 MW lämpölaitosten teollisuusjätevesiselvitys. Pienten lämpölaitosten jätevesien laatu, käsittely ja johtaminen. Ramboll Finland Oy 4.11.2008. Available (in Finnish): http://energia.fi/sites/default/files/alle_50_mw_lampolaitostenteollisuusjatevesiselvitys_ramboll_20081104.pdf

Equasis, 2015. The world merchant fleet in 2014 – Statistics from Equasis. Available online at http://www.emsa.europa.eu/implementation-tasks/equasis-a-statistics/item/472.html. Cited March 2, 2016.

ESSF, 2014. European Sustainable Shipping Forum. 3rd Plenary Meeting Brussels, 04 December 2014. Final Report Submission from the ESSF Sub-Groups. Submission from:

ESSF sub-group on EGCS. Available: http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=17035&no=3

ESSF, 2015. European Sustainable Shipping Forum 7th meeting of the Sub-Group of Exhaust Gas Cleaning Systems (EGCS). 4.11.2015, Brussels. Kokousraportti TRAFI/63362/04.05.01/2015 (17.11.2015).

ESSF, 2016a. European Sustainable Shipping Forum's Sub-Group of Exhaust Gas Cleaning Systems - Round 7 proposals for amendments to the 2015 Guidelines for EGCS.

ESSF, 2016b. European Sustainable Shipping Forum 8th meeting of the Sub-Group of Exhaust Gas Cleaning Systems (EGCS). 2.3.2016, Brussels. Kokousraportti TRAFI/15633/04.05.01/2016 (8.3.2016).

EU, 2012. Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels. Official Journal of the European Union. 27.11.2012.

Finnish Environment Institute, 2011. Finnish Expert Report on Best Available Techniques in Large Combustion Plants. The Finnish Environment 458. Available: https://helda.helsinki.fi/bitstream/handle/10138/40632/FE_458.pdf?sequence=1

Finnlines, 2014. Press release on May 15, 2014. Finnlines Invests in Environmental Technology. Available online at: http://www.finnlines.com/company/news_press/press_releases/finnlines_invests_in_environmental_technology [cited 28.4.2016].

Hamburg Port Authority, 2015. Personal e-mail from Anika Beiersdorf / Hamburg Port Authority AöR to Saara Hänninen 28.10.2015.

Heiskanen, Mika. 2009. Lisäarvon tuottaminen risteilylaivakonseptin energiatehokkuutta kehittämällä. Diplomityö. Insinööritieteiden ja arkkitehtuurin tiedekunta, Teknillinen Korkeakoulu.

Helsinki Region Environmental Services Authority HSY, 2015a. Untypical wastewaters. Last updated 16.11.2015. (in Finnish). Available: https://www.hsy.fi/fi/yhteisollejayritykselle/vesihuolto/Sivut/poikkeavat-jatevedet.aspx

Helsinki Region Environmental Services Authority HSY, 2015b. Limit values for wastewaters delivered to Viikinmäki and Suomenoja wastewater treatment plants. 3.11.2015 (in Finnish). Available: https://www.hsy.fi/fi/yhteisollejayritykselle/vesihuolto/Documents/jateveden_raja-arvot.pdf

Henriksson, Torbjörn. 2016. Personal e-mails from Torbjörn Henriksson / Wärtsilä to Saara Hänninen 11.2.2016 and 25.2.2016.

ICS, 2016. International Chamber of Shipping. Available online at http://www.ics-shipping.org/shipping-facts/shipping-and-world-trade. Cited March 2, 2016.

IMO, 2011. Resolution MEPC.199 (62). 2011 Guidelines for reception facilities under MARPOL Annex VI. Adopted on 15 July, 2011.

IMO, 2015. Resolution MEPC.259 (68). 2015 Guidelines for Exhaust Gas Cleaning Systems, adopted on 15 May 2015.

Intovuori, Ville-Veikko. 2016. Personal e-mail from Ville-Veikko Intovuori / Trafi to Saara Hänninen 13.1.2016.

Kjølholt, J., Aakre, S., Jürgensen, C. and Lauridsen, J. 2012. Assessment of possible impacts of scrubber water discharges on the marine environment. Danish Environmental Protection Agency. Environmental Project No. 1431, 2012. Available: http://www2.mst.dk/Udgiv/publications/2012/06/978-87-92903-30-3.pdf

Klopott, M. 2015. Scrubbers as Shipowners' Response to the Sulphur Directive and its Implications for the Waste Management in Baltic Ports. Contemporary Economy Vol. 6 Issue 4 (2015) 87-94 Electronic Scientific Journal ISSN 2082-677X. Available: http://www.wspolczesnagospodarka.pl/wp-content/uploads/2015/12/7_M_Klopott_WG_4_2015_GM.pdf

Kämäräinen, J. 2016. Personal e-mail from Jorma Kämäräinen / Trafi to Saara Hänninen 31.3.2016.

Lahtinen, J.M. 2016a. Closed-loop Exhaust Gas Scrubber Onboard a Merchant Ship – Technical, Economical, Environmental and Operational Viewpoints. Doctoral Thesis. Acta Wasaensia, 342. ISBN 978-952-476-658-6.

Lahtinen, J.M. 2016b. Personal communication (phone conversation) between Jari M. Lahtinen and Saara Hänninen 2.3.2016.

Lange, B., Markus, T., and Helfst, L.P. 2015. Impacts of scrubbers on the environmental situation in ports and coastal waters. Report No. (UBA-FB) 002015/E, Project No. (FKZ) 33913. TEXTE 65/2015, Umwelt Bundesamt. Available: http://www.umweltbundesamt.de/publikationen/impacts-of-scrubbers-on-the-environmental-situation

Langh-Lagerlöf, L. 2016. Personal e-mails from Laura Langh-Lagerlöf / Langh Ship Group Oy Ab to Saara Hänninen 6.4.2016 and 4.5.2016.

Marine Propulsion & Auxiliary Machinery. (2015-07-28). EU aid for ferry scrubber projects. Available online at http://www.mpropulsion.com/news/view,eu-aid-for-ferry-scrubber-projects_38755.htm. [Cited 2.3.2016]

Niemi, S. Hänninen, S. Haahti, H. Kankaanpää, H. Mäkelä, K. 2006. Environmental effects of caustic soda and sea water scrubbers. VTT-R-08868-06. Espoo 23 November, 2006. Confidential research report (in Finnish).

Nordström, N., 2015. Development and testing of granules for sulphur removal in a pilot-scale dry scrubber. Master's Thesis. Aalto University, School of Chemical Engineering. Available online at https://aaltodoc.aalto.fi/bitstream/handle/123456789/16619/master_Nordstr%C3%B6m_Nenne_1970.pdf?sequence=1. [Cited 1.3.2016]

Port of Helsinki Ltd. 2015a. Waste management plan for the South Harbour. Draft 2.12.2015. In Finnish.

Port of Helsinki Ltd. 2015b. Waste management plan for the West Harbour. Draft 2.12.2015. In Finnish.

Port of Helsinki Ltd. 2015c. Waste management plan for the Vuosaari Harbour. Draft 3.12.2015. In Finnish.

Port of Helsinki Ltd. 2015d. Instruction for vessels. Updated 18.2.2015. Available: http://www.portofhelsinki.fi/instancedata/prime_product_julkaisu/helsinginsatama/embeds/helsinginsatamawwwstructure/13553_instructions_for_vessels.pdf

Port of Helsinki Ltd. 2016. Price list 2016. Available: http://www.portofhelsinki.fi/instancedata/prime_product_julkaisu/helsinginsatama/embeds/helsinginsatamawwwstructure/37387_Price_List2016GB.pdf

Port of Helsinki Ltd. 2016a. Yearly reporting according to the environmental permit. Annual report 2015, South Harbour, 29 February, 2016, (in Finnish).

Port of Helsinki Ltd. 2016b. Yearly reporting according to the environmental permit. Annual report 2015, West Harbour, 29 February, 2016, (in Finnish).

Port of Helsinki Ltd. 2016c. Yearly reporting according to the environmental permit. Annual report 2015, Vuosaari Harbour, 29 February, 2016, (in Finnish).

Ritchie A., de Jonge E., Hugi C., Cooper D., 2005. Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments, Task 2cSO2 Abatement. European Commission Directorate General Environment.

Rettig, 2014. Available online at http://www.rettig.fi/en/media/news/2014/first-ship-scrubbers-based-on-dry-desulphurisation-technology-to-be-commissioned-nordkalk-supplies/. [Cited 1.3.2016]

Ship Technology, 2016. Available online at http://www.ship-technology.com/projects/oceanex-connaigra-conro-ship/. [Cited 1.3.2016]

USEPA, 2011. Exhaust Gas Scrubber Washwater Effluent. EPA-800-R-11-006. November 2011. Available: http://nepis.epa.gov/Exe/ZyPDF.cgi/P100DCMY.PDF?Dockey=P100DCMY.PDF

Tikka, O., Lipponen, J., 2009. Marine exhaust gas scrubber tests at M/T “Suula”. April 20-22 and 24-26, 2009. Report 60O60184.01.Q850-001. Rev01 July 13, 2009. Pöyry Energy Oy.

Vuorivirta, K., 2011. What is the Port’s view on scrubbers? Case Helsinki. Kaarina Vuorivirta Quality and Environment Manager, Port of Helsinki. Available: http://www.trafi.fi/filebank/a/1322419984/1d4ae7eac935e4be4c0b3e2f43ce1e68/1685-Vuorivirta.pdf

Wärtsilä, 2010. Exhaust Gas Scrubber Installed Onboard Mt “Suula”. Public Test Report, 20 June, 2010. Available: http://www.annualreport2010.wartsila.com/files/wartsila_2010/Docs/Scrubber_Test_Report_onboard_Suula.pdf

Wärtsilä, 2014. Wärtsilä Scrubber Product Guide, November 2014. Available: http://cdn.wartsila.com/docs/default-source/default-document-library/w%C3%A4rtsil%C3%A4-scrubber-product-guide-rev-e-approvedf374954a7f0f601bb10cff00002d2314.pdf?sfvrsn=0