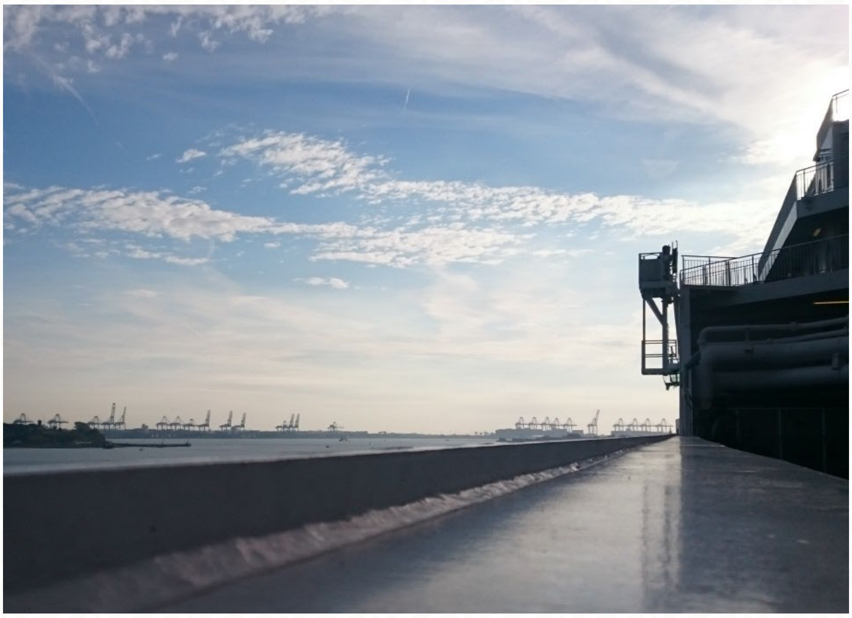

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Scrubbers: Closing the loop

Activity 3: Summary

Environmental analysis of marine exhaust gas scrubbers on two Stena Line ships

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This report has been reviewed and approved in accordance with IVL's audited and approved management system.

Preface

This report contains a summary of Activity 3 in the CEF funded project "Scrubbers – Closing the loop". Activity 3 is the Integrated Life Cycle Balance (ILCB) of the project, evaluating environmental aspects of the project from different perspectives. More detailed method descriptions, results and conclusions of the work presented in this summary are found in the four reports:

- Scrubbers: Closing the loop; Activity 3. Task 1; Air emission measurements. IVL report B2318, by Winnes H., Fridell E., Moldanová J., Peterson K., and Salberg H., 2018
- Scrubbers: Closing the loop; Activity 3. Task 2; Risk assessment of marine exhaust gas scrubber water. IVL report B2319, by Magnusson K., Thor P., and Granberg M., 2018
- Scrubbers: Closing the loop; Activity 3. Task 3; Cost benefit analysis. IVL report B2320, by Yaramenka K., Mellin A., Malmaeus M., and Winnes H., 2018
- Scrubbers: Closing the loop; Activity 3. Task 4; Evaluation of exhaust gas scrubber systems for ship applications in a system perspective. IVL report B2321, by Zhang Y and Stripple H. 2018

IVL Swedish Environmental Research Institute has been the leading organisation of the activity and has performed the studies in this report with support from representatives from the project partners Lloyd's Register EMEA and Wärtsilä Sweden AB, and the project coordinator Stena UK Ltd.

We gratefully acknowledge our funders at European Commission/Connecting Europe Facility and the SIVL foundation, and the insightful and dedicated support from the project coordinator Stena, our partners Lloyd's Register and Wärtsilä. Especially acknowledged are Andy Wright at LR who has supported with his specialist knowledge regarding air emissions measurements and Stian Aakre at Wärtsilä who has supported with technical knowledge of the system. The project coordinator has been much involved in the task with appreciated efforts from Per Stefenson and Björn Asplind at the Gothenburg office. Warm thanks also to the captains, chief engineers and crew on Stena Britannica for their support during emission measurements and water sampling, as well as the Stena Line personnel on shore in Hook of Holland for their assistance.

Table of contents

Exhaust gas scrubbers in an environmental context

This is a summary and a joint analysis of four studies on environmental aspects of the use of exhaust gas SO_2 -scrubbers on ships. Based on measurements and analyses of emissions and effluents from scrubber systems on ferries in Stena's fleet we draw conclusions on environmental effects of the installations. The studies are part of the EU-funded project *"Scrubbers: Closing the loop"*.

The use of exhaust gas scrubbers on ships is an alternative to the use of low sulphur fuels from a legal perspective. Both options fulfil existing international standards on sulphur emissions from ships in the Sulphur Emission Control Areas (SECA) implemented by the IMO. The environmental effects of a wide spread use of exhaust gas scrubbers are relevant topics for discussion as the limit for sulphur in marine fuel will be reduced globally 2020 and a large increase in the use of scrubbers is likely to follow.

This study includes an extensive measurement scheme on emissions to air from a marine engine fitted with a scrubber. Our results show that the emissions of sulphur dioxide to air are lower when using high sulphur fuel together with a closed loop scrubber than when a low sulphur fuel oil is used. However, the study also concludes that other important air emissions, apart from sulphur dioxide, are at higher levels than emissions from a low sulphur fuel. These emissions are mainly particles and particle components such as organic and elemental carbon.

We also conducted an analysis of energy and material flows related to the full life cycles of the different alternatives. The life cycle assessment showed that from a system perspective, the overall energy requirements for operating a ship on heavy fuel oil together with a scrubber are lower than to run the ship on low sulphur fuel oil. It is however less clear if the low sulphur fuel or the scrubber alternatives have the lowest global warming potential, which depends on the energy carriers used. Environmental impacts related to the emissions from energy use dominate the life cycle analysis. Emissions to the marine environment and their potential toxic effects are not included in the used methodology and are therefore not assessed in the life cycle assessment. In a cost benefit analysis we excluded upstream processes and evaluated the costs and benefits related to the capital and operational expenditure on board a ship and potential external costs. The external costs were to a large extent influenced by the fuel needed to run the scrubbers. The fuel penalty associated with the use of scrubbers causes more emission than the low sulphur fuel oil option, followed by more external costs.

Most exhaust gas scrubber designs include an effluent of washwater to the sea. In a scrubber system of an "open" design, large volumes of sea water are used to clean the exhaust gases from sulphur dioxide. In a "closed loop" system the water volumes are smaller, but there is often an effluent flow also from these systems. The effluent water is monitored in order to make sure it fulfils internationally agreed standards and the washwater may be treated on board in order to remove harmful substances before it is discharged. Both open and closed systems are equipped with holding tanks for the possible occasions when standards are not met. Holding tanks can also be used if the ship is in an area where scrubber water discharge is not allowed. Effluent water can then be pumped ashore.

We tested ecologic toxicity of effluent waters, from both an open loop system and a closed loop system, on a selection of marine organisms. In a risk assessment, the effluents from open loop scrubbers were concluded to cause larger risks for the marine environment than those from the closed loop systems. The risk assessment included data on effect concentrations and discharged volumes together with a simple and static model on mixing in sea water. Although the discharges from the open loop systems are accompanied with significantly higher risks, the treated water from the closed loop system was also found to compromise vital functions in marine organisms. The risks to the marine environment from the releases of effluent waters are concluded to be a concern that need further attention specially to protect sensitive and enclosed areas with heavy ship traffic.

Additional scrubber water treatment methods, such as high efficiency filters, or keeping the water stored in a tank on-board could reduce or eliminate the risks. Such options are not evaluated in this study.

Methodological approaches

This study focuses the use of closed-loop scrubbers on board two ferries in traffic between Hook of Holland in the Netherlands and Harwich in the UK, Stena Britannica and Stena Hollandica. Our emission measurements and analyses on washwater sampled on Stena Britannica have been the basis for many of the analyses made, as described in the following. For complementary analyses, samples of effluent water from the ships Stena Transporter and Stena Forerunner were used.

Air emissions from one of the diesel engines on Stena Britannica, upstream and downstream a scrubber, were measured in order to quantify the effect of the scrubbing process on gases and particles. At these measurements, a rather typical heavy fuel oil (HFO) with 2.8% sulphur content was used. A similar measurement scheme was used for emissions from the same engine at combustion of a low sulphur fuel oil with a sulphur content of 0.1%.

Consecutive tests with the same scope were carried out at different engine loads:

- Low sulphur fuel oil trials were carried out at engine loads 85%, 75%, 50%, and 34% of maximum continuous rating (MCR),
- Tests on HFO upstream the exhaust gas scrubber were conducted at 76%, 49%, and 32% MCR,
- Tests on HFO downstream the scrubber were conducted at 76%, 48%, and 41% MCR.

Concentrations of the gases SO_2, SO_3, NO_X, CO, CO_2, total hydrocarbons (THC), and CH_4, are part of the measurement scheme. Further particulate matter (PM) emissions are determined by gravimetric sampling and characterized as PM_{tot}, and PM with a cutoff around 1.5 µm. Particle size distributions are determined for a limited number of trials in size distributions from 2.5 nm to >30 µm. Particle elemental contents are determined as well as contents of sulphate, black carbon, elemental carbon and organic carbon. Sampling for polycyclic aromatic hydrocarbons (PAH) analyses giving concentrations in gas and particulate form are made at all trials.

IVL Report B2318 covering Task 1 of this study gives full details of the measurements.

The effluent water from the closed loop system is treated on board before discharge. We have made chemical analyses of the water from several sampling points in this system. From these results we can describe the effect of different treatment steps on the concentrations of compounds during the exhaust gas scrubbing. More comprehensive tests, including toxicity tests, are done on the effluent water; the water that reaches the sea. The toxic effects of the scrubber effluent water are tested on blue mussels and copepod zooplankton. Planktonic copepods are especially relevant test species due to their crucial function as a link between primary producers and higher trophic levels such as e.g. fish in the marine food web. They are also among the animals that run the highest risk of being affected by the discharged scrubber water in the field. Similar tests are done on effluent water from an open loop system without the on-board treatment steps. The results from the toxicity tests show the effect of exposure to the mixture of different compounds that are found in the effluent water. Conclusions can thus be drawn on exposure to the scrubber water as a unit rather than in relation to specific substances that are found in the effluent. By this setup comparisons between the two scrubber systems designs, open and closed loop, can be made. The chemical analyses and the toxicity tests are described in full in IVL Report B 2319, which covers task 2 of this study.

The potential environmental impact is analysed by three main means. An environmental risk assessment on the water emissions is carried out using the results from both the chemical analyses and the toxicity tests. The approximate volumes of effluent water that are discharged from the studied scrubber systems are known and the mixing zone around the ship is estimated. From this procedure we calculate a potential concentration in a mixing zone behind the ship that is compared with threshold concentrations. These threshold levels are calculated according to the recommendations in the EU Water Framework Directive. Although this Directive only covers waters up to twelve nautical miles from the shoreline, we consider the argumentation on ecologic risks therein to be the best available. We therefore apply the methods presented in the Directive on the assessments in our analysis of ecological risk in open seas. The risk assessment is described in IVL Report B 2319, which covers task 2 of this study. Air emissions and water emissions are further jointly analysed using life cycle assessment methodology and a cost benefit analysis. Both analyses compare scenarios where ships use low sulphur fuel oil with scenarios where exhaust gas scrubbers are used.

The scrubbers on Stena Britannica and Stena Hollandica are closed loop systems as previously mentioned. In the cost benefit analysis we compare the closed loop system to combustion of low sulphur fuel oil and to an open loop scrubber system. In order to make the comparison fair, we use technical data from an open loop system and scale them to be comparable to a ship of the same size as Stena Britannica. All data are related to fuel consumption of the ships, which serves as the basis for scaling the values.

The cost benefit analysis is then done using two different approaches. One specifically studies costs and benefits from fuel consumption and scrubber operations of Stena Britannica and the sister ship Stena Hollandica. This analysis mainly uses results from tests on board and direct information from Stena Line on the technical system as input values. The other approach investigates costs and benefits from a more or less extensive future use of scrubbers in 2030. The scope of this study comprises all ships in traffic in the North Sea and the Baltic Sea. More generic data on fuel consumption and emission factors are used in this approach.

The cost benefit study estimates external costs of health effects and environmental effects by applying values on damages developed in previous studies. Evaluations of potential environmental damage of emissions to the marine environment are rarely incorporated in cost benefit assessments. Values on damages for water pollution are therefore more uncertain than values on air pollution.

The shipping costs are primarily not calculated from a ship owner perspective but use longer times of depreciation and lower interest rates than what is practice in the ship industry. This is done for a better comparison with external costs. Due to expected high variations in values for many input parameters an uncertainty analysis using a Monte Carlo simulation was used in order to quantify the uncertainties involved with the cost benefit analysis.

Details on the cost benefit analysis are found in IVL report B2320 on task 3 of this study.

In the life cycle assessment the setup of alternatives is similar to the cost benefit analysis. The main objective of the life cycle assessment is to quantify environmental impacts from removing sulphur from the exhaust gas in a scrubber system and compare them to impacts from removing sulphur from the fuel in a land based oil refinery. In the LCA model we use input data from the measurement studies of air and water emissions conducted on Stena Britannica. Further the technical information specific to the scrubbers installed on Stena Britannica and Stena Hollandica are used. As customary in LCAs, all input data is related to a functional unit that is a measure of the utility of the studied system. In our study, the functional unit of one MJ of energy produced by the engine and relates all investigated aspects with environmental impact to this unit.

Material and energy inputs and outputs that can be related to the different alternatives are mapped. This can be materials needed to construct the scrubber, or extra energy needed for water pumps, to give two examples. Differences between the studied alternatives are important to map. An example of this is the use of different fuels in the different options. Therefor data on energy use, material use, emissions, and waste from the involved processes and activities are quantified and related to the energy output of the engine in the unit MJ. The impacts are assorted to the following categories:

- Abiotic Depletion Potential (elements)
- Abiotic Depletion Potential (fossil energy)
- Primary energy resource use - renewable and non-renewable
- Global Warming Potential from a 100 year perspective
- Acidification Potential
- Eutrophication Potential
- Photochemical Ozone Creation Potential
- Ozone layer Depletion Potential

The effects of the different SECA compliance options that are analysed are compared for each impact category. We analyse two different options for low sulphur fuel oil (LSFO) production. One option uses refinery data on production of a diesel fuel in Brazil. This option is called "LSFO 1". The other option includes a data set on energy requirements for treating HFO in a hydrocracking process to produce a LSFO. We call this option "LSFO 2".

A more detailed description of the life cycle assessment approach is given in IVL report B2321 on Task 4 of this study.

Results

The results are presented for four parts of the work separately; air emissions, water emissions and toxicity tests, cost benefit analysis, and life cycle assessment.

Air emissions

The main purpose of installing an exhaust gas scrubber on a ship is to reduce emission of sulphur dioxide to levels equivalent to emission levels from combustion of a fuel with 0.1% sulphur. The closed loop scrubber system on Stena Britannica was shown to accomplish and outperform the emission limit. SO_2 emissions are reduced significantly with the exhaust gas cleaning system (EGCS) on board Stena Britannica.

The emission factor for SO_2 downstream the scrubber was 83% lower than at combustion of low sulphur oil at 75% engine load. The emission factor is specific for the engine and represents mass of emission per unit of work produced by the engine, often expressed as g/kWh. Also, the specific emissions of total hydrocarbons were lower downstream a scrubber compared to emissions from LSFO combustion, approximately 40% lower at 75% engine load. No significant differences in specific emissions of CO_2 and NO_x could be concluded from the measurements, while the specific emission of CO was around 50% higher downstream the scrubber than at LSFO combustion. The specific emissions of PM were higher downstream the scrubber compared to a situation with LSFO combustion, 0.27 g/kWh compared to 0.12 g/kWh. Also emission factors of PAHs , elemental carbon and black carbon, and sulphur in particles were significantly higher downstream the scrubber compared to the LSFO, while results are less clear on emissions of total organic carbon. The metal emissions are lower downstream the scrubber compared to LSFO combustion at 75% engine load.

Tests at lower engine loads in large indicate a similar situation although the SO_2 removal seems even more efficient at lower engine loads, and the differences in PM emissions are less manifested. Metal emissions at low engine loads are higher downstream the scrubber compared to at combustion of LSFO, i.e. the opposite of the situation at 75% engine load. A summary of specific emissions of gases and PM from the trials at different engine loads are presented in **Table 1**/**Figure 1** and **Table 2**/**Figure 2**, respectively.

Table 1. Emission factors in kg/kWh (CO_2) and g/kWh (SO_2, SO_3, NO_x, nmHC, and CO) of gases at the different tests.

Test	LSFO	LSFO	LSFO	LSFO	HFO up-stream scrubber	HFO up-stream scrubber	HFO up-stream scrubber	HFO down-stream scrubber	HFO down-stream scrubber	HFO down-stream scrubber
Engine load	85%	75%	50%	34%	76%	49%	32%	76%	48%	41%
CO_2 (kg/kWh)	0.60	0.60	0.66	0.79	0.62	0.69	0.85	0.62	0.69	0.74
SO_2 (g/kWh)	0.36	0.36	0.4	0.48	10	12	14	0.06	0.03	0.02
SO_3 (g/kWh)	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.37	0.13	0.16	0.08	0.05	0.06
NO_x (g/kWh)	11.8	9.73	11.9	15.4	11.0	12.6	16.3	10.9	12.4	14.6
nmHC (g/kWh)	0.24	n.d.	0.30	0.45	0.36	0.30	0.40	0.16	0.24	n.d.
CO (g/kWh)	0.42	0.53	0.88	0.96	0.93	1.72	1.87	0.79	1.40	1.50

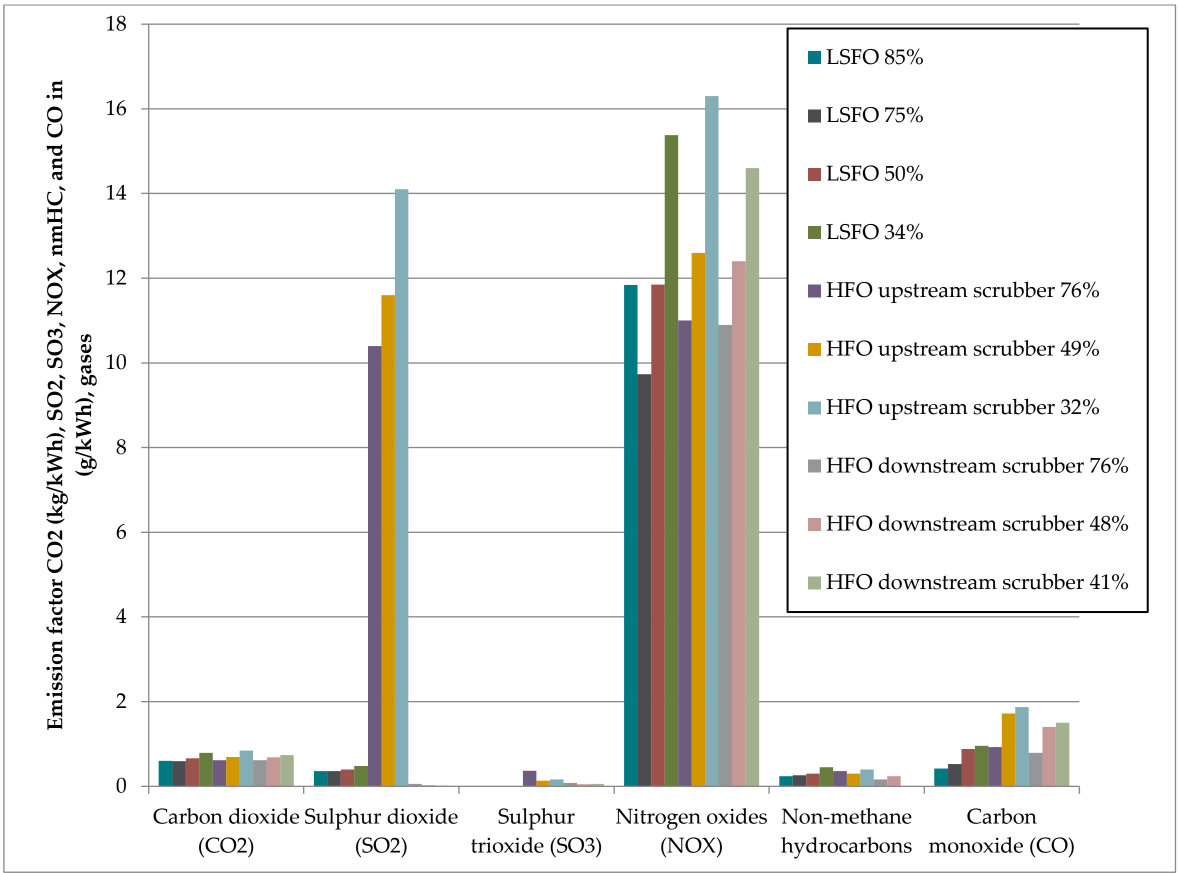

Figure 1. Emission factors of gaseous emissions from exhaust gas measurements on Stena Britannica at the different settings.

Table 2. Emission factors in g/kWh of particulate matter and individual particulate components at the different tests.

Test	LSFO	LSFO	LSFO	LSFO	HFO up-stream scrubber	HFO up-stream scrubber	HFO up-stream scrubber	HFO down-stream scrubber	HFO down-stream scrubber	HFO down-stream scrubber
Engine load	85%	75%	50%	34%	76%	49%	32%	76%	48%	41%
PM (g/kWh)	0.17	0.12	0.17	0.17	0.41	0.36	0.44	0.27	0.23	0.25
BC (g/kWh)	0.006	0.004	0.010	0.012	0.022	0.035	0.065	0.022	0.022	0.028
EC (g/kWh)	0.005	0.009	0.004	0.007	0.022	0.052	0.099	0.015	0.017	n.d.
OC (g/kWh)	0.098	0.078	0.092	0.22	0.084	0.13	0.25	0.085	0.11	0.041
Metals (g/kWh)	n.d.	0.00735	n.d.	0.0025	0.0017	n.d.	0.003	0.0018	n.d.	0.0060
Sulphur (g/kWh)	0.0012	0.0006	0.0002	0.0003	0.034	n.d.	0.0099	0.021	n.d.	0.016

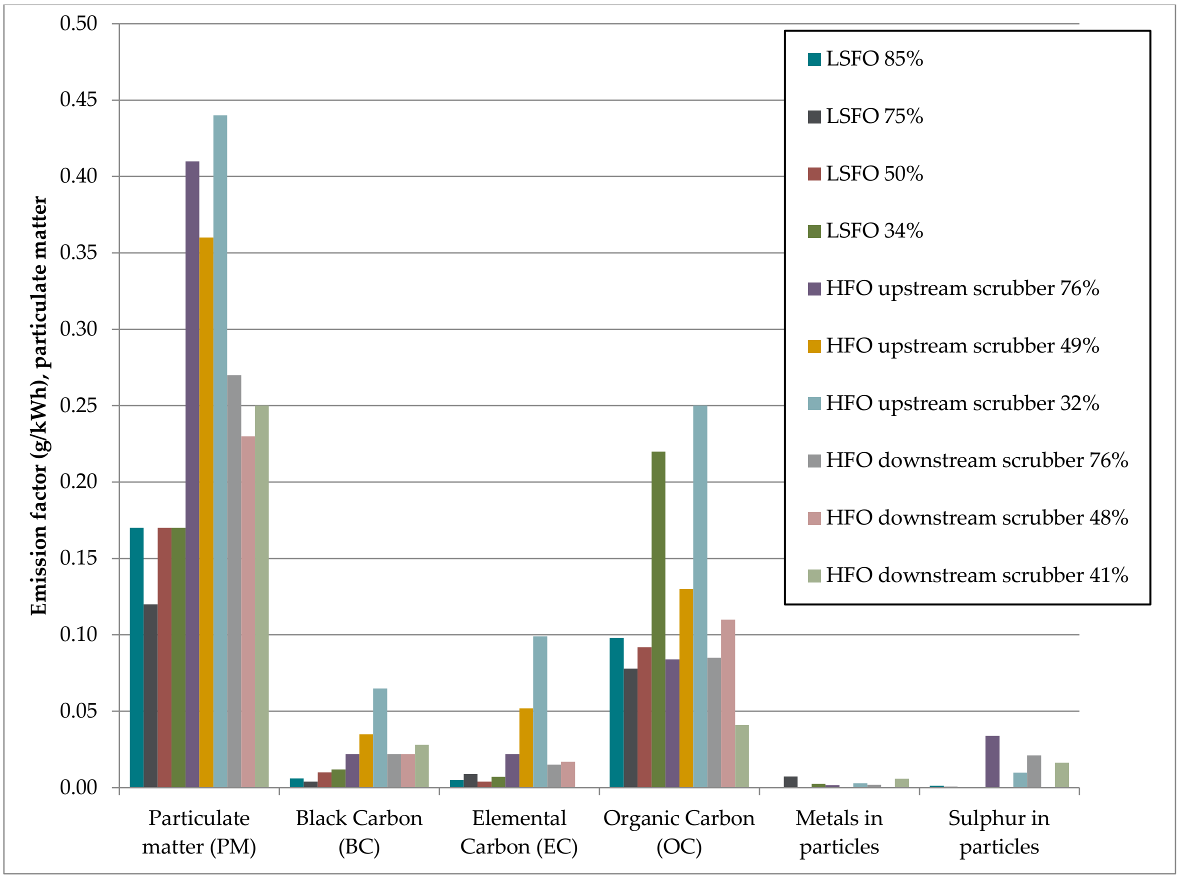

Figure 2. Emission factors of particle emissions from exhaust gas measurements on Stena Britannica at the different settings.

Further, volatile particles were efficiently removed in the scrubber. Volatile particles can be distinguished from solid particles after heating the sample gas, which makes volatile particles evaporate. We use this procedure before measurements of number of particles. Solid particles are also exemplified by contents of black carbon and elemental carbon. Organic carbon content of particles is more or less volatile. Particle numbers are equally efficiently reduced over the scrubber at different engine loads. Organic carbon is removed more efficiently at lower engine loads than at higher. Solid particulate matter (BC and EC) seems to be more efficiently removed in the scrubber at low and medium engine loads than at high engine loads. Also, metals are solid material in the particles. While the trend is that there is a reduction of particulate matter in the scrubber, metal contents were in our analyses indicated to increase in the scrubber process. The reason for this is unclear. Solid particles are suggested to cause higher health risks than volatile particles.

Uncertainties of the results include the emission measurement methods used that are little tested on cold exhaust gases. The gases downstream the scrubber is approximately 20° C. No applicable standard for such measurements exists.

”Scrubbers: Closing the loop; Activity 3. Task 1; Air emission measurements” (IVL report B2318) includes an extensive presentation and discussion of results from the air emission study.

Water emissions and toxicity tests

Several samples on process and effluent waters were taken and analysed. In **Table 3** we present results from the chemical analyses from the bleed off water before it enters the water treatment units (bleed off treatment unit (BOTU) feed), effluent wash water that reaches the sea, and sea water. Results from additional analyses are presented in IVL report 2319.

The BOTU efficiently removes most metals. Exceptions are copper (Cu) and mercury (Hg) that increase in concentration after the scrubber. Total hydrocarbons are also efficiently removed; many of the analysed species to between 90% and 100%. The groups of the lightest hydrocarbon molecules tested are least efficiently removed, see **Table 3**. The straight chain hydrocarbons with 12 carbon atoms or less (Aliphatic hydrocarbons >C5-C12) even occurred in higher concentration after the BOTU than before. The reason for this is uncertain but it might be the result of long chained hydrocarbons being degraded to shorter chains during the water treatment. It may also be related to the addition of flocculant and coagulant chemicals during the water treatment.

Effects from the exposure of marine organisms to scrubber effluent water were seen in all test setups. The lowest concentration of scrubber water found to have a toxic effect varied between the tests. The most sensitive indicator was found to be mortality rate in juvenile stages of copepods. Toxic effects on copepods were not caused by the water sulphur content but were the result of other components in the effluent. In all tests the lowest tested concentration resulted in toxic effects on the juvenile copepods, which means that even lower concentrations may have an environmental risk. The effects on blue mussels were less clear than for the copepods. Only one endpoint that relates to the ability for mussels to attach to the ground demonstrated a significant effect from exposure to the exhaust gas scrubber effluent. This effect was detected at a washwater concentration of 1.25% and only in exposure of water from the closed loop system on Stena Transporter.

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

Table 3. Results from chemical analyses of the water entering the bleed off treatment unit (BOTU) on Stena Britannica, the effluent water for discharge, the seawater and the calculated reduction efficiency of the treatment system on board.

Parameter	BOTU feed	Effluent washwater	Seawater	Reduction efficiency (%)
Turbidity (NTU)	**255**	**9.3**	**<2**	**96.4**
pH	**5.1**	**7.6**	**7.9**	
Alkalinity (mmol·L^{-1})	**0**	**6**	**2.5**	
NO_{2-} *(mg N·L-1)	**<30**	**49**	**<30**	**>-64.6**
NO_{3-} * (mg N·L-1)	**27**	**<1**	**<1**	**>96**
Microtox (EC50, 5 min) (%)	13	15.5	>45	16.1
Al (µg·L^{-1})	120 000	8 300	39	93.1
As (µg·L^{-1})	66	20	1.9	69.7
Cd (µg·L^{-1})	0.34	<0.2	0.11	>41.2
Cu (µg·L^{-1})	41	150	17	-265.9
Cr (µg·L^{-1})	90	9	<1.2	90
Ni (µg·L^{-1})	7 400	830	0.61	88.8
Pb (µg·L^{-1})	18	<6	0.098	66.7
V (µg·L^{-1})	27 000	9 800	3.7	63.7
Zn (µg·L^{-1})	1 200	<70	6.2	94.2
Hg (ng·L^{-1})	1.9	5.2	0.84	-173.7
S (mg·L^{-1})	22 000	19 000	1 100	13.6
Total hydrocarbon (µg·L-1)	**211 960**	**7 103$_{max}$/6 499$_{min}$**		**96.9$_{max}$/96.7$_{min}$ %**
Fraction of different sizes of hydrocarbons :				
Aliphatic >C5-C8 (µg·L-1)	<4.0	<4.0	<4.0	-
Aliphatic >C8-C10 (µg·L-1)	<4.0	49	<4.0	<-1125%
Aliphatic >C10-C12 (µg·L-1)	1 400	2 900	<10	-107.10%
Aliphatic >C12-C16(µg·L-1)	6 800	1 700	<10	75.00%
Aliphatic >C16-C21 (µg·L-1)	23 000	<100	<10	>99.6%
Aliphatic >C21-C36 (µg·L-1)	95 000	720	<30	99.20%
Aliphatic >C36-C40 (µg·L-1)	24 000	<100	<10	>99.6%
Aromatic >C10-C12(µg·L-1)	860	630	<10	26.7
Aromatic >C12-C16 (µg·L-1)	4 900	500	<10	89.8
Aromatic >C16-C21 (µg·L-1)	16 000	<100	<10	>99.4
Aromatic >C21-C36 (µg·L-1)	40 000	<300	<30	>99.3
Naphtalene (ng·L-1)	18 000	4 400	<5.0	75.6
Acenaftylen (ng·L-1)	3 900	360	<1,0	90.8
Acenaften (ng·L-1)	35 000	2 100	<1,0	94
fluoren (ng·L-1)	49 000	3 200	<1,0	93.5
fenanthren (ng·L-1)	520 000	10 000	<1,0	98.1
Anthracen (ng·L-1)	16 000	400	<1,0	97.5
Fluoranthen (ng·L-1)	99 000	220	<1,0	99.8
Pyrene (ng·L-1)	360 000	540	4.3	99.9
Benzo(a)anthracen (ng·L-1)	210 000	210	<1,0	99.9
Chrysen (ng·L-1)	400 000	330	<1,0	99.9
Benzo(b)fluoranthen (ng·L-1)	100 000	100	<1,0	99.9
Benzo(k)fluoranthene (ng·L-1)	21 000	70	<1,0	99.7
Benzo(a)pyrene (ng·L-1)	39 000	<100,0	<5,0	>99.7
Dibenzo(a,h)anthracene (ng·L-1)	17 000	<100,0	<5,0	>99.4
Benzo(g,h,i)perylene (ng·L-1)	76 000	<100,0	<5,0	>99.9
Indeno(1,2,3-c,d)pyrene (ng·L-1)	20 000	<100,0	<5,0	>99.5

On the other hand, the risk assessment based on eco-toxicity of the total discharge indicates something else. The combined effects of the substances in the effluent, points to that the marine environment in the vicinity of shipping lanes or busy areas such as ports and river mouths, may be altered due to discharged scrubber washwater in the lane. Concentrations exceed a calculated threshold levels in the mixing zone, in which exceedance is acceptable according to the Water Framework Directive. Levels of concern are not likely outside the mixing zone from a single passing ship, but can be expected if a few tens of ships are in the same area within a time frame of a few hours. The open-loop scrubbers are larger emitters with higher environmental risks than closed-loop scrubbers. Scrubber effluent from 1 ship with open system exceeds the calculated threshold concentration by 6.3 times and closed system effluents exceed the level by 1.9 – 3.8 times. Further modelling of the dilution process in sea water is required for a more detailed analysis.

”Scrubbers: Closing the loop; Activity 3. Task 2; Risk assessment of marine exhaust gas scrubber water” (IVL report B2319) includes further results from water analyses and tests and a more in depth analysis of results.

Cost benefit analysis

Total annual shipping costs can be expected to be higher using low sulphur fuel oil than using a scrubber together with heavy fuel oil. The total annual shipping costs for Stena Hollandica and Stena Britannica are estimated to be 0.9 million € lower per ship if using a closed loop system compared to running the ships on LSFO. The corresponding reduced cost in an assumed scenario with an open loop scrubber is 1.4 million €. Operation and management costs are higher in the case of the closed loop scrubber, mainly due to the costs of chemicals such as sodium hydroxide (NaOH) needed for the abatement process.

There is also a difference in the external costs caused by the different options. With a closed loop scrubber the external costs attributable to environmental effects from Stena Hollandica and Stena Britannica are estimated to be approximately 0.6 million € higher than if low sulphur oil is used per vessel and year. We include external cost estimates of emissions to air and emissions to water in the analysis. External costs for related activities, such as from refinery activities are not included. In an assumed setting with an open loop scrubber on the ships the external costs are 0.5 million € higher per year than if the ship would use low sulphur fuel oil.

The results indicate that use of scrubbers on these particular two vessels increase health and environmental costs compared to the case when vessels use LSFO, despite a more efficient control of SO_2 emissions. The major contributing factor to external costs for ships with and without scrubbers relate to emissions of NO_X and CO_2. Since a scrubber has a minor effect on these emissions the fuel consumption is of major importance when comparing different alternatives. High fuel consumption will cause higher emissions than lower fuel consumption in the same engine. The fuel consumption will be different if the ship uses low sulphur fuel oil or heavy fuel oil with a closed or an open loop scrubber. The most important factors are the energy needed to run pumps and cooling water in the scrubber scenarios and the differences in energy content between the fuels. The closed loop scrubber studied in this report needs more energy than the open loop scrubber, causing it to be a less attractive option from an external cost perspective.

In an analysis of external costs of environmental effects in water, these are valuated as less significant than those caused by emissions to air. The reason is expected to be partly that methods for economic valuation of effects from emissions to water are not fully developed and the results are therefore not comprehensive. In a comparison between the emissions from the closed loop system and the open system, the open loop discharge causes twice the costs of the closed loop due to eco-toxic effects. Eutrophication effects are higher from the closed loop discharge causing total differences between the systems to be only marginally higher in the open loop scenario than in the closed loop scenario. The eutrophication effect depends on the amount of nitrogen that is discharged to the sea. Our samples from the closed loop system had significantly higher levels that those from the open loop scrubber. A chemical explanation to this difference is lacking and these results should therefore primarily be considered representative for these samples.

The total shipping costs and total external costs for each of the scrubber scenarios and the low sulphur fuel oil scenario is presented in Figure 3.

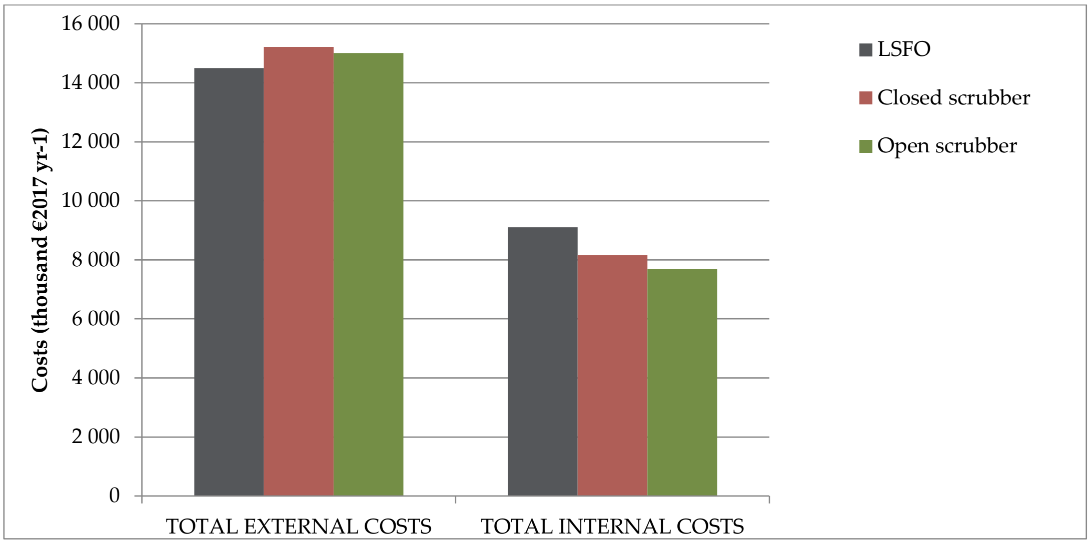

Figure 3. Total external costs and total internal costs (shipping costs) of the investigated SECA compliance alternatives.

The open scrubber scenario is associated with lower shipping costs and lower external costs than the closed scrubber scenario. The total annual shipping costs and external costs allocated to emissions to air and water from Stena Hollandica and Stena Britannica are presented in Table 4 and in Figure 4/Figure 5. All investigated options are presented.

Table 4. Total annual shipping costs and external costs for Stena Hollandica and Stena Britannica, thousand € 2017.

Type of cost		LSFO	Closed scrubber	Open scrubber
Investment costs	Shipping costs	-	540	540
O&M costs	Shipping costs	-	520	50
Fuel costs	Shipping costs	9 100	7 100	7 100
TOTAL SHIPPING COSTS		**9 100**	**8 200**	**7 700**
Health, crops, materials	Externality, air	8 900	9 400	9 300
Climate effect	Externality, air	5 600	5 800	5 700
Eco-toxicity	Externality, water	-	3.8	9.0
Ocean acidification (pH)	Externality, water	-	0.0002	0.1
Eutrophication	Externality, water	-	5.4	2.6
TOTAL EXTERNAL COSTS		**14 500**	**15 100**	**15 000**

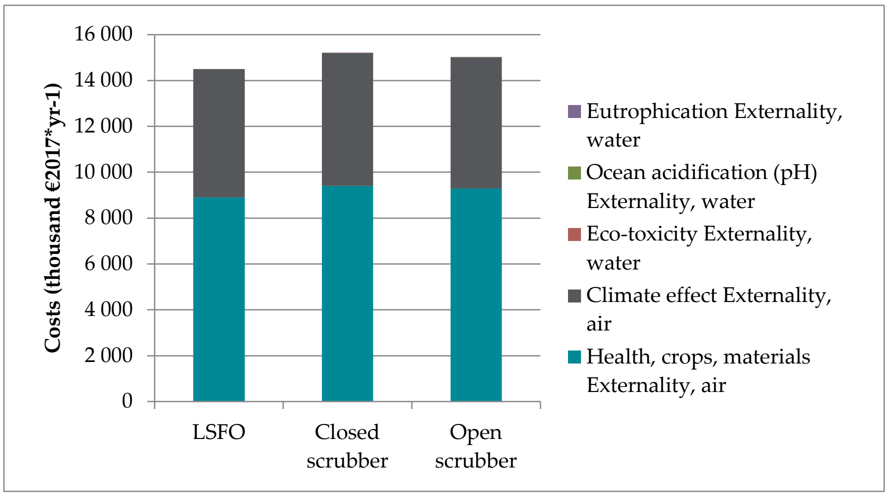

Figure 4. Contribution of costs in different impact categories to total external costs of the investigated SECA compliance alternatives.

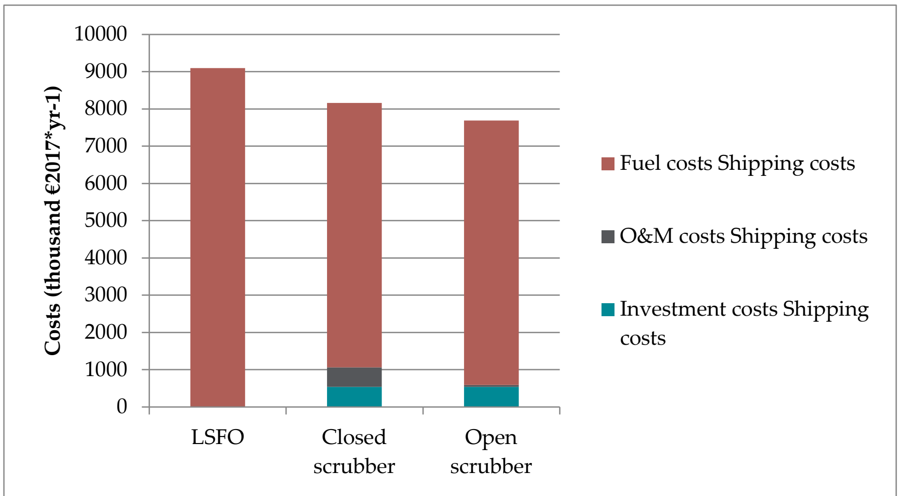

Figure 5. Contribution of cost posts to internal costs (shipping costs) of the investigated SECA compliance alternatives.

Shipping costs are associated with high uncertainty intervals due primarily to fuel price variations. The resulting difference between the scrubber and LSFO scenarios is therefore not necessarily negative as indicated by our results, see **Table 5**. This means, one cannot by certainty say that the scrubber scenarios are associated with higher or lower shipping costs than the LSFO scenario. The difference in the external costs, on the contrary, remains positive when parameter values are varied. The robustness of the resulting values to variations in shipping costs and external costs were tested using Monte Carlo simulation. The difference between the alternatives can be considered as more robust for external costs than for internal costs.

A comparison of two significantly different adoption rates of scrubbers in the industry was also made in a cost benefit analysis. Two emission scenarios covering shipping in the North Sea and the Baltic Sea in 2030 were studied. One of the scenarios applied a scrubber adoption rate of 20% considered as a baseline scenario, and in the other the adoption rate was set to 70%. An extended use of scrubbers is estimated to result in higher external costs due to more air and water emissions. The difference is estimated to be around 260 million Euro per year in a span from 80 to 520 million €. The wide span is due to large differences in different valuation estimates of health effects. Compared to total external costs, these differences are small. Both scenarios are estimated to cause external costs of approximately 966 000 million euro year 2030.The shipping costs are lower in the scenario with a high adoption rate of scrubbers. An interval between 140 and 350 million € per year is estimated with a central value of 330 million €.

The results from the scenario sets studied in the cost benefit analysis are presented in detail in "Scrubbers: Closing the loop; Activity 3. Task 3; Cost benefit analysis" (IVL report B2320).

Life Cycle Assessment

The LCA is primarily made to compare three different options of compliance with the sulphur regulations in the SECA. Different environmental impacts from operating a ship on heavy fuel oil in combination with a scrubber system are compared with those from operations on low sulphur fuel oil. Two alternative production ways for LSFO were investigated. Toxic effects from the discharge of effluent water to the sea are not included in the modelling. The quantitative analysis is therefore foremost a comparison of effects relating to the energy need and the effects of removing sulphur in a refinery compared to removal in the exhaust gases on the ship.

The operational phase dominates the impact analyses. This is due to the combustion of fuel used to run the ship. In the operational phase, the energy use in both scrubber alternatives, closed- and open loop, is higher than in the low sulphur fuel oil alternative. This relates to the previously mentioned extra fuel needed to run pumps for the process water and cooling water for the scrubbers. Further, the energy need is higher in the closed loop system than in the open loop system. From a system perspective though, the energy requirements in the refinery to produce a hydrocracked low sulphur fuel oil from heavy fuel oil (LSFO alt 2.) still contributes a significant part of all energy input to the system. This causes the alternative with LSFO from hydrocracking to require more energy than the other alternatives. Subsequently, this alternative has the highest global warming potential.

The internal order of the compared systems' performances in the other impact categories varies. The differences between the alternatives are small compared to total impacts in all studied categories. In **Figure 6** the impacts of the four alternatives are compared in the categories acidification potential, global warming potential, eutrophication potential, and depletion of fossil energy. The alternative in which LSFO is produced similar to marine gasoil (LSFO alt. 1) performs well in the illustrated impact categories in **Figure 6** except in the category depletion of fossil energy.

Assumptions made in a life cycle assessments study significantly influence the results. There are uncertainties in many of the input data. Discussions on assumptions made, explanations and analyses of the results from the study are presented in "Scrubbers: Closing the loop; Activity 3. Task 4; Evaluation of exhaust gas scrubber systems for ship applications in a system perspective" (IVL report B2321).

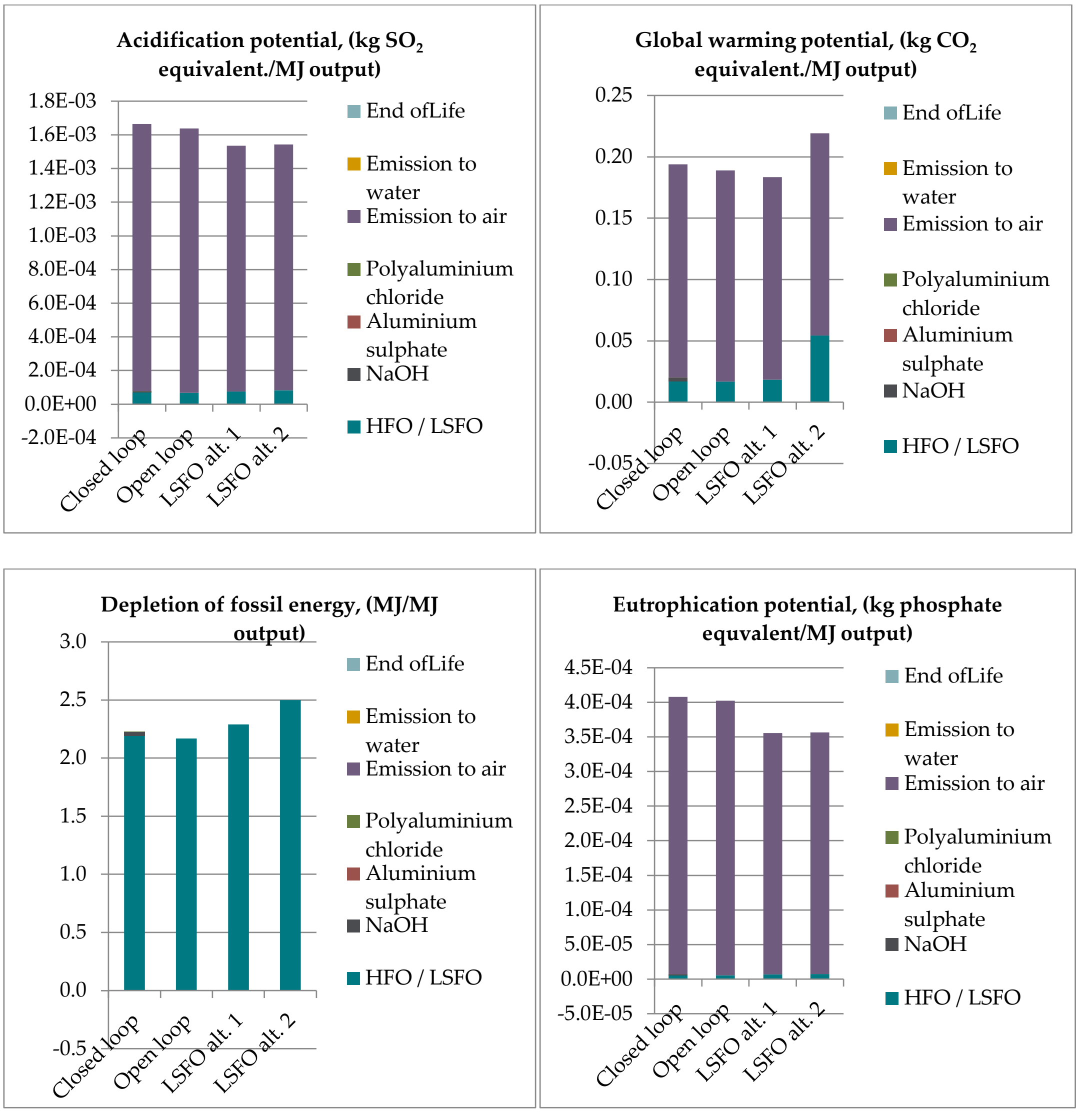

Figure 6. Comparison of the impact categories acidification potential, global warming potential, potential abiotic depletion of elements, and potential abiotic depletion of fossil energy. Four different cases in the study are compared ("LSFO 1", "LSFO 2", closed-loop scrubber, and open-loop scrubber).

Conclusions

Our environmental analyses indicate that the use of a low sulphur fuel oil as marine fuel is favourable compared to the use of heavy fuel oil in combination with an exhaust gas scrubber, from an environmental risk perspective. This statement is valid for closed loop scrubbers and open loop scrubbers and mainly based on the studies performed on eco-toxicity of effluent water.

Importantly, SO_2 emissions are reduced significantly with the exhaust gas cleaning system on board Stena Britannica. Our results show that the emissions of sulphur dioxide to air are lower at the use of high sulphur fuel together with a scrubber than when a low sulphur fuel oil is used. Other emission levels are increased. Combusting a low sulphur fuel causes lower emissions of harmful particle to air than the use of a heavy fuel oil together with an exhaust gas scrubber. Further, our studies point to that the effluent waters from scrubber systems are an environmental risk. These effluents are avoided by the use of the low sulphur oil. The combined effects of the substances in the discharged water, suggests that the marine environment in the vicinity of shipping lanes or busy areas such as ports and river mouths, may be altered due to discharged scrubber washwater in the lane. Conclusions are that there is cause for precaution concerning discharges from marine exhaust gas scrubbers in areas with heavy traffic.

The increased need for energy causes increased emissions of CO_2, NO_X, and particles from ship operations on HFO together with an exhaust gas scrubber compared to a ship combusting a low sulphur fuel oil. The situation is reversed when including upstream energy requirements from hydro-cracked LSFO. This production process has high energy requirements and causes operations on LSFO to be accompanied by higher emissions of CO_2 than the scrubber alternatives. In an analysis of external costs, the low sulphur fuel option is less costly than the two scrubber options. The use of scrubbers on the vessels increased health and environmental costs from emissions compared to the case when they used LSFO. The major contributing factor to external costs for ships with and without scrubbers relate to emissions of NO_X and CO_2. Due to a high efficiency in SO_2 reduction, ships fitted with scrubbers have lower overall emissions of SO_2 despite the fuel increase. This conclusion is highly dependent on the energy needed for scrubber operations. It is valid for the particular ships in this study but its generic value is more uncertain.

Overall, the life cycle assessment indicated only minor differences between the studied SECA-compliance alternatives in all impact categories. The LSFO produced in a hydrocracking process were the most energy demanding of the compared alternatives. This was reflected in the calculated global warming potential of the system but not in the impact categories eutrophication potential and acidification potential. An LSFO produced similarly to marine gasoil has less life cycle emissions to air than the other alternatives.

Uncertainties relating to the issues described in this report will be reduced as more studies are conducted. Many studies following this one could be recommended. A more detailed modelling of dilutions and exchange rates of emitted scrubber water volumes should be of high priority for continued work.

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