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Scrubbers: Closing the loop
Activity 3: Task 3
Cost benefit analysis

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Preface

This is a project report covering exhaust gas emission measurements on Stena Britannica as part of the project Scrubbers: Closing the loop.

This report covers Task 3 “Cost benefit analysis” of Activity 3 (Integrated Life Cycle Balance) in the CEF funded project “Scrubbers – Closing the loop”. Together with this report the Activity is presented in:

- Scrubbers: Closing the loop; Activity 3. Summary; Environmental analysis of marine exhaust gas scrubbers on two Stena Line ships. IVL report B2317, by Winnes H., Granberg M., Magnusson K., Malmaeus M., Mellin A., Stripple H., Yaramenka K., and Zhang Y., 2018
- 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 4; Evaluation of exhaust gas scrubber systems for ship applications in a system perspective. IVL report B2321, by Zhang Y and Stripple H., 2018

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We gratefully acknowledge our funders at 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. The CBA project team is very thankful to all who have contributed to this study with valuable input data and advice, in particular: Björn Asplind (Stena), Mike Holland (EMRC), and Laura Langh-Lagerlöf (Langh Tech).

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Summary

This report is part of the project 'Scrubbers – Closing the loop' funded by the European Commission via Connecting Europe Facility. The overall aim of the project is to test SO_2 scrubber technique in practice on board operating vessels, and analyze the environmental effects to both air and water. This is a relevant topic since regulations that ban the use of high-sulphur heavy fuel oil (HFO) will be introduced globally in 2020. The compliance strategy for ship owners is either to use a low sulphur fuel, or to continue operations on HFO and install exhaust gas SO_2 scrubbers on board their ships. Regulations are already today effective in so called emission control areas (ECAs). This report presents the results of a cost benefit analysis (CBA) of ship operations on HFO together with open-loop and closed-loop scrubbers, compared to low sulphur fuel oil (LSFO). Closed-loop scrubbers are more complex technical systems than open-loop systems. A closed-loop system recirculates the scrubber fluid and applies sensors to operate process water bleed off and addition of chemicals, and often includes water treatment before any discharge to the marine environment. An open system pumps large volumes of seawater to scrub the exhaust gases, and immediately discharge of the scrubber fluid to sea. The natural alkalinity of sea water is used and addition of chemical is most often not necessary.

The analysis is done for two different scenario sets, each including one baseline (reference) scenario and one alternative scenario implying scrubbers as main SO_2 abatement technology. The first scenario set is for the two ships Stena Britannica and Stena Hollandica operating in the English Channel and the North Sea. The second is a scenario analysis for the impact of large scale introduction of scrubbers on ships in the Emission Control Area (ECA) comprising the Baltic Sea, the North Sea and the English Channel. This area is a designated Sulphur Emission Control Area (SECA) from 2015, and a Nitrogen Emission Control Area (NECA) from 2021 by the IMO. In this scenario forecasts of emissions in 2030 are considered. This "ECA 2030" scenario setting was chosen in order to analyse how an increased use of marine exhaust gas scrubbers could affect emissions, water discharges, and related costs and benefits in the studied area. For all scenarios, we have analysed the shipping (internal) costs and the external costs. We include costs for environmental- and health damage in our external cost calculations. The differences in internal and external costs between the baseline and the alternative scenarios have then been compared to the corresponding costs for shipping companies.

The total annual shipping costs of each of the Stena sister ships Stena Hollandica and Stena Britannica are lower if HFO and scrubbers are used than if the ships are operated on LSFO. The difference is 1.4 million € for an open scrubber, and 0.9 million € for closed-loop systems. This is mainly due to the difference in fuel price between HFO and LSFO. Operation and management costs are higher in the case of the closed loop scrubber, mainly due to the costs of materials such as sodium hydroxide (NaOH) needed for the abatement process. The total annual external costs for emissions and discharges from Stena Hollandica and Stena Britannica, were estimated to a value of 15.0 million € for the open-loop scenario, 15.1 million € for the closed loop scenario, and 14.5 million € for the LSFO scenario per vessel. The results thus indicate only minor differences between the alternative solutions. These estimates are based on results of measurements on board the ships.

The setting of scenarios compiled for "ECA 2030" shows higher external effects at an assumed higher implementation rate of scrubber technologies in the future. Annual external costs are 270 million € higher in the scrubber scenario than in the baseline, mainly due to the adverse health effects from air pollution. The annual shipping costs are 330 million € lower in the scrubber scenario than in the baseline.

Our results show the rationale behind shipowners' choice of installing a scrubber instead of switching to a low sulphur fuel in order to comply with the sulphur regulation. From the private perspective, open-loop scrubber has higher benefit-to-cost ratio than LSFO while closed-loop scrubber has lower ratio due to higher operation and management costs.

At present, LSFO is considered as a baseline that both of the scrubber types are compared to in the "Hollandica/Britannica" scenario set. Differences in shipping costs between the alternatives open-loop scrubber and closed-loop scrubber, compared to LFSO, are twice as large as differences in external costs, but uncertainties are important. Our uncertainty analysis indicates that while shipping costs may be higher or lower for scrubbers than for LSFO depending on the fuel prices, corresponding additional external costs is higher. This means, one cannot certainly say that the scrubber scenarios are associated with higher shipping costs than the LSFO scenario due to uncertainties – but the results regarding the external costs can be considered as more robust. Our Monte Carlo uncertainty simulation, however, does not cover uncertainties associated with air emission measurements.

The resulting external costs of environmental and health damage associated with air and water emissions are higher for the scrubber scenarios than in the case of low-sulphur fuel use. From an environmental and health perspective and in line with the precautionary principle, operations on low sulphur fuels therefore seem to be more preferable than operations on HFO together with an exhaust gas scrubber.

Compared to previous cost benefit analyses of scrubbers, the novelty of this study is that it includes monetary valuation of emissions to the marine environment. In the scenario set "Hollandica/Britannica", the monetary value of water-related effects is estimated at 12 thousand € for open-loop scrubber, and 9 thousand € – for closed-loop scrubber. For "ECA 2030", the monetary value of water-related effects is estimated at 1 million € in the baseline scenario, and 4 million € – in the scenario where extensive use of scrubbers is assumed. There is a need for further research within this area e.g. in dispersion and exposure modelling and valuation studies and models of water emissions.

1 Introduction

1.1 Background

This report is part of the project 'Scrubbers – Closing the loop' funded by the European Commission via Connecting Europe Facility. The overall aim of the project is to test exhaust gas scrubber technique (hereinafter "scrubbers") in practice on board operating vessels. The motivation for installing scrubbers is that it 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 northern European Sulphur Emission Control Area (SECA). The environmental effects of a wide spread use of scrubbers are a relevant topic for discussion as the limit for sulphur in marine fuel will be reduced globally 2020. The regulation is described in the MARPOL Annex VI Regulation 14 on sulphur content in marine fuels used for operations in emission control areas. Stena Line's two RoPax ferries Stena Britannica and Stena Hollandica in service between Hook of Holland and Harwich are the subjects of the 'Scrubbers – Closing the loop' project and are studied in detail in this report.

The part of the project which this report is covering is a cost benefit analysis (CBA) of the installed techniques. There are several alternative ways of complying with the new regulation, where the use of scrubbers is one of many. In our analysis we are comparing open and closed loop scrubbers with other available options – mainly fuels with low sulphur content such as low sulphur fuel oil (LSFO, also called SECA oil). Our analysis of costs and benefits from the scrubbers are mainly based on findings from the performed case studies and conducted measurements onboard the Stena vessels, mentioned above, of emissions to both air and water. These measurements were performed during 2017-2018.

There have been a few studies earlier that have assessed scrubber technique onboard ships from financial and environmental perspectives (see e.g. Panasiuk & Turkina 2015; Lahtinen 2016; Hansen et al. 2016; Lindstad & Eskeland 2016; Gu & Wallace 2017; Turner et al. 2018). Fewer studies have done CBA for scrubbers versus other options to comply with sulphur regulations (see e.g. Bosch et al. 2009; Jiang et al. 2014; den Boer. & 't Hoen 2015). A novelty of our study, compared to previous, is that we also include monetary valuation of emissions to water. To our knowledge this has not been done before, apart from emissions of oil spills.

1.2 Aim

The aim of this part of the project is to analyze the scrubber technique from a socio-economic point of view. We do this by conducting a cost benefit analysis for open and closed-loop scrubbers and use low sulphur fuel oil as a baseline. Our analysis is done for two different scenario settings. The first scenario setting is for two particular vessels operating in the English Channel and the North Sea, i.e. Stena Britannica and Stena Hollandica. The second is a scenario analysis for the impact of scrubbers on a large scale – in the Emission Control Area (ECA) comprising the Baltic Sea, the North Sea and the English Channel. This area is a designated Sulphur Emission Control Area (SECA) from 2015, and a Nitrogen Emission Control Area (NECA) from 2021 by the IMO.

1.3 Disposition

The report starts with a presentation of the methodologies used in our analysis. Chapter 2 first introduces our different scenario settings to be analysed, which is followed by descriptions of data set used as well as shipping costs and monetary values used for estimations of the total external costs. The last part is divided into air pollution and water pollution. In Chapter 3 we continue with presenting our results of the cost benefit analysis for the case studies conducted, whereas Chapter 4 gives the results for our ECA 2030 scenarios. Finally, a discussion is presented based on our results and work in Chapter 5, which are concluded in Chapter 6.

2 Methodology

In this chapter we describe in detail how the cost benefit analysis is performed, including choice of scenarios, necessary assumptions and simplifications, data sources, and methods used for calculations of the main results as well as for the uncertainty analysis.

2.1 The concept of external costs

The concept of **external costs**, or externalities, is used by environmental economists to capture negative or positive impacts of consumption and production that are not included in the price of the goods or services produced. Costs for environmental degradation and human health impacts from air pollution are typical examples of external costs. In the present study, we include monetary valuations of both air pollution and water pollution caused by shipping. Methods for monetarization of water pollution are not yet well-developed, so within this study a broad literature review has been conducted in order to compile monetary values for relevant effects, and to apply them in the cost benefit analysis.

We assume that estimates for air-related and water-related externalities are comparable, even though the underlying methods are not always the same. Many of the valuations are based on a so called stated preferences approach where people’s willingness to pay in monetary terms for a change is captured using different methodologies, read more in e.g. Breidert et al. (2006).

2.2 Scenarios and method

Cost benefit analysis in this report is performed for two different scenario settings – one setting for each of two Stena sister ships (Stena Hollandica and Stena Britannica) operating the same route in the North Sea between Hook-of-Holland in the Netherlands and Harwich in the UK and one setting for the entire fleet navigating in the Baltic Sea and the North Sea, including the English Channel (hereinafter – ECA 2030). These two settings are very different in terms of target year, number of scenarios and main assumptions used – the methods and results are therefore presented in the report separately, in different sub-chapters. The major difference is that the scenario setting for Stena Hollandica and Stena Britannica is focused on the present situation (year 2017) and two vessels with a specific route, while the ECA 2030 scenario setting explores future scenarios with normal (baseline) and high rates of scrubbers in the entire ECA fleet as a possible response to the global 0.1% sulphur cap from 2020.

The main elements of the analysis are, however, the same. In both cases, we estimate annual shipping costs associated with technologies and fuel use, and annual external costs.

Shipping costs comprise total fuel costs and costs of abatement technologies (e.g. scrubbers). The latter is calculated as a sum of annualized investment and installation costs (fixed costs) as well as operation and management costs. Methodological details are presented in Chapter 2.4.

External costs in this study are divided into costs associated with air pollution and climate effects (health, effect on crops and materials, and climate effect due to air emissions) and water pollution (eco-toxicity, acidification, and eutrophication due to water discharge). For external costs of water and air pollution in the Stena Hollandica and Stena Britannica scenario setting, we use unit cost values derived from the literature e.g. costs of 1 kg SO_2 emitted in a certain region. For air pollution costs on a larger scale – in the ECA 2030 scenario setting – instead of unit cost values we use models that calculate health costs based on the population-weighted pollutant concentrations and costs of corresponding specific health effects – mortality, asthma cases etc. The methodology is presented in detail in Chapter 2.5.2.2.

In both scenario settings, for both shipping and external costs, we calculate the differences between one scenario corresponding to "business as usual" development and considered as baseline, and one or two scenarios describing alternative development involving scrubbers (chosen scenarios are described in detail in Chapters 2.2.1 and 2.2.2.). The socio-economic effects are then analyzed in the following ways:

- By comparing the total shipping costs and external costs estimated for each scenario;
- By considering the difference in the external costs alone – to see whether scrubbers seem to be better or worse for health and environment than LSFO;
- By comparing the differences in the shipping cost and in the external costs (compared to the baseline) to each other, for each alternative scenario. The differences indicate whether an alternative scenario is associated with higher or lower costs for shipping companies and for society (environmental and health costs); the relationships between the differences indicate whether shipping companies' costs (or savings) overweighs corresponding external cost changes.

2.2.1 Scenarios and method for Stena Hollandica and Stena Britannica

Scenarios for cost benefit analysis of scrubbers installed on Stena Hollandica and Stena Britannica are chosen with respect to the main options available for these vessels that need to comply with 0.1% sulphur cap:

1. LSFO as main fuel, no scrubber – this scenario is a baseline that two other scenarios are compared to;
2. Heavy fuel oil (HFO) with 2.8% sulphur content and closed-loop scrubber;
3. Heavy fuel oil (HFO) with 2.8% sulphur content and open-loop scrubber.

In the cost benefit analysis we estimate shipping costs and external costs associated with each vessel's annual operation in the North Sea, in normal conditions. The main CBA results in this setting are therefore shipping and external costs per vessel per year, presented for each of the considered scenarios. Calculations represent year 2017.

The methodology and data flows used in the analysis are illustrated in Figure 1. In this scenarios setting, results of the measurements performed onboard (air emissions, water flows, fuel use), and laboratory tests of the collected samples (scrubber effluent water, sludge, fuel), have been used wherever possible – those can be found in the report on task 1 and 2 of this project (Winnes et al., 2018; Magnusson et al., 2018). In particular, measured emission factors for air pollutants are combined with fuel consumption data and unit costs per tonne pollutant, in order to get an estimate for air-related external costs. In a similar way, water test results are used in combination with derived monetary valuations for each of the water-related effects, to calculated total water-related externalities. For shipping cost estimates, data provided by Stena are used in combination with measured fuel consumption and certain literature-based values. Detailed descriptions of the calculation method for each of the CBA components – shipping costs, air-related externalities and water-related externalities – are presented in the Chapters 2.4, 2.5 and 2.6 of this report, respectively.

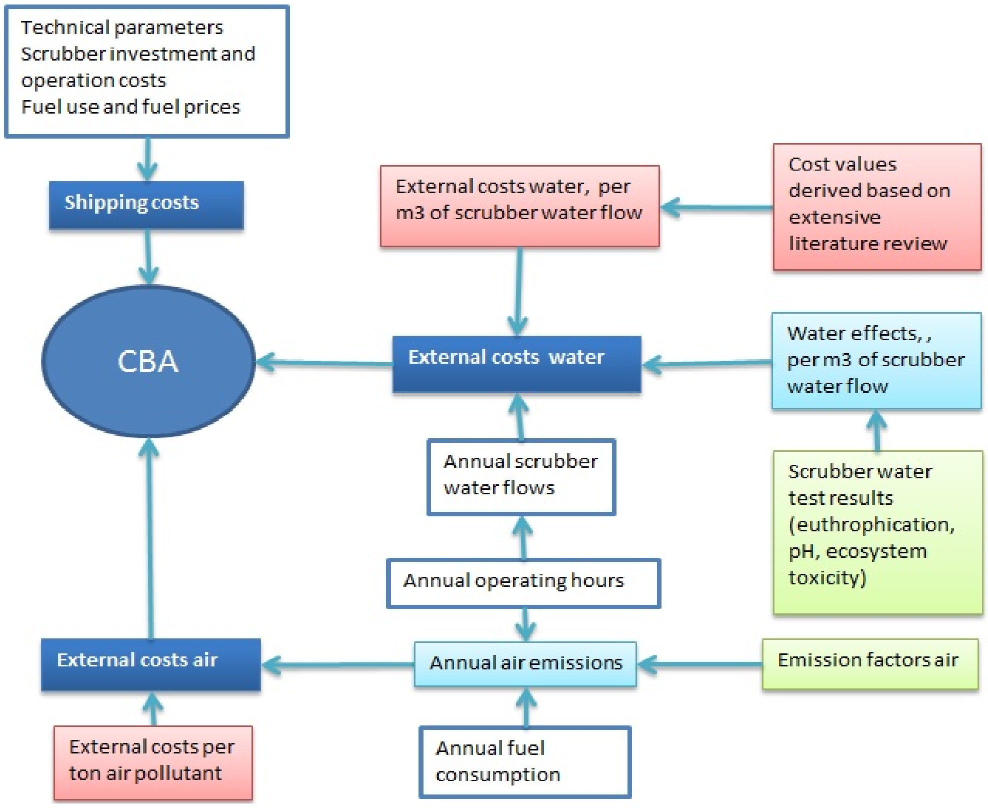

Figure 1: CBA flow-chart for the scenario setting with Stena Hollandica and Stena Britannica. Colour marking: green – the results of the measurements of air emissions on-board and scrubber water laboratory test results (air and water samples from Stena Hollandica and Stena Britannica); white – other parameters specific for Stena Hollandica and Stena Britannica; red – values regarding external costs obtained from the literature; light blue – calculated annual air emissions and water effects; dark blue – calculated annual shipping costs and external costs.

In some parts of the analysis we have also considered a scenario where vessels run on heavy fuel oil without a scrubber. This is not a realistic option for the North Sea after 2015, but is used here to estimate effects and costs of using scrubbers vs. not using scrubbers on vessels running on high sulphur heavy fuel oil.

2.2.2 Scenarios and method for ECA in 2030

In order to scale up scrubber system costs, effects on health and environment and related external costs, cost benefit analysis has also been performed for the whole vessel fleet navigating the Baltic Sea and the North Sea (including the English Channel) in 2030. For this analysis, two different scenarios are considered:

1. Baseline scenario, where 20% of fuel is assumed to be used by vessels with scrubbers installed;
2. Scrubber scenario, where scrubbers are assumed to be used for 70% of the fuel consumed in the area.

The expected industry adoption of scrubber technology in the two scenarios is taken from a report produced in the SHEBA project (Fridell et al. 2018). In large, the business as usual scenario includes assumptions that current trends in the development of shipping continues and that already decided legislations will enter into force. The use of scrubbers in the business as usual scenario is determined from using described criteria on conditions that make scrubbers favorable for investment compared to using low sulphur marine fuels (Reynolds, 2011). In the scrubber scenario described in the SHEBA report, a much larger use of scrubbers are assumed. The assumption made is that the fraction of fuel being HFO in 2014, per ship type, is kept constant until 2030 and that the use of HFO is combined with the use of scrubber to meet the sulphur regulations. Details on the underlying assumptions are explained in a report from SHEBA.

In general, the method is similar to what's used for the Stena vessels: shipping costs are combined with external costs to estimate the total costs or benefits from the scrubber scenario compared to the baseline. Due to a large scale there are many more generalizations and simplifications used in this scenario setting. More fuel options are available in addition to LSFO and heavy fuel oil – in both scenarios we also include marine gasoil (MGO) and liquified natural gas (LNG). In this scenario setting, we have to consider NOx abatement technologies because of NECA in place from 2021 onwards. Air-related externalities are calculated for the whole fleet with the help of models GAINS and ALPHA RiskPoll[1] instead of applying "ready-to-use" unit external costs per tonne pollutant. Detailed description of the method is given in Chapters 2.3 – 2.6 below.

2.3 Data and assumptions

For both scenario settings, there is a range of assumptions and simplifications made in the presented cost benefit analysis. Some of them are valid for both Stena's sister ships Hollandica and Britannica in 2017 and for the whole ECA fleet in 2030 – those we call generic assumptions (see

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[1] GAINS is an integrated assessment model used to identify and explore cost-effective emission control strategies for air pollutants (Amann et al. 2011). ALPHA RiskPoll (ARP) is an economic valuation tool (Holland et al. 2013). Both models are actively used within the UNECE Convention on Long-Range Transboundary Air Pollution (UNECE CLRTAP) and within the EU air quality work. The models are further described in Chapter 2.5

Chapter 2.3.1), they mainly refer to currency conversions and the issue of discounting future effects.

Annual fuel use and annual emissions are the basic, input data for further calculations of all types of costs. For the scenario setting "Hollandica/Britannica", the method for estimating fuel use and emissions is described in Chapter 2.3.2 below. For the cost benefit analysis for ECA in 2030, a simplified fleet model is built – it is described in Chapter 2.3.3. The most important methodological differences between the two scenario settings are summarized in Table 1.

Table 1. Scenario settings: Hollandica/Britannica 2017 vs ECA 2030 – main differences.

Aspect	Hollandica/Britannica (2017)	Emission Control Area 2030
Scenarios included	-HFO + Scrubber, open -HFO + Scrubber, closed -LSFO (baseline) (extra scenario - HFO without scrubber)	-20% of scrubbers in the fleet -70% of scrubbers in the fleet (by fuel use)
Fuels considered	LSFO, HFO	LSFO, HFO, MGO, LNG
Input data	Mainly results of measurements and tests conducted in 2017-2018	Set of cost-related data based on literature, complemented with recent measurement results
Data on annual fuel use	Measurements for LSFO, estimates for HFO + scrubber	Based on projections in the project SHEBA (Fridell et al., 2018 and Kalli et al., 2013)
Abatement technologies considered	Open and closed scrubber systems	Open and closed scrubber systems, SCR for NOx abatement, LNG engines
Fuel prices	Current prices (Rotterdam, summer 2018)	Estimates from Hansen et al. (2016), based on the projections by the US Energy Information Administration (EIA 2014)
Treatment of running modes	Different fuel consumption rates and emission factors for modes at sea, manoeuvring and at berth	Only at sea mode is included for simplicity
Consideration of auxiliary engines	Different fuels for scrubber scenarios (MGO) and LSFO scenario (LSFO) are taken into consideration	Not considered, same fuel assumed in both scenarios
Engine load and engine efficiency	Most engines are run on an engine load lower than 75%	75% engine load in average, 44% engine efficiency
Treatment of uncertainties	Uncertainty analysis by Monte-Carlo method	Low, high and central values

2.3.1 Currencies and discounting

In this chapter we give a short description on how we present our monetary values and prices, as well as why we have not chosen to discount our valuations of external costs.

First, all results of our calculations are presented in € 2017. For recalculation between valuations from different years, we use GDP deflators by OECD, and for recalculation between USD and € as well as SEK to € exchange rates of the European Central Bank has been used. Values in other currencies are translated into € and then, when needed, adjusted to 2017 prices with European-average inflation rates.

Some of our selected values for water emissions could be value (benefit) transferred using e.g. the unit value transfer method (NEEDS, 2009). In our study we have chosen not to transfer values since they are stated as generic values. The benefit transfer would generate only minor differences in results and we have no dispersion model for water emission.

Second, there is an ongoing discourse among academics concerning the use and not use of **discounting external costs and benefits** in CBA. Discount rates are usually related to market interest rates, and discounting future costs and benefits are usually done for two reasons:

1) Due to a time preference we tend to regard the present higher than the future and
2) Due to the expectation of economic growth future generations are expected to be richer than current generations and hence more capable of taking on a given cost.

Recent discussions regarding the prospects for economic growth in the 21st century suggest that lower growth rates than today are likely (Alfredsson & Malmaeus, 2017). Hence, arguing that discount rates should be set at lower levels than usually done, using a declining rate over time or even not use it at all. Discounting future effects means that they are valued less, generating a lower incentive for implementing measures today with long term positive environmental effects. Hence, arguments for low or no discounting is part of an ethical discussion on how we value impact on future generations, the so called intergeneration problem (Attema et al. 2018; Sterner & Persson 2008; Stern et al. 2006; Mattson 2006; Broome, 1992).

In our case we are weighting all costs and benefits of different sulphur emission reduction measures for the target year 2017. This approach assumes that the costs and benefits are distributed equally over time. Therefore, there is no need to discount future willingness to pay (WTP) values used for estimating the external costs. Another method when conducting a CBA is to instead calculating net present values based on e.g. the technical life time of the project; when this is done discounting as well as variations between different years can be captured. However, in general, the further into the future impacts emerge the greater are the uncertainties. Hence, we have chosen to assume equal distributions over time and a target (average) year.

Discounting of shipping costs depends on a chosen perspective on investment costs. The societal perspective implies that the decision is made by a public planner and results in maximum benefits for all members of society, while private investor's decisions are mainly driven by economic benefits, risks are viewed in a much shorter time perspective, and external costs are not always considered. The cost estimate methodologies for these two perspectives differ by applying different interest rates (discounting) and investment lifetime to calculate the annual cost of investment.

For the societal cost perspective, the accepted values of 4 % interest rate and an investment lifetime equal to the equipment lifetime are used for annualization (Bosch et al. 2009; Amann et al. 2011). This is what we use in the main analysis, for a better comparison to external costs. Shipping companies, however, usually consider a much shorter time period when annualising investment costs in order to make a choice between available options. Shipping (internal) costs are the main factor for companies when they choose a specific abatement technology. There is, however, no common agreement on which values should be used for the private investors' perspective in socio-economic analyses: the choice is quite subjective and is affected by factors such as the current economic situation in a country, uncertainties in fuel prices and branch-specific circumstances. In Åström et al. (2014), the values of 10 % interest rate and 2 years investment lifetime were used to calculate costs from the company perspective – a quite cautious approach based on a very short investment lifetime. In Winnes et al. (2016), 7 % and 5 years were used – these numbers are based on discussions with Swedish shipping company representatives. In a study by Höglund-Isaksson (2012), which also presented emission abatement costs from two different perspectives (in another sector), 10 % interest rate and 10 years investment lifetime are chosen for analysis. In our study, a private perspective is only used to make a retrospective CBA calculation similar to the calculation made by Stena in 2014 before the decision on scrubber installation. We apply 7.5 % interest rate and 10 years investment lifetime.

2.3.2 Hollandica/Britannica – fuel use and emissions

2.3.2.1 Annual fuel consumption

For the Hollandica/Britannica scenario setting, available measurement results have been used where available. To estimate annual consumption of LSFO on a vessel, data from onboard measurements are used directly: the total value of LSFO consumed in January 2017 is multiplied with 12 resulting in the annual amount of ~14 800 tonnes LSFO used by main engine. Annual consumption of auxiliary engines, also running on LSFO, is estimated at ~2 200 tonnes fuel per year. **Annual LSFO consumption** is further split by **three modes** (at sea, maneuvering, at berth), in order to apply mode-specific emission factors and external unit costs for air pollution. Mode split is performed based on a detailed data set for hourly fuel consumption rates at Britannica.

For the two scrubber scenarios, we estimate **annual HFO** (and for auxiliary engines – MGO) **consumption** by multiplying the annual LSFO consumption with two coefficients:

1. Energy content coefficient, reflecting the difference in the calorific values of LSFO (42 MJ/kg), MGO (43 MJ/kg), and HFO (40 MJ/kg);
2. Fuel penalty coefficient consisting of several components, in particular extra fuel use needed for electricity to scrubber (1.3% for open scrubber and 2.2% for closed scrubber). These numbers are calculated based on technical data provided by Stena and described in more detail in the report covering task 4 of this project (Zhang and Stripple, 2018). The fuel penalty is slightly higher for the closed-loop scrubber although values available in the literature imply the opposite (see Appendix 1). Fuel penalties do not apply when the scrubber is stopped (vessel at berth).

Hypothetical annual fuel consumption of a vessel running on HFO[2] without a scrubber has been calculated as well, with respect to fuel penalties. Scenario- and mode-specific fuel consumption and operating hours are summarized in Table 2.

Table 2. Hollandica/Britannica 2017 – annual fuel consumption.

	At sea		At berth		Maneuvering		Total	
	ME	**AE**	**ME**	**AE**	**ME**	**AE**	**ME**	**AE**
Hours	5200		2700		790		8700	
Fuel use, tonnes								
-LSFO	14 100	1 300	-	700	700	200	14 800	2 200
-HFO + closed scrubber	15 000	1 200	-	700	800	200	15 800	2 100
-HFO + open scrubber	14 900	1 200	-	700	700	200	15 600	2 100
-HFO without scrubber	14 700	1 200	-	700	700	200	15 400	2 100

2.3.2.2 Emissions to air

To further calculate emissions, **emission factors** mainly based on measurements performed in 2017 within this project and covered in full in the report on Task 1(Winnes et al. 2018) are used, see Table 3. There were no measurements of emission factors from auxiliary engines running on MGO,

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[2] Same HFO as used now in combination with scrubber – with 2.77% of sulphur content. This is what meant with "HFO" throughout the report except for Table 26 and the correspondent text giving a retrospective analysis of a shipowner choice between scrubber and MGO/LSFO

so here the following literature sources are used instead (Cooper & Gustafsson, 2004; IVL internal database on PM emissions from marine engines)

Table 3. Emission factors used for calculation of annual emissions from Hollandica/Britannica (from Winnes et al. 2018).

Fuel	Engine load, %	Emission factors, g/kWh			
		SOx	NOx	$PM_{2.5}$	CO_2
LSFO	75	0.36	9.7	0.12	598
	50	0.4	11.9	0.17	659
	30	0.48	15.4	0.17	793
MGO (AE)	all	0.5	11.8	0.34	690
HFO, after scrubber	75	0.06	10.9	0.27	618
	50	0.03	12.4	0.23	690
	30	0.02	14.6	0.25	739
HFO, before scrubber	75	10.31	10.9	0.41	617
	50	11.8	12.6	0.36	687
	30	14.70	16.3	0.44	739

For further application of external unit costs, it is important to know **emission distribution by area** – i.e. whether emissions take place close to the UK or to the Netherlands, or in the North Sea. To estimate number of hours spent at berth in each country, and maneuvering close to the country coast, we again use fuel consumption measurements performed on one of the vessels during 2017. During a 24-hour period, a vessel spends about 14 hours at sea, 4.5 hours – close to /in the UK, and 5.5 hours – close to/in the Netherlands. Using these values, we distribute mode-specific emissions by area, see Table 4.

Table 4. Annual emissions from Hollandica/Britannica distributed by area, tonnes.

		North Sea	UK	Netherlands	Total
LSFO	SOx	30.7	1.6	1.9	34.2
	NOx	841	51	62	954
	PM2.5	10.3	0.6	0.7	11.6
	CO2	50 900	2 600	3 200	56 700
HFO + closed scrubber	SOx	7.2	1.0	1.2	9.4
	NOx	930	44	52	1 026
	PM2.5	23.3	1.0	1.2	25.5
	CO2	52 900	2 400	2 900	58 100
HFO + open scrubber	SOx	7.1	1.0	1.2	9.4
	NOx	923	43	52	1 018
	PM2.5	23.1	1.0	1.2	25.3
	CO2	52 400	2 400	2 900	57 600
HFO without scrubber	SOx	818.4	20.4	23.8	862.6
	NOx	912	45	54	1 011
	PM2.5	33.8	1.3	1.5	36.6
	CO2	51 700	2 400	2 800	56 900

Presented in this way, emissions are further used for cost calculations.

2.3.2.3 Water discharge from scrubbers

In order to calculate annual water pollution costs, derived monetary effect valuations per m^3 are multiplied with annual volumes of water discharged from scrubber systems. Water discharge volume from the closed-loop scrubber installed on Stena Britannica is estimated at 10 m^3 /hour (B. Asplind, personal communication). Water discharge volume from an open-loop system is not available for Stena Britannica but is documented for Stena Forerunner of 350 m^3 per hour (B. Asplind, personal communication). This number cannot be directly applied to other vessels; instead, we have calculated water discharge per unit fuel use of 0.17 m^3/ kg HFO based on available data on water discharge and fuel use at both vessels (fuel use for Forerunner is available in Jönsson & Törnmalm 2018). Related to the fuel consumption of the main engines on Hollandica or Britannica, it results in 475 m^3 water discharge per hour. Both values (10m^3/ h and 475 m^3/ h) are further multiplied with 6000 hours per year which is an approximation of the time that the scrubber is in operation, to get an estimate of water pollution costs per vessel for year 2017.

For the scenario setting **ECA 2030**, we use the following water discharge volumes per hour, 0.2 m^3/ MWh for closed systems, and 45 m^3/ MWh for open systems (B. Asplind, personal communication; Lloyd’s Register Marine, 2015) – those are applied to the total annual power output in ECA, with respect to the shares of open and close scrubber systems. Monetary valuations of water effects are the same for ECA 2030 as those used for the case of Hollandica and Britannica (see Chapter 2.6).

Tests were conducted on the effluent water in order to determine the contents of chemical compounds and toxicity on marine animals. The relevant parameters for the analysis of external costs from effluent water include toxicity from standardized Microtox-tests, eutrophication (NO_3) and pH. The effluent water from closed scrubber systems was represented by a sample from Stena Britannica taken in September 2017. The content in effluent water from open scrubber systems was represented by a sample from Stena Forerunner, taken in March 2018. The pH results were later translated into concentration of H^+ ions. Ecotoxicity was measured using Microtox tests. Microtox is a bacterial bioluminescence test which is often used as a screening method for acute aquatic toxicity. We refer to the report covering task 2 of this project (Magnusson et al., 2018) for further information about the test. Based on a methodology developed in the ZEB project (Stripple H., 2017), Microtox results were translated into 1,4-dibenzene equivalents. Measurement results are presented in Table 5.

Table 5. Results from measurements and toxicity approximations in effluent water in closed (Britannica) and open (Forerunner) scrubber systems.

Effect / parameter	Britannica	Forerunner
1,4-dibenzene eq (mg/L)	55	2.3*
pH	7.6	6.5
NO_3-N (mg/L)	18**	0.18

* The toxicity in the Forerunner effluent was below detection with Microtox, but based on a variety of toxicity tests it was concluded that the toxicity was 1/20 of the closed scrubber water (Magnusson et al., 2018)

** For NO_3-N closed scrubber was represented by Stena Transporter due to measurement problems with the Britannica sample.

2.3.3 ECA 2030 – assumptions, fuel use, and emissions

Scenarios for 2030 are focused on consumption of different types of fuels in the Baltic Sea and the North Sea – this is the starting point of the analysis. The calculations of total energy use in the Baltic Sea and the North Sea in 2030 are based on estimates valid for 2011 (Jalkanen et al. 2016). In 2011, the fuel used in the North Sea was approximately 6.5 million tonnes. The corresponding value for the Baltic Sea is 4.7 million tonnes.

Future energy use per ten different ships types are estimated according to a description in a report from the SHEBA project (Fridell et al., 2018). The same report is used for values and extrapolations on expected annual efficiency increase and growth rates of number of ships. All calculations are done separately for the different ship types. An expected lifetime of different ships types are used in the forecasts in order to have include a value on how fast new ships will replace old ships. The studied ship types and the values used in the forecast are presented in Table 6.

Table 6. The studied ship types and the values used in the forecast.

Ship type	Number of ships annual growth rate (%)			Efficiency increase	Efficiency increase assuming only EEDI[3]	Lifetime
	2015-2019	**2020-2029**	**2030-2040**	**% yearly up to 2040**	**% Yearly up to 2040**	**years**
Bulk carrier	0.20	0.20	0.20	1.90	0.99	26
Chemical tanker	1.20	1.20	1.20	1.90	0.73	26
Container ship	1.00	1.00	1.00	2.25	0.82	25
General Cargo	0.00	0.00	0.00	1.30	1.04	26
LG tanker	1.20	1.20	1.20	1.90	0.68	28
Oil tanker	1.20	1.20	1.20	1.90	0.73	26
RoRo cargo	1.20	1.10	1.00	2.25	0.69	27
Ferry	1.20	1.10	1.00	2.25	0.69	27
Cruise	1.00	1.00	1.00	1.30	0.74	26
Vehicle carrier	1.20	1.10	1.00	2.25	0.65	27

The fuel distribution per ship type interpreted from Fridell et al. (2018) and used for estimates in the scrubber scenario is presented in Table 7.

Table 7. The fuel distribution per ship type used in the calculations in the scrubber scenario setting ECA 2030.

Ship type	MGO	LSFO	HFO + scrubber	LNG
Bulk carrier	12%	12%	76%	1%
Chemical tanker	15%	15%	67%	2%
Container ship	17%	17%	60%	5%
General Cargo	12%	12%	74%	2%
LG tanker	16%	16%	67%	1%
Oil tanker	13%	13%	72%	2%
RoRo cargo	8%	8%	81%	4%
Ferry	8%	8%	81%	4%
Cruise	10%	10%	79%	2%
Vehicle carrier	15%	15%	68%	2%

The total fuel use by fuel type and the shares consumed in the both seas are presented in Table 8 below. 43% of the total energy in fuel is consumed in the Baltic Sea, and the remaining 57% – in the North Sea and the English Channel. The assumptions about the use of energy of ships in the two areas are from Jalkanen et al., 2016.

Table 8. ECA in 2030 – fuel use, TJ.

	Baseline			Scrubber scenario		
	Baltic Sea	**North Sea**	**TOTAL**	**Baltic Sea**	**North Sea**	**TOTAL**
MGO	56 700	75 100	131 800	19 800	26 300	46 200
LSFO	56 700	75 100	131 800	19 800	26 300	46 200
HFO*	31 100	41 200	72 400	115 300	152 800	268 100
LNG	14 800	19 600	34 400	4 900	6 500	11 400

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[3] EEDI = Energy Efficiency Design Index

* HFO implies using scrubbers

In the baseline scenario, HFO + scrubbers are assumed to be used in 20% of all shipping activities (by fuel use). In the scrubber scenario, a relatively high rate of scrubber installations is assumed, and 70% of all shipping activities are assumed to use scrubbers. This extra 50% are assumed to replace all other options (LSFO, MGO and LNG) equally.

We assume that in the Baltic Sea all scrubber systems are closed (or run in the closed mode) due to certain problems with low water alkalinity and also pipe-blocking ice on high latitudes. For the North Sea and English Channel we assume that most scrubbers are open (or run in the open mode) since it is much less expensive. There are, however, certain areas where it is prohibited to discharge scrubber effluent water as close to German and some Belgian ports. In the model, we assume that share of closed-loop systems in the North Sea is 10%.

Although there is a variety of vessel categories and different types of engines used in the area, in this particular analysis we have not taken this into consideration. We do distinguish between three vessel sizes, small, medium and large, depending on installed main engine power, see Table 9. According to personal communication with Stena, there are no technical limitations for scrubber installations regarding vessel size – so we assume exhaust gas scrubbers are installed on vessels of all three sizes.

Table 9. ECA in 2030 – vessel sizes.

	Small	Medium	Large
Power installed on main engine, kW	3 000	10 000	25 000
Power installed on main engine, kW	560	1 500	3 800
Share of the total fuel use in ECA in 2030	21%	25%	54%

Considering the situation during the target year of 2030, we need to take into account the historical development of regulations in the area. In 2015, the 0.1% sulphur cap was introduced. We therefore imply that vessels running on HFO by 2015 were later retrofitted by scrubber systems, and those built after 2015 have been equipped with new scrubbers systems from the beginning. This division into new vessels and retrofits affects investment costs as retrofitting existing vessels with scrubbers is usually more expensive than embedding scrubbers systems in new-builds. Year 2021 is also important since this is when a NECA is to be introduced in the area. For vessels built after 2021 there is a need for NOx abatement technologies onboard (or fuel that ensures compliance with NOx regulations – such as LNG), which implies additional costs compared to elder vessels that are not obliged to have such technologies installed – for proper calculation of the total scenario costs share of vessels equipped with NOx reduction technologies should be accounted as well. In the current analysis, we use the following shares of **age classes**: 41% of vessels built before 2015; 15% of vessels built between 2014 and 2021, and 44% of vessels built after 2021.

Regarding **NOx abatement**, we assume that Selective Catalytic Reduction (SCR) is used as main technology. The costs of SCR and EGR (Exhaust Gas Recirculation – an alternative technology) seem comparable (Åström et al. 2014), but SCR has been present on the market for rather long time while EGR is still new and not as well-proven. Here, we assume that SCR is compatible with scrubbers and is installed on all vessels built after 2021 and running on HFO, LSFO and MGO.

To calculate **annual emissions** of main air pollutants and some greenhouse gases, consumption of each fuel is translated into power output using the value of ~122 000 MWh/PJ (corresponding to engine efficiency of ~44% at about 80% engine load), and then multiplied with relevant emission factors. Emission factors are summarized in Table 10.

Table 10. ECA in 2030 – emission factors, g/kWh.

Fuel	SO_x*	NO_x**	$PM_{2.5}$***	CH_4****	CO_2*****
MGO	0.40	8.80	0.34	0.004	608
LSFO	0.40	8.80	0.34	0.004	641
HFO + scrubber	0.10	8.36	1.02	0.004	647
LNG	0.002	1.40	0.05	5.30	464

* Calculated from 0.1% sulphur in fuel and assuming an SFOC of 200 g/kWh; for LNG – calculated based on Brynolf et al. (2014)

**Calculated assuming that all ships follow the MARPOL NO_x regulation and that ships are replaced according to above described rates; for LNG – from Stenersen & Thonstad (2017)

***From Winnes & Fridell (2009): for LNG – from Andersson et al. (2015)

**** Cooper & Gustavsson (2004); for LNG – from Stenersen & Thonstad (2017)

*****Calculated from information on CO_2 emissions in g/MJ from Brynolf et al. (2014), and estimates on SFOC of 210 g/kWh HFO, 202 g/kWh LSFO and 199 g/kWh MGO. Estimates of energy content in different fuel types: HFO – 40 MJ/kg, LSFO – 41 MJ/kg, LNG – 48 MJ/kg, and MGO – 42 MJ/kg

For open and closed scrubber systems, we use the same emission factors for air emissions but different water flow estimates – 45 m^3/MWh and 0.2 m^3/MWh, respectively.

Since the estimates we use for forecasting emissions are more moderate concerning fleet growth and more positive in estimating increases in energy efficiency, the resulting emissions generates lower baseline values compared to values presented in other studied on emission scenarios for the Baltic Sea and the North Sea in 2030. In Table 11, there are emission estimates for 2030, as used in the further analysis in this study, compared to relevant projections available in other studies. Some of the differences between emissions in our study and in other literature sources are explained in the notes below the table. For the main two scenarios in this study – baseline and scrubber scenario – the emission differences follow major differences in the emission factors presented above; in particular, much less SO_x and much more $PM_{2.5}$ are emitted by HFO + scrubbers than in the case of other fuel use. For CH_4 the picture is the opposite since HFO + scrubbers replace a part of LNG with very high CH_4 emissions.

Table 11. ECA in 2030 – total emissions, ktonnes.

Study	SO_x	NO_x	$PM_{2.5}$	CH_4***	CO_2
This study - baseline	**13.7**	**363**	**20.2**	**560**	**27 700**
-Baltic Sea	5.9	156	8.7	241	11 900
-North Sea	7.8	207	11.5	319	15 800
This study - scrubber	**7.8**	**374**	**37.2**	**189**	**28 800**
-Baltic Sea	3.4	161	16.0	81	12 400
-North Sea	4.4	213	21.2	108	16 400
Fridell et al.2018 (Baltic Sea only)	7.4	161	2.7	-	12000
Jonson et al. 2015, NECA scenario	29	674	-	-	-
Winnes et al. 2016, NECA scenario	24.8	524	5.9**	-	-
Campling et al. 2013, baseline	24	708*	36.5	-	-

*NECA is not considered in this baseline (high NO_x emissions)

**No HFO in the baseline (low $PM_{2.5}$ emissions)

***in CO_2 equivalents

2.4 Shipping costs

Shipping costs are costs paid by shipowners for running their vessels. In this study, we only focus on the cost components that differ for the considered scenarios – e.g. costs of abatement equipment such as scrubbers and SCR. Shipping costs included in the study can be divided into fuel costs, technology-related investment & installation costs and operation & management (OM) costs.

2.4.1 Investment & installation costs (fixed costs)

Investment and installation costs refer to abatement equipment or engines (e.g. LNG-engine). These are fixed costs that do not depend on vessels operation pattern. To estimate annual investment costs, the total investment costs are annualized with Equation 1 (Bosch et al. 2009):

$$I_{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1}$$ **Equation 1**

Where
Ian = Annual investment costs (€)
I = Total investment costs (€)
q = Investment interest rate (shares)
lt = Investment lifetime (years)

Investment and installation costs vary depending on whether equipment is installed on a new vessel or used to retrofit a vessel. It can also be different for open and closed scrubber installations.

2.4.2 Operation & management costs

Operation & management (O&M) costs of equipment depend on actual operating hours, navigation patterns and similar factors. They can vary considerably depending on the type of a scrubber system. Main components in the operation and management costs of an open scrubber are labour, and extra maintenance. In a closed-loop system, operation and management costs include also consumption of NaOH, often fresh water, flocculants, and coagulants, and treatment of the generated sludge.

Regarding SCR as NOx abatement equipment (SCR costs are calculated in the ECA 2030 scenario setting), main O&M cost components here are labor, catalyst replacement, and consumption of urea.

2.4.3 Fuel costs

Fuel costs are usually the essential part of the total shipping costs. These are also very uncertain in the long run since it entirely depends on the fuel prices. Some abatement technologies – in particular scrubbers – require extra energy in the form of electricity that is produced onboard and thus increase total fuel use, a so called fuel penalty. In the current analysis, we sum up fuel penalties with “normal” fuel consumption, to see the difference in the total fuel consumption caused by a scrubber system.

For the Britannica/Hollandica scenario setting, we use fuel prices for Rotterdam[4] in June 2018, while for the ECA 2030 scenario setting there is a need for price projections. We estimate fuel prices in 2030 based on the numbers presented in Hansen et al. 2016. Those are, in turn, based on the projection by the US Energy Information Agency (EIA, 2014) and a range of assumptions on the future fuel price spreads. We use central values for HFO and LNG and similar assumptions regarding fuel price spreads, to calculate prices fir MGO and LSFO. Values used in the current

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[4] https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam

analysis are presented in Table 12. Numbers adopted directly from Hansen et al. (2016) are color-marked.

Table 12. ECA in 2030 – fuel price projections used.

Fuel	Prices in USD 2013/t			Prices in € 2017/t			Comment / assumption
	Low	**Central**	**High**	**Low**	**Central**	**High**	
MGO	744	890	1 132	574	687	874	200-300 USD price spread between HFO and MGO
LSFO	694	790	982	536	610	758	150 USD price spread between HFO and LSFO
LNG	553	650	845	427	502	652	+30%, -15%
HFO	544	640	832	420	494	642	+30%, -15%

Appendix 1 summarizes values of **all main parameters** described above and chosen for shipping costs calculations in each scenario setting. In order to calculate **annual shipping costs for** a certain category (e.g. vessels equipped with retrofit scrubbers, or LNG vessels), all cost components are presented in €/MWh or in €/PJ fuel[5], summed up and multiplied by power output or by fuel use, respectively.

2.5 External costs: Air pollution and climate

In this Chapter, the general methodology for calculation of external costs related to air pollution and climate is presented.

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[5] When presenting investment costs in this way, it is important to take into consideration actual operating hours of a technology (the more a technology is used, the lower its investment cost recalculated per MWh would be). For NOx abatement technologies that can be switched off outside NECA (such as SCR), it can differ between vessel categories as they spend different number of hours in NECA. Here we do not consider these differences assuming that an average vessel spends about 32% of its time at sea in NECA (estimate based on studies by Åström et al. (2014), Winnes et al. (2016)).

2.5.1 Methods for monetary valuation of air pollution and climate effects

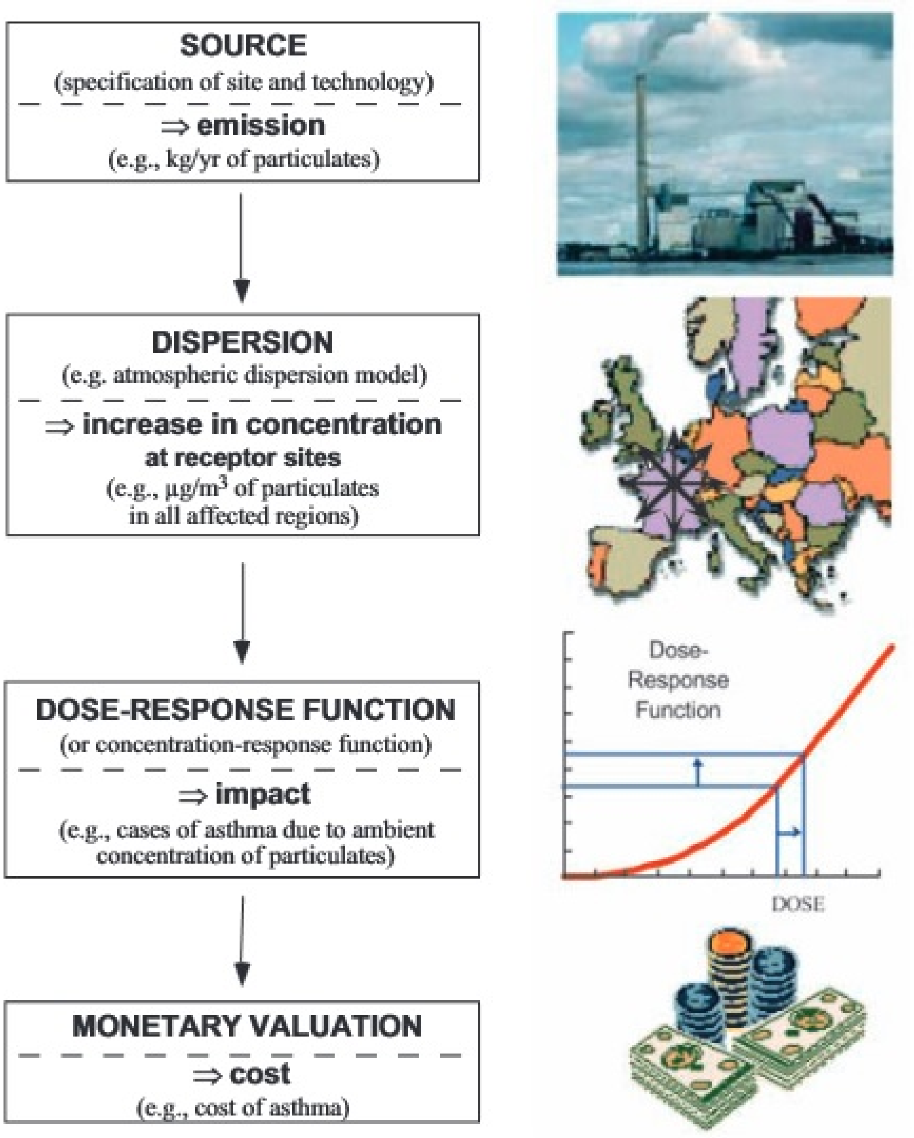

Figure 2. Impact pathway approach (source – Bickel &Friedrich, 2005).

Methodology for monetary valuation of air pollution effects is well-developed and widely used, in particular in Europe in cost-benefit analyses underlying policy decisions at the EU level (Holland et al., 2005; Holland, 2014). It is based on so called **impact pathway approach** illustrated in Figure 2. This approach follows a logical progression from emission, through dispersion and exposure to quantification of impacts and their valuation (Holland, 2014).

2.5.1.1 Health impacts

For assessment of health impacts and their economic valuation, we use values obtained with the ALPHA RiskPoll (ARP) model (Holland et al., 2013), which enables analysis of a wide range of chronic and acute health effects from exposure to $PM_{2.5}$, ozone and NO_2. Health effects per country are calculated by combining data on age distribution of population, population-weighted concentrations of secondary $PM_{2.5}$ and effect-specific dose-response relationships (Holland et al., 2013; Heroux e t al., 2015; WHO, 2013). The model's main outputs are quantified impacts of air pollution (e.g. asthma cases, premature deaths) and their monetary valuation.

Economic values used in the ALPHA RiskPoll model, and the underlying methods, are specified in Appendix 2. The health impact with highest monetary value (and thus the highest input into total health-related external costs) is avoided mortality in adults, which is valued by either estimating the Value of Statistical Life (VSL) or the Value of Life Year lost (VOLY)[6]. Other considered health impacts from air pollution include infant mortality, bronchitis, asthma cases, cardio-vascular and pulmonary diseases, and restricted activity.

The model does not quantify all possible health effects. In particular, health effects attributable to the black carbon fraction, chronic morbidity (in addition to chronic bronchitis), infant morbidity from $PM_{2.5}$, and effects attributable to NO_2 are not included (Holland 2014). They may however be associated with significant healthcare costs.

2.5.1.2 Damage to crops

Crop damage is valued per tonne of NO_X emissions from a specific region. NO_X is one of the substances needed for the formation of ground-level ozone, which in turn causes damage to crops. The economic valuation of these damages is based on aggregate market prices for a number of crops. Estimates for country-specific crop damage from ozone have been reported in Holland (2011). These estimates are done based on crop maps and European agricultural statistics (Holland et al., 2013). The valuation does not take into account all possible damage aspects either – for instance, change in the productivity of grassland, which may impact production of livestock and associated goods, is not included (Holland 2014).

2.5.1.3 Other damage from air pollution

Damage to buildings, constructions and materials can be associated with acid corrosion, ozone damage of polymeric materials, and soiling. Acid damage for constructions of utilitarian application may in principle be valuated with the market prices for maintenance. Damage to cultural heritage is much more difficult to quantify – this is one of the impacts usually not included in the valuation numbers due to the lack of studies; the same applies to soiling of buildings (Holland 2013).

2.5.1.4 Climate effect

Greenhouse gas emissions can also be assigned monetary value – although estimates vary considerably in different estimates. A current market price of tonne CO_2 can be considered as unit climate change cost proxy; however, it is very low compared to other available estimates. In other studies (e.g. Kuik et al., 2009), unit costs are based on estimates of avoidance costs corresponding to efforts required to stabilize global warming at 2°C (maximum CO_2 equivalent concentration in the atmosphere of 450 ppm). This is the goal currently supported by the United Nations Framework Convention on Climate Change (UNFCCC).

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[6] The VOLY and VSL approaches differ in terms of how many life years that are assumed to be lost when a fatality occurs. The VOLY method is based on life tables; it takes into account at what age people die from air pollution and gives results in terms of life expectancy. The VSL method does not use life tables and instead operates with mortality rates. As the VSL method doesn't take into account age or death reasons, it is sometimes considered to be overestimating health benefits from air pollution reduction (Desaigues 2011) while VOLY approach is considered as more conservative.

2.5.2 External cost values used in the studied scenarios – Air emissions

In this study, we use different methods for calculation of the total annual air pollution and climate costs for the two different scenario settings. For ECA 2030, we use the models GAINS (Amann et al., 2011) and ALPHA RiskPoll (Holland et al., 2013) to calculate air pollution effects and related externalities in the whole area, while for Stena vessels' scenario setting we apply "ready-to-use" area-specific unit external costs to emission estimates from the two specific vessels. Major differences between these two methods, as well as their advantages and disadvantages, are described below.

2.5.2.1 Unit costs for air emissions in "Hollandica/ Britannica" scenario setting

The unit external costs for air pollutants are from EEA (2014) and include health effects, ozone impact on crops and SO_2 effects on utilitarian buildings. In this scenario setting, we have calculated the externalities attributable to the air emissions of SO_2, NOx, and $PM_{2.5}$ from Stena Britannica and Stena Hollandica. The unit external costs used for these calculations are summarized in Table 13. Costs for the North Sea and the English Channel, the Netherlands and the UK are presented since the ships are assumed to cause emissions divided between these areas.

Table 13. Unit external costs used for estimating externalities due to air emissions in the North Sea and the English Channel, the Netherlands and the UK, €/tonne pollutant (source – EEA 2014).

Pollutant	North Sea + English Channel			UK			Netherlands		
	low	**central**	**high**	**low**	**central**	**high**	**low**	**central**	**high**
SO_2	15 100	26 400	44 600	17 800	30 600	51 600	31 100	54 200	91 700
NOx	4 400	7 600	12 800	4 400	7 400	12 300	6 000	10 600	18 200
$PM_{2.5}$	23 200	40 100	67 800	47 300	81 700	137 800	67 200	114 000	190 100

This method is rather simplified and does not include any modelling. Its advantage, however, is that by applying unit external costs for specific countries (UK, Netherlands) to emissions occurring in the coastal areas, we avoid underestimation of adverse health effects due to emissions occurring close to coasts (within the 12-mile zone), which would happen is case if the GAINS model was used (see more details under Discussion). Our study estimates that in the case of Britannica/Hollandica, 10% of the total annual emissions occur in the coastal areas rather than at sea – proper allocation of these emissions can thus make a significant difference for resulting health effects. This method, also used in e.g. Jiang et al. 2014, is suitable when we consider a specific shipping route with known number of hours spent at sea and in each of the relevant coastal areas. However, when we analyze the whole area including the Baltic Sea and the North Sea, we consider modelling as more appropriate method, see Chapter 2.5.2.2.

2.5.2.2 Costs estimates for air emissions in the "ECA 2030" scenario setting

We use the online[7] version of the GAINS model (Amann et al, 2011) to calculate population weighted $PM_{2.5}$ exposure and exposure to ground-level ozone (SOMO35 metric[8]) for each European country that would follow from the scenario-specific shipping emissions. The $PM_{2.5}$

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[7] http://gains.iiasa.ac.at/gains/EUN/index.login?logout=1

[8] The SOMO35 metric quantifies the yearly sum of the daily maximum 8-hour ozone concentrations exceeding a 35 ppb (70 µg/m³) threshold

concentration in ambient air is caused by primary $PM_{2.5}$ emissions, but it is also caused by emissions of NO_x and SO_2 since these form secondary $PM_{2.5}$ during their residence time in the air. Ground-level ozone formation is directly affected by NO_x concentrations.

Country-specific population-weighted $PM_{2.5}$ and ground-level ozone exposures are then introduced to the Swedish version of the ALPHA RiskPoll (Holland et al., 2013) for further calculation of health impacts and monetary valuation for the year 2030. We use low VOLY (40 thousand $€_{2005}$, see Appendix 2) as low-end value, high VSL (4.2 million $€_{2005}$) as high-end value, and low VSL (1.1 million $€_{2005}$) as a central value. The latter corresponds to the median VSL estimate from Friedrich (2004) and Hurley (2005) and is quite close to the middle of the interval used in the Cost-Benefit Analysis of Final Policy Scenarios for the EU Clean Air Package (Holland, 2014). To avoid risk of double-counting health effects from $PM_{2.5}$ and ground-level ozone, chronic mortality from ozone exposure is not included in the valuation.

Since impact on crops is not included in the ALPHA RiskPoll mode, it is estimated separately based on the unit costs specified in (Holland, 2011) – ~146 $€_{2010}$ / tonne NOx in the Baltic Sea and ~35 $€_{2010}$ / tonne NOx in the North Sea.

2.5.3 External cost values used the studied scenarios-Climate

In both scenario settings costs of climate effects are estimated with the unit costs as presented in Table 14. As central and high ends we have chosen numbers presented in Korzhenevych et al. (2014) (the Handbook developed for the European Commission) – these are based on estimates of avoidance costs corresponding to efforts required to stabilize global warming at 2°C, see reasoning in Chapter 2.5.1.4.

Table 14. Economic values per tonne of GHG emissions (CO_2 eq) used in this analysis.

Economic value of GHG		Unit	Source
Low	12.7	$€_{2017}$/t CO_2 eq	Current (Febr. 2018) EU ETS market price[9]
Central	99.1	$€_{2017}$/t CO_2 eq	Korzhenevych et al. 2014, central value
High	185.0	$€_{2017}$/t CO_2 eq	Korzhenevych et al. 2014, high-end value

2.6 External costs: Water pollution

To capture the effects of water pollution from the exhaust gas scrubber effluents in the CBA, we have conducted a literature review to explore the possibilities to use methods and valuations from previous studies.

Compared to air pollution there is much less research conducted for external costs of water pollution. This is especially true for toxicity, partly explained by the limited knowledge of the dose

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[9] http://www.nasdaqomx.com/transactions/markets/commodities, as of 2018-02-23

response function, i.e. the impacts the different hazardous chemicals have on the human health and the environment (Noring et al. 2016; Navrud, 2017).

However, in our literature review we have found a few studies which cover generic monetary valuations of relevant substances and pathways, as well as models that could be used to derive these values. The geographical coverage of the derived values varies from national to global. Since we do not have access to relevant dispersion models for marine pollution, we have made the choice to use generic values for individual polluting substances. These generic values are multiplied with the amount of pollutants released with the scrubbers' effluent water. The total emitted mass of each substance is then used in the CBA.

Our findings from the literature review are described in the chapters below and our selected values are summarized in Chapter 2.6.2. 2.6.2.

2.6.1 Monetary valuation of water pollution effects

The results of the literature review on monetary valuation of the impacts of different substances in marine environments are presented in this chapter. The values are presented per impact category, and we briefly describe how they have been derived in their original study. Since this is more or less transparent in different studies, the depth and details of the descriptions varies.

2.6.1.1 Aquatic ecotoxicity

In the ESPREME project (Friedrich, 2008), data on emissions of heavy metals to air, water and soil as well as the dispersal of heavy metals in the environment are presented for the whole of Europe. Most of the external costs of emissions to water are related to impacts on drinking water, which we consider to be unrelated to emissions in marine waters. Ecotoxicity is calculated using aquatic ecotoxicity potentials which together with Swedish tax rates on pesticides are used to estimate specific costs for heavy metal emissions to fresh water (Table 15). It should be noted that the numbers are not necessarily relevant for marine waters since it is partly based on fresh water rather than marine water, and they depend on Swedish tax rates.

Table 15. Specific costs of heavy metal emissions to water using the Ecotax Method and the tax on the active substance in pesticides. Friedrich (2008).

Substance	€/kg
Arsenic	0.2
Cadmium	222.2
Chromium	1.1
Lead	2.2
Mercury	555.5
Nickel	33.3

2.6.1.1.1 Marine ecotoxicity

In the valuation set EcoValue several relevant impacts for our case are captured. The purpose of EcoValue is to present a monetary weighting set using impact categories from LCA and values of the related damage costs of environmental degradation (Finnveden et al, 2013).

Ahlroth and Finnveden (2011) presented a new valuation set for environmental system analysis tools, called Ecovalute08. This set included estimates of the value of different externalities in, amongst others, human toxicity. This set was updated in Finnveden et al. (2013) adding marine water toxicity and marine eutrophication which both are relevant for our scrubber case. The valuation in Finnveden et al. (2013) has been further described in Noring (2014). The value was derived from a study representing *marine water toxicity*. The estimation is based on a valuation study (contingent valuation, CV) of tributyltin compounds (TBT) impacts on the Swedish coastal waters, with a focus on ecotoxicological impacts (Noring et al, 2016). According to the Marine Strategy Framework Directive (MSFD) good environmental status is not achieved in the sea surrounding Sweden's coast, partly due to TBT since the threshold value for TBT is exceeded. A CV survey was sent out in Sweden, and 536 swedes answered the survey on their willingness to pay (WTP), as an annual tax per household 2013 – 2020, for improved coastal waters. The good environmental status (GES) is in fact only assessed as good or not, meanwhile in their study they assume four different levels: good, moderate, poor and bad. The respondents were asked questions about two different scenarios.

> Scenario 1: Prevention of the release of paint flakes from boats, generating one (long term) increase in the level towards GES.
>
> Scenario 2: Combination of remediation of sediment as well as prevention of paint flakes to the sea to achieve GES by 2020.

Information on the topic and current status was given both in text and on maps. The respondents could choose to give an exact value or a range, this since previous studies shows that many respondents are not certain of their valuation. The survey also included questions on the opinions on coastal waters (e.g. if they visit the seaside, has a boat etc), socio-economic factors as well as question to evaluate the validity of the study. The results indicates an annual WTP per household of 119 USD (92 EUR[10]) for scenario 2 and 108 USD (83 EUR) for scenario 1.

Hence, in Noring (2014) the following steps were conducted to derive the generic value of 1 EUR/ kg 1.4 DB eq. The total WTP[11] was divided with the total amount of released TBT between the years 1965 – 2001. This generated an amount of SEK/kg TBT, which in the final step was divided by the characterisation factor for TBT[12] in the ReCiPe method[13]. The final step, transforming TBT value into a toxicity equivalent, makes it feasible to use the value for other substances as well.

The value of 1 EUR/kg 1.4 DB eq. is addressing marine water toxicity. In Malmgren (2017) an update of marine water toxicity valuation to 2017's monetary value has been done to 1.15 EUR/kg 1.4 DB eq. This generic value derived for marine water toxicity is very rough, however, it is still the best available estimate we have found.

2.6.1.2 Human toxicity

In Noring (2014) an update has also been done for the weighting factor for human toxicity, suggesting a value of 2.1 EUR/kg 1.4 DB eq. That is the mean value within the interval of 0.09 – 6.99 EUR/kg 1.4 DB eq. The update is based on damage costs based on the Impact Assessment Pathway method for the metals: Lead, Arsenic, Cadmium and Mercury. Characterization factors for the metals are derived from the ReCiPe data base, like in the previous study by Noring (2014) based on

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[10] ECB exchange rate, January 2012. https://www.ecb.europa.eu/stats/exchange/eurofxref/shared/pdf/2012/01/20120102.pdf

[11] Based on the mean WTP for scenario 1, multiplied with the number of households in Sweden and discounted for the time period 2013-2020 (3.5%).

[12] Read more about the characterisation factor in Noring (2014) page 22. Using: 8390 kg 1,4 DB eq. per kg TBT.

[13] See: http://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe

TBT. The study is however based on air emissions of metals and neither via water nor depletion on marine water which makes this value less relevant for our case.

2.6.1.3 Marine eutrophication

Marine eutrophication is also captured in EcoValue, and in Ahlroth (2009a) the method and derivation of a generic value for eutrophication is explained. Based on travel cost studies conducted in Sweden, where the willingness to pay for increased (marine) water quality is explored. The water quality was illustrated by nutrient concentration, and Secchi depth was used as an indicator. It should be noted that these studies are over 10 years old. All studies have surveyed residents in Sweden and the water areas which have been in focus are: the Stockholm archipelago, the Swedish coast line and the Baltic Sea.

To derive a generic damage value for the specific pollutant, the total damage value for each ecosystem is divided by annual deposition of each pollutant (Ahlroth, 2009a). Since the impact on eutrophication for the different pollutants[14] varies, each pollutant needs to be weighted by its eutrophication potential. This has been done by using generic characterization factors by a method used by Helcom (see more in Kiirikki et al. 2003 in Ahlroth 2009a). Benefit transfer of the monetary valuations from one coastal region to another has been conducted via structural benefit transfer. In practice the authors have used the studies mean values (from travel cost study) and a calibrated parameter β and adjusted for the county-specific income and water quality, where the water quality is measured by sight depth. In addition to valuations of the coastal waters via travel cost method, also estimates of the WTP for an increased visibility in the whole Baltic Sea are taken into account via contingent valuation study. These studies' estimation of the WTP for increased visibility (i.e. sight depth) is connected to levels of pollution, and is used to compute a damage value on a national level. The values capture eutrophication in marine, fresh and ground water. These values are represented in version EcoValue09. For further details see Ahlroth (2009a). In the study of Malmgren (2017) the monetary values in the different versions of EcoValue is presented, with EcoValue14 being the most updated version, see Table 16.

Marine eutrophication is also valued in the Environmental Priority Strategies (EPS) database, which likewise EcoValue is providing weighting factors of externalities for the use in mainly LCA and LCC. The purpose of EPS is to give product developer an indication of the environmental impact. In a systematic way the different factors have been derived and expressed in monetary values. Compared to EcoValue, which has more focus on Sweden, EPS is aiming at capturing global effects and using OECD valuations to become as generic as possible and valid in an international perspective (Steen, 2015). The value of nitrogen to sea is based on the impact of eutrophication on fish production and is presented in Table 17.

Table 16. Generic values of marine eutrophication, in EUR 2017 per kg of pollutant (EcoValue14).

Pollutant	Value
N	11.45

Table 17. Generic values of marine eutrophication per kg (EPS).

Pollutant	Value
N	0.01

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[14] Nitrogen (N), phosphorus (P), nitrogen oxides (NO_x) and ammonium (NH_3)

2.6.1.4 Ocean acidification

Impacts studies on the effect of ocean acidification from climate change are rather rare, and even rarer for economic impacts (Armstrong et al, 2012). The oceans are absorbing a lot of the global emissions of CO_2 and this generates a more acid ocean (increase in H^+ ions) and decreasing concentration of carbonate ions (Armstrong et al, 2012). There are several mechanisms that lead to increased ocean acidity, but the main one is the oceans absorption of CO_2 (Brander et al, 2009). Previous studies indicate that the ocean pH has decreased by 0.1 units in comparison to preindustrial times, and the decreasing concentration of carbonate ions affects organisms' possibilities to build shells or other structures of carbonate (Armstrong et al, 2012). Early calculations indicate that the global average pH of surface seawater (approximately 8.1) would be reduced by 0.3-0.4 by the end of the twenty-first century under the business-as-usual emission scenario (Caldeira and Wickett 2003, 2005). Armstrong et al. (2012) tries to estimate the economic impact for Norway due to ocean acidification. Their results are showing that it can generate both economic loss and profit, where the main loss is due to the oceans reduced capacity as carbon storage. This impact is indicated to be several orders of magnitude higher than impact on fisheries and aquaculture.

In a study by Brander et al. (2012) the global economic impacts of ocean acidification on coral reefs is estimated. This was done by applying a meta-analysis of 45 valuation studies on coral reefs. Approximately half of the studies had used a contingent valuation method, meanwhile others used gross revenue methods, travel cost method, net factor income, production function. The studies uses different metrics, hence Brander et al. (2009) standardized these into a common one; US\$/km^2/year (2000 prices), where km^2 refer to area of coral cover. The values are analysed with a regression analysis for how different explanatory values is explaining the value. The explanatory variables are: geographical (location), ecological (area of coral cover, biodiversity), socio-economic (GDP per capita, population density, goods and services provided, number of visitors), and methodological variables (valuation method used). They are estimating the economic value of ocean acidification on coral reefs for the four IPCC marker scenarios the IPCC Special Report on Emission Scenarios (Nakicenovic & Swart, 2001). Resulting in an average value of \$177 000/km^2, with a range of \$39 to 804 000/km^2.

Due to the ocean circulation it can be assumed that a change in the amount of H^+ ions will affect the whole volume of ocean water. The pH in the ocean varies with depth primarily due to uptake of CO_2 in organisms in the surface water. In one of the scenarios used by Brander et al. (2012), pH decreases by 0.25 units. Since ocean pH is around 7.9 at the surface this corresponds to a change in H^+ concentration by $7.8*10^{-9}$ molar. Given that the ocean water volume is around $1.3*10^9$ km^3 of sea water, this means that the amount of H^+ in the ocean increases by $1.0*10^{13}$ moles. The annual economic impact of this acidification is estimated to around 900 billion US\$, or 0.07 US\$ per mol H^+.

2.6.2 External cost values selected for emissions to water

Out of these previous studies the most relevant results for our case study, geographical area as well as compatible with the results from the water samples, is presented in Table 18. We choose to go with generic values in order to be able to use the same kind of method for all emissions.

Table 18. Summary of selected cost values for emissions to marine water

Impact	Pollutant	Value
Marine water toxicity	1, 4 DB eq.	1.15 EUR2017/kg*
Marine eutrophication	N	Min. 0.01 EUR2017/kg** Max. 11.45EUR2017/kg*
Ocean acidification	pH (H+)	0.12 EUR2017/mole***

Reference: *Malmgren (2017), ** Steen (2015), ***Brander et al. (2012)

2.7 Uncertainty analysis

The calculations of technical and external costs are associated with uncertainties which can be analyzed. Sensitivity analyzes have been done using Monte Carlo simulation. In the sensitivity analysis, parameters that control external and internal costs have been randomly varied within a relative standard deviation (Coefficient of Variation, CV) based on assumed uncertainties of the individual parameters. For each tested variable, 100 simulations were performed and the resulting uncertainty in the costs was calculated. The analysis provides a measure of how sensitive the cost assessment is for the value of different variables. In Table 19 the assumed uncertainty in different variables is presented.

Table 19. Relative standard deviation (CV) of different variables used in the uncertainty analysis.

Parameter	Relative standard deviation (%)	Comment
Fuel costs	19	Based on experienced variation
Investment costs	31	Based on experienced variation
External costs SO_2	25	Assumed uncertainty
External costs NO_x	25	Assumed uncertainty
External costs $PM_{2.5}$	25	Assumed uncertainty
External costs CO_2	43	Assumed uncertainty
pH Open Scrubber	1 000	Corresponding to 1 pH unit
pH Closed Scrubber	1 000	Corresponding to 1 pH unit
NO_3 Open Scrubber	100	Assumed uncertainty
NO_3 Closed Scrubber	100	Assumed uncertainty
Toxicity Open Scrubber	21	Based on measurement variations
Toxicity Closed Scrubber	21	Based on measurement variations
Effluent flow Open Scrubber	22	Based on experienced variation
Effluent flow Closed Scrubber	22	Based on experienced variation
External costs pH	100	Assumed uncertainty
External costs Toxicity	100	Assumed uncertainty
External costs NO_3	100	Assumed uncertainty

3 Results - CBA for Hollandica and Britannica

In this Chapter, we present the results of the cost-benefit analysis for Stena's sister ships Stena Hollandica and Stena Britannica.

3.1 Shipping costs

The method for calculation of annual shipping costs is described in Chapter 2.4, and main cost parameters used in Appendix 1. Here, we present the resulting costs for each of the vessels Stena Hollandica and Stena Britannica. Table 20 summarizes fixed costs (investment and installation, operation & management costs and fuel costs including fuel penalties), for each of the compliance scenarios, including the hypothetical scenario where HFO is used without scrubber for comparison.

Table 20. Annual shipping costs, scenario setting for Hollandica/Britannica 2017.

Cost component		Scenario, Hollandica/Britannica 2017			
		HFO + Closed scrubber	**HFO + Open scrubber**	**LSFO**	**HFO without scrubber**
Investment costs, total					
€, total	Investment	4 272 000	4 272 000	-	-
€, total	Installation	5 004 000	5 004 000	-	-
Fuel costs (including fuel penalty)					
€/year	ME fuel	5 961 000	5 908 000	7 907 000	5 832 000
€/year	AE fuel	1 187 000	1 187 000	1 196 000	1 187 000
O&M costs					
€/year	Labour	102 000	51 000	-	-
€/year	Sludge disposal	29 0000	-	-	-
€/year	NaOH	358 000	-	-	-
€/year	Fresh water	29	-	-	-
€/year	Flocculent	12 000	-	-	-
€/year	Coagulant	21 000	-	-	-
Investment costs, annual, th € (societal)		540	540	-	-
Investment costs, annual, th € (private)		1 400	1 400		
O&M costs, total annual, th €		520	51	-	-
Fuel costs , total annual, th €		7 150	7 100	9 100	7 000
Total annual costs, th €		**8 200**	**7 700**	**9 100**	**7 000**

The annual investment costs used in the calculation of the total annual costs (~540 thousand €), are calculated from a societal perspective for a better comparison to external costs. In these calculations, the interest rate is set to 4% and the investment lifetime is set to 30 years, which represents the assumed remaining lifetime of a scrubber. The private perspective on cost annualization includes an estimated interest rate of 7.5% and 10 year investment lifetime. The results are presented in Table 20 as well. The private perspective it results in ~1 400 thousand €/year, which is in line with Stena's own previous estimates presented in Stena (2014).

Fuel costs are by far the largest post in the annual expenses for running the vessels. Since projected price for LSFO (~610 €/t) is 23% higher than projected price for HFO (~490 €/t), the total annual fuel costs are higher in the LSFO scenario than in the scrubber scenarios. Auxiliary engines are running on either MGO (the scrubber scenarios) or LSFO (the LSFO scenario). Although the projected MGO price (~690 €/t) is higher than the LSFO price, the energy content of MGO (42.6 MJ/kg) is 5.3% higher than the energy content of LSFO (41.5 MJ/kg) resulting in the higher total costs of the fuel to auxiliary engines in the LSFO scenario as well.

According to our basic assumptions (Chapter 2.3.2), the closed scrubber system is associated with higher fuel penalties than the open-loop system – 2.2% and 1.3%, respectively. This can be seen in the resulting costs associated with the annual fuel use by main engine, which is slightly higher in the closed scrubber scenario. Annual fuel use in case of HFO without scrubber is lower than in each of the scrubber scenarios, which is also seen in Table 20.

Investment and installation costs are, according to Stena, the same for open and closed scrubber types. Annualized investment costs are estimated at ~540 thousand € in both cases. The significant part of the fixed costs is attributable to the installation of a Glassfiber Reinforced Epoxy (GRE) pipe system (B. Asplind, personal communication). Figure 3 illustrates annual costs for the three scenarios split by cost categories.

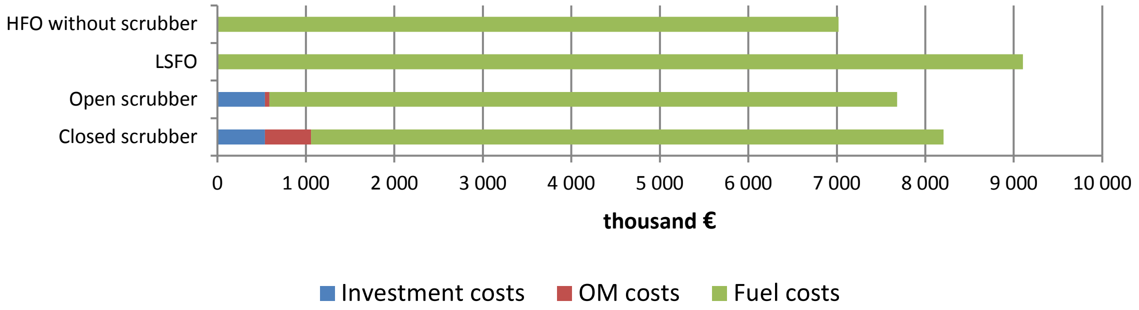

Figure 3. Annual shipping costs, scenario setting for Hollandica/Britannica 2017.

The annual O&M costs for the closed-loop scrubber (~520 thousand €) are slightly lower than the investment and installation costs. O&M costs differ significantly between the open-loop and the closed-loop scenarios: open-loop scrubber require a certain number of working hours (labor) but has no other significant cost posts. To operate the closed-loop scrubber, on the hand, entails a continuous sodium hydroxide (NaOH) consumption as well as use of flocculants and coagulants to treat the effluent water.

Furthermore, there is a cost of the sludge disposal. Scrubber sludge from Stena Britannica and Stena Hollandica is submitted for treatment on shore; after dehydration and removal of organic fraction it is burnt in cement kilns. The treatment prices are rather uncertain and usually higher than prices for treatment of "regular" oil sludge (B. Asplind, personal communication). Oil sludge treatment cost is not included in the current estimates due to the lack of the price information.

A detailed specification of the O&M costs of the closed scrubber system is presented in Table 21 as well as in Figure 4. NaOH contributes about 70% of the total O&M costs. NaOH costs are hence contributing more than any other cost post. It is followed by costs for labour, sludge disposal, coagulant chemicals, and flocculent chemicals in decreasing order.

Table 21. Annual O&M costs of the closed scrubber, scenario setting for Hollandica/Britannica 2017.

OM cost component	€/TJ to ME	€/TJ total (AE+ME)	€/ t HFO to ME	€/MWh	Share of total
Labour	160	140	6.5	1.2	19%
Sludge disposal	47	41	1.9	0.36	6%
NaOH	580	507	23	4.4	69%
Flocculent	20	18	0.81	0.15	2%
Coagulant	34	29	1.34	0.25	4%
TOTAL	**840**	**740**	**34**	**6.4**	**100%**

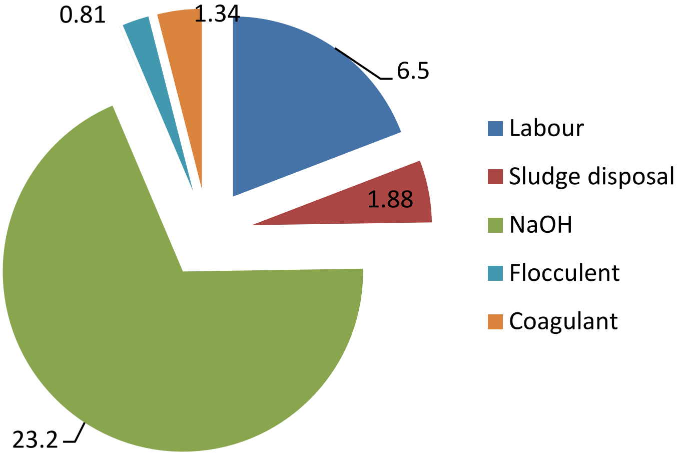

Figure 4. Distribution of the annual shipping O&M costs, scenario setting for Hollandica/Britannica 2017, €/t HFO to main engine.

Costs of scrubber technologies can also be presented as technical costs (fixed costs + O&M costs) per tonne removed pollutant, in relation to a today hypothetical (in the considered sea area) option with high-sulphur (2.77%) heavy fuel oil without abatement. This type of costs is presented in Table 22 and based on the estimated annual costs (Table 20) and calculated annual emissions in the considered scenarios (Table 4).

Table 22. Technical costs of scrubber, €/kg removed pollutant.

Pollutant	Closed scrubber	Open scrubber
SO_2	1.3	0.7
$PM_{2.5}$	96	52

3.2 External costs in the Hollandica/Britannica scenario setting

External costs related to the three considered compliance scenarios (LSFO, closed-loop scrubber, open-loop scrubber) for Stena Hollandica/Britannica 2017 are calculated separately for air and water pollution related effects.

3.2.1 Air pollution and climate related costs

A detailed description of the method for estimation of air pollution and climate related external costs for Hollandica and Britannica is given in Chapter 2.5.2. Here, the results are presented. Annual external cost attributable to air pollution and climate effect in the three considered scenarios are summarized in Table 23, together with the estimates for the "HFO without scrubber" option given for comparison. A more detailed specification of the external costs, illustrating their geographical distribution, is presented in Appendix 3.

Table 23. Annual external costs related to air pollution and climate effects from scrubbers on Hollandica/Britannica 2017, thousand €; "Low", "Central" and "High" refer to variations in cost estimates as specified in Table 13.

Pollutant	LSFO	Closed scrubber	Open scrubber	HFO without scrubber
Low				
SO_x	550	160	160	13 500
NO_x	4 300	4 600	4 500	4 500
$PM_{2.5}$	310	670	660	950
CO_2	720	740	730	720
TOTAL	5 900	6 200	6 100	19 700
Central				
SO_x	960	290	290	23 490
NO_x	7 400	7 900	7 900	7 800
$PM_{2.5}$	540	1 160	1 150	1 630
CO_2	5 620	5 760	5 710	5 640
TOTAL	14 500	15 100	15 000	38 600
High				
SO_x	1 630	480	480	39 760
NO_x	12 500	13 400	13 300	13 200
$PM_{2.5}$	910	1 950	1 940	2 750
CO_2	10 500	10 750	10 670	10 530
TOTAL	25 500	26 600	26 400	66 300

Total external costs, according to our estimates (central values), are highest in the closed scrubber scenario – 15.1 million €, followed by the open scrubber scenario (15.0 million €) and the LSFO scenario (14.5 million €). The difference between the LSFO scenario and the two scrubber scenarios thus constitutes 0.5-0.6 million €, which is about 3-4% of the external costs from air pollution in the LSFO scenario.

Contributions from different pollutants and CO_2 for the central case of different scenarios are given in Figure 5. In the three main scenarios, about 50% of the total external costs are attributable to the effects of NOx – mainly adverse health effects via formation of secondary particles, but also effects on crops. Climate costs constitute around 40% of the total external costs, while effects of SO_x and primary $PM_{2.5}$ – about 2-8%. The costs of SO_x are 3-5 times higher in the LSFO scenarios than in the scrubber scenarios, while for $PM_{2.5}$ it is' the opposite – external costs in the scrubber scenarios are twice as high as in the LSFO case. This is explained by corresponding differences in the measured emission factors.

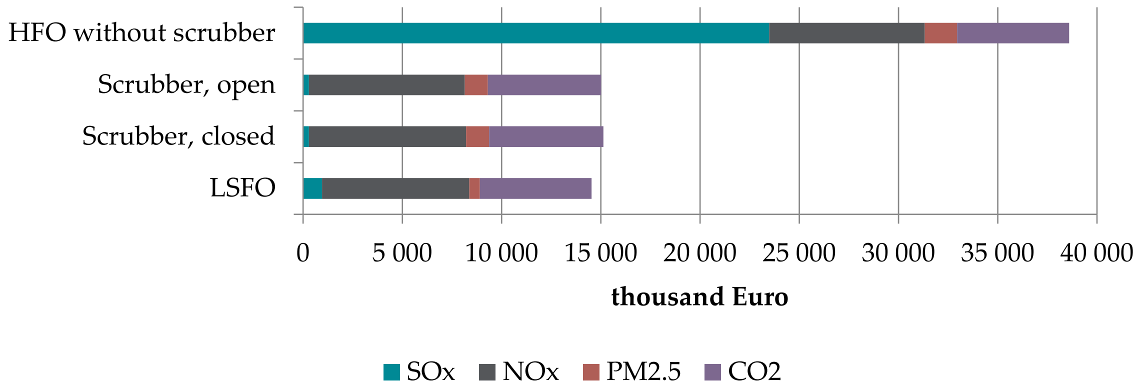

Figure 5: Contributions of pollutants and CO_2 to the total external costs, Hollandica/Britannica 2017

External costs due to SO_x effects are visibly higher in the LSFO scenario than in the scrubber scenarios. However, this difference does not overweigh the costs of higher NO_x, $PM_{2.5}$ and CO_2 emissions in the scrubber scenarios compared to LSFO – so the total external costs are higher in the both scrubber scenarios.

In the hypothetical scenario when heavy fuel oil is used with no scrubber, the largest contribution to the total costs is made by SOx (61%) for which no abatement is applied in this case, followed by NOx (20%). The costs attributable to primary $PM_{2.5}$ are ~45% higher than in the scrubber scenarios – also due to the lack of abatement.

3.2.2 Water pollution

Based on assumed effluent water flow and characteristics (Chapter 2.3.2.3) combined with monetary valuations of water pollution effects (Chapter 2.6) annual external costs for water pollution were calculated for closed and open scrubber systems (Table 24)

Table 24. Annual external costs related to water pollution from scrubbers on Hollandica/Britannica 2017, €.

Parameter	Closed scrubber	Open scrubber
Eco-toxicity	3 800	9 000
pH	0.16	94
Eutrophication	5 400	2 580
Total	9 200	12 000

In total, the annual external cost for the open scrubber is higher (€12 000) than for the closed scrubber (€9 200). Ecotoxicity dominates the external cost for the open scrubber while eutrophication is the largest component of the closed scrubber external cost. Although the ecotoxicity is higher in the closed scrubber system the external cost is higher for the open scrubber system due to a larger effluent water flow. Compared with ecotoxicity and eutrophication, pH is a minor component of the external cost.

3.3 CBA results for Hollandica/Britannica 2017

Total annual costs attributable to thee considered scenarios are presented in the Table 25. Shipping costs are divided into investment costs, O&M costs and fuel costs while the list of external costs includes effects of air pollutants on health, crops and materials, climate effect of CO_2, and water related externalities – eco-toxicity, ocean acidification, and eutrophication.

Table 25. Total annual shipping costs vs external costs, Hollandica/Britannica 2017, 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	-	3.79	9.01
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

Total annual shipping costs are higher in the LSFO scenario, due to the significant price difference between LSFO and HFO. At the same time, the external costs are higher in the scrubber scenarios (both open and closed scrubbers) – both costs attributable to air pollution and climate, and those related to the water effects. The relative differences in shipping and external costs between each of the scrubber scenarios and the LSFO scenario are presented in Figure 6. The open scrubber scenario is associated with lower shipping costs and lower external costs than the closed scrubber scenario.

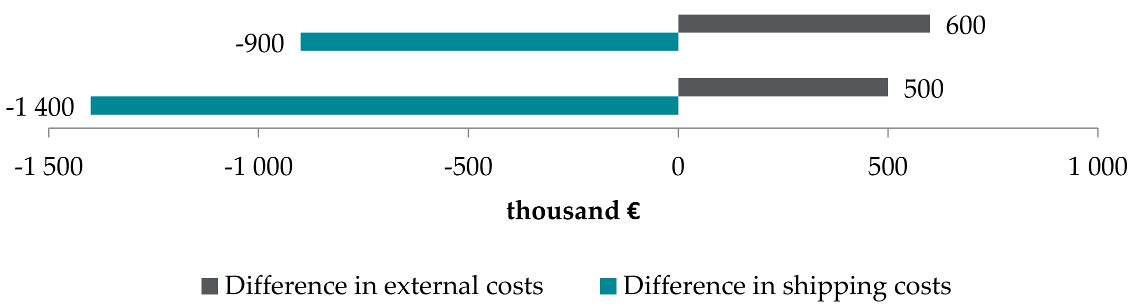

Figure 6: Differences in the shipping costs and external costs, in relation to the LSFO scenario, thousand €. Upper bars – closed scrubber, lower bars – open scrubber.

Although the scenario of HFO use without scrubber is no longer a realistic case for the North Sea, it is reasonable to make comparisons to external and shipping costs in this scenario, in order to make **retrospective conclusions on whether a scrubber was a more cost-effective choice than LSFO**,

compared to HFO with 1% sulphur content[15] without scrubbing, from a shipowner perspective. To calculate investment costs from private perspective, we use 10 years investment life-time and an interest rate at 7.5%. This results in the annual shipping costs of 9000 thousand € for closed-loop scrubber and 8500 thousand € for open-loop scrubber, of which 1350 thousand € is attributable to annualized investment costs (same for both scrubber cases). The total annual fuel costs of "HFO 1% without scrubber" scenario are estimated at 7300 thousand €.

The results of the retrospective CBA are presented in Table 26. The numbers can be compared to the estimates in Stena, 2014 – Stena's own CBA before scrubber installations. Benefit-to-cost ratios in Stena (2014) are 2.6 and 1.2 for a scrubber option and for MGO, respectively. Correspondent values in our study are higher – 5.0 for closed-loop scrubber, 7.4 for open-loop scrubber and 5.1 for LSFO. The main reason is different assumptions on unit external cost per tonne removed SOx. Stena 2014 uses the European average values from Korzhenevych et al. 2014 – ~10 thousand €2010/tonne SOx, while we apply country-specific values from EEA 2014 – 31, 54 and 26 thousand €2017/tonne SOx for UK, Netherlands and the North Sea, respectively (central values derived from the given intervals and adjusted to the relevant currency year as described in Chapter 2.5.1). Another reason is that our results are based on own recent measurements onboard and include valuation of NOx and particles, as well as valuation of water releases – these are not considered in Stena 2014. Besides, Stena 2014 considers MGO as alternative fuel while we compare scrubbers with LSFO. The latter two reasons, however, make less contribution to the observed differences than the assumptions on SOx external unit costs.

Table 26. Costs and benefits of scrubber and LSFO compared to HFO, as alternatives to comply with stricter sulphur regulations that prohibit use of HFO without scrubber; low, central end and high values refer to external cost values.

Parameter		LSFO	Scrubber, private perspective (10 years, 7.5%)		Scrubber, societal perspective (30 years, 4%)	
			Open	**Closed**	**Open**	**Closed**
Increase in shipping costs, th €		1 800	1 200	1 700	360	890
Low	Decrease in external costs – gross benefits, th €	5 300	5 000	5 000	5 000	5 000
	Net benefits, th €	**3 500**	**3 800**	**3 200**	**4 600**	**4 000**
	Benefit-to-cost ratio*	**3.0**	**4.3**	**2.9**	**13.8**	**5.5**
Central	Decrease in external costs – gross benefits, th €	9 100	8 700	8 500	8 700	8 500
	Net benefits, th €	**7 400**	**7 500**	**6 800**	**8 300**	**7 600**
	Benefit-to-cost ratio*	**5.1**	**7.4**	**5.0**	**23.9**	**9.6**
High	Decrease in external costs – gross benefits, th €	15 500	14 600	14 400	14 600	14 400
	Net benefits, th €	**13 700**	**13 700**	**12 700**	**14 300**	**13 500**
	Benefit-to-cost ratio*	**8.7**	**12.4**	**8.4**	**40.5**	**16.2**

*Decrease in external costs/increase in shipping costs

The numbers presented in Table 26 indicate that, with the current level of fuel prices, cost-effectiveness of scrubber versus LSFO in terms of net benefits for environment and human health

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[15] Since HFO with 1% sulphur content (fuel used in the North Sea before 2015) was not included in the scope of this study, there are no measurement results regarding this fuel. We adjust emission factors measured for HFO with 2.77% sulphur (before scrubber) with respect to sulphur content. Fuel price is estimated as MGO price is 40% higher than HFO price, as assumed in Stena 2014)

per unit shipping costs depends on the chosen assumptions at investment costs annualisation (economic perspective). LSFO seems to be more cost-effective than closed scrubber if we look at the short-term investment lifetime; with longer investment lifetime annualized scrubber costs become lower and both scrubber options seem more cost-effective than LSFO.

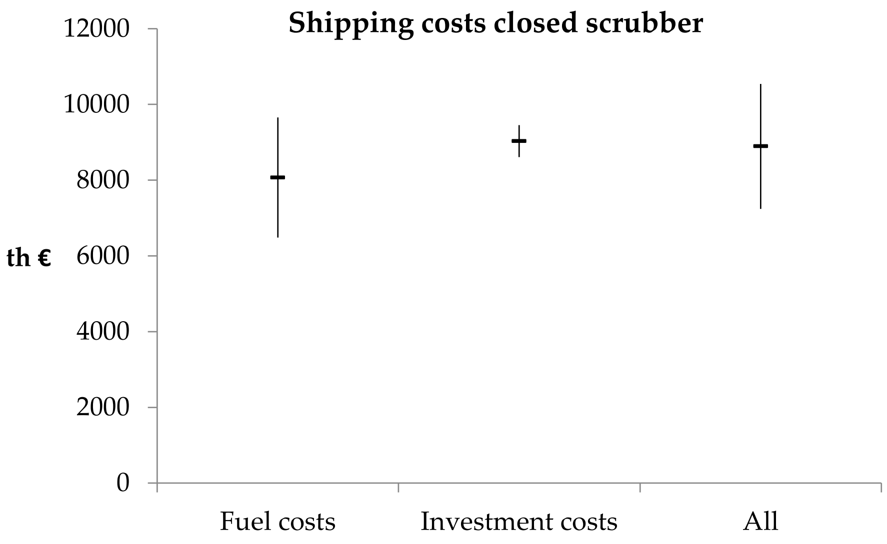
Water-related externalities attributable to shipping are rarely considered in the CBA context. In our analysis, inclusion of this type of external costs increases the total external costs in the scrubber scenarios (especially for the open-loop scrubber) – but even without water-related externalities the total annual external costs in the scrubber scenarios are higher than in the LSFO scenario. It should be noted that not all identified water-related externalities are included in the analysis – e.g. impacts on human health and potential adverse effects of heavy metals in the effluent water are excluded.

LSFO and the two scrubber alternatives ensure that vessels comply with current sulphur emission regulations. **According to our calculations, the total negative impact expressed as external costs (including those effects that could be valued) is higher for scrubbers.**

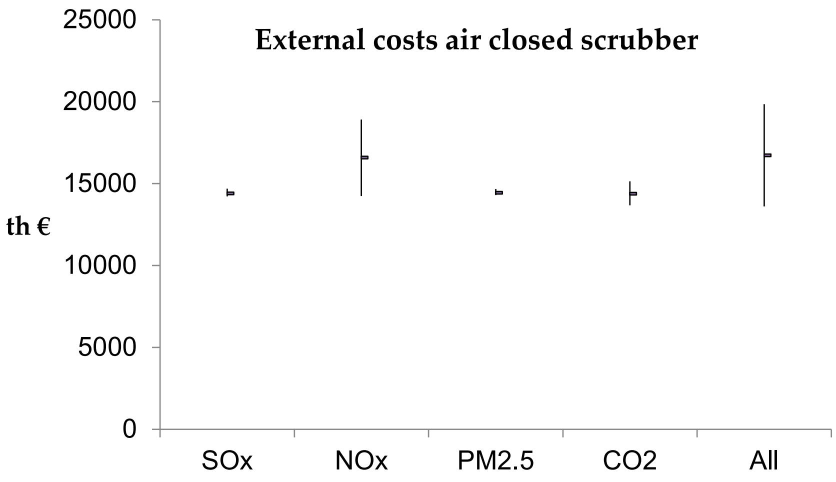
3.4 Uncertainty analysis

The uncertainty in the calculations resulting from the uncertainty in input parameters were evaluated with Monte Carlo analysis illustrated in the following. In Figure 7a the uncertainty in shipping costs for a closed scrubber system is shown. It can be seen that the calculated cost is more sensitive to the uncertainty in fuel costs than to the uncertainty in investment costs. The total uncertainty of the calculation is shown to the right in the figure (”All”). Results are similar for open scrubber (not shown). In Figure 7b the uncertainty in external costs related to air emissions for a closed scrubber system is shown. It is seen that NO_x is the parameter that is most important for the uncertainty, followed by CO_2. Results are similar for open scrubber (not shown). In Figure 7c the uncertainty in external costs related to water emissions for a closed scrubber system is shown. The measured concentration of NO_3 emissions is the most important uncertainty followed by the uncertainty in the monetary valuation of NO_3 emissions (“Cost NO_3”) and the effluent water flow. In Figure 7d the difference in external costs between a closed scrubber system compared with LSFO is shown. Uncertainties related to air emissions outweigh uncertainties related to water related emissions in the estimate of total uncertainty.

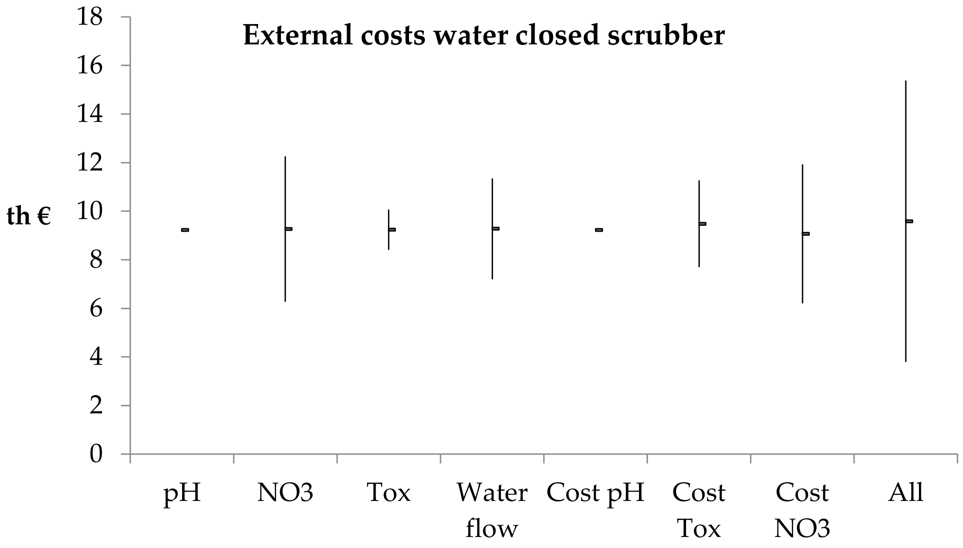
a)


Shipping costs closed scrubber
th €
12000
10000
8000
6000
4000
2000
0
Fuel costs
Investment costs
All

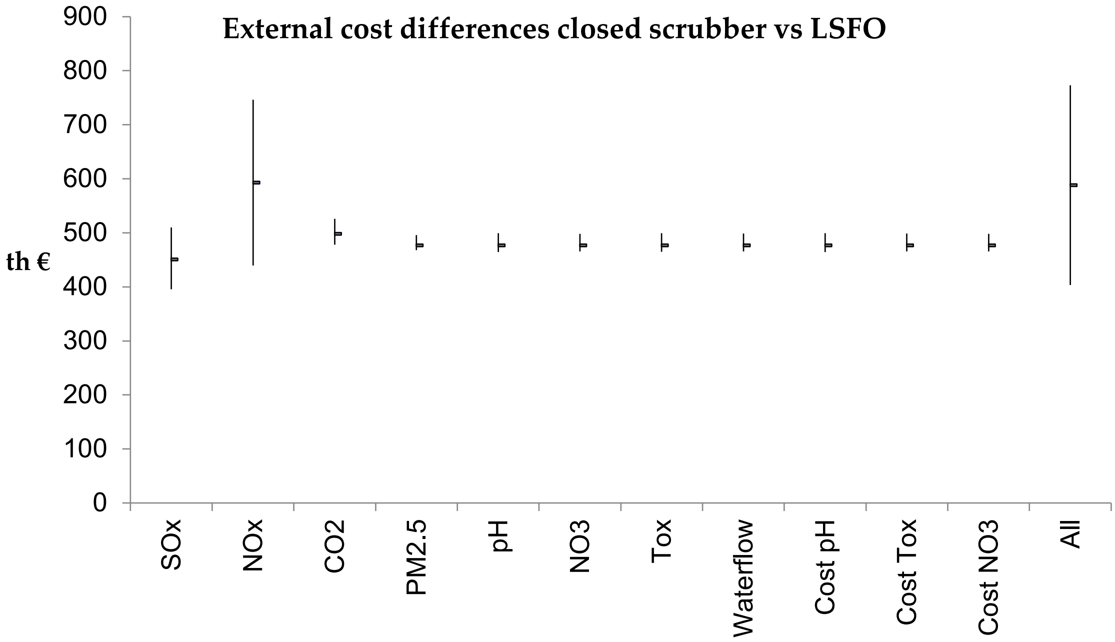
b)


External costs air closed scrubber
th €
25000
20000
15000
10000
5000
0
SOx
NOx
PM2.5
CO2
All

c)


External costs water closed scrubber
th €
18
16
14
12
10
8
6
4
2
0
pH
NO3
Tox
Water flow
Cost pH
Cost Tox
Cost NO3
All

d)



e)

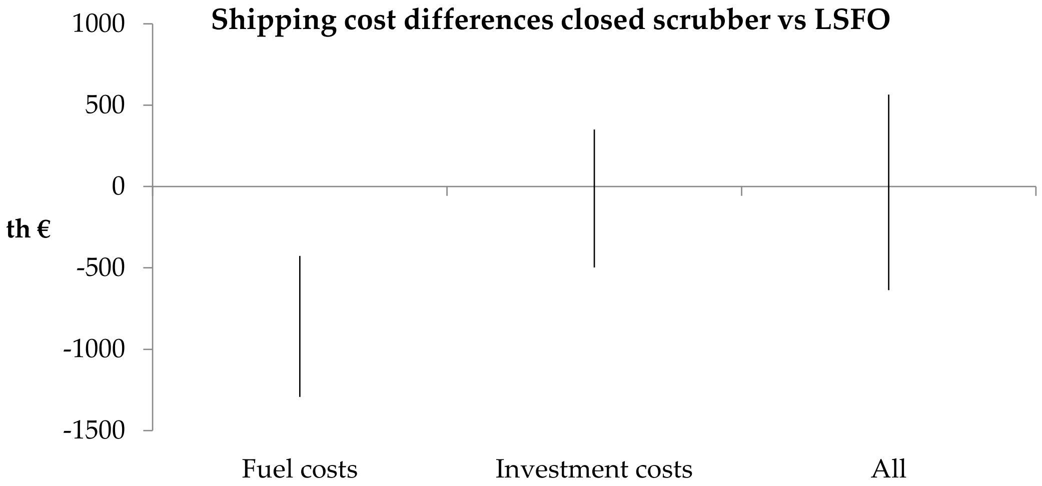


Figure 7: Results from Monte Carlo simulations, units on Y-axis – thousand €. Input parameters shown on horizontal axis where "All" indicates that all parameters are varied together. Vertical bars indicate uncertainty (+/- one standard deviation) around the mean (-). Uncertainty in a) calculated shipping costs for a closed scrubber system, b) calculated external costs related to air emissions for a closed scrubber system, c) calculated external costs related to water emissions for a closed scrubber system, d) difference between calculated external costs related to air and water between a closed scrubber system and LSFO and e) difference between calculated shipping costs related to air and water between a closed scrubber system and LSFO.

Shipping costs are associated with high uncertainty intervals so that the resulting difference between the scenarios is not necessarily negative as in Figure 6. This means, one cannot certainly say that the scrubber scenarios are associated with lower shipping costs than the LSFO scenario – this depends mainly on the fuel price variations – see Figure 7e illustrating the difference in shipping costs between the closed scrubber and LSFO scenarios. The difference in the external costs, on the contrary, remains positive when parameters are varied (as illustrated in Figure 7d) so that the results indicating that external costs in the two scrubber scenarios are higher than external costs in the LSFO scenario can be considered as more robust.

It is, however, important to remember that the conducted Monte-Carlo simulation does not take into consideration all possible uncertainties – for instance, uncertainties related to air emission measurements are not included. Besides, several effects have been measured but not valued in the monetary terms – such as, for instance, possible impacts from e.g. releases of heavy metals to water. This means, potential higher external costs related to emissions in the scrubber scenarios should not be neglected when interpreting the CBA results presented in this study.

4 Results for ECA 2030

In this Chapter, we present the results of the cost-benefit analysis for the scenario setting ECA 2030 – baseline scenario and scrubber scenario for the whole fleet in the Baltic Sea and the North Sea (including British Channel) in 2030.

4.1 Shipping costs in ECA2030 scenario setting

The method for calculation of annual shipping costs is described in Chapter 2.4, and details on main cost parameters used are presented in Appendix 1. Here, we present the resulting costs for the ECA 2030 scenario setting. Table 27 summarizes fuel-related costs, technology-related costs (including both investment costs and O&M costs) and total costs for the baseline and the scrubber scenarios. Low, central and high values correspond to the range of cost estimates provided in the literature. The baseline scenario includes an assumption that 20% of the energy used for shipping in the studied area in 2030 is HFO used on ships fitted with exhaust gas scrubbers. In the scrubber scenario the corresponding share is 70%.

Table 27. Total annual shipping costs for the ECA 2030 scenario setting, million €.

Cost type	Baseline	Scrubber	Difference
Low			
Fuel	4 531	4 087	444
Technologies	109.0	204.4	-95.4
Total	4 640	4 292	348
Central			
Fuel	**5 308**	**4 826**	**482**
Technologies	**225.5**	**380.9**	**-155.4**
Total	**5 534**	**5 207**	**327**
High			
Fuel	6 749	6 283	466
Technologies	376.6	701.0	-324.4
Total	7 126	6 984	142

Total shipping costs in the baseline scenario are 5500 million €, and in the scrubber scenario – 5200 million €.Technology-related costs are 70% higher in the scrubber scenario than in the baseline – 380 million € vs. 230 million €, respectively. Fuel costs are much higher in the baseline case, where more MGO and LNG are used as main fuel.

Distribution of technology-related costs by technology is illustrated in Figure 9. Costs attributable to scrubber installations amount to 64 million € in the baseline (20% of scrubbers, by fuel use) and to 239 million € in the scrubber scenario (70% of scrubbers, by fuel use). Since HFO +scrubbers are assumed to partly replace LNG fueled vessels, the cost of LNG engines decreases from 41 million € in the baseline to 14 million € in the scrubber scenario. NOx abatement costs are affected as well since HFO, MGO and LSFO fueled vessels with scrubbers that are built after 2021 would require NOx abatement technology installed (SCR) to navigate in NECA, while for LNG fueled vessels there is no need in additional NOx abatement – and thus their shipping costs are lower. This is why NOx abatement costs increase from 120 ktonnes to 129 ktonnes between the baseline and the scrubber scenarios.

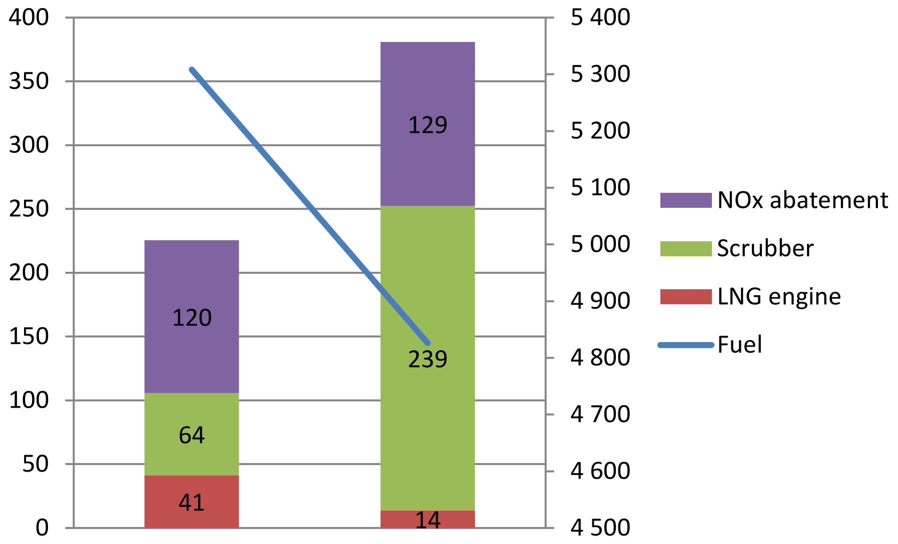


Figure 8: Distribution of the annual technology costs for the ECA 2030 scenario setting, central case, million €; left column – Baseline (20% of scrubbers, by fuel use), right column – Scrubber scenario (70% of scrubbers, by fuel use); left axis – technology-related costs, right axis – fuel-related costs.

4.2 External costs in ECA 2030 scenario setting

For calculation of air pollution costs in this scenario setting, we use modelling rather than unit external costs per region – the method is described in detail in Chapters 2.3.3 and 2.5.2.2.

Table 28 presents the costs of the negative health effects from **air pollution** in the two scenarios. Emissions of air pollutants in the scrubber scenarios result in additional adverse health effects valued at approximately 190 million € per year, compared to the baseline. This is mainly higher mortality caused by exposure to $PM_{2.5}$ and ozone.

Table 28. Valuation of the health effects in the ECA 2030 scenarios, million €.

Value range*	Baseline	Scrubber	Difference
Low	366 963	367 030	67
Central	962 600	962 788	187
High	1 934 429	1 934 813	384

*Low – low VOLY; high – high VLS; central value is assumed to be in the middle of the interval used in the Cost-Benefit Analysis of Final Policy Scenarios for the EU Clean Air Package (Holland 2014)

Estimated external costs attributable to different aspects of **water pollution** are presented in Figure 10. Costs attributable to eco-toxicity and eutrophication are higher in the scrubber scenario than in the baseline scenario by factor 3.7, while ocean acidification costs are twice as high. Ecotoxicity accounts for over 80% of the total external costs attributable to water pollution from scrubber use. Contribution of ocean acidification is considered insignificant.

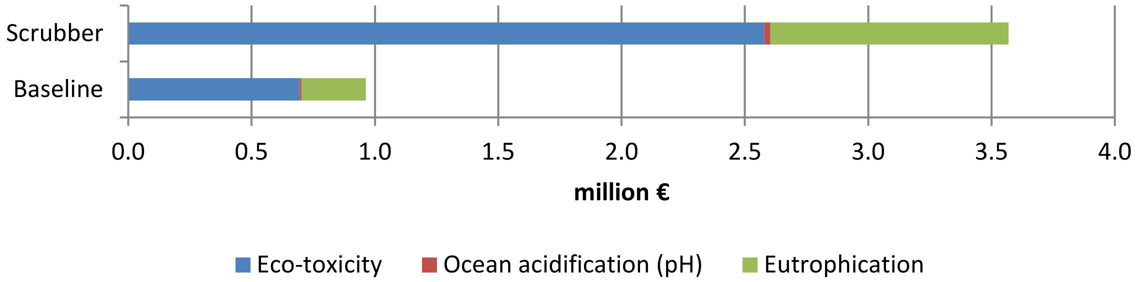


Figure 9: Annual water-related external costs in the ECA 2030 scenarios.

Total annual external costs for shipping in the ECA in 2030 are summarized in Table 29. Both air pollution and water pollution effects are higher in the scrubber scenario, resulting in the total extra external costs of approximately 260 million €, compared to the baseline – mainly due to negative health effects that corresponds to 70% of the total difference. Additional effects related to water pollution are estimated at 2% of the total difference in the external costs.

Table 29. Total annual external costs in the scenario setting ECA 2030, central estimates, million €.

Type of external costs		Baseline	Scrubber	Difference
Health effects	Air pollution	962 600	962 788	187
Crop damage	Air pollution	33.0	34.1	1.1
Climate effect	Air pollution	2 804	2 877	73
Eco-toxicity	Water pollution	0.70	2.58	1.88
Ocean acidification (pH)	Water pollution	0.007	0.025	0.018
Eutrophication	Water pollution	0.26	0.97	0.71
TOTAL EXTERNAL COSTS		**965 438**	**965 702**	**264**

4.3 CBA results for ECA 2030 scenarios

The total annual shipping costs and the total annual external costs attributable to the ECA 2030 scenarios are presented in Figure 11. The shipping costs in the scrubber scenario are approximately 330 million € lower than in the baseline. This is to a large extent due to the fuel savings. However, the scrubber scenario does not result in additional positive effects on the environment, climate or health. The total annual additional external costs in the scrubber scenario are estimated at approximately 260 million €, compared to the baseline.

Like in the case of Stena vessels Hollandica and Britannica, the use of scrubber technologies results in lower shipping costs due to the price difference between HFO and other fuels (LSFO, MGO, LNG). Also similar to the results for the Hollandica/Britannica 2017, lower emissions of air pollutants such as SOx does not seem to compensate for higher emissions of other pollutants (NO_x, $PM_{2.5}$), in terms of the monetary values of the related health and environmental impacts.

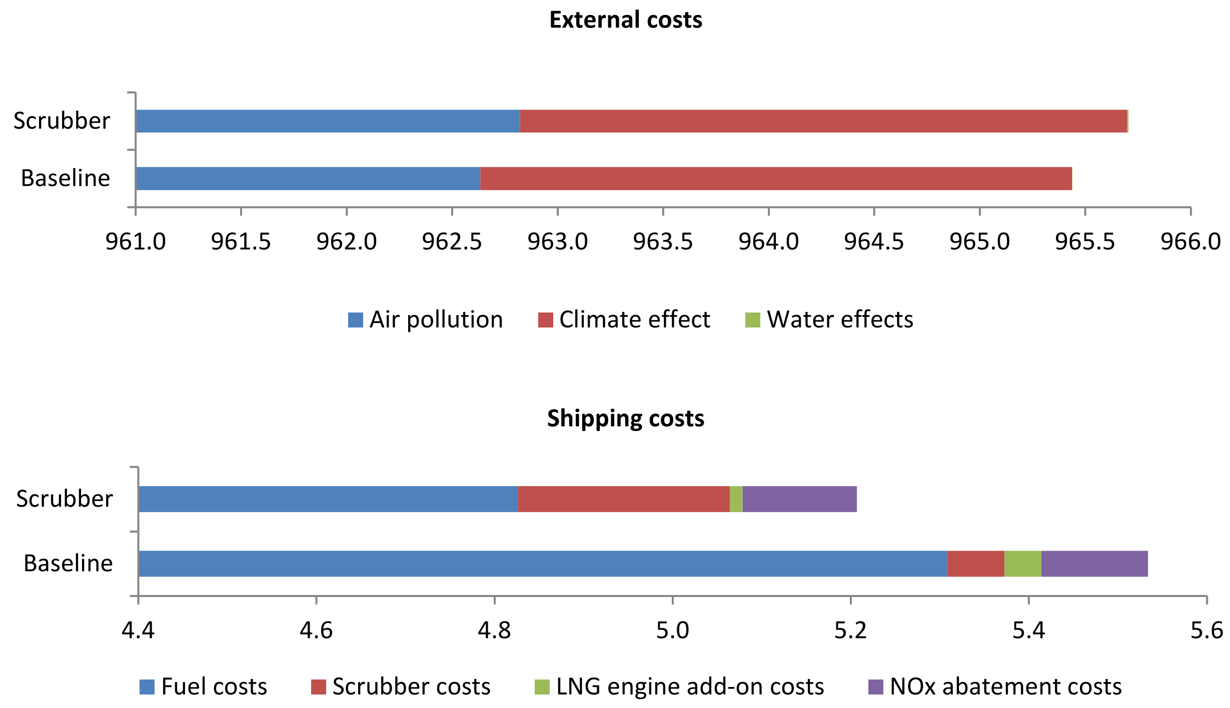
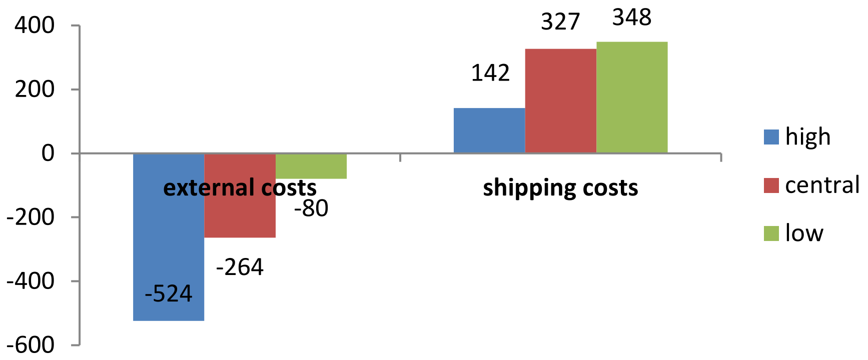


Figure 10. Total annual costs in the ECA 2030 scenario setting (central values for external costs), billion €.

Both cost types are associated with large uncertainties so we used low to high intervals, as shown in Table 27 and Table 28. Although the extended use of scrubbers seem to result in higher external costs due to more air and water emissions (according to our calculations), the difference may vary from ~80 to ~520 million €, depending on the health effects valuation – see Figure 12. The shipping costs are higher in the scrubber scenario – the interval is estimated at ~140 to ~350 million €.

Figure 11. Difference between the scrubber scenario and the baseline, million €.



5 Discussion

Choice of the cost-effective option to comply with sulphur regulations

From our results we can see the rationale behind the choice of scrubber instead of LSFO from a **shipowners' perspective** when switching from HFO to one of the alternatives, since it is the least expensive approach to comply with current regulation. From the private perspective, open-loop scrubber has higher benefit-to-cost ratio than LSFO while closed-loop scrubber has lower ratio due to higher operation and management costs. Analysis presented in Stena (2014), conducted before the scrubber installation, show similar results in terms of cost-effectiveness: shipowners' perspective on investment cost annualization (10 years investment lifetime) results in a benefit-to-cost ratio of 2.6 for the scrubber scenario compared to 1.2 for the MGO option. Our corresponding estimates are 7.4 for open-loop scrubber, 5.0 for closed-loop scrubber and 5.1 for LSFO meaning that the main difference in our results is that closed-loop scrubber seems less cost-effective than LSFO. A societal perspective on scrubber investment costs increases benefit-to-cost ratio of scrubbers even more, so that it becomes higher than the ratio for LSFO option for closed-loop scrubber as well. Both in our estimates and in Stena (2014), the results regarding difference in the shipping costs depend mainly on assumed price differences between HFO and LSFO/MGO. The two scrubber scenarios include an investment cost which includes a financial risk assuming that the future is uncertain regarding, e.g. future regulations and fuel prices. Even if the scrubber alternatives seem more profitable under current circumstances than LSFO this may not hold true in the future. The risk involved concerns the sunk investment costs that cannot be recovered even if the scrubber alternative becomes unfavourable in the future.

An exhaust gas scrubber system reduces SO_2 emissions to lower levels than is accomplished at combustion of a fuel with 0.1% sulphur content (i.e. LSFO). Emissions of particles and CO_2 are on the other hand higher from combustion of HFO in combination with a scrubber, than from LSFO combustion. NO_x emissions from the measurements on board Britannica (Winnes et al. 2018) did not indicate a reduction in the scrubber although this has been observed in previous studies. The **resulting external costs** of environmental and health damage associated with air emissions and water releases are higher for scrubber scenarios than in the case of low-sulphur fuel use. This also applies for both the Hollandica/Britannica scenario setting and the ECA 2030 scenario setting. This means, from a strictly environmental and health perspective, operations on low sulphur fuels seem to be more preferable than operations on HFO together with an exhaust gas scrubber.

The **relationships between external and shipping costs** of scrubbers, in comparison to LSFO, do not significantly differ between scrubber types. In both cases, the additional external cost of using scrubber is lower than the gain related to shipping cost.

Closed-loop scrubbers are more expensive than open-loop scrubbers due to high operation and management costs. At the same time, closed-loop scrubbers may result in higher external costs due to higher fuel consumption. Fuel penalty is claimed to be higher for closed-loop scrubbers than for open-loop scrubbers in Jönsson & Törnmalm (2018) – this study explores Stena vessels, including Hollandica. This is also confirmed by measurements within our project – higher fuel penalty values for closed-loop scrubbers are used both in the current report and in Zhang and Stripple (2018). Other studies, however, report higher fuel penalty for open-loop scrubbers – e.g. Bosch et al. (2009), Lloyd's Register (2012), and IMO (2015). Monetarised valuations of emissions to water are on the other hand higher for open-loop scrubbers, mainly due to eco-toxicity which accounts for about 80% of the total water-related external costs, according to our analysis.

The choice of the most cost-effective alternative to comply with current sulphur regulations is only relevant if both alternatives are **within the legislative framework** and do not contribute to breaching any of the existing regulations on water or air environment. At the moment there are no indications of such rule violations when using scrubbers. However, there is a knowledge gap for water emissions from scrubbers and their effects on the marine environment. Since lowered water quality will have impacts human health and the environment. More tests are needed in order to narrow this gap before the use of scrubbers become more widespread in the industry. Meanwhile, the precautionary principle favors the low sulphur fuels in a comparison with scrubbers. The uncertainties associated with scrubber water releases and its potential impact on health and environment, and monetary valuations of the effects, should not be neglected when estimating costs and benefits from scrubber use.

Effect valuation and uncertainties

Uncertainties in the calculations were analyzed using Monte Carlo simulations. The uncertainty analysis confirmed the importance of the **fuel costs as the most influential factor** on the result. Other important uncertainties were the valuation of external costs of NO_x SO_x and CO_2 emissions. The uncertainty analysis regards uncertainties in numbers only, and does not address the uncertainty of our assumptions. Uncertainties associated with air measurements were not included either.

One area worth discussing is the monetary valuations of the external effects. In this study we have included effects from both air pollution and pollution to the marine environment. The methodology for monetary **valuation of air pollution effects** is well-developed and widely used. The valuations capture the effects on human health as well as on crops, and partly on materials. However, it does not quantify the effects of certain particle fractions (black carbon) or include all known effects of exposure to particles and ozone. Despite a rather established methodological framework, the uncertainty range associated with health effects from air pollution is high. Some emissions cannot be valued in monetary terms due to a lack of external cost estimates those are for instance PAHs.

For **emissions to sea water** we have captured the eco toxicity (however, not human toxicity), the acidity and eutrophication effects from the effluent water. The impact from the effluent water might, however, be underestimated due to lack of valuation studies of all substances released. For this study we could e.g. not find relevant values for heavy metals and PAH. Further, there are also few valuation studies for the effects of pollutants to marine environment, partly due to lack of knowledge on the cause effect relationships. Another obstacle is to convert the results from the risk assessment of scrubber water into the same units as identified in the literature on valuations. For the valuation of eco toxicity, results from standardized Microtox test were used to convert the effect into the same unit as found in the valuation studies. This is a way forward, but it is also related with increased uncertainty and limitations. It cannot be ruled out that there are toxic qualities in the effluent water that are not detected by the Microtox tests. If this is the case, the external costs are underestimated. The risk assessment of scrubber water is described and discussed further in Magnusson et al., 2018.

Method & assumptions

Our analysis is to a large extent based on the measurement results from Winnes et al 2018 and Magnusson et al., 2018, especially regarding the Britannica/Hollandica scenarios sets. One of the necessary method adjustments was using results from analysis in open-loop scrubber effluent water from another ship, Stena Forerunner. These results were, further scaled up to correspond with the higher fuel consumption of the larger ships Stena Hollandica and Stena Britannica.

Estimates in the **ECA 2030 scenarios** are based on a number of assumptions and simplifications. The whole fleet in the Baltic Sea and the North Sea was specified in a rather simple model that didn't distinguish between different engine types (affects emissions) or vessel categories (affects time spent in the area that in turn affects annualized investment costs of certain technologies). An assumption was made about the share of closed-loop scrubbers in the North Sea of10%, based on expert estimation. We furthermore assumed that effluent water flows from scrubbers do not depend on any other factors than scrubber type. We use the values 0.2 m^3/MWh and 45 m^3/MWh, for all vessels with closed respectively open scrubber systems. Due to the implementation of IMO's NO_x regulation entering into force in 2021, we also have to make some assumption about NO_x abatement in this scenario set. Scrubbers are supposed to be compatible with SCR, which is an issue still under discussion. We also assume that SCR and EGR[16] have relatively similar costs so we have chosen SCR as more established option. LSFO is supposed to be one of the main fuels used 2030 (together with MGO, HFO and LNG) although this fuel is not standardized and thus emission factors are very uncertain when we apply them to the whole fleet. To this, one should add high uncertainties in the future fuel price estimates, as described above. We did not conduct an uncertainty analysis for this scenario setting in the same way as we did for the Britannica/Hollandica scenario settings. The results for the ECA 2030 scenario settings are instead presented as intervals based on the intervals in the included parameters (see Appendix 1).

Using models imposes certain simplifications and embedded assumptions. For instance, we have to allocate all emissions from the Baltic Sea and the North Sea to the exclusive economic zones and reduce the total emissions in the 12-mile zone accordingly. This adaptation is necessary since the entire European 12-mile zone is modelled as one emitting region in the GAINS model. With this model, a scenario for the Baltic Sea and the North Sea would thus imply emission reductions along the coastline of the Mediterranean Sea, for example. To avoid this we assume that all emissions take place outside the territorial seas. The health impacts calculated in this – and consequently the calculated monetary benefits – are therefore underestimations. In our study, this concerns the results for the ECA 2030 scenario setting.

Using measurement-based emission factors result in the total annual **air emissions that differ** quite a lot from values for the same areas presented in other studies (see Chapter 2.3.3). However, there are other factors affecting the resulting emissions – in particular changing regulations (sulphur requirements, NECA, energy efficiency standards, etc.) that result in constant changes in the underlying assumption when producing baseline scenarios.

Our study shows that the most crucial factor that impacts the CBA results is fuel price difference. This is **in line with other assessments** of scrubber cost-effectiveness (e.g. Jiang et al, 2014; Boer & 't Hoen 2015, and Lindstad, (2016). At the current fuel price rates, scrubber is more viable option from a shipowner perspective. However, estimates of future fuel prices are accompanied with high uncertainties.

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[16] SCR = Selective Catalytic Reduction, EGR = Exhaust Gas Recirculation

6 Conclusions

Scrubber technologies are wide-spread on land but relatively new for exhaust gas treatment on ships. Technical costs of scrubber installations and related external costs have been estimated previously, e.g. Bosch et al, 2009 and Jiang et al, 2014. The cost benefit analysis presented in this study is to a large extent based on the measurements and analyses of air, water and fuel flows onboard Stena's vessels Hollandica, Britannica and Forerunner. Both open and closed scrubber systems have been investigated and compared to a baseline where using low-sulphur fuels (such as LSFO) is considered as an alternative. However, in some analyses we also make comparisons with heavy fuel oil (HFO). Furthermore, we have two scenario settings: one case study for Stena's vessels (Hollandica/Britannica) and one representing the entire emission control area (ECA) fleet in 2030. Both scenario settings have been analysed from a socio economic perspective.

Compared to the case when heavy fuel oil (HFO) is used without further abatement, use of scrubber results in significantly lower **emissions to air -** especially regarding particles and SO_x (as shown in Chapter 2.3.2). According to our calculations the technical costs of removal of SO_x are estimated at 0.7-1.3 €/kg, where the low-end corresponds to the open scrubber, and high-end corresponds to the closed-loop system. The related total annual benefits to human health and the environment for the case study Hollandica/Britannica are estimated to ~23 million €. However, this case of running HFO without scrubber can only be considered as hypothetical in the area comprising the Baltic Sea and the North Sea. In reality, vessels have to choose low-sulphur fuels such as LSFO, MGO, and LNG, or combine HFO with scrubbers.

Compared to previous cost benefit analyses of scrubbers, our analysis is also including monetary valuation of emissions to the **marine environment.** The use of scrubbers introduces emissions of substances present in the effluent water. No emissions to water are included in the baseline scenario (LSFO). Valuation studies of emissions to water are less frequent than studies related to air emissions. Therefore, our calculations of external costs for these new emissions should be considered with caution. The issues associated with external cost calculations is addressed in our uncertainty analysis and elaborated in the discussion.

The total annual **shipping costs of each of the Stena sister ships Hollandica/Britannica** are lower if scrubbers are used instead of LSFO – by 1.4 million € for open scrubber, and by 0.9 million € – for closed. This is mainly due to the difference in fuel price between HFO and LSFO. The total annual technical costs of the open scrubber system are estimated at 0.59 million €, while for the closed scrubber the corresponding number is 1.1 million €.These numbers comprise fixed investment costs as well as operations and management costs – the latter are approximately 0.48 million € higher in the case of the closed-loop scrubber, mainly due to the costs of materials such as sodium hydroxide (NaOH) needed for the abatement process.

The total annual **external costs attributed to Hollandica/Britannica (per vessel)** are estimated at 15.0 million € for the open-loop scenario, 15.1 million € for the closed-loop scenario, and 14.5 million € for the LSFO scenario. The difference between the scrubber scenarios and the LSFO scenario is therefore 0.5 million € for open-loop and 0.6 million € for closed-loop scrubbers. These results indicate that use of scrubbers on these particular two vessels do not bring increased health or environmental benefits compared to the case when vessels use LSFO, i.e. total external cost are higher in each of the scrubber scenarios. Although external costs attributable to certain air emissions (SO_x) are lower in the case of scrubber use, these positive effects do not seem to overweigh the negative effects due to higher air emissions of other substances (CO_2, NO_x, $PM_{2.5}$)

and water emissions. Even including uncertainties, there is always a positive difference between scrubber and LSFO indicating that from an environmental perspective the LSFO scenario is preferable.

The set of scenarios compiled for **ECA 2030** show negative external effects at an assumed higher implementation rate of scrubber technologies in the future. Meanwhile the annual shipping costs are lower when fewer scrubbers are used – due to assumptions on fuel prices in 2030. The difference in shipping costs between the baseline (20% of scrubbers) and the scrubber scenario (70% of scrubbers) amounts to 330 million €. Again, this difference is positive due to the significant fuel price split between HFO and LSFO assumed for 2030. The difference in the total external costs is 270 million €. External costs are higher in the scrubber scenario compared to the baseline, mainly due to the adverse health effects from air pollution.

The results obtained in both scenario settings (see Table 30) imply that more extended use of scrubbers systems, open or closed, being associated with lower costs for shipping companies due to the (current) fuel price difference, however, it does not seem to result in decreased external costs associated with air and water pollution.

Table 30. Total annual shipping costs and external costs in all scenarios included in the analysis.

Scenario setting	Britannica/Hollandica			ECA 2030		
Scenario	**Scrubber, open**	**Scrubber, closed**	**LSFO**	**HFO without scrubber**	**Baseline**	**Scrubber**
Unit	th €	th €	th €	mln €	mln €	mln €
Shipping costs	**7 700**	**8 200**	**9 100**	**7 000**	**5 500**	**5 200**
-fuel	7 100	7 100	9 100	7 000	5 300	4 800
-technical	600	1 100	-	-	200	400
External costs	**15 000**	**15 100**	**14 500**	**58 500**	**965 400**	**965 700**
-air-related	15 000	15 100	14 500	58 500	965 400	965 700
-water-related	11.7	9.21	-	-	1.0	3.6

Our results show the rationale behind shipowners' choice of installing a scrubber instead of switching to LSFO to comply with the sulphur regulation. From the private perspective (shipowners), open-loop scrubber has higher benefit-to-cost ratio than LSFO while closed-loop scrubber has lower ratio due to higher operation and management costs – both cases compared to the "previous baseline" case of HFO with 1% sulphur content (the starting point for shipowners' choice). The societal perspective on scrubber investment costs increases the benefit-to-cost ratios of scrubber even more, with resulting higher ratio for both types of scrubbers compared to LSFO.

At present, LSFO is considered as a baseline that both of the scrubber types are compared to in the case of Hollandica/Britannica. Differences in shipping costs between the alternatives open-loop scrubber and closed-loop scrubber, compared to LFSO, are larger than differences in external costs, but uncertainties (in both fuel prices and external cost valuations) are important. The uncertainty analysis indicates that while shipping costs at the current fuel price level are lower for scrubbers than for LSFO, correspondent additional damage to health and environment is higher. This means, one cannot certainly say that the scrubber scenarios are associated with lower shipping costs than the LSFO scenario due to uncertainties – but the results regarding the external costs can be considered as more robust. Our Monte Carlo uncertainty simulation, however, does not cover uncertainties associated with air emission measurements.

The resulting external costs of environmental and health damage associated with air and water emissions are higher for the scrubber scenarios than in the case of low-sulphur fuel use – this applies for both the Hollandica/Britannica and the ECA 2030 scenario settings, with regard to emission factors used in the analysis. This means, from a strictly environmental and health perspective and in line with the precautionary principle, operations on low sulphur fuels seem to be more preferable than operations on HFO together with an exhaust gas scrubber.

This study is also a first attempt, according to our knowledge, to show that it is possible to include marine/water emissions in CBA for shipping. We see a need for **further research** within this area e.g. in dispersion and exposure modelling and valuation studies and models of water emissions.

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Appendix 1. Shipping cost parameters.

Scenario setting	Hollandica/Britannica in 2017		Emission control area in 2030			Unit
	Central value	Source	Low	Central	High	
INVESTMENT COSTS						
Investment, installation and other fixed costs (retrofit)	237	Stena personal communication	153** 237***	222** 304***	306** 608***	€/kW
Investment, installation and other fixed costs (new)	-		119** 152***	132** 265***	152** 304***	€/kW
Equipment lifetime (retrofit)	30		-	24	-	Years
Equipment lifetime (new)	-		-	27	-	Years
Interest rate	0.04		-	0.04	-	Shares
Investment & installation, new LNG engine (add-on)	-	-	369	726	940	€/kW
Investment & installation, SCR	-	-	20.5	67.6	107.5	€/kW
OPERATION AND MANAGEMENT COSTS						
Labour, open scrubber	10 172	Stena personal communication	0.82*	0.91*	1.00*	€/year
Labour, closed scrubber	20 434		0.82*	0.91*	1.00*	€/year
Extra maintenance	40 686		-	-	-	€/year
Extra maintenance	81 373		-	-	-	€/year
Fresh water consumption	0.14		0.1	100	300	l/MWh
Fresh water price	0.0025		0	0.0025	0.0047	€/l
NaOH consumption	13.9		6.58	13.78	17.60	l/MWh
NaOH price	0.32		0.31	0.36	0.76	€/l
Coagulant consumption	0.10		0.10	0.10	0.10	l/MWh
Coagulant price	2.54		2.54	2.54	2.54	€/l
Flocculent consumption	0.01		0.01	0.01	0.01	l/MWh
Flocculent price	15.3		15.26	15.26	15.26	€/l
Sludge generation	3.5		0.08	1.80	3.50	l/MWh
Sludge treatment price	0.10		0.10	0.25	0.46	€/l
Catalyst replacement, SCR	-	-	0.31	0.73	0.92	€/MWh
Urea price, SCR	-	-	0.19	0.25	0.31	€/kg
Urea consumption, SCR	-	-	6.5	10.9	16.5	kg/MWh
Labour demand, SCR	-	-	8	8	8	hours/year
Labour price, SCR	-	-	50.6	50.6	50.6	€/h
FUEL COSTS						
Price for HFO	379	Rotterdam values as of 2018-06-27	420	494	642	€/t
Price for LSFO	533		536	610	758	€/t
Price for MGO	557		574	687	874	€/t
Price for LNG	-		427	502	652	€/t
Fuel penalty, open scrubber	1.99	Stena, personal communication	1.00	1.98	3.50	%
Fuel penalty, closed scrubber	2.15		0.50	1.24	3.00	%

*€/MWh

** open, *** - closed

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Appendix 2. Monetary valuation of health impacts in the ARP model.

Valuation of health impacts in the Alpha RiskPoll (Holland 2014)

Impact	Unit	Valuation, €$_{2005}$/unit		
		Low	**Central**	**High**
Mortality in adults, VOLY metrics	Life Years Lost	40 000[2]	57 700[1]	138 700[1]
Mortality in adults, VSL metrics	Deaths	1 090 000[1]	2 220 000[1]	2 800 000[3]
Infant mortality, VSL metrics	Deaths	1 635 000[1]	3 330 000[1]	4 200 000[1,3]
Chronic bronchitis in adults	Cases	53 600[4]	53 600[4]	53 600[4]
Bronchitis at children	Added cases	588[4]	588[4]	588[4]
Hospital admissions – respiratory and cardiovascular	Cases	2 200[1]	2 200[1]	2 200[1]
Restricted activity days (RAD)	Days	92[1]	92[1]	92[1]
Minor restricted activity days (MRAD)	Days	42[1]	42[1]	42[1]
Asthma symptom days at children	Days	42[1]	42[1]	42[1]
Lost working days	Days	130[5]	130[5]	130[5]

[1]Holland et al. 2005 (CAFE CBA), [2]Desaigues 2011, [3]OECD 2012, [4]Holland 2014, [5]CBI 2013

Premature mortality at adults (>30 years) is the impact with the highest input into total external health-related costs. It can be valued in VOLY or VSL metrics. Low VOLY estimate is taken from Desaigues 2011 based on willingness-to-pay surveys conducted in 9 European countries. Central VOLY values, used in Holland et al. 2005, are based on derivations from VSL (that has much stronger empirical basic for monetarization) – in particular, from extensive study of mortality risk valuation surveys reported in Alberini 2005. OECD 2012 conducted meta-analysis of VSL approach based on willingness to pay literature – those estimates are used for the high end of VSL and VOLY.

Infant mortality is valued with VSL. VOLY approach is not appropriate given the anticipated reduction in life expectancy of deaths before the age of 1 year (Holland et al., 2013).VSL values in the model are based on willingness to pay (WTP); however, conventional approach where individuals evaluate their own WTP is not applicable to infants. Based on studies estimating WTP of society, parents, or adults placing themselves in the position of children, ARP valuation for infant mortality is assumed to be 1.5 times higher than VSL for an adult (Holland et al., 2013).

Morbidity costs cover (1) hospitalization and medication costs, (2) ‘opportunity costs’ – costs to employer due productivity loss at employees, and (3) ‘dis-utility costs’ - other social and economic costs including any restrictions on or reduced enjoyment of desired leisure activities, discomfort or inconvenience (pain or suffering), anxiety about the future, and concern and inconvenience to family members and others (Schucht et al., 2015; Holland et al., 2013). Health care costs and employers’ expenses are based on the market prices whereas dis-utility costs are subject to WTP studies – in particular, many results from Ready 2004 were used, with more recent updates for bronchitis documented in Holland (2014). Cost of a lost working day is derived from the CBI (2013) study summarizing the salary cost of absent individuals and replacement costs in 153 organizations. The valuation of work loss days does not include indirect costs related to a potential loss of future business due to poorer quality of products or services (Holland, 2014).

WTP based results used in the ARP model are representative for EU member states and are income-dependent.

Appendix 3. External costs of air pollution and climate effect, Hollandica/Britannica 2017.

Scenario	**Pollutant**	**North Sea**				**UK**				**Netherlands**			
		Emissions, t	**External cost, th €**			**Emissions, t**	**External cost, th €**			**Emissions, t**	**External cost, th €**		
			low	**central**	**high**		**low**	**central**	**high**		**low**	**central**	**high**
LSFO	SOx	30.7	464	808	1 368	1.6	28	49	83	1.9	60	104	177
	NOx	841	12 734	22 166	37 527	51	912	1 571	2 646	62	1 923	3 345	5 662
	PM2.5	10.3	156	271	458	0.6	10	18	30	0.7	22	38	64
	CO2	50 911	645	5 046	9 420	2 643	33	262	489	3 182	40	315	589
	TOTAL		13 999	28 292	48 774		984	1 900	3 247		2 045	3 803	6 491
Scrubber closed	SOx	7.188	109	189	321	1.0	18	31	52	1.225	38	66	112
	NOx	930	14 091	24 528	41 525	44	774	1 335	2 248	52	1 626	2 829	4 789
	PM2.5	23.27	352	614	1 039	1.0	18	31	52	1.2	38	66	112
	CO2	52 851	670	5 238	9 779	2 386	30.2	236	441	2 864	36.3	284	530
	TOTAL		15 222	30 569	52 663		841	1 633	2 793		1 739	3 246	5 543
Scrubber open	SOx	7.145	108	188	319	1.000	18	31	52	1.225	38	66	112
	NOx	923	13 974	24 325	41 182	43	771	1 329	2 238	52	1 620	2 818	4 769
	PM2.5	23.08	350	609	1 030	1.01	18	31	52	1.22	38	66	112
	CO2	52 415	664	5 195	9 698	2 376	30.1	236	440	2 854	36.2	283	528
	TOTAL		15 096	30 317	52 229		837	1 627	2 782		1 732	3 233	5 522
HFO without scrubber	SOx	818.4	12 395	21 576	36 528	20.4	362	624	1 051	23.8	742	1 291	2 186
	NOx	912	13 806	24 032	40 685	45	808	1 393	2 346	54	1 695	2 949	4 992
	PM2.5	33.8	512	891	1 508	1.3	23	39	65	1.5	47	82	139
	CO2	51 706	655	5 125	9 567	2 363	30	234	437	2 838	36	281	525
	TOTAL		27 368	51 624	88 288		1 223	2 291	3 900		2 521	4 604	7 842

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