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Scrubbers: Closing the loop

Activity 3: Task 4

Evaluation of exhaust gas scrubber systems for ship applications from a system perspective

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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 2 Risk Assessment of marine exhaust gas scrubber water 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 3; Cost benefit analysis. IVL report B2320, by Yaramenka K., Mellin A., Malmaeus M., and Winnes H., 2018

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Summary

The environmental performance of ship engines is partly due to the engine design (such as combustion conditions) and partly to the fuel characteristics. To some extent, the environmental performance can therefore be changed through the choice of fuel and the choice of gas cleaning technologies. Thus, there are several different options available. As regards petroleum-based fuels, one can distinguish between heavy fuel oils with high sulphur content and light fuel oils with lower sulphur content. Today, the heavy fuel oils are mainly used in shipping, as the cost aspect is an important factor for transports and these oils are less costly than refined alternatives. The legislation and the competitive situation play a crucial role here. Environmental legislation also changes over time, and tightening requirements are imposed on shipping. Internationally uniform requirements are also an important aspect when shipping operates in an international market. Special requirements are also imposed on vessels used in particularly sensitive areas. An example of this is the SECA and NECA requirements¹.

For this reason, it is of special interest to the shipping industry to investigate various possible alternatives to reduce emissions and fuel consumption from the vessels. In this project two conventional methods are investigated to reduce emissions where conventional ship engines can be used without major modifications and where conventional petroleum-based fuels can be used. The main option investigated in this study is to continue to use heavy fuel oils with high sulphur content and to clean the flue gases with conventional scrubber technology. This method is then compared with the use light desulfurized fuel oils e.g. marine gas oil. In the latter technology, fuel oil is refined and purified at the refinery instead of cleaning the flue gases from the vessels. In order for the comparison to be as comprehensive as possible, a system perspective is used in the analyses and computer models are developed using Life Cycle Assessment (LCA), which mainly covers energy resources, material resources, and emissions.

The present project is part of a larger project where the scrubber technology is tested in practice by an installation on one of Stena Line's RoRo ferries. This overall project also includes a technical evaluation of the scrubber cleaning technology.

In this study, three different SO₂/SO₃ reduction systems are compared and analysed. The systems are:

- Closed-loop scrubber system with sea water and a scrubber water cleaning system, which produce a sludge that is assumed to be used in a cement kiln and some of the substances in the sludge will end up in concrete. The main engine of the ship running on heavy fuel oil.
- Open-loop scrubber system operating with sea water and no scrubber water cleaning. The main engine of the ship running on heavy fuel oil.
- Use of SECA fuel², which is a fuel containing not more than 0.1 wt-% sulphur. The sulphur cleaning takes place in the crude oil refinery. We investigate two different refinery processes

¹ **Sulfur Emission Control Areas (SECAs) or Nitrogen Emission Control Areas (NECAs)** are sea areas in which stricter controls were established to reduce airborne emissions (SO_x, NO_x) from ships as defined by Annex VI of the 1997 MARPOL Protocol, which came into effect in May 2005.

² The SECA Fuel can also be referred to as Low Sulphur Fuel Oil (LSFO), or Ultra Low Sulphur Fuel Oil (ULSFO).

that can be used to produce the SECA fuel and call them SECA fuel method 1, SECA fuel method 2.

The systems are compared and evaluated in a system perspective.

For the SECA fuel, the sulphur reduction is achieved by desulfurization of the fuel in the refinery during the production of the fuel. Different production processes exist, all with slightly different environmental aspects that will meet the sulphur specification. This is exemplified by method 1 and 2. Method 1 exemplifies an ordinary refinery production of marine gas oil (MGO) with a sulphur content of 0.1 % while method 2 shows a SECA fuel production based on heavy fuel oil treated in a residue hydrocracker with an additional energy use. The data from the SECA fuel include activities from crude oil extraction to the SECA fuel product. No SO_2/SO_3 cleaning is needed. Due to the lighter fuel, some other emissions can also be reduced to some extent such as particles, heavy metals, HC, PAH, NO_x etc. The exact emission levels depend on the fuel and on the combustion conditions in the engine. However, no further scrubber cleaning is present in this method under study.

For the scrubber alternatives, heavy fuel oil is used for the main engine of the ship. This fuel can have a high content of sulphur, approximately 2.5 wt.-%, which is mainly converted to SO_2 in the combustion process of the main ship engine and removed from the exhaust gases by the scrubber process to a large extent. In the closed-loop scrubber system, the removed SO_2 is neutralized by NaOH in the scrubber water while in the open-loop scrubber system, the dissolved SO_2 is discharged directly into the sea and neutralized by the alkalinity of the sea water. The neutralization with NaOH is an advantage from an environmental (acidification) point of view but requires an effort for the production of NaOH. The combustion of the heavy fuel oil also forms other pollutants as mentioned above. These are, to some extent, removed by the scrubber process. In the open-loop scrubber system, the scrubber water containing the pollutants are directly discharged to the sea, which means that, in reality, there are no removal effects, only an accelerated transport from air pollution to water pollution preventing the pollutants to reach land areas. In the closed-loop scrubber system, the scrubber water is cleaned in the water treatment system, on-board the vessel, prior to discharge. The pollutants are, in this way, concentrated to a sludge, which will be further treated on shore. The emissions to the environment depends thus very much on the handling and further treatment of the sludge. In the assumed case for this study, the sludge is combusted in a cement kiln and the remaining part will be a part of the cement. Thus, the heavy metals in the heavy fuel oil will end up in concrete. This will significantly slow down the emission rate of the metals, but in a very long time perspective, the metals will leak out.

Figure A shows the primary energy resource use for the different cases. The main resource is of course the use of crude oil. The SECA fuel method 2 shows relatively high energy use due to the high energy use required for the residue hydrocracker to process HFO. For the closed-loop scrubber case, there are additional energy needs to operate the scrubber system and water cleaning as well as to produce the chemicals needed for the cleaning. For the open-loop scrubber case, there are additional energy needs for the scrubber system and the increased scrubber water flow compared to the closed-loop scrubber case. The energy use for the production of the heavy fuel oil compared to the SECA fuel oil is lower. The SECA fuel cases include the fuel use in the engine and the energy for the production of the fuel.

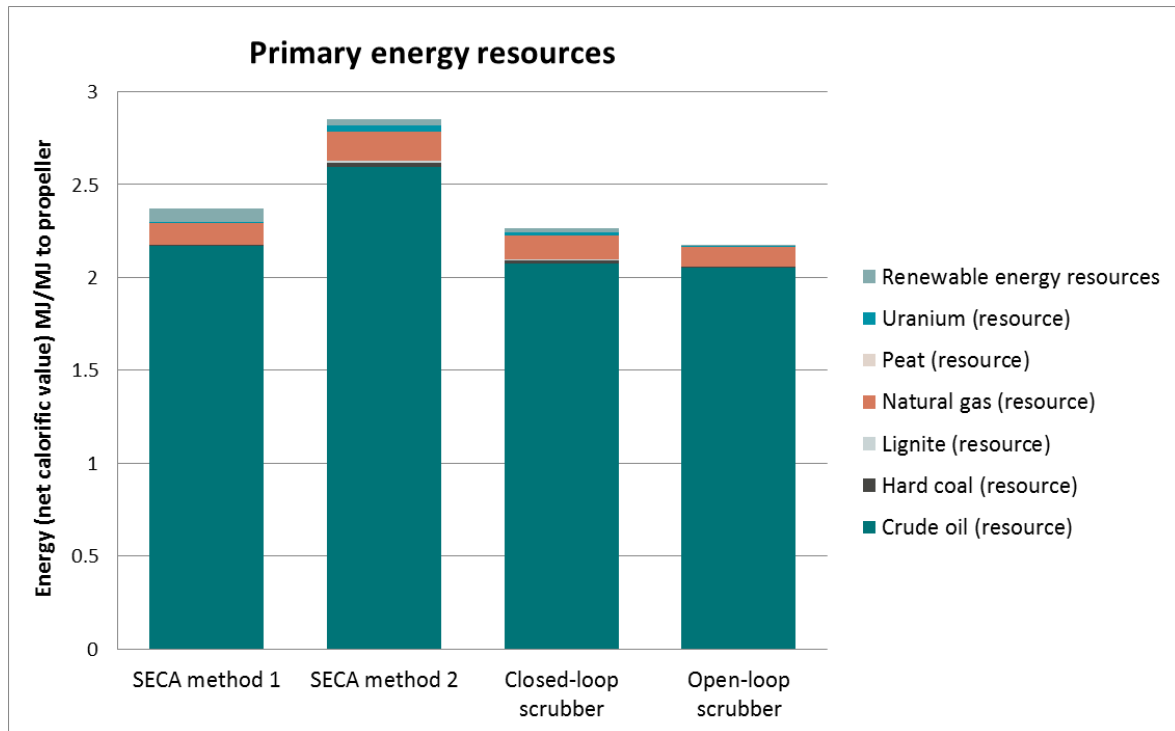


Figure A Comparison of Primary energy resource use (in MJ) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown.

The Global Warming Potential (GWP) results cover mainly CO₂ from combustion of fossil fuels but also emissions of CH₄ and N₂O. In this case, the combustion of fuel oil is an important aspect. In the SECA fuel case, it covers the combustion in the main engine of the ship and emissions from the fuel production from crude oil extraction to refining to SECA fuel quality. For the scrubber case, it covers the combustion in the main engine of the ship, the emissions from the heavy fuel oil production from crude oil extraction to refining to heavy fuel oil quality, emissions from the production of the chemicals used in the closed-loop scrubber system, and the emission from the extra energy use needed for the entire scrubber process (incl. scrubber water cleaning in the closed-loop and extra scrubber water flow in the open-loop). The GWP results from the different cases are shown in figure B. As shown in the figure, the GWP results are relatively equal between the different cases even if the SECA fuel alternative (method 2) is slightly higher. This can be explained by the additional use of refinery gas for heating in the residue hydrocracker. GWP emanates also from the operation of the scrubber systems (including the combustion in the main engine) but less from the scrubber system production or the end-of-life (EoL) parts.

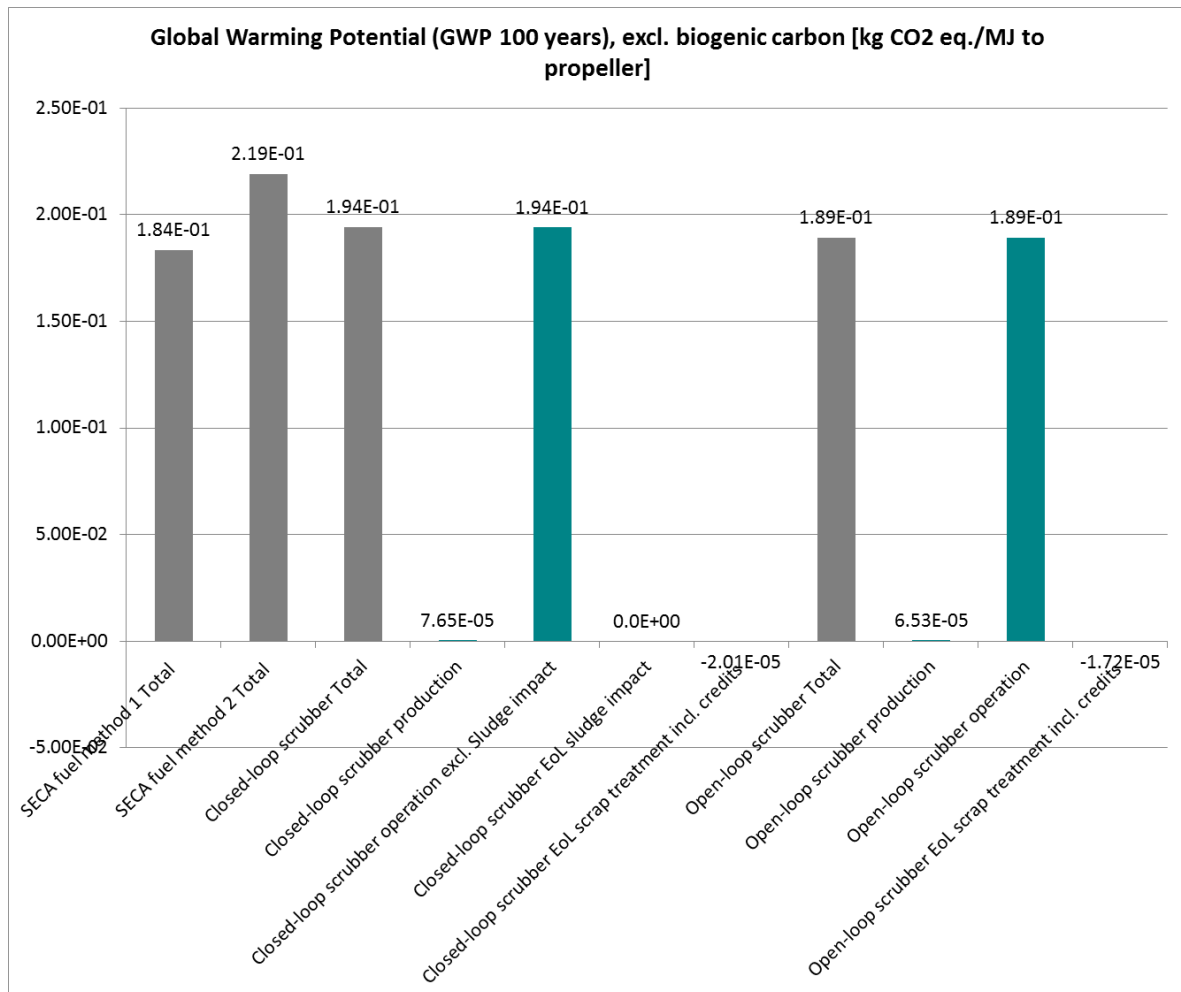


Figure B Comparison of Global Warming Potential (GWP 100) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

The acidification potential (AP) shows a similar pattern as GWP and energy, which is shown in figure C. The main contributors to acidification are the emissions of SO₂ and NO_x. Both GWP and AP are very much related to the combustion of the fuel oil with a defined emission level of SO₂/SO₃ and with the same type of engine i.e. relatively equal NO_x emissions however, with a difference between heavy fuel oil and SECA fuel. The NO_x emissions are not reduced or changed by the scrubber. The differences in Acidification potential can thus mainly be explained by the differences in energy use.

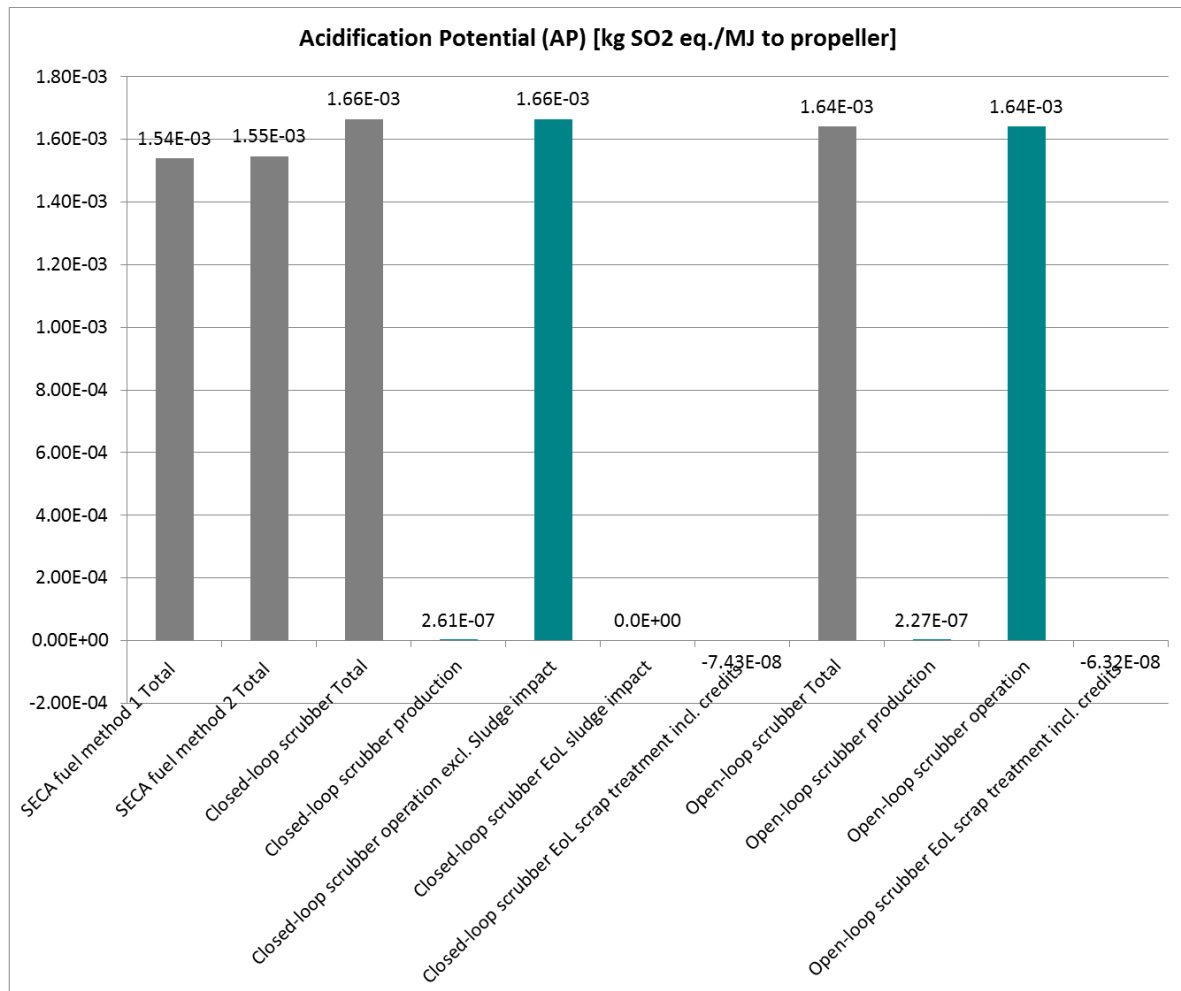


Figure C Comparison of Acidification Potential (AP) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

Also the eutrophication potential (EP) shows a similar pattern as GWP and AP with a small favour for the SECA fuel, see figure D. The main contributor to EP is the emission of NO_x. It is still the operation of the scrubber including the main engine that causes the main EP. An explanation to the higher EP values for the scrubber cases can be the higher NO_x emission levels for the heavy fuel oil used in the scrubber cases in combination with the different energy use.

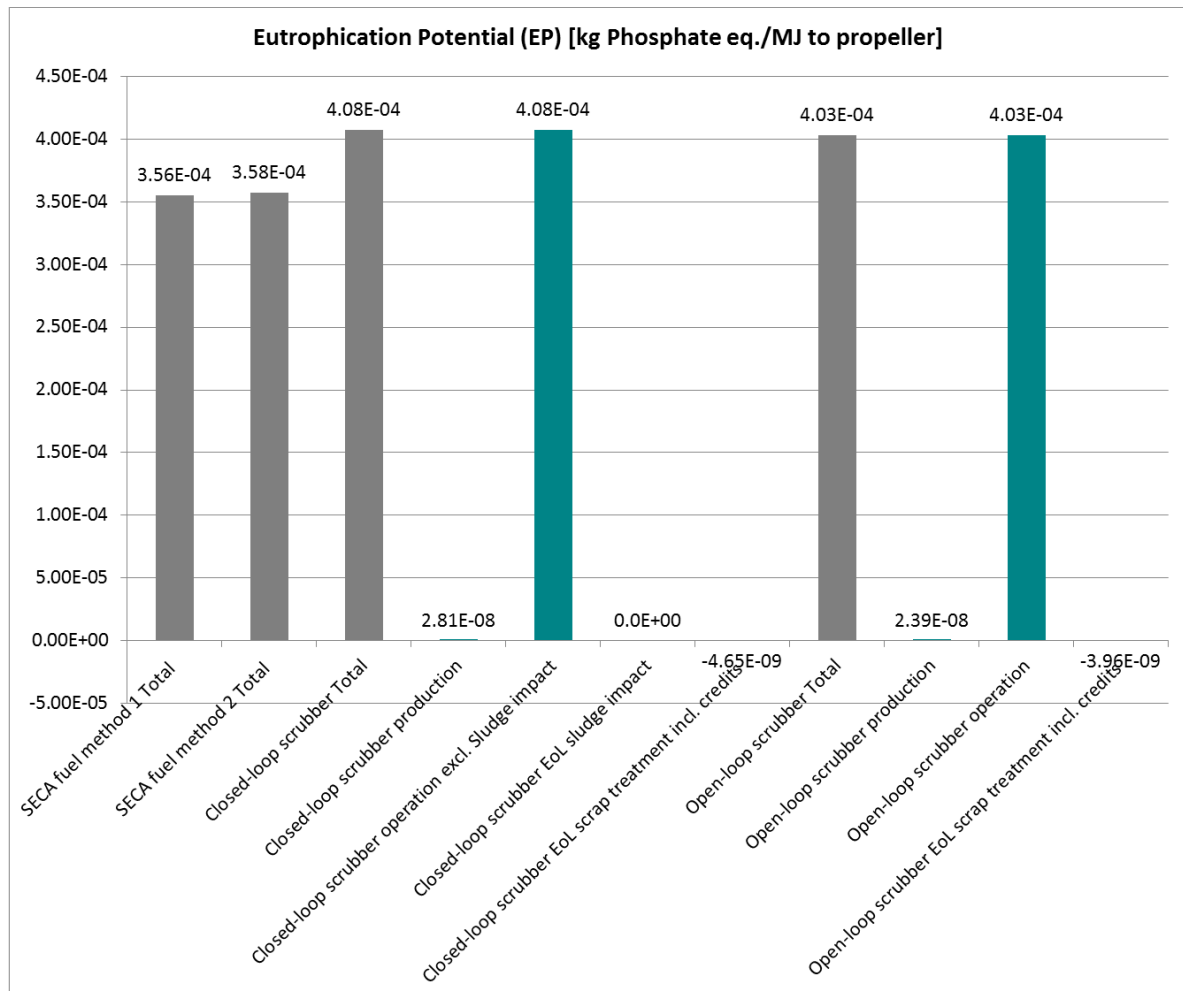


Figure D Comparison of Eutrophication Potential (EP) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

Sammanfattning

Miljöprestanda för fartygsmotorer beror dels på motorkonstruktionen (exempelvis förbränningsbetingelserna) och dels på bränslets sammansättning. Således kan miljöprestanda förändras genom valet av bränsle och valet av olika reningstekniker. Här finns flera olika alternativa möjligheter. Beträffande råoljebaserade bränslen kan man särskilja tunga eldningsolja med hög svavelhalt från lättare eldningsolja med lägre svavelhalt. Idag används många gånger de tunga men billigare eldningsoljorna inom sjöfarten då kostnadsaspekten är en viktig faktor för transporterna. Lagstiftningen och konkurrenssituationen spelar här en avgörande roll. Miljölagstiftningen förändras också med tiden och skärpta krav ställs på sjöfarten. Internationellt likformiga krav är också en viktig aspekt då sjöfarten verkar på en internationell marknad. Speciella krav ställs också på fartyg som används i speciellt känsliga områden. Ett exempel på detta är SECA/ECA-kraven³. Områden som omfattas av sådana krav är t.ex. Östersjön, Nordsjön, nordamerikanska ECA inkluderande merparten av USAs och Kanadas kuster samt "the US Caribbean ECA".

Av denna anledning är det av speciellt intresse för sjöfartsnäringen att utreda olika tänkbara alternativ för att minska emissionerna och bränsleförbrukningen från fartygen. I detta projekt, som är delfinansierat av Europeiska Unionen, analyseras två konventionella metoder att minska emissionerna där konventionella fartygsmotorer kan användas utan större modifieringar. Det ena alternativet som undersöks i denna studie är att fortsätta att använda tunga eldningsolja med en hög svavelhalt och att samtidigt rena rökgaserna med konventionell skrubberteknik. Denna metod jämförs sedan med att i stället använda lätta avsvavlade eldningsolja t.ex. marine gas oil, MGO. Vid den senare tekniken raffinerar och avsvavlar bränslet på ett raffinaderi i stället för att rena rökgaserna från fartygen. För att jämförelsen skall bli så heltäckande som möjligt används ett systemperspektiv vid analyserna och datormodeller tas fram med livscykelanalysmetodik (LCA).

Det föreliggande projektet är en del av ett större EU-projekt där skrubbertekniken testas i praktiken genom en installation på en av Stena Lines RoRo färjor. I detta större projekt ingår också en teknisk utvärdering av skrubberreningstekniken.

I denna studie jämförs och analyseras tre olika SO₂/SO₃ reduktionssystem. Systemen är:

- Slutet skrubbersystem (closed-loop scrubber) där rökgasrening sker med havsvatten och ett reningssystem för skrubbervattnet, vilket ger ett slam som antas användas i en cementugn och några av ämnena i slammet hamnar således i någon betongprodukt. Tung eldningsolja används för fartygets huvudmotor.
- Öppet skrubbersystem (open-loop scrubber) där rökgasrening sker med havsvatten och utan rening av skrubbervattnet. Tung eldningsolja används för fartygets huvudmotor.
- Användning av SECA-bränsle (SECA fuel), vilket är ett bränsle som innehåller mindre än 0,1 vikt-% svavel. Svavelreningen sker i detta fall i råoljeraffinaderiet.

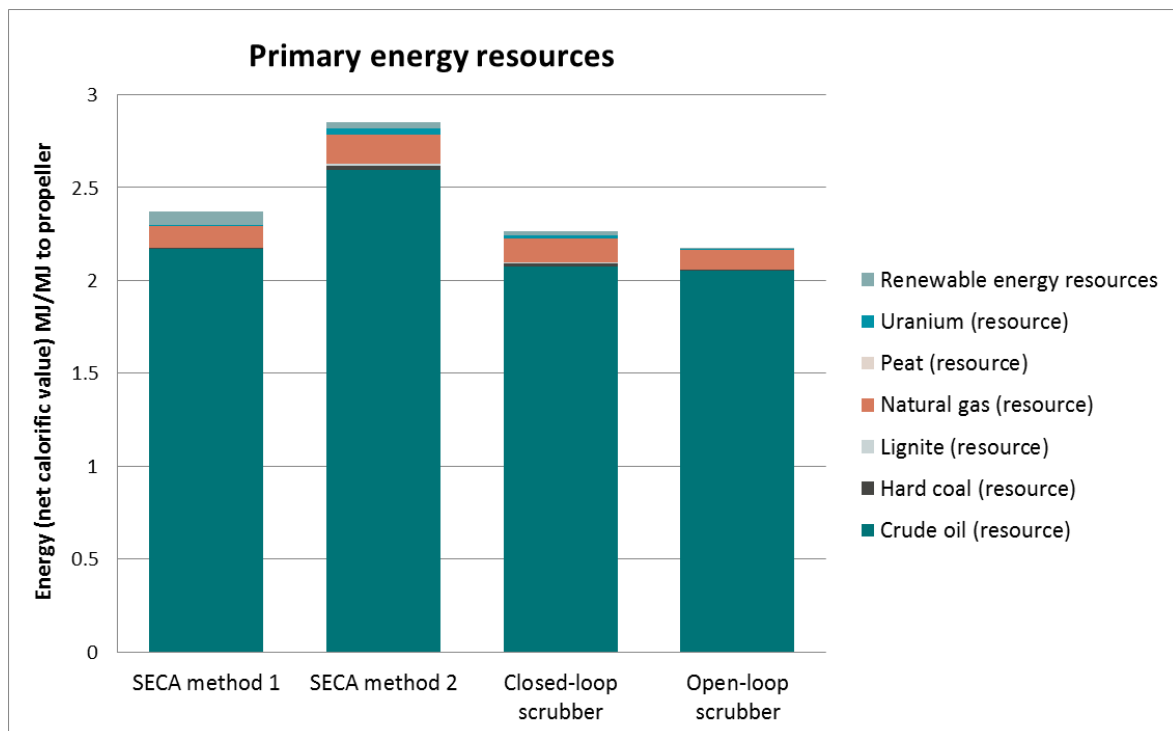
I den här studien jämförs och utvärderas SECA-bränsle metod 1, SECA-bränsle metod 2, ett slutet skrubbersystem och ett öppet skrubbersystem i ett systemperspektiv. För SECA-bränslet uppnås

³ Sulfur Emission Control Areas (SECAs) or Emission Control Areas (ECAs) are sea areas in which stricter controls were established to minimize airborne emissions (SO_x, NO_x, ODS, VOC) from ships as defined by Annex VI of the 1997 MARPOL Protocol, which came into effect in May 2005.

svavelreduktionen genom avsvavling av bränslet i raffinaderiet vid bränsleproduktionen. Olika produktionsprocesser finns med olika bränslekvaliteter som uppfyller svavelspecifikationen. Detta exemplifieras av metod 1 och 2. Metod 1 exemplifierar en vanlig raffinaderiproduktion av marin gasolja (MGO) med en svavelhalt av 0,1 %, medan metod 2 visar en produktion av SECA-bränsle baserad på tung återstodsolja behandlad i en vätekracker för återstodsolja med ytterligare energianvändning. Data från SECA-bränslet innefattar aktiviteter från råoljeutvinning till SECA-bränsleprodukten. Ingen SO_2/SO_3 rening behövs då ombord. På grund av det lättare bränslet kan vissa andra utsläpp också minskas till viss del, t.ex. partiklar, tungmetaller, HC, PAH, NO_x etc. De exakta utsläppsnivåerna beror på bränslet och förbränningsförhållandena i motorn. Det finns i dessa fall ingen ytterligare skrubberrening.

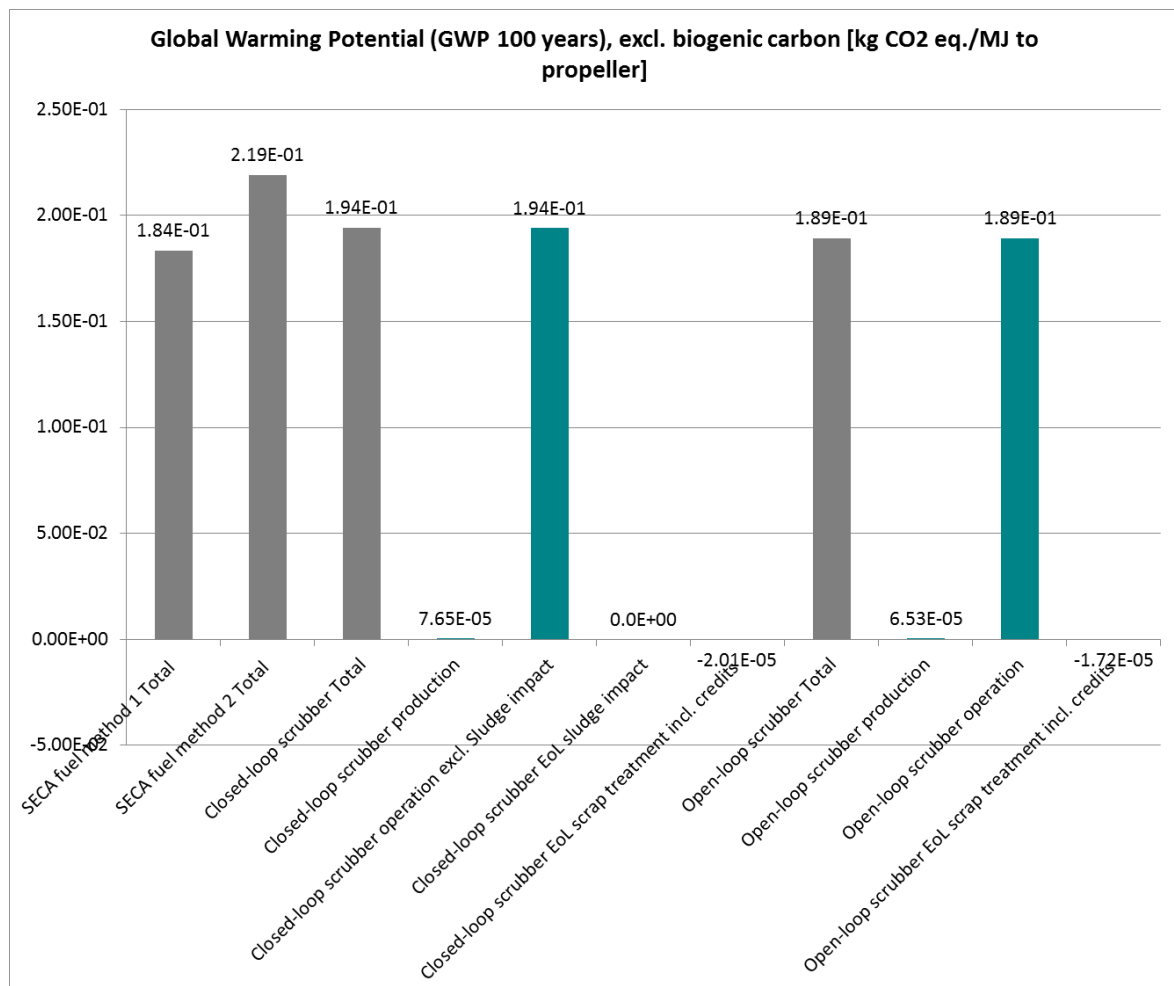
För skrubberalternativen används tung eldningsolja för fartygets huvudmotor. Detta bränsle kan då ha ett högt svavelinnehåll, i storleksordningen 2,5 viktprocent, vilket i huvudsak omvandlas till SO_2 vid förbränningen i fartygsmotorn och avlägsnas i stor utsträckning från avgaserna genom skrubbing. I det slutna skrubbersystemet neutraliseras avlägsnad SO_2 med NaOH i skrubbevattnet medan i det öppna skrubbersystemet så släpps avlägsnad SO_2 direkt ut i havet och neutraliseras genom havsvattnets alkalinitet. Neutralisering med NaOH är en fördel ur miljösynpunkt (försurning) men kräver extra resurser för produktion av NaOH. Förbränningen av den tunga eldningsoljan bildar också andra föroreningar som nämns ovan. Dessa avlägsnas i viss utsträckning av skrubberprocessen. I det öppna skrubbersystemet släpps skrubbevattnet som innehåller föroreningarna direkt ut i havet, vilket innebär att det i verkligheten inte finns någon rening, bara en ökad transport från luftföroreningar till vattenföroreningar som förhindrar att föroreningarna når landområden. Miljöpåverkan på havet kommer fortfarande att vara kvar. I det slutna skrubbersystemet renas skrubbevattnet i en vattenreningsanläggning före utsläpp. Föroreningarna är på detta sätt koncentrerade till ett slam som kommer att behandlas ytterligare i land. Utsläppen till miljön beror sålunda mycket på hanteringen och vidarebehandlingen av slammet. Om slammet inte behandlas kommer utsläppen i princip att vara desamma som för det öppna skrubbersystemet. I det antagna fallet, för denna studie, förbränns slammet i en cementugn och resterande del kommer att vara en del av cementprodukten. Sålunda kommer tungmetallerna i den tunga eldningsoljan att hamna i betongen. Detta kommer att avsevärt sänka utsläppshastigheten för metallerna, men i ett mycket långt tidsperspektiv kommer metallerna att läcka ut förr eller senare.

Figur A visar den primära energianvändningen för de olika fallen. Den huvudsakliga resursen är naturligtvis användningen av råolja. SECA-bränsle med metoden 2 visar på en relativt hög energianvändning på grund av den höga energianvändningen i vätekrackern för återstodsoljan. För det slutna skrubbersystemet finns det ett extra energibehov för driften av skrubbersystemet och rening av skrubbevattnet samt för att producera de kemikalier som behövs för reningen. För det öppna skrubbersystemet finns det ett extra energibehov för skrubbersystemet och det högre skrubbevattenflödet i jämförelse med det slutna skrubbersystemet. Energianvändningen för produktionen av den tunga eldningsoljan bör dock vara lägre än för SECA bränslet. Data för SECA bränslet inkluderar bränsleanvändningen i motorn och energin för produktionen av SECA bränslet.



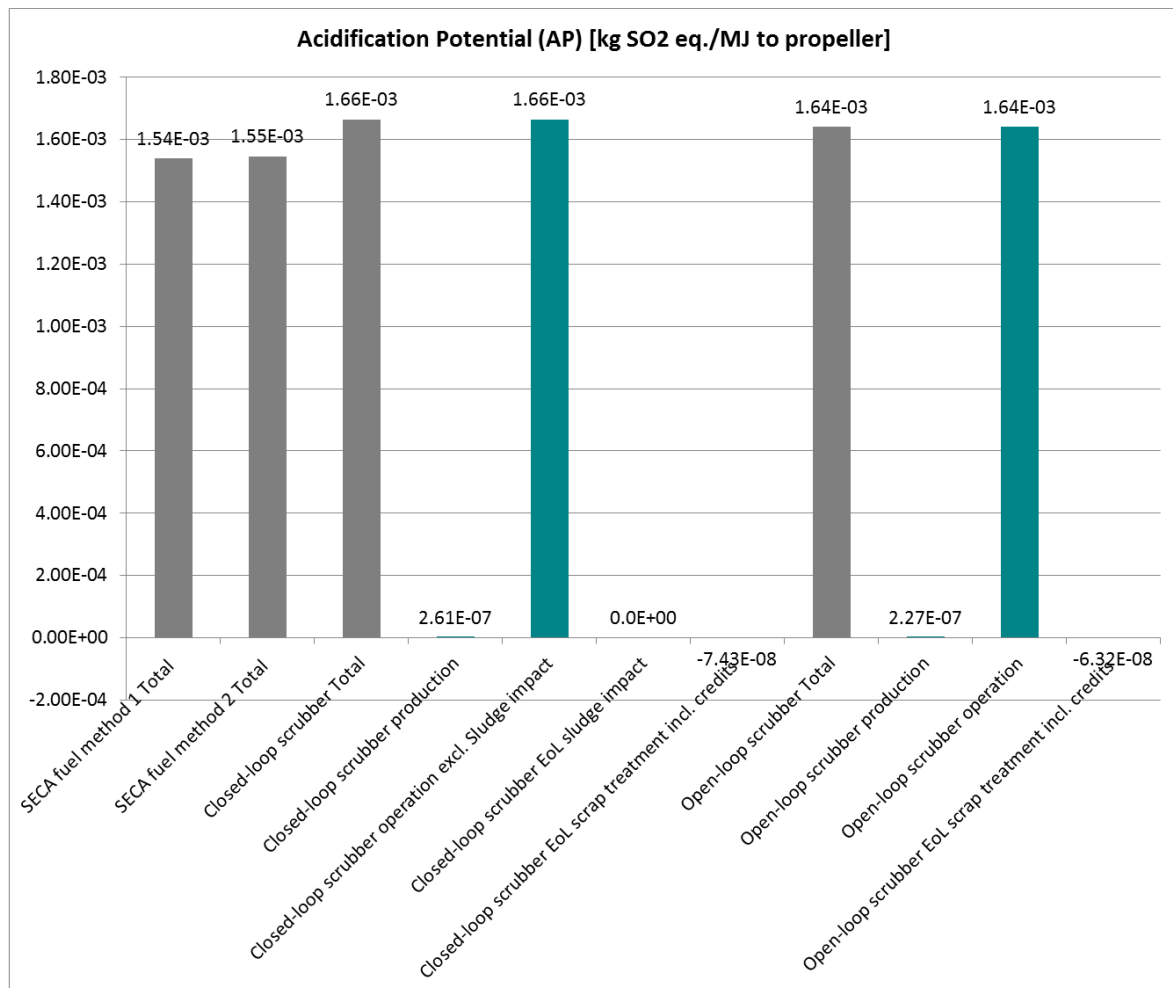
Figur A Jämförelse av användningen av primära energikällor (i MJ) mellan de tre olika fallen i studien (SECA-bränsle, Closed-loop scrubber och Open-loop scrubber). För SECA-bränslet visas två olika metoder. För skrubberfallen visas den totala effekten samt de olika bidragande delarna (produktion, drift och avfallshantering/återvinning).

Klimatgasresultaten (GWP) omfattar främst koldioxid från förbränning av fossila bränslen, men även utsläpp av CH₄ och N₂O. I detta fall är förbränningen av eldningsolja en viktig aspekt. I SECA-bränslefallet inkluderar detta förbränningen i fartygets huvudmotor och utsläpp från bränsleproduktionen från råoljeutvinningen till raffinering till SECA-bränslekvaliteten. För skrubberfallet inkluderar detta förbränningen i fartygets huvudmotor, utsläppen från tungoljeproduktionen, utvinning av råolja, raffinering till tung eldningsoljekvalitet, utsläpp från produktionen av de kemikalier som används i det slutna skrubbersystemet och utsläpp från den extra energianvändning som behövs för hela skrubberprocessen (inklusive skrubbevattenrening för den slutna processen och för det extra skrubbevattenflödet i den öppna processen). GWP-resultaten från de olika fallen visas i figur B. Som framgår av figuren är GWP-resultaten relativt lika mellan de olika fallen, även om metod 2 av SECA-bränslealternativen är något högre. Detta kan förklaras av ytterligare användning av raffinaderigaser i vätekrackern. GWP härrör också från driften av skrubbersystemen (inklusive förbränning i huvudmotorn) men mindre från tillverkningen av skrubbersystemen eller från avfall-/återvinningsdelarna.



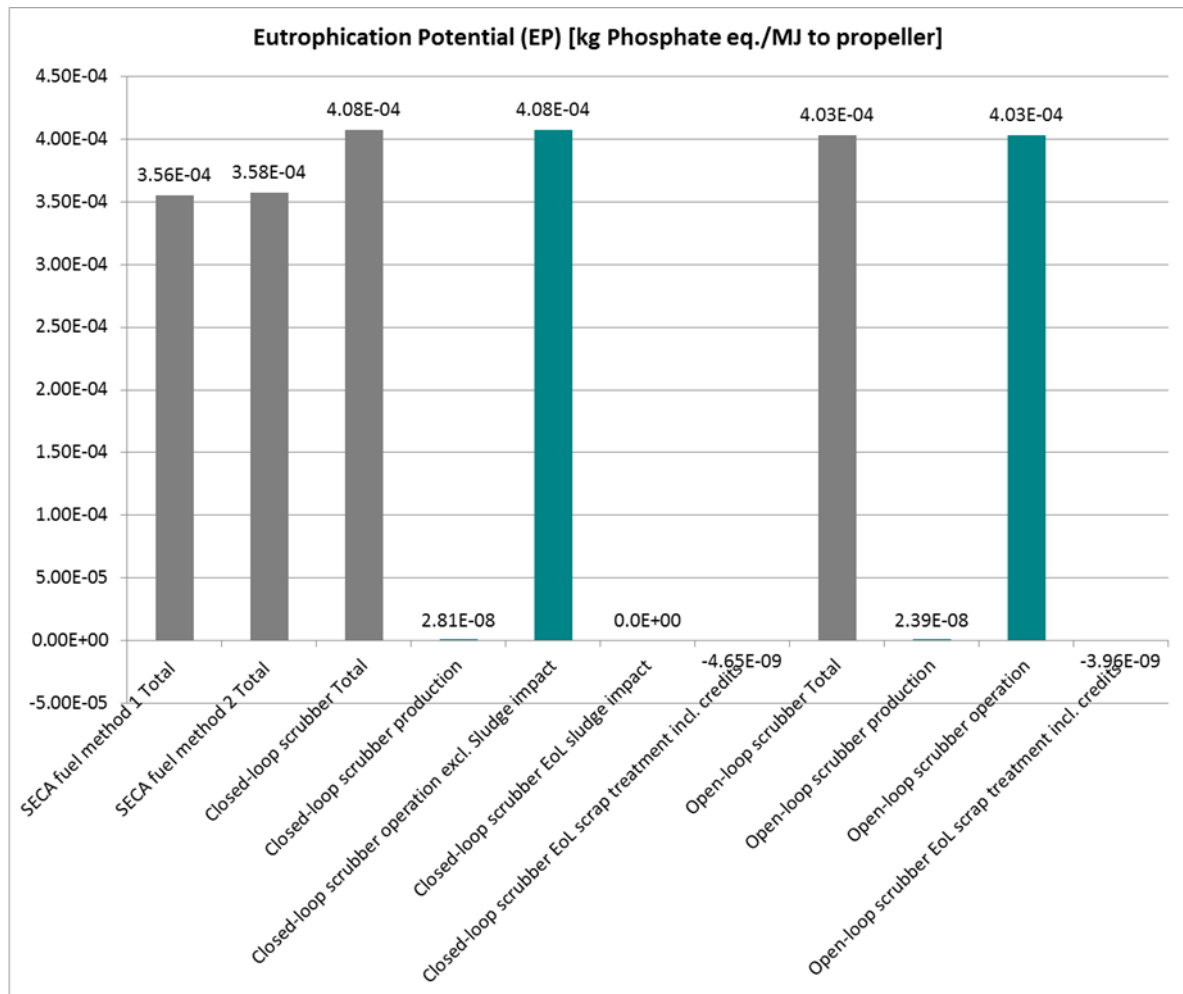
Figur B Jämförelse av Global Warming Potential (GWP 100) mellan de tre olika fallen i studien (SECA-bränsle, Closed-loop scrubber och Open-loop scrubber). För SECA-bränslet visas två olika metoder. För skrubberfallen visas den totala effekten samt de olika bidragande delarna (produktion, drift och avfallshantering/återvinning). Negativa värden kommer från undvikna processer i avfallshantering och återvinningen. Gråa staplar visar totaler.

Försurningspotentialen visar ett liknande mönster som GWP och energi, vilket framgår av figur C. De främsta bidragen till försurning är utsläppen av SO₂ och NO_x. Både GWP och försurningspotentialen är framförallt relaterade till förbränningen av eldningsolja med en definierad utsläppsnivå för SO₂/SO₃ och med samma typ av motor, d.v.s. relativt lika NO_x-utsläpp, dock med en skillnad mellan tung eldningsolja och SECA-bränsle. NO_x-utsläppen minskar inte eller ändras av skrubberprocessen. Skillnaderna i försurningspotentialen kan därmed huvudsakligen förklaras av skillnaderna i energianvändning.



Figur C Jämförelse av försurningspotential mellan de tre olika fallen i studien (SECA-bränsle, Closed-loop scrubber och Open-loop scrubber). För SECA-bränslet visas två olika metoder. För skrubberfallen visas den totala effekten samt de olika bidragande delarna (produktion, drift och avfallshantering/återvinning). Negativa värden kommer från undvikna processer i avfallshantering och återvinningen. Gråa staplar visar totaler.

Även övergödningspotentialen visar ett liknande mönster som GWP och förbrukningspotentialen med en liten fördel för SECA-bränslet, se figur D. Huvudbidraget till övergödningspotentialen är utsläppet av NO_x. Det är fortfarande driften av skrubbersystemen inklusive huvudmotorn som huvudsakligen orsakar övergödningspotentialen. En förklaring till de högre övergödningsvärdena för skrubberfallen kan vara högre NO_x-utsläpp för den tunga eldningsoljan som används i skrubberfallen i kombination med energianvändningen.



Figur D Jämförelse av övergödningspotential mellan de tre olika fallen i studien (SECA-bränsle, Closed-loop scrubber och Open-loop scrubber). För SECA-bränslet visas två olika metoder. För skrubberfallen visas den totala effekten samt de olika bidragande delarna (produktion, drift och avfallshantering/återvinning). Negativa värden kommer från undvikna processer i avfallshantering och återvinningen. Gråa staplar visar totaler.

1 Introduction

Transports represent today a very important part of a modern society both in terms of passenger transports and freight transports. People's mobility and transport of goods play a decisive role in the development of the society both nationally and internationally. Trade and industrial activities are important components in our society and transports play a crucial role here. Shipping represents an important part of the world's transport and lots of goods are transported by ships over long distances. Maritime transports are often both energy and cost effective. Some transports also takes place in coastal areas, in lakes and in particularly sensitive areas. The importance of the environmental issues has also increased as the environmental problems have increased. The population in the world is increasing and the standard of living is also increasing. This means an increased industrial activity globally and thus also increased transports. This also means increased global pressure on the environment, and increased material and energy resource use. The environmental issues and the resource issues are thus often closely linked. It is therefore important to analyze this entire complex situation at the same time to get an overall picture of the entire environmental situation.

The shipping industry is currently working actively to develop and analyze future sustainable solutions for tomorrow's ships. Today there is an open approach where several alternative solutions are investigated. Various research projects have also been launched to develop different alternative solutions. Here, for example, there are different fuel alternatives⁴, different gas cleaning alternatives⁵ and different engine alternatives, but also the design and operation of the vessels can be changed, which can affect the efficiency of transportation. One can for example reduce the speed of the ships, which reduces energy use, but this measure also has an impact on transport times, thus affecting the economic situation of transport. Thus, there are also links to the business models used in transport. The purpose of the development activities is thus to reduce emissions, to reduce energy and material use, and to develop renewable fuels that work in ship operation. Different alternatives also involve greater or lesser technological changes in relation to existing fleets, and this also affects the time and opportunities for change.

For the shipping industry, the environmental legislation and the competitive situation play a crucial role. Environmental legislation also changes over time, and tightening requirements are imposed on shipping. Internationally uniform requirements are also an important aspect when shipping operates in an international market. Special requirements are also imposed on vessels used in particularly sensitive areas. An example of this is the SECA/ECA requirements**Error! Bookmark not defined..** Areas covered by such requirements are, for example, the Baltic Sea, the North Sea, the North American ECA, including most of the US and Canadian coast and the US Caribbean ECA. Due to the increased levels of CO₂ in the atmosphere, a general acidification of the oceans is in progress. Negative effects of this have been observed especially for coral reefs and other limestone-requiring organisms. This has also accelerated international legislation on acidifying emissions in other marine areas. International Maritime Organization (IMO) is an agency of the United Nations,

⁴ Examples of alternative fuels for shipping: The ones most commonly considered today are Liquefied Natural Gas (LNG), Electricity, Biodiesel, and Methanol. Other fuels that could play a role in the future are Liquefied Petroleum Gas (LPG), Ethanol, Dimethyl Ether (DME), Biogas, Synthetic Fuels, Hydrogen (particularly for use in fuel cells), and Nuclear fuel. Reference: EU EMSA European Maritime Safety Agency.

⁵ Filters, scrubbers, catalytic cleaning, exhaust gas recirculation etc.

which has been formed to promote maritime safety including environmental issues. IMO ship pollution rules are contained in the “International Convention on the Prevention of Pollution from Ships”, known as MARPOL 73/78, “1997 Protocol”, annex VI titled “Regulations for the Prevention of Air Pollution from Ships”. Annex VI limits emissions of NO_x, SO₂ and ozone depleting substances. Annex VI also includes mechanisms that will reduce the emissions of greenhouse gases by regulating the efficiency of the ships. In the IMO/MARPOL regulations, the emission of SO_x is regulated by regulating the content of sulfur in the fuel. In the regulation, a distinction is made between regulation for SECA/ECA regions and global regulations. Today (year 2017), the SECA/ECA limit is 0.1 wt.-% sulfur in the fuel. The corresponding global limit is today 3.5 wt.-% sulfur in the fuel. The global limit will be reduced to 0.5 wt.-% sulfur in the fuel year 2020. The development of the limits can be found in table below. The highest sulfur limit (4.5 wt.-%) corresponds to the maximum sulfur content for heavy fuel oils or residue oils.

Table 1.1 The development of IMO/MARPOL annex VI sulfur limits for fuels.

Year	Sulfur limit in fuel (wt.-%)	
	SECA/ECA	Global
2000	1.5 %	4.5 %
2010	1.0 %	
2012	0.1 %	3.5 %
2015		
2020		0.5 %

Most of all ships are powered by large-scale diesel engines for two-stroke or four-stroke operations. The fuel for the engines is based on crude oil and is available in different grades and pricing on the market. The availability of different grades may also vary depending on supply, demand and the current production situation at the fuel refineries. The environmental performance of ship engines due partly to the engine design (such as combustion conditions) and partly to the fuel characteristics. The environmental performance can therefore be changed through the choice of fuel and the choice of gas cleaning technologies. Thus, there are several different options available. As regards petroleum-based fuels, one can distinguish between heavy fuel oils with high sulfur content and light fuel oils with lower sulfur content. Today, the heavy but cheaper fuel oils are mainly used in shipping, as the cost aspect is an important factor for transports. The legislation and the competitive situation play a crucial role for this situation. Environmental legislation also changes over time, and tightening requirements are imposed on shipping. Internationally uniform requirements are also an important aspect when shipping operates in an international market.

For these reasons, it is of special interest to the shipping industry to investigate various possible alternatives to reduce emissions and fuel consumption from the vessels. In this project, two conventional methods are investigated to reduce emissions where conventional ship engines can be used without major modifications and where conventional petroleum-based fuels can be used. The main option investigated in this study is to continue to use heavy fuel oils with high sulfur content and to simultaneously clean the flue gases with conventional scrubber technology. This method is then compared by using light desulfurized fuel oils e.g. marine gas oil. In the latter technology, fuel oil is refined and purified at the refinery instead of cleaning the flue gases from the vessels. Thus, in the study, a comparison is made between a refinery process to improve and desulfurize the fuel and a scrubber gas cleaning process. In order for the comparison to be as comprehensive as possible, a system perspective is used in the analyses and computer models have been developed using LCA.

2 Overview description of system analysis and LCA

The use of different products, materials, or processes is often very complex and may involve many different activities in the society such as extraction of raw materials, operation of production plants, power generation and transportation etc. Due to this complexity, it can be difficult to calculate emissions and energy use in a relevant way for an entire process or production system. The complexity may increase when various process or production systems are compared, or when different process changes have to be evaluated and assessed.

A system is a unit that consists of different parts interacting with each other. By applying a system perspective, i.e. taking the entire system into account, one can get a better and more accurate picture of a production system and one can for example avoid sub-optimization. For example, when evaluating a process in terms of energy and environmental aspects, it is important not to evaluate only the production process but also ensure that the environmental load does not increase due to e.g. increased upstream activities prior to the process or change in raw materials. The same applies when analyzing and evaluating gas or water treatment equipment. The overall efficiency of the treatment process must be good and the treatment process itself may not cause more environmental problems than those reduced by the treatment process, viewed from a systems perspective. Analyzing production systems rather than individual production processes, demands more from a methodology and implementation perspective. A logical and structured methodology and a well thought-out analysis are required. Computer-based calculations and models are also required.

For this type of system analysis, the most common method is Life Cycle Assessment (LCA). In this study, Life Cycle Assessment (LCA) methodology has been chosen as the base for the analysis of the different means for fulfilling the SECA sulfur requirements.

A system analysis is a tool that allows a product to be analyzed through its entire life cycle, from raw material extraction and production, via use of the product/process, to waste handling and recycling. The most common tool for system analysis is the Life Cycle Assessment (LCA) methodology. The LCA methodology is described in, for example, the standards EN ISO 14040:2006 and 14044:2006⁶. In a life cycle assessment, a mathematical model of the system is designed. This model is of course a representation of the real system, including various approximations and assumptions. The results from the model are, of course, also dependent on the input data and assumptions being applied. The LCA methodology allows us to study complex systems, where interactions between different parts of the system exist, to provide as complete a picture as possible of the environmental impacts of, for example, a product or process. A more detailed description of an LCA can be found in Appendix A.

An LCA is usually made in three steps with an additional interpretation step, see ISO 14044. In the *goal and scope* definition, the model and process layout are defined. The functional unit is also

⁶ ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework.
ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines.

specified. The functional unit is the measure of performance that the system delivers. In this case, the functional unit has been defined as a specific amount of fuel energy to the main engine for propulsion of the ship during operation. In the *Life Cycle Inventory* analysis (LCI), materials, emissions and energy flows are quantified. Each sub-process has its own performance unit and several in- and out-flows. The processes are linked together to form the mathematical system being analyzed. The final result of the model is the sum of all in- and out-flows calculated per functional unit for the entire system. The *life cycle impact assessment* (LCIA) is defined as the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product/process system throughout the life cycle of the product/process. The LCIA is performed in consecutive steps including classification, characterization, normalization, and weighting. The LCIA phase also provides information for the life cycle interpretation phase, where the final environmental interpretation is made. In this study, only classification and characterization have been included in the LCIA part. In this study, the following impact assessment categories and indicators are used:

1. Abiotic Depletion Potential (ADP elements), kg Sb (antimony) eq.
2. Abiotic Depletion Potential (ADP fossil), MJ
3. Primary energy resource use - renewable and non-renewable, MJ (using net calorific values)
4. Global Warming Potential (GWP 100), kg CO₂ eq.
5. Acidification Potential (AP), kg SO₂ eq.
6. Eutrophication Potential (EP), kg phosphate eq.
7. Photochemical Ozone Creation Potential (POCP), kg ethene eq.
8. Ozone layer Depletion Potential (ODP), kg R11 eq.

The above mentioned impact assessment categories and indicators are used to calculate the environmental performance of the different gas and water cleaning systems and to evaluate the respective cleaning method. In this study, both conventional environmental parameters and toxicological parameters from specific substances need to be evaluated. The conventional environmental parameters emanate mainly from operation of the main engine while the toxicological parameters are needed to evaluate the environmental impact of the different gas and water treatment systems. There is thus an environmental “cost” also for a gas or water treatment process. This environmental treatment cost has to be weighed against a reduced emission of contaminating substances from the exhaust gases. The question is how these overall effects look like in a system perspective where all effects are handled simultaneously.

The traditional impact assessment categories and indicators representing 2-8 in the list above can be calculated with ordinary quantitative methods, which make the calculations relatively reliable and free from assumptions. The impact category “1. Abiotic depletion potential (ADP elements)” is used to summarize the use of non-biotic resources (e.g. elements and minerals). This category has been included as a method to select and evaluate the most significant resource uses. The category is expressed in kg antimony (Sb) equivalents, which mean that it is based on a developed method including various data and assumptions, see **Error! Bookmark not defined.**. This also indicates an increased uncertainty for this category.

In the overall evaluation of the treatment processes, it is important to conclude that it is very difficult to compare the different impact categories. For example, is it better to increase the global warming potential and reduce the toxicity levels? In this study, we will not go deeper into this issue. The study will only categorize and quantify the different impact categories and indicators. Further research has to show the overall impact of different cleaning solutions.

3 Goal and scope

3.1 Aim and objectives of the study

The purpose of the present project is to evaluate and analyze various technologies to reduce SO_2/SO_3 emissions from ships with a particular focus on the SECA (Sulfur Emission Control Areas) regulations. The purpose of the analyzes has been to provide further information and guidance in the selection of technologies to reduce sulfur emissions and thus also the various environmental impacts that these contribute to, for example, acidification of both land and water areas. The choice for shipping companies to cope with the new harsher emission requirements often occurs between switching to lighter and desulfurized fuels (often called SECA fuels) or continuing to use heavier fuel oils with high sulfur content, but instead cleaning the SO_2/SO_3 exhaust gases by means of a flue gas scrubber of any kind. The problem for the shipping companies is both technical/environmental and economic. Both of these aspects affect the choice of technology. The present report mainly addresses the environmental and energy aspects of the choice of flue gas cleaning technology.

Switching to a lighter low-sulfur fuel is relatively easy for shipping companies, but can lead to increased costs. The environmental aspects of this technology can instead be found in the refineries where the low-sulfur fuel is produced. In an evaluation, the effects at the ship and at the refinery must be weighed together into an overall assessment. Similarly, the scrubber technology must be weighed together and also include, for example, the manufacture of scrubber equipment on the ship, the operation of scrubber including electricity consumption and the use of various scrubber and water purification chemicals, disposal of residues from the purification and final disposal/recycling of the scrubber equipment when the scrubber plant and the ship are to be scrapped. To make such a complete analysis, the analysis must be based on system thinking. In this case, Life Cycle Analysis methodology (LCA) is used for the analyzes.

3.2 Functional unit

In a life cycle assessment (LCA) one can compare different products or processes. In such a comparison, it is important that the products or processes fulfil the same requirements or deliver the same function. For that reason, a functional unit is defined for all LCA models or studies. The functional unit is the measure of performance that the LCA model system delivers. The functional unit is thus the reference to which all other data in the product systems are related to. The functional unit should include the desired function of the system and should be designed to include also the efficiency of the system and to be able to compare also completely different techniques. Ship engine processes are highly related to transports and its different functions. For a transport, the functional unit is usually set to the delivered transport work in for example passenger-km or tonne-km. However, such a broad functional unit will, for this study, introduce several unnecessary uncertainties. In this case, a functional unit closer to the engine operation but related to the transport is to be preferred. The functional unit chosen for this study is the propulsion energy⁷ used for the ship in the main engine. The functional unit is thus defined as the energy direct to the propeller (after possibly electricity production for the scrubber taken out from the propeller shaft). The functional unit is given in MJ. However, it is important to notice that the study evaluate both the situation with and without a scrubber but also the impact of two different fuels; heavy fuel oil (HFO) and a marine gas oil (MGO) that apply to the SECA requirements. From a scrubber perspective it is relevant to compare with and without scrubber for an equal amount of fuel. However, this requires that the engine efficiency is equal for heavy fuel oil and the SECA gas oil. Otherwise, it is better to use the shaft energy to the propeller (after electricity generation from the main shaft) produced by the engine as a functional unit. In this case, the former alternative has thus been chosen.

⁷ The functional unit only includes the energy to the propeller and thus not e.g. energy for electricity generation from the main engine propeller shaft.

3.3 System boundary

The present study covers three different LCA models, one for each method of reducing emissions of SO_2 and SO_3 i.e. closed-loop scrubber system, open-loop scrubber system, and use of low-sulfur fuels (SECA fuels). The models include the entire service life of the cleaning systems. Parts covered by the models are:

- Production of scrubber water chemicals (NaOH).
- Production of waste water purification chemicals (coagulants and flocculants).
- Transport of chemicals and other materials.
- Production of the scrubber system.
- Operation of the scrubber and water treatment system during its service life (use of electricity and on-board production of electricity, use of chemicals).
- Emissions to air and water.
- Operation of the ship's main engine with different fuels.
- Energy and material resource use.
- Sludge amounts and handling from the water treatment plant.
- End-of-life handling of the scrubber system.
- Production of different fuels for the main engine (heavy fuel oil and SECA oil) including production equipment and operation at the refinery.

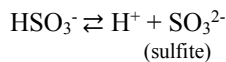
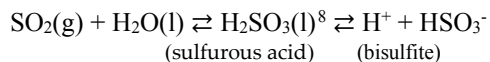
A more detailed description can be found in Chapter 5.

4 Technical description of exhaust gas cleaning with scrubber or other technology

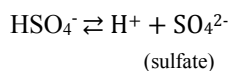
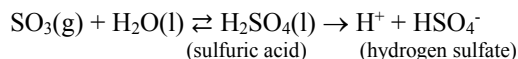
The aim of the overall project “Scrubber: Closing the loop” is to analyze and evaluate exhaust gas scrubber technology for ships from a practical and theoretical point of view. The present study analyses and evaluates this exhaust gas cleaning technique mainly from a theoretic point of view but use real measurement data from the practical experiments and tests in a real ship operation situation. Two scrubber techniques are investigated; closed loop and open loop exhaust gas techniques. In addition, these scrubber techniques are compared to using desulfurized light fuel oil, a product that is further processed at the refinery, instead of using heavy fuel oil as in the scrubber case. The various techniques are described below in this chapter.

Crude oil has normally a sulfur content lower than 3.5 wt.-%. The majority of the sulfur in crude oil is bonded to carbon atoms. A small amount occurs as elemental sulfur in solution and as hydrogen sulfide gas. In combustion of these oil products in e.g. a diesel engine, the sulfur is oxidized to SO_2 (sulfur dioxide). A small amount of the formed sulfur dioxide (about 3-5 %) is then further oxidized to sulfur trioxide (SO_3) in the engine or in the exhaust gas ducts. The total amount of $\text{SO}_2 + \text{SO}_3$ is often referred to as SO_x . In the scrubber cleaning process, a water based cleaning process of the exhausted gas is used to remove SO_2 and SO_3 from the exhaust gases. The solubility of SO_2 in water

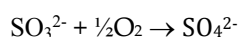
is relatively low. Dissolved SO₂ in water results in the formation of sulfurous acid, which in turn is ionized in the water solution. The chemical reaction can be summarized as follows:



SO₃(g) is more readily absorbed in a water phase and will form sulfuric acid according to the following chemical reaction:



In oxygen rich seawater, sulfite will, to a large extent, be further oxidized to sulfate according to the chemical reaction below.



Due to a low solubility of SO₂ in pure water and a low formation of SO₃, the practical scrubber applications need to be modified to increase the cleaning efficiency. For fresh water scrubber system (closed loop), sodium hydroxide (NaOH) is used to bind/neutralize SO₂ and SO₃. For the open loop scrubber system, the alkalinity of the seawater used for the scrubber is used to increase binding of SO₂ and SO₃. Seawater can also be used in a closed loop system in combination with NaOH. This is the case for the application used in this study. In such a system, both NaOH and the alkalinity of the added seawater contribute to the binding of SO_x.

The different cleaning techniques analyzed in this study are not only affecting the emissions of SO₂ and SO₃. Scrubber technology also has a cleaning effect on several different substances. Scrubber techniques works well for particles and thus also for particulate substances such as metals, heavy hydrocarbons, PAH, soot, ash etc. Also a fuel change from heavy fuel oil to light fuel oil has an effect on many emission substances. All these effects are taken into consideration in the analysis in this study.

4.1 SO_x scrubbers - open loop⁹

A schematic figure of an open loop wet SO_x scrubber system is shown in Figure 4.1. In an open loop scrubber system for SO_x, seawater is usually used as scrubbing liquid. The water is pumped on-board and used in the scrubber to clean the exhaust gases from the main engine(s). The used scrubbing liquid is collected in a storage tank and cleaned in a water treatment plant before it is

⁸ There is little evidence that sulfurous acid (H₂SO₃) really exists in a water solution.

⁹ Karle, Ida-Maja and Turner, David, Seawater Scrubbing – reduction of SO_x emissions from ship exhausts, Göteborg 2007, ISBN 978-91-976534-1-1.

discharged overboard. The residue from the water treatment plant (sludge) contains mainly solid parts from the exhaust gases and is taken ashore for waste treatment or reuse.

Freshwater is taking up SO_x poorly and is therefore difficult to use as scrubbing liquid in this application. Seawater has a pH of approximately 8 and is thus slightly alkaline. It contains several ions that can bind and neutralize SO_x from the exhaust gases. In Table 4.1, typical concentrations of major ions in seawater (ocean type) are presented. The amount of salt in waters is usually referred to as the salinity of the water and is usually measured in percent or g salt/kg solution. The major salt in seawater is sodium chloride (NaCl) and the salinity of seawaters in the oceans is typically 3.5 wt.-%. However, the salinity of the waters for ship traffic can vary significantly. This occurs mainly when freshwater and seawater are mixed in local areas to form brackish water. In brackish water, the salinity can vary between 0.05 wt.-% and 3 wt.-%. In such areas or in fresh water areas, the open loop scrubber system can be difficult to use. Large brackish water areas are the Black Sea and the Baltic Sea and fresh water areas exist in river and lake water traffic as for example in the Great Lakes of the United States.

Table 4.1 Typical concentrations of major ions in seawater¹⁰.

Major ions in seawater	Typical seawater concentrations (mg/litre)
Chloride (Cl^-)	18 980
Sodium (Na^+)	10 556
Sulfate (SO_4^{2-})	2 649
Magnesium (Mg^{2+})	1 262
Calcium (Ca^{2+})	400
Potassium (K^+)	380
Bicarbonate (HCO_3^-)	140
Strontium (Sr^{2+})	13
Bromide (Br^-)	65
Borate (BO_3^{3-})	26
Fluoride (F^-)	1
Silicate (SiO_3^{2-})	1
Iodide (I^-)	<1
Total dissolved solids (TDS)	34 483

As shown in Table 4.1, seawater contains a lot of ions that can contribute to the absorption/neutralization of SO_x in the scrubbing liquid. The concentration of sulfate ions is also relatively high in the oceans so the additional sulfate ions from the flue gas purification of SO_x are relatively small. The ability to neutralize SO_x in seawater is usually determined by the alkalinity of the seawater. The total alkalinity (A_T) of seawater (Salinity = 35 g/kg, pH = 8.1, Temperature = 25 °C) can be calculated by the equation below.

$$A_T = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{B}(\text{OH})_4^-] + [\text{OH}^-] - [\text{H}^+] + [\text{X}]$$

¹⁰ Magazine - Water Condition & purification, January 2005, Lenntech.

The parameters show concentration of the different substances. The equation is a simplification where phosphates and silicate have been neglected and $[\text{HSO}_4^-]$ and $[\text{HF}]$ also can be neglected due to the $\text{pH} = 8.1$. This is indicated in the equation by $[\text{X}]$. The main contributor to the alkalinity of seawater is the carbonate ions. Typical values of temperature, salinity and alkalinity for different natural surface waters are shown in Table 4.2.

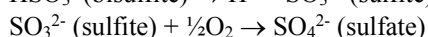
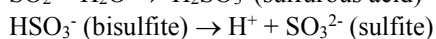
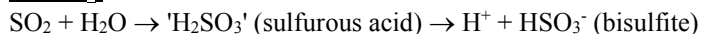
Table 4.2 Typical values of temperature, salinity and alkalinity for different natural surface waters⁹.

	Seawater	Baltic sea	Estuarine waters	Freshwater
Temperatur (°C)	5-15	0-20	1-20	0-20
Salinity (g/kg)	32-37	3-9	0.5-17	0-0.5
A_T (μmol/kg)	2300-2600	700-2000	0.1-5000	0.1-5000

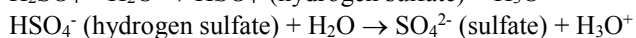
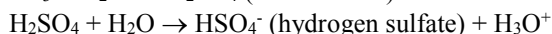
The various ions in seawater originate from weathering and erosion of different rocks around the world's oceans. Thus, there is an addition of ions to the oceans through weathering and erosion (e.g. dissolving of CaCO_3), but this is a relatively slow process. How the oceans are affected in the long term and how this is influenced by other types of environmental impact such as acidification due to formation of carbonic acid from dissolved carbon dioxide is a very complex issue that is important to ensure, before implementing this scrubber technology in large scale. However, $\text{H}_2\text{CO}_3(\text{aq.})$ from $\text{CO}_2(\text{g})$ can contribute to the change in pH but will not contribute to a change in alkalinity.

In this way, SO_2 and SO_3 can react with the seawater in the scrubber and be neutralized by the seawater alkalinity. Sulfur dioxide (SO_2) is dissolved and ionized to bisulfite and sulfite, which is then readily oxidized to sulfate in seawater containing oxygen. Similarly sulfuric acid, formed from SO_3 , and hydrogen sulfate dissociate completely to sulfate.

For SO_2 :



For SO_3 :



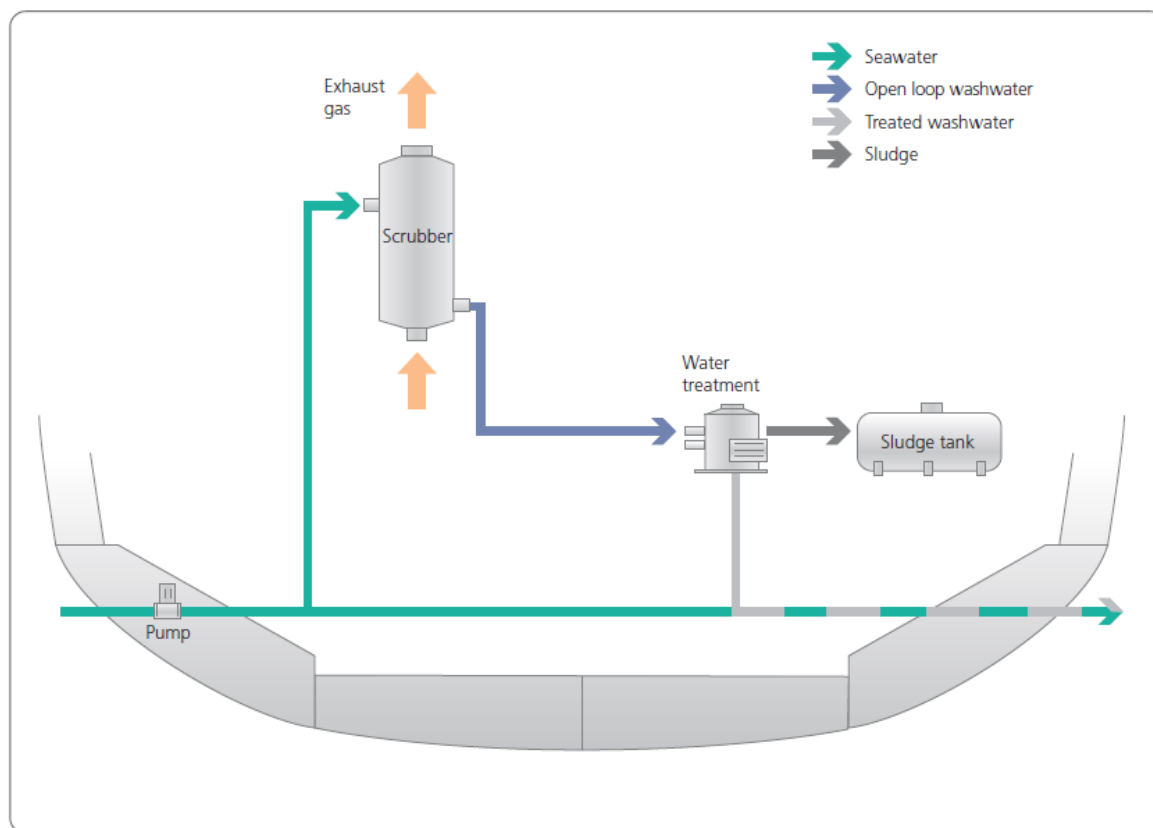
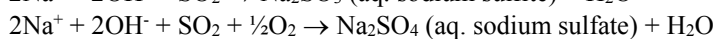
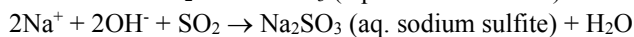


Figure 4.1 A schematic figure of an open loop wet SO_x scrubber system¹¹.

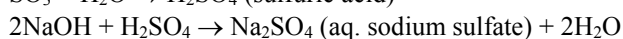
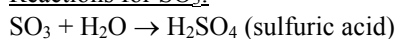
4.2 SO_x scrubbers - closed loop¹¹

In a closed loop SO_x scrubber system, freshwater or seawater dosed with sodium hydroxide (NaOH) is used as scrubbing liquid. Such a system can thus be used for ship traffic in rivers and lakes. The formed sulfur oxides (SO₂+SO₃) are dissolved in the scrubbing liquid and react to form sodium bisulfite, sodium sulfite and sodium sulfate according to the chemical reactions below. The proportion of each is dependent on the pH and available oxygen.

Reactions for SO₂:



Reactions for SO₃:



¹¹ Lloyd's Register Group, Understanding exhaust gas treatment systems - Guidance for shipowners and operators, June 2012.

A schematic figure of the closed loop scrubber system for ships is shown in Figure 4.2. The scrubbing liquid is circulating in a closed loop from the exhaust gas scrubber, via a process tank, a circulation pump and a seawater cooler, back to the scrubber. The sodium hydroxide additive, which usually consists of a 50 %/50 % NaOH/freshwater solution, is dosed and added before the scrubbing liquid is entering the scrubber. The circulating scrubbing liquid is cleaned from e.g. particles and hydrocarbons in an ordinary water treatment plant based on coagulants/flocculants and sedimentation. The used scrubbing liquid is passed to the water treatment plant via a bleed off from the process tank. The sludge from the water treatment plant is collected in a sludge tank and taken ashore for reuse or destruction. In this study, the sludge is assumed to be recycled in a cement kiln and the substances in the sludge will, at least partly, end up in concrete. The cleaned scrubbing liquid is stored in the holding tank and released to the sea when the legal specifications are met. The cleaned sulfur substances are released to the sea as sodium bisulfite (NaHSO_3), sodium sulfite (Na_2SO_3) and sodium sulfate (Na_2SO_4). In the presence of oxygen in the water, the sulfite will oxidize to sulfate leaving mainly sulfate in the seawater. Scrubbing water losses in the closed loop are replaced as fresh water or seawater to the process tank (in this case as seawater). The losses mainly occur as outgoing water from the water treatment plant and as evaporation losses in the exhaust gas scrubber.

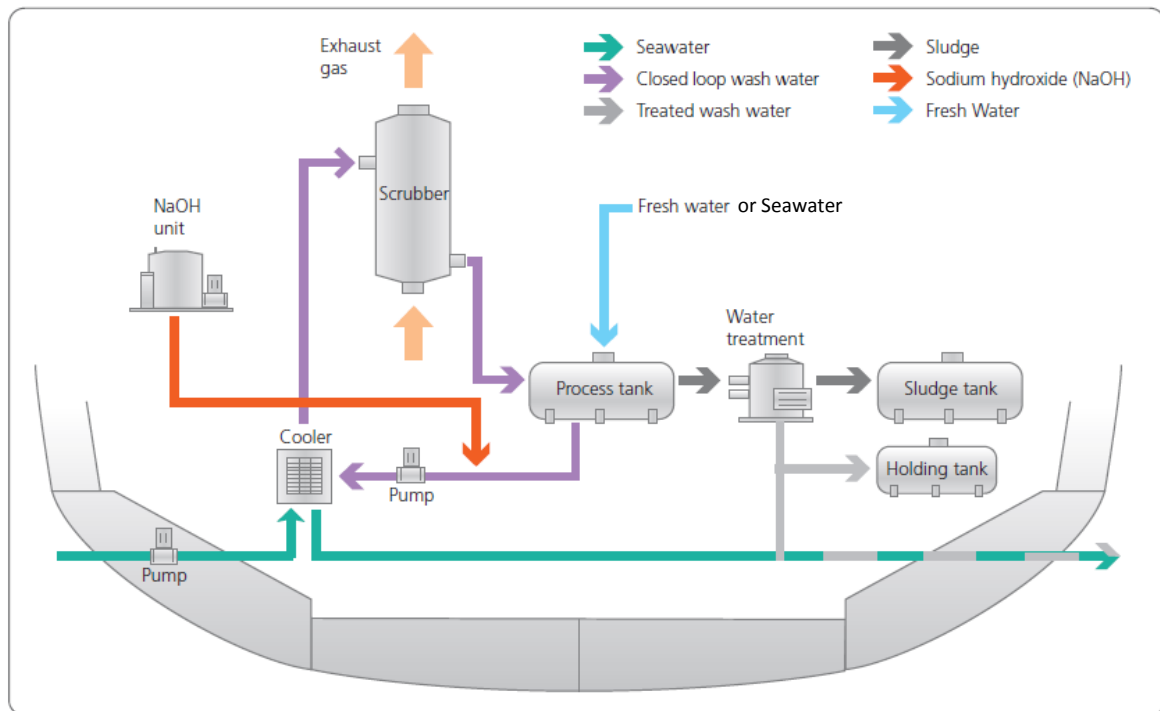


Figure 4.2 A schematic figure of a closed loop wet SO_x scrubber system using NaOH^{11} .

4.3 Light, low sulfur fuel oil

As an alternative to using high sulfur heavy fuel oil with exhaust gas scrubber cleaning, light low sulfur fuel oil can be used for the ship main engine. The latter alternative will include different processes in the refinery, which will also have some environmental and economic impacts. The crude oil used for the fuel oil production at the refinery can be of different quality mainly depending on the location of the oil well. An important quality aspect is the sulfur content. In crude oil classification one distinguishes between sour and sweet crude oil. The sweet crude oil contains less than 0.5 wt.-% sulfur; other crude oils are classified as sour crude oil. Crude oil can usually contain up to 4 wt.-% sulfur. The lighter crude oil products are the most sought after as one easily can produce light low sulfur products as gasoline, diesel, kerosene etc. by fractional distillation.

As the demand for the lighter, low sulfur products is high, it is necessary to further process also the heavy parts of the crude oil. In the refinery processing, the heavy residual oil from the fractional distillation is cracked into lighter molecules by catalytic or thermal cracking. To reduce the sulfur content in the light fuel oil products, they are treated in a hydrodesulfurization (HDS) process. HDS is a hydrogenolysis reaction where organosulfur compound in the oil is reacted with hydrogen under formation of H_2S . HDS is a catalytic process performed in a fixed bed reactor with cobalt and molybdenum on alumina as the catalyst. The reaction takes place at 300 to 400 °C and an absolute pressure of 30 to 130 atmospheres. The H_2S gas is separated and concentrated by gas separators and an amine treatment plant. The purified H_2S is then usually treated in a Claus process to produce elementary sulfur. The sulfur can be sold to produce e.g. sulfuric acid. The sulfur content of the treated oil products can be as low as 1 ppm (0.0001 %).

The above described process also can have some effect on reducing the nitrogen content in the fuel oils (hydrodenitrogenation) and thus also reducing the NO_x emissions from the engine. However, in an engine operated in a diesel cycle, the combustion temperature is very high and the main NO_x formation emanates from thermal formed NO_x i.e. nitrogen in the combustion air is oxidized to NO_x . The NO_x formation from fuel nitrogen will probably be reduced but contributes probably only little to the total NO_x emission from the engine.

5 Presentation of the LCA models and the study boundaries

This chapter includes a description of how the models for the three scenarios were designed. GaBi ts software was used for modelling the closed-loop scrubber, the open-loop scrubber and the SECA fuel models.

5.1 Closed-loop scrubber model

Figure 5.1 below shows the closed-loop scrubber production part modelled in GaBi ts. It includes all upstream materials and transportations for the production of the scrubber system. Electricity used for the scrubber manufacturing was also included.

01. Closed-loop scrubber production

Process plan: Reference quantities
The names of the basic processes are shown.

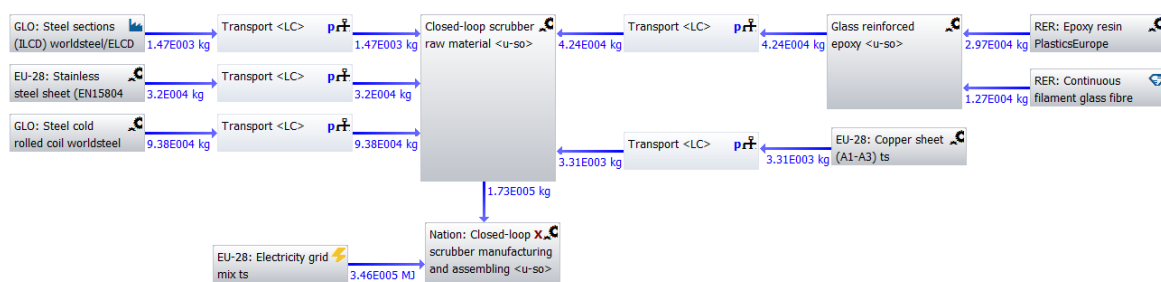


Figure 5.1 Closed-loop scrubber production part modelled in GaBi ts software

In the operation phase of closed-loop scrubber, inputs are heavy fuel oil (2.5 wt.-%), (used as energy source for on-board electricity generation), Sodium hydroxide (used to bind/neutralize SO_2 and SO_3), Aluminium sulphate and polyaluminium chloride (used for waste water purification). The outputs of the closed-loop scrubber system are emissions to air (see Appendix B), emissions to water (see Appendix B) and sludge (see Appendix B).

Figure 5.2 below shows modules required in the operation part of closed-loop scrubber system. Every single modular represents one input (HFO or chemicals) or output (air emissions, water emissions, or sludge). All modules were consistent with the functional units.

01. Closed-loop scrubber use phase

Process plan: Reference quantities
The names of the basic processes are shown.

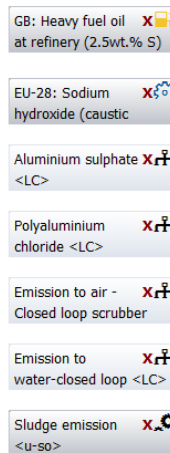


Figure 5.2 Closed-loop scrubber operation part, modelled in GaBi ts software

Table 6.2 in Chapter 6 is the list of inputs and outputs of the closed-loop scrubber system. More detailed information can be found in Appendix B.

The scrubber end-of-life treatment is based on the assumption that metals will go to recycling and plastics will go to incineration. For both closed-loop scrubber and open-loop scrubber, steel (black steel, stainless steel and normal steel) covers around 74 % of total weight, copper covers around 2 % and the rest is GRE. Steel and copper are assumed to go to recycling station and generate credits back. The GRE will go to incineration, in which the epoxy resin will generate electricity and steam, while the glass fibre was treated as zero heating generating no energy. See Figure 5.3 .

Scrubber EOL with credits

Process plan: Mass [kg]
The names of the basic processes are shown.

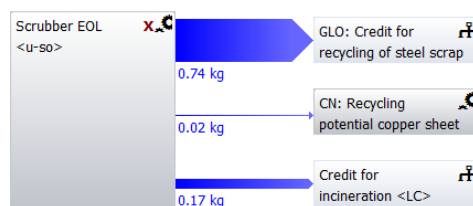


Figure 5.3 Scrubber End-of-Life part, modelled in GaBi ts software

5.2 Open-loop scrubber model

Figure 5.4 is the open-loop scrubber production part modelled in GaBi ts. The open-loop scrubber weigh slightly less than the closed one but the material composition is quite similar. Transportation and electricity use are also included.

02. Open loop scrubber production

Process plan: Reference quantities
The names of the basic processes are shown.

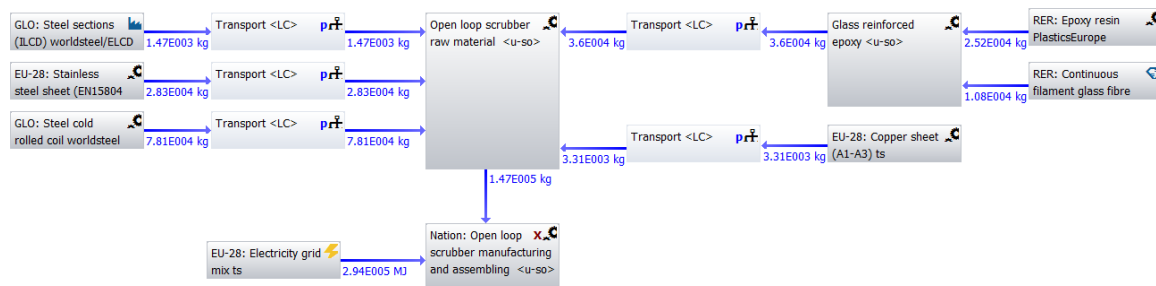


Figure 5.4 Open-loop scrubber production part, modelled in GaBi ts software

For the open-loop scrubber operation, seawater is usually used as scrubbing liquid for SO_x. For detailed technical descriptions, see Chapter 4.1. The input to the system is only energy, which is used to pump water on-board and used in the scrubber system to clean the exhaust gases from the main engine(s). After scrubbing, all waste water is discharged into sea. The emissions from the engine exhaust gases and especially SO₂ have thus been transferred from the gas phase into a water phase. After scrubbing, there are thus reduced emissions to air and emissions to water. No sludge removal exists in this system. See Figure 5.5 below.

02. Open loop scrubber use phase

Process plan: Reference quantities
The names of the basic processes are shown.

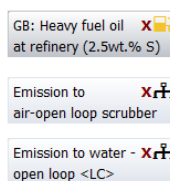


Figure 5.5 Open-loop scrubber operation part, modelled in GaBi ts software

For the scrubber end-of-life, it is assumed to be treated in the same way as the closed scrubber system, see Chapter 5.1.

5.3 SECA fuel model

“SECA fuel” represents the fuel which meets the fuel standard requirement that can be used in SECA areas. Today (year 2017), the SECA/ECA limit is 0.1 wt.-% sulfur in the fuel. Since “SECA fuel” is a general name of a group of fuels, that is produced by mixing different type of fuels to meet the SECA requirements but with many similarities to Marine Gas Oil (MGO). Thus, it can be difficult to exactly specify a “SECA fuel”. Therefore two methods have been used to model the production of “SECA fuel”.

Method 1 was to use an LCA dataset of “diesel mix in refinery” with 10 ppm sulfur content as an approximation to “SECA fuel” with 1000 ppm sulfur content. See Figure 5.6 SECA fuel modelled by diesel proxy. This will thus be a conservative estimation of the refinery impacts from production of SECA fuel, which can slightly overestimate the environmental impacts.

Method 2 was performed through SECA fuel produced in a residue hydrocracker plant from HFO to a low sulfur gas oil product. Electricity and heat are used in the residue hydrocracker unit for cracking and desulfurization of the heavy fuel oil. See Figure 5.7, which shows the models for producing 1 kg “SECA fuel” from heavy fuel oil.

For the refinery LCA datasets used for production of heavy fuel oil and diesel/gas oil production, LCA datasets from refineries with a similar level of energy use and CO₂ emissions have been chosen to avoid effects of different energy use for different refineries, which otherwise can be significantly.

For the SECA fuel scenario, only the air emission is included in the study. There was no water emission or sludge output. Detailed air emission can be found in Appendix B.

Method 1:

Data approximation with diesel with dataset GR: diesel mix at refinery

03A. SECA fuel scenario (approximation with diesel)

Process plan: Mass [kg]
The names of the basic processes are shown.

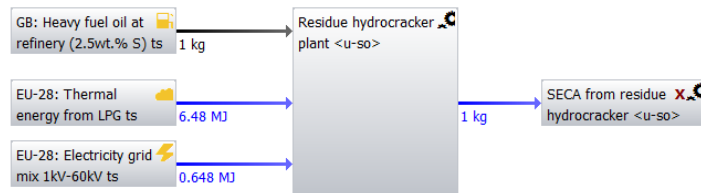


Figure 5.6 SECA fuel modelled by adjusting dataset of diesel production.

Method 2:

SECA from residue hydrocracker

Process plan: Reference quantities
The names of the basic processes are shown.



03B. SECA procured from residue hydrocracker

Process plan: Mass [kg]
The names of the basic processes are shown.

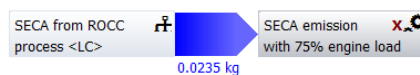


Figure 5.7 1 kg of SECA fuel modelled by processing from heavy fuel oil or residue oil by a residue hydrocracker using heat and electricity in a catalytic reactor.

6 LCA inventory data and data quality

The overall technical scrubber project, to which this project is part of, includes technical installations of on-board exhaust gas scrubber equipment as well as technical, energy, and environmental related measurements on the vessels and on the scrubber equipment. In addition, the ships' own operating data have been used for the LCA models. Prior to installation of the scrubber equipment on board, the ships have been operated on low sulphur light fuel oil that meets today's environmental requirements. Ship measurements have thus been made both before scrubber installation with light fuel oil for operation and after the scrubber installation with operation on heavy, high sulphur fuel oil and flue gas cleaning with scrubber. Measurements have been made on both Open-loop and Closed-loop scrubber systems.

The data inventory part includes lists of data for the three models. The data cover specific data as well as generic data. The upstream material data for the scrubber were taken from databases of generic data. Even though database data are not specific ship data and the material quality can vary, the data can be considered as reliable and have also little influence on the total results.

Amount of chemicals and fuel used during scrubber operation were based on theoretical calculation. For the emissions; air emissions, water emissions, and sludge were site specific data, which were obtained through onboard measurements, which have a high accuracy.

The Geographic boundary is Europe. The scrubber including materials is produced in Europe and EoL is also taking place in Europe. The operation part relates to SECA area even if chemicals and fuels are produced in Europe.

The time boundary was set to 30 years. It was assumed the scrubber will have the same service life as the ship, which is around 30 years.

6.1 Closed-loop scrubber

6.1.1 Closed-loop scrubber production phase

The data of scrubber material composition was obtained from Stena line. For the electricity used for manufacturing and assembling, an estimated value of 2 MJ per kilogram weight of the scrubber was applied. Direct emissions from scrubber production factory were not included. The primary reason was that emission data could not be obtained. The second reason was that these emissions were assumed to be small compared to the impact from the scrubber materials and even smaller compared to emissions from the scrubber operation phase.

In terms of transportation, a distance of 1500 km by truck was assumed for all raw material transports from material production to scrubber manufacturing site. 1500 km represent approximately an average distance between the European countries. When the scrubber is produced, it will be transported from scrubber manufacturing site to an installing site (usually a ship yard), in an assumed distance of 500 km.

See Table 6.1 and Table 6.7 below for more detailed information. The material composition of the open loop scrubber system is quite similar to the closed scrubber system and the information about the open scrubber system was also provided by Stena Line. In order to keep the same principle and results comparable, same assumption of transportation and energy used for manufacturing was applied as for the closed one.

Table 6.1 Production phase: closed-loop scrubber data collection

Closed-loop Scrubber inputs (Unit: 1 scrubber)				
Material input	Dataset used in model	Raw material weight (kg/scrubber)	Transportation (km)	Type of transport
Steel	GLO: Steel sections (ILCD) worldsteel/ELCD	1 470	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Black steel	GLO: Steel cold rolled coil worldsteel	93 783	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Stainless Steel	EU-28: Stainless steel sheet (EN15804 A1-A3) ts <p-agg>	31 956	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
GRE	RER: Epoxy resin PlasticsEurope RER: Continuous filament glass fibre (wet chopped strands) APFE/ELCD	42 439	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Copper	EU-28: Copper sheet (A1-A3) ts	3 308	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Energy use	Dataset used in model	Energy amount (MJ)		
Electricity	EU-28: Electricity grid mix ts	345 913		
Output		Weight (kg)	Transportation (km)	Type of transport
Closed-loop scrubber		172 967	500	TruckTrailer 28-34 t, MPL 22 t, Euro 4

6.1.2 Closed-loop scrubber operation phase

For the closed-loop scrubber operation, heavy fuel oil is used as energy source (electricity generation by shaft energy from main engine) and sodium hydroxide and water purification chemicals are also used in the system for gas and water cleaning. The input amounts are based on theoretical calculations. See Table 6.2.

Table 6.2 Closed-loop scrubber inputs during operation phase. Calculated as per MJ energy to propeller as functional unit.

Closed-loop Scrubber inputs (Unit: per 1 MJ energy to the propeller)				
Input	Dataset used in model	Amount	Unit	Data source
Heavy fuel oil	GB: Heavy fuel oil at refinery (2.5wt.% S) ts	5.06E-02	kg	Theoretical calculation
Sodium hydroxide	EU-28: Sodium hydroxide (caustic soda) mix (100 %) ts	3.27E-03	kg	Theoretical calculation
Aluminium sulphate	GLO: aluminium hydroxide production ecoinvent 3.4 EU-28: Sulfuric acid (100 % H ₂ SO ₄) Fertilizers Europe	2.75E-07	kg	Theoretical calculation
Polyaluminium chloride	GLO: aluminium hydroxide production ecoinvent 3.4 DE: Hydrochloric acid mix (100 %) ts	2.06E-06	kg	Theoretical calculation

Additional fuel use with closed-loop scrubber cleaning

An extra fuel use is needed for the “HFO + closed-loop scrubber” scenario, compared to HFO without scrubber cleaning. The additional fuel use is due to the extra electricity use of the scrubber system.

The scrubber system is using 750 kW. The ship has 4 engines in total. 2 engines are 9600 kW and another 2 engines are 7200 kW. This results in the following approximate calculation:

$$\text{Additional fuel use} = \frac{750 \text{ kW}}{2 * 9600 \text{ kW} + 2 * 7200 \text{ kW}} = 2.2 \%$$

Thus, 2.2 % extra fuel is needed for the ship when using the closed-loop scrubber cleaning compared to no exhaust gas cleaning. This figure corresponds to full load operation and can vary somewhat for other engine loads. This can probably result in an increase of the additional fuel use.

Heavy fuel oil use

Heavy fuel oil (HFO) is used on ships with closed-loop scrubber installations. The heavy fuel oil used in this application is a fuel with 2.5 wt.% S, which is a common HFO available on the market.

The energy content of HFO used on Stena Britannica was 41.4 MJ/kg as net heat of combustion (lower heating value). The main engine efficiency was analyzed as 48.37 %. Data used to calculate HFO energy input needed for 1 MJ energy to the propeller is shown in Table 6.3 below.

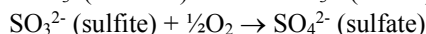
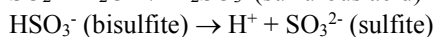
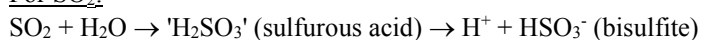
Table 6.3 Heavy fuel use per MJ energy to propeller for closed-loop scrubber

Category	Data	Unit
HFO energy content	41.4	MJ/kg
Converting factor	2.11	MJ input/MJ to propeller
Additional fuel use for closed-loop scrubber	2.2 %	
HFO, used amount	5.06E-02	kg/MJ to propeller

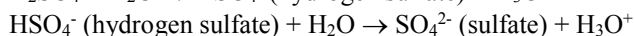
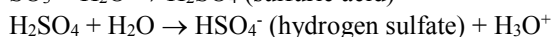
Sodium hydroxide use

Sulfur dioxide (SO₂) is dissolved and ionized to bisulfite and sulfite, which is then readily oxidized to sulfate in seawater containing oxygen. Similarly sulfuric acid, formed from SO₃, and hydrogen sulfate dissociate completely to sulfate. The dissolving reactions are shown below.

For SO₂:



For SO₃:



The different ions from dissolved SO₂ and SO₃ then react with NaOH to form corresponding sodium salts and will in this way be neutralized. The amount of NaOH has been calculated theoretically based on the sulfur content in the fuel. See Table 6.4.

Table 6.4 Calculation steps for sodium hydroxide (NaOH) input per MJ energy to the propeller

Category	Data	Unit
HFO energy content	41.4	MJ/kg
S	0.0250	kg S/kg fuel
S weight	0.0006255	kg S/MJ fuel
Scrubber removal efficiency	99	%
Removed S per MJ fuel	0.0006192	kg S/MJ fuel
Converting factor	2.11	MJ input/MJ to propeller
NaOH used amount	3.27E-03	kg NaOH/MJ to propeller

Use of chemicals

Chemicals that are included in the study are aluminium sulphate and polyaluminium chloride, which are all used to clean waste water from the scrubber. The dose amount information was obtained from Stena Line and also based on theoretical calculations. See Table 6.5 and Table 6.6 below.

Table 6.5 Aluminium sulphate, used amount and calculation steps

Aluminium sulphate			
Category	Amount	Unit	Comment
Consumption	2	L/day	From Stena Line
Fuel required per day trip	8 441 729	MJ to propeller	Assumption
Convert to per MJ	1.05E-06	L/MJ	Calculation
Concentration	0.2		From Stena: 20-25 %
Density of solution	1.3	kg/L	Assumption
Consumption of 100 % Aluminium sulphate	2.74E-07	kg/MJ to propeller	Calculation

Table 6.6 Polyaluminium chloride, used amount and calculation steps

Polyaluminium chloride			
Category	Amount	Unit	Comment
Consumption	10	L/day	From Stena Line
Fuel required per day trip	8 441 729	MJ to propeller	Assumption
Convert to per MJ	5.27E-06	L/MJ	Calculation
Concentration assumption	0.3		From email 20-40 %
Density of solution	1.3	kg/L	Assumption
Consumption of 100 % polyaluminium chloride	2.06E-06	kg/MJ	Calculation

Air emission, water emission and sludge

Emissions from closed-loop scrubber include emissions to air, water and also accumulated heavy metals into sludge. The detailed monitoring emission data were shown in Appendix B2.

6.2 Open loop scrubber

6.2.1 Open loop scrubber production phase

The material composition of the open loop scrubber system is quite similar to the closed scrubber system and the information about the open scrubber system was also provided by Stena Line. In order to keep the same principle and results comparable, same assumption of transportation and energy used for manufacturing was applied as for the closed one.

Table 6.7 Production phase: open-loop scrubber data collection

Open-loop Scrubber inputs (Unit: per 1 scrubber)				
Material input	Dataset used in model	Raw material weight (kg/scrubber)	Transport distance (km)	Type of transport
Steel	GLO: Steel sections (ILCD) worldsteel/ELCD	1 470	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Black steel	GLO: Steel cold rolled coil worldsteel	78 104	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
St Steel	EU-28: Stainless steel sheet (EN15804 A1-A3) ts	28 320	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
GRE	RER: Epoxy resin PlasticsEurope RER: Continuous filament glass fibre (wet chopped strands) APFE/ELCD	36 008	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Copper	EU-28: Copper sheet (A1-A3) ts	3 308	1500	TruckTrailer 28-34 t, MPL 22 t, Euro 4
Energy use	Dataset used in model	Energy amount (MJ)		
Electricity	EU-28: Electricity grid mix ts	294 419		
Output		Weight (kg)	Transport (km)	Type of transport
Closed-loop scrubber		147 209	500	TruckTrailer 28-34 t, MPL 22 t, Euro 4

6.2.2 Open-loop scrubber operation phase

Heavy fuel oil (HFO) is also used in open-loop scrubber systems. Unlike the closed-loop system, no water purification chemicals are required since the open-loop scrubber is using the alkalinity of the seawater to increase binding of SO₂ and SO₃. After seawater cleaning of the exhaust gases in the scrubber, the waste water (scrubber water) is discharged to the sea. Thus, no waste water is collected or treated and no sludge is formed.

Additional fuel use with open-loop scrubber cleaning

The calculation of the extra fuel needed for the open-loop scrubber alternative i.e. (HFO + open-loop scrubber) compared to HFO without scrubber cleaning was using same methods as for the closed-loop calculations.

There are 2 open-loop scrubbers installed, each of them with a power requirement of 80 kW. The boat has 2 engines in total, both with a power of 6000 kW. This results in the following approximate calculation:

$$\text{Additional fuel use} = \frac{2 * 80 \text{ kW}}{2 * 6000 \text{ kW}} = 1.3 \%$$

Thus, 1.3 % extra fuel is needed for the ship when using the open-loop scrubber cleaning compared to no exhaust gas cleaning. Minor variations can exist due to operation at different loads.

Table 6.8 Heavy fuel use per MJ energy to propeller for open-loop scrubber

Category	Data	Unit
HFO energy content	41.4	MJ/kg
Converting factor	2.09	MJ input/MJ to propeller
Additional fuel use for open-loop scrubber	1.3 %	
HFO, used amount	0.0502	kg/MJ to propeller

Air emission and water emission

Air emission and water emission of open-loop scrubber was shown in Appendix B.

6.3 Heavy fuel oil for operation with scrubber cleaning

The scrubber cleaning systems are used in combination with heavy fuel oil for the operation of the ship's main engine. As previously stated, the heavy fuel oil contains a much higher content of sulfur than the desulfurized SECA fuel and therefore, a SO₂/SO₃ exhausted gas cleaning is needed. However, this is not the only difference between heavy fuel oil and SECA fuel. The refinery production for the two products involves different processes and therefore, the energy and environmental profile are also different for the two products. To be able to analyze these differences, the LCA datasets must cover an analysis on a process level. This is the case for both the heavy fuel oil and the SECA oil in this study. The computational prerequisites for the GaBi ts-datasets used for the modeling of the fuels are described in the database to GaBi ts software and cited below for a full description of the calculations. This description applies to both the heavy fuel oil and the SECA fuel.

“For all products of the refinery, allocation by mass and net calorific value is applied. The feedstock (crude oil) is allocated by energy, the refinery efforts (emissions) by mass to each product. The production route of every refinery product is modelled in detail, and therefore it is possible to track the energy efforts for operating each single unit processes of the refinery. These energy demand and the corresponding emissions, can be allocated causer-oriented to each refinery product.

*The feedstock of the respective unit process, which is necessary for the production of a product or an intermediate product, is allocated by energy (i.e. mass of the product * net calorific value of the product). In this way, products with high caloric values, e.g. gasoline or gases, are assigned to higher feedstock consumption and hence higher environmental upstream impacts compared with low caloric value products (e.g. asphalt, residual oil).*

The energy demand (thermal energy, steam, electricity) of a process, e.g. atmospheric distillation, being required to create a product or an intermediate product, are allocated according to the share of the throughput of the unit process (mass allocation). In general, products which are more complex to produce and therefore pass a lot of refinery facilities e.g. gasoline, are assigned with a higher energy consumption values (and hence higher emissions) compared with e.g. straight-run products. For the combined crude oil, natural gas and natural gas liquids (NGL) production, allocation by net calorific value is applied.”

6.4 SECA fuel

6.4.1 SECA fuel dataset modelled

The SECA/ECA limit is 0.1 wt.-% sulfur in the fuel. There is not a specific fuel called “SECA fuel”. “SECA fuel” is a fuel that meets the sulfur limitation of 0.1 wt.-% and can be used in SECA areas. For the moment, the refineries produce and mix different types of fuels that meet the “SECA fuel” requirements. These processes usually include some sort of desulfurization of heavier petroleum products.

Due to lacking of specific refinery information about SECA fuels, the LCA model for SECA fuel was based on theoretical calculations and modifications of existing LCA datasets.

Two methods have been applied on SECA fuel for the LCA analysis:

Method 1: Modified dataset of diesel to fit SECA fuel sulfur content

A diesel LCA datasets from United Kingdom (“GB: diesel mix at refinery”) has been used as an approximation to SECA fuel. It is assumed that the “SECA fuel” has similar upstream process steps (energy use, emissions, etc.) even though the diesel has a lower sulfur content (10 ppm) compare to “SECA fuel” (1000 ppm), while this difference was neglectable.

Method 2: Assuming the SECA fuel is processed by a residue hydrocracking plant

The method is based on the modelling of “SECA fuel” produced by a residue hydrocracking plant from HFO. In the residue hydrocracking plant, an additional amount of electricity and heat is used for cracking and desulfurization of HFO to “SECA fuel”. Table 6.9 below lists the assumed extra energy required to process SECA fuel from HFO in the residue hydrocracker.

Table 6.9 Material and energy input to produce 1 kg SECA fuel by the residue hydrocracking plant.

Input	Dataset	Amount *)	Unit
Heavy fuel oil	GB: Heavy fuel oil at refinery (2.5wt.% S) ts	1	kg/kg SECA fuel
Thermal energy	EU-28: Thermal energy from LPG ts	6.48	MJ/kg SECA fuel
Electricity	EU-28: Electricity grid mix 1kV-60kV ts	0.648	MJ/kg SECA fuel

*) In the use of heavy fuel oil, the formed residue from the residue hydrocracker are not allocated to the SECA fuel, but are assumed to be used in other applications. The thermal energy for the process is actually supplied by refinery gas but is approximated by liquefied petroleum gas (LPG). However, both Heavy fuel oil and Thermal energy originate from use of crude oil in refinery.

6.4.2 SECA fuel operation phase

The operation impact from SECA fuels includes mainly the direct emissions from the ship main engine (usually a diesel engine) without scrubber cleaning of the exhaust gases. Thus, only air emissions from the engine are included. These emissions can be assumed to be equivalent to operation with ordinary Marine Gas Oil (MGO) and the specified sulfur content. In this case, specific ship engine measurement data from this project have been used. See Appendix B.

7 Results from the LCA model scenario calculations

Results from the three different scenarios for exhaust gas cleaning for ships will be presented below. The scenarios are closed-loop scrubbing, open-loop scrubbing and use of SECA fuel, which is a low-sulfur fuel oil. The closed-loop and open-loop scrubber scenario will be presented into several parts; upstream part, operation part, and End-of-Life part.

The results are mainly presented in the functional unit (per MJ energy to propeller). The scrubber scenarios modelled in GaBi ts software cover one scrubber unit adapted to one engine with its specific fuel use, exhaust gas flow and power output to the propeller. The electricity generation to the scrubber (and to other part of the ship) takes place through a generator on the main engine propeller shaft, thus increasing fuel consumption to the main engine.

7.1 Results with closed-loop scrubber cleaning

7.1.1 Closed-loop scrubber production

The environmental impact results of one closed-loop scrubber unit are shown in Figure 7.1. The life cycle stages included in this part are production of raw materials, transportation and energy used for scrubber manufacturing.

The scrubber is assumed to have a service life of 30 years (same as the ship). A calculation was also performed to calculate the results from one scrubber unit to one functional unit, 1 MJ to propeller, for each impact category. The calculated results for the scrubber production part per functional unit for each impact category are shown in Figure 7.2.

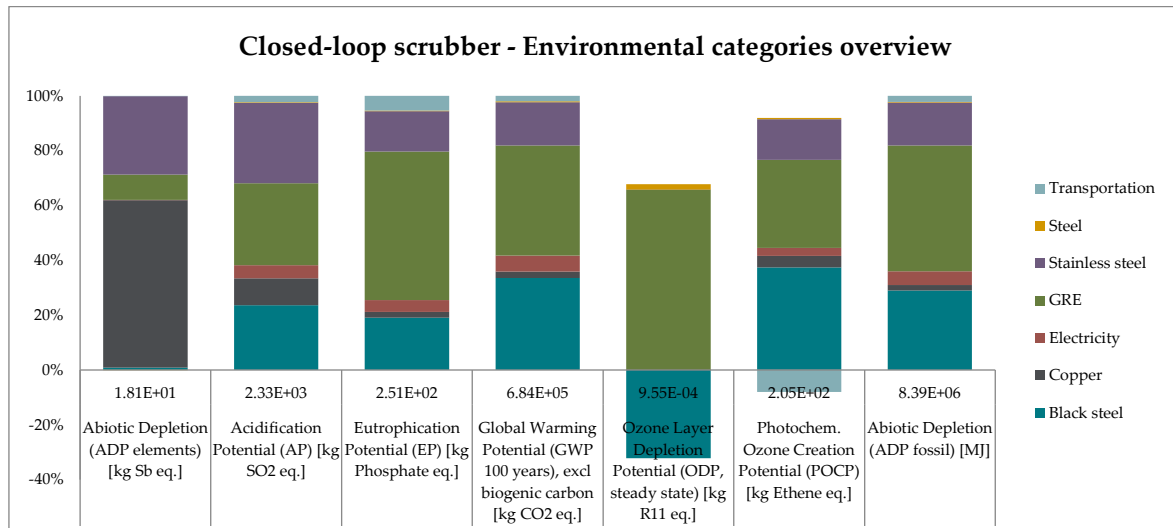


Figure 7.1 Environmental category overview for closed-loop scrubber production including upstream parts for one scrubber unit

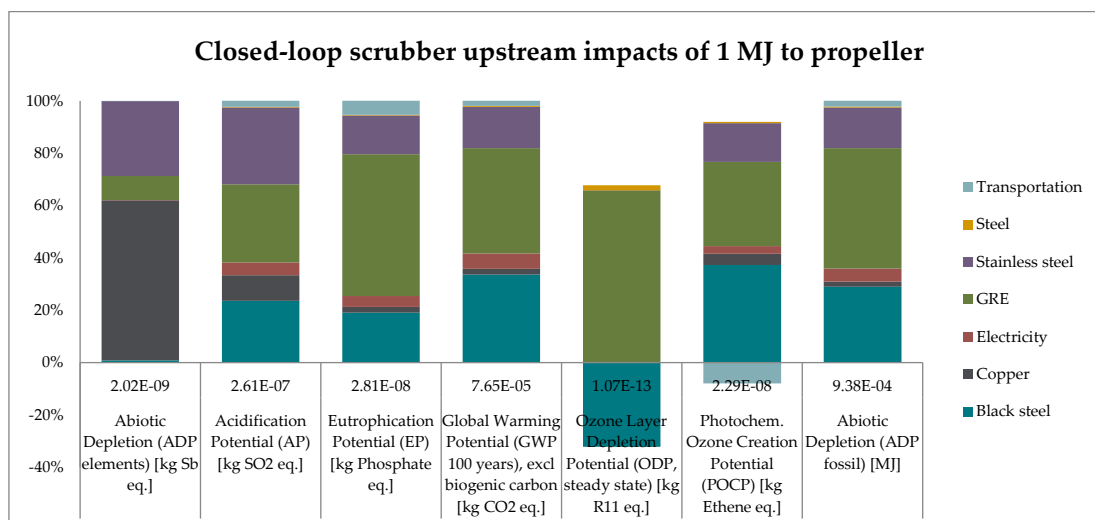


Figure 7.2 Environmental category overview for closed-loop scrubber production including upstream parts per functional unit – 1 MJ to propeller

The resource use in the results above is presented as Abiotic Depletion Potential in kg Sb eq. (kg antimony equivalents). As this unit may be difficult to interpret, energy and material resources are also reported for one scrubber unit in MJ or kg in the tables below.

Table 7.1 Primary energy resource use for one closed-loop scrubber unit

	Black steel	Copper	Electricity	GRE	SS Steel	Steel	Transport
Non-renewable energy resources (MJ)	2.87E-04	2.03E-05	8.56E-05	5.00E-04	1.73E-04	3.29E-06	2.17E-05
Crude oil resources (MJ)	7.25E-06	7.98E-06	3.28E-06	1.03E-04	2.23E-05	-4.84E-09	1.99E-05
Renewable energy resources (MJ)	7.60E-06	2.39E-06	3.06E-05	7.31E-06	2.87E-05	9.68E-08	1.12E-06

Table 7.2 Material resource use for one closed-loop scrubber unit

	Black steel	Copper	Electricity	GRE	SS Steel	Steel	Transport
Non-renewable elements (kg)	9.55E+04	4.92E+03	1.78E+01	2.62E+02	3.67E+04	7.17E+02	5.22E+00
Iron (kg)	9.44E+04	1.41E+01	3.28E+00	1.09E+02	1.02E+04	7.16E+02	3.04E+00
Non-renewable resources (kg)	5.99E+05	1.17E+06	1.84E+05	9.62E+04	8.07E+05	6.20E+03	9.13E+02
Renewable resources (kg)	6.64E+07	7.61E+06	1.99E+08	1.23E+07	1.77E+08	4.95E+03	7.90E+05
Water (kg)	6.61E+07	7.53E+06	1.99E+08	1.23E+07	1.76E+08	1.91E+03	7.87E+05

7.1.2 Closed-loop scrubber operation

The closed-loop scrubber operation part includes impacts of using heavy fuel oil (HFO), sodium hydroxide and other chemicals. It also includes emissions to air and water. In terms of sludge, impacts from this part were not included since sludge will be handled and used as cement material. Toxic components such as heavy metals will be retained inside the concrete for a relatively long time. However, the metals will slowly leak out from the concrete and finally end-up in the environment when the concrete deteriorate. The time frame as well as the leakage rate for this process can be difficult to estimate. Thus, this part of the impacts was therefore not included in the total impacts. The results presented in Figure 7.3 are an overview of the categories. Detailed results are shown in Table 7.3 .

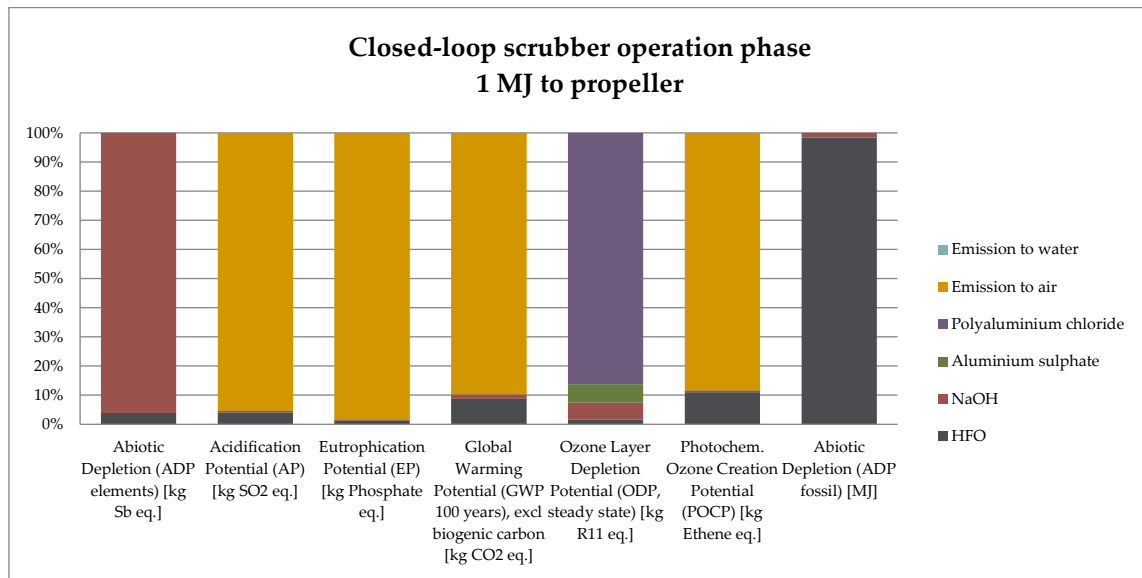


Figure 7.3 Environmental category overview for closed-loop scrubber operation including upstream parts for chemicals and HFO per functional unit – 1 MJ to propeller (excluding sludge impacts)

Table 7.3 Environmental category results for closed-loop scrubber operation including upstream parts (production of) for chemicals and HFO per functional unit – 1 MJ to propeller

Environmental categories	Total (excl. impact from sludge)	HFO	NaOH	Aluminium sulphate	Polyaluminium chloride	Emission to air	Emission to water
Abiotic Depletion (ADP elements) [kg Sb eq.]	4.46E-08	1.75E-09	4.28E-08	1.50E-11	2.38E-12	0.00E+00	0.00E+00
Acidification Potential (AP) [kg SO ₂ eq.]	1.66E-03	6.92E-05	8.44E-06	2.66E-09	9.35E-09	1.59E-03	0.00E+00
Eutrophication Potential (EP) [kg Phosphate eq.]	4.08E-04	5.61E-06	1.18E-06	2.19E-10	3.02E-09	4.01E-04	3.76E-12
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	1.94E-01	1.69E-02	3.00E-03	4.24E-08	1.34E-06	1.74E-01	0.00E+00
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1.58E-13	2.68E-15	8.97E-15	1.03E-14	1.37E-13	0.00E+00	0.00E+00
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	1.12E-04	1.23E-05	6.25E-07	1.12E-10	5.44E-10	9.87E-05	0.00E+00
Abiotic Depletion (ADP fossil) [MJ]	2.23E+00	2.19E+00	3.59E-02	1.13E-07	1.53E-05	0.00E+00	0.00E+00

7.1.3 Closed-loop scrubber End-of-Life

The End-of-Life of scrubber includes the scrubber equipment handling after its service life and the sludge handling for the closed-loop scrubber.

7.1.3.1 Sludge End-of-Life impact

Sludge is produced during the operation of the closed-loop scrubber system. In this case, the sludge is the residue from the cleaning of the scrubber water and consists mainly of unburned particles (e.g. soot) from the exhaust gases of the ship using heavy fuel oil and some scrubber water. It includes heavy metals from the scrubber waste water, which has been further processed into sludge. As mentioned above, the sludge will be further processed and used as raw materials in cement production. Thus, this part of impact was not included in the total impact of the closed-loop scrubber system because it is difficult to estimate and evaluate the amount of pollutants that actually will end-up in the recipient and cause an environmental impact. The leakage rate from the used concrete and thus the concentrations in the recipient can also be difficult to predict. However, the maximum impact from the substances in the sludge can still be interesting to check. The amount of sludge formed in the process is about 0.00097 kg sludge output per MJ energy input to the main engine, which correspond to about 0.002 kg sludge output per MJ to propeller. The main impact can be assumed to emanate from the heavy metals in the sludge. The sludge composition can be found in Table B3 in Appendix B. The impact from the sludge will thus mainly be found as toxicity impact. This has not been further evaluated. The impact results from the sludge per MJ to propeller are shown in Table 7.4 below. As shown from the table, there are almost no traditional environmental impacts, only impact from the heavy metals as toxicity values.

Table 7.4 Environmental category results of sludge from closed-loop scrubber per functional unit-1 MJ to propeller

	Sludge ^{*)} (impact per MJ to propeller)
Abiotic Depletion (ADP elements) [kg Sb eq.]	~0
Acidification Potential (AP) [kg SO ₂ eq.]	~0
Eutrophication Potential (EP) [kg Phosphate eq.]	~0
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	~0
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	0
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	~0

*) Amount of sludge formed is about 0.002 kg sludge output per MJ to propeller.

7.1.3.2 Close-loop scrubber scrap treatment

After the service life of 30 years, the scrubber was assumed go to waste treatment station. Valuable materials will be recycled and the remaining part will go to incineration.

The environmental impacts of recycling metals includes impacts from recycling process and also the credits derived, which means the environmental impact savings from avoided production of virgin materials.

For the incinerated materials, impacts from the incineration process are included but, at the same time, credits are also achieved from the electricity and steam produced by avoiding alternative energy production.

For the closed-loop scrubber, the potential EoL environmental impacts are shown in Table 7.5.

Table 7.5 Environmental impact of closed-loop scrubber end-of-life (EoL) scrap treatment per scrubber unit and Total per MJ to propeller

Impact category	Total EoL incl. credits (per MJ to propeller)	Total EoL incl. credits (per scrubber unit)	EoL incl. credits for incineration (per scrubber unit)	EoL incl. credit for recycling of steel scrap (per scrubber unit)	EoL incl. credit for recycling of copper (per scrubber unit)
Abiotic Depletion (ADP elements) [kg Sb eq.]	-1.16E-09	-1.04E+01	-1.09E-02	-5.95E-01	-9.80E+00
Acidification Potential (AP) [kg SO ₂ eq.]	-7.43E-08	-6.64E+02	-6.54E+01	-4.04E+02	-1.94E+02
Eutrophication Potential (EP) [kg Phosphate eq.]	-4.65E-09	-4.16E+01	-7.34E+00	-3.02E+01	-4.05E+00
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	-2.01E-05	-1.80E+05	3.68E+04	-2.07E+05	-1.07E+04
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1.38E-13	1.23E-03	8.14E-05	1.15E-03	1.11E-10
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	-1.22E-08	-1.09E+02	-5.98E+00	-9.50E+01	-8.40E+00
Abiotic Depletion (ADP fossil) [MJ]	-3.29E-04	-2.94E+06	-9.43E-05	-2.24E-04	-1.16E-05

7.2 Results with open-loop scrubber cleaning

7.2.1 Open-loop scrubber production

The environmental impact results of one open-loop scrubber unit are shown in Figure 7.4. The life cycle stages included in this part are production of raw materials, transportation and energy used for scrubber manufacturing.

The scrubber is assumed to have a service life of 30 years (same as the ship). A calculation was also performed to calculate the results from one scrubber unit to one functional unit, 1 MJ to propeller, for each impact category. The calculated results for the open-loop scrubber production part per functional unit for each impact category are shown in Figure 7.5.

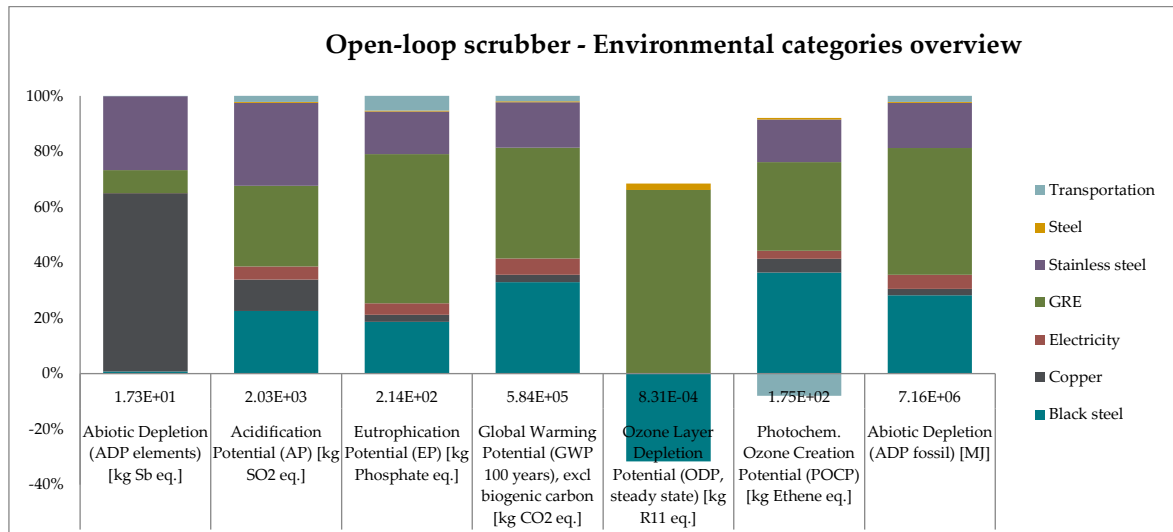


Figure 7.4 Environmental category overview for open-loop scrubber production including upstream parts for one scrubber unit

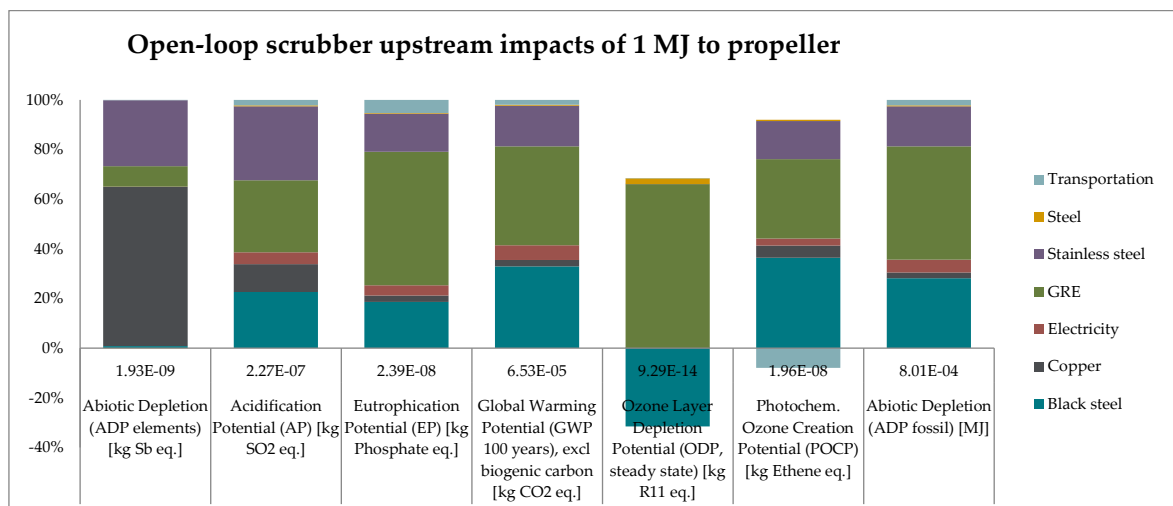


Figure 7.5 Environmental category overview for open-loop scrubber production including upstream parts per functional unit – 1 MJ to propeller

The resource use in the results above is presented as Abiotic Depletion Potential in kg Sb eq. (kg antimony equivalents). As this unit may be difficult to interpret, energy and material resources are also reported for one scrubber unit in MJ or kg in Table 7.6 and Table 7.7 below.

Table 7.6 Primary energy resource use for one open-loop scrubber unit

	Black steel	Copper	Electricity	GRE	SS steel	Steel	Transport
Non-renewable energy resources (MJ)	2.28E-04	1.89E-05	6.93E-05	3.90E-04	1.45E-04	3.13E-06	1.72E-05
Crude oil resource (MJ)	5.64E-06	7.45E-06	2.61E-06	8.13E-05	1.85E-05	-4.52E-09	1.59E-05
Renewable energy resources (MJ)	6.33E-06	2.39E-06	2.61E-05	6.06E-06	2.55E-05	9.68E-08	9.51E-07

Table 7.7 Material resource use for one open-loop scrubber unit

	Black steel	Copper	Electricity	GRE	SS steel	Steel	Transport
Non-renewable elements (kg)	79 508	4922	15	222	32 485	717	4.4
Iron (kg)	78 636	14	2.8	92	9000	716	2.6
Non-renewable resources (kg)	499 152	1 169 227	156 207	81 656	715 425	6201	777
Renewable resources (kg)	55 286 700	7 607 254	1.7E+08	10 455 319	1.57E+08	4948	672 267

7.2.2 Open-loop scrubber operation

Open-loop scrubber operation part includes impacts of using HFO and emissions to air and water. In an open-loop scrubber, the exhaust gas from the main engine is cleaned with the scrubber water (sea water) removing e.g. SO₂, SO₃, particles, heavy metals etc. In this case, the scrubber water is directly released back to the sea without further cleaning of the scrubber water. The main effect compared to a situation without exhaust gas cleaning is that the main emissions will be released to water instead of to air, which will reduce the emission to land areas. The total emission will mainly be the same as for the case without exhaust gas cleaning and heavy fuel oil (HFO) as engine fuel. The results presented in Figure 7.6 are an impact category overview. Detailed results are shown in Table 7.8.

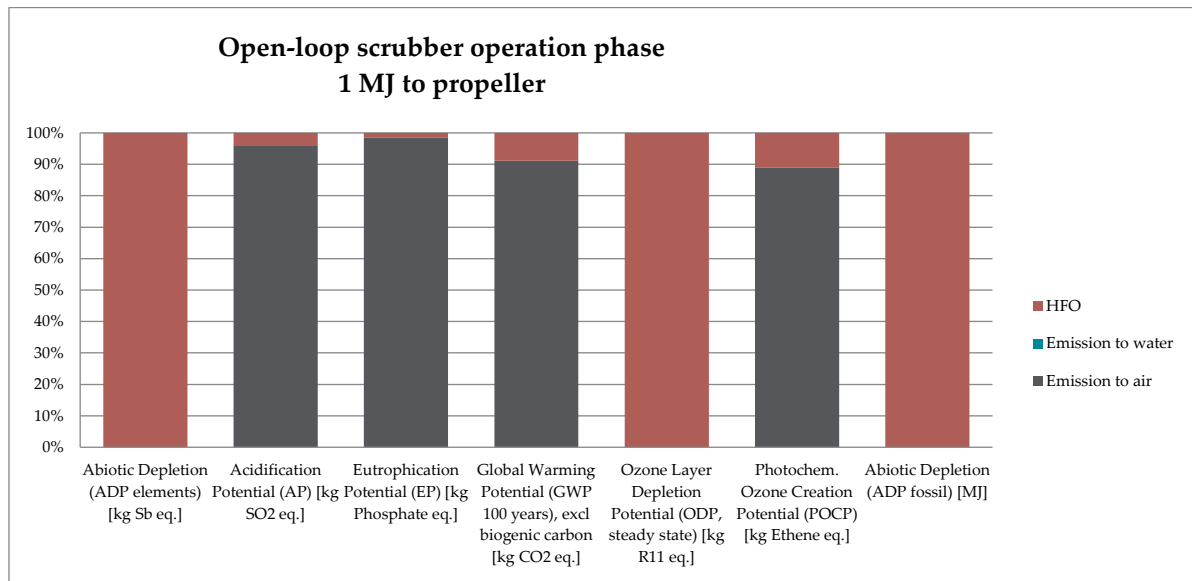


Figure 7.6 Environmental category overview for open-loop scrubber operation including upstream parts for HFO per functional unit – 1 MJ to propeller

Table 7.8 Environmental category results for open-loop scrubber operation including upstream parts per functional unit – 1 MJ to propeller

Environmental categories	Total	Emission to air	Emission to water	HFO production
Abiotic Depletion (ADP elements) [kg Sb eq.]	1.73E-09	0.00E+00	0.00E+00	1.73E-09
Acidification Potential (AP) [kg SO ₂ eq.]	1.64E-03	1.57E-03	0.00E+00	6.86E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	4.03E-04	3.97E-04	7.46E-11	5.56E-06
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	1.89E-01	1.72E-01	0.00E+00	1.68E-02
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2.65E-15	0.00E+00	0.00E+00	2.65E-15
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	1.10E-04	9.78E-05	0.00E+00	1.22E-05
Abiotic Depletion (ADP fossil) [MJ]	2.17E+00	0.00E+00	0.00E+00	2.17E+00

7.2.3 Open-loop scrubber End-of-life

The open-loop scrubber end-of-life is assumed to be treated in the same way as the closed-loop scrubber. Metals will go to recycling and the remaining part will go to incineration. Environmental impact performance of open-loop scrubber end-of-life is shown in Table 7.9.

Table 7.9 Environmental impact of open-loop scrubber end-of-life (EoL) scrap treatment per scrubber unit and Total per MJ to propeller

Impact category	Total EoL incl. credits (per MJ to propeller)	Total EoL incl. credits (per scrubber unit)	EoL incl. credit for Incineration (per scrubber unit)	EoL incl. credit for recycling of steel scrap (per scrubber unit)	EoL incl. credit for recycling of copper (per scrubber unit)
Abiotic Depletion (ADP elements) [kg Sb eq.]	-9.90E-10	-8.85E+00	-9.24E-03	-5.06E-01	-8.34E+00
Acidification Potential (AP) [kg SO ₂ eq.]	-6.32E-08	-5.65E+02	-5.57E+01	-3.44E+02	-1.65E+02
Eutrophication Potential (EP) [kg Phosphate eq.]	-3.96E-09	-3.54E+01	-6.25E+00	-2.57E+01	-3.45E+00
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	-1.72E-05	-1.54E+05	3.13E+04	-1.76E+05	-9.08E+03
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1.17E-13	1.05E-03	6.93E-05	9.77E-04	9.48E-11
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	-1.04E-08	-9.31E+01	-5.09E+00	-8.09E+01	-7.15E+00
Abiotic Depletion (ADP fossil) [MJ]	-2.81E-04	-2.51E+06	-8.02E-05	-1.90E-04	-9.89E-06

7.3 Results of using SECA-fuel

The impact of using SECA fuel on the ship includes crude oil extraction, refining, and also emissions from SECA fuel combustion in the main engine of the ship. An important part of the refining is, in this case, the desulfurization of the fuel oil to meet the emission requirements of SECA. As mentioned above, there are two methods applied for the SECA fuel scenario, see Chapter 6.3.1. Results from both methods, “Method 1” and “Method 2”, are shown below.

Results from Method 1 using a diesel dataset with 0.001 % sulfur content:

GaBi ts dataset: Data approximation from GB: diesel mix at refinery.

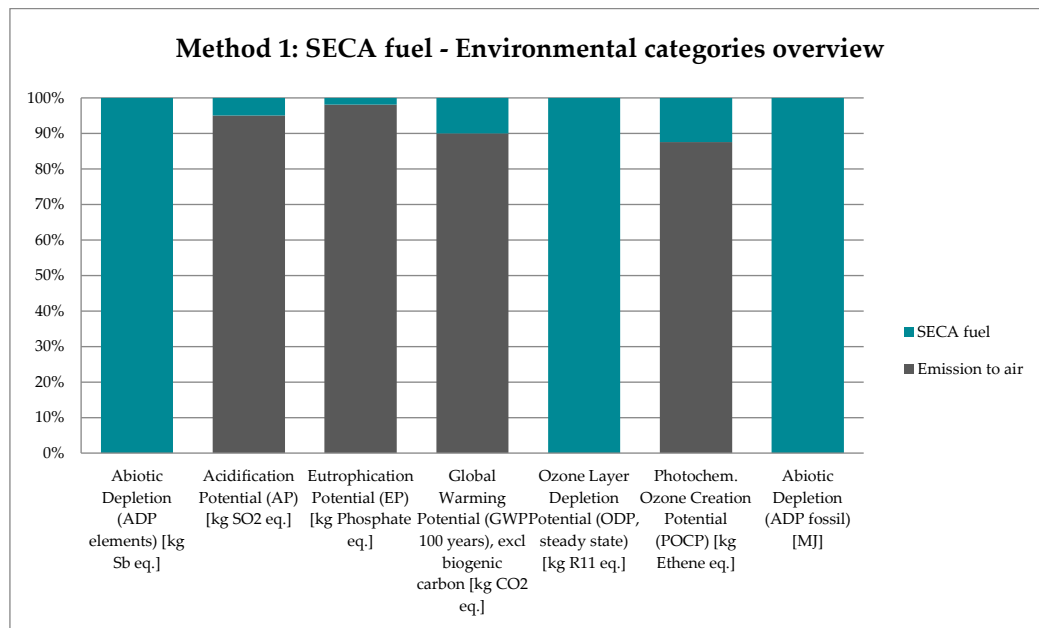


Figure 7.7 Environmental category overview for SECA fuel scenario of Method 1, per functional unit – 1 MJ to propeller

Table 7.10 Environmental impact category results for SECA fuel scenario of Method 1, per functional unit – 1 MJ to propeller

Impact category	Total	Emission to air	SECA fuel production
Abiotic Depletion (ADP elements) [kg Sb eq.]	2.60E-09	0.00E+00	2.60E-09
Acidification Potential (AP) [kg SO ₂ eq.]	1.54E-03	1.46E-03	7.59E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	3.56E-04	3.49E-04	6.80E-06
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	1.84E-01	1.65E-01	1.84E-02
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	2.96E-15	0.00E+00	2.96E-15
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	1.05E-04	9.22E-05	1.31E-05
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	2.29E+00	0.00E+00	2.29E+00

Results from Method 2 where the SECA fuel is produced in a residue hydrocracking unit and desulfurized to 0.1 % sulfur content.

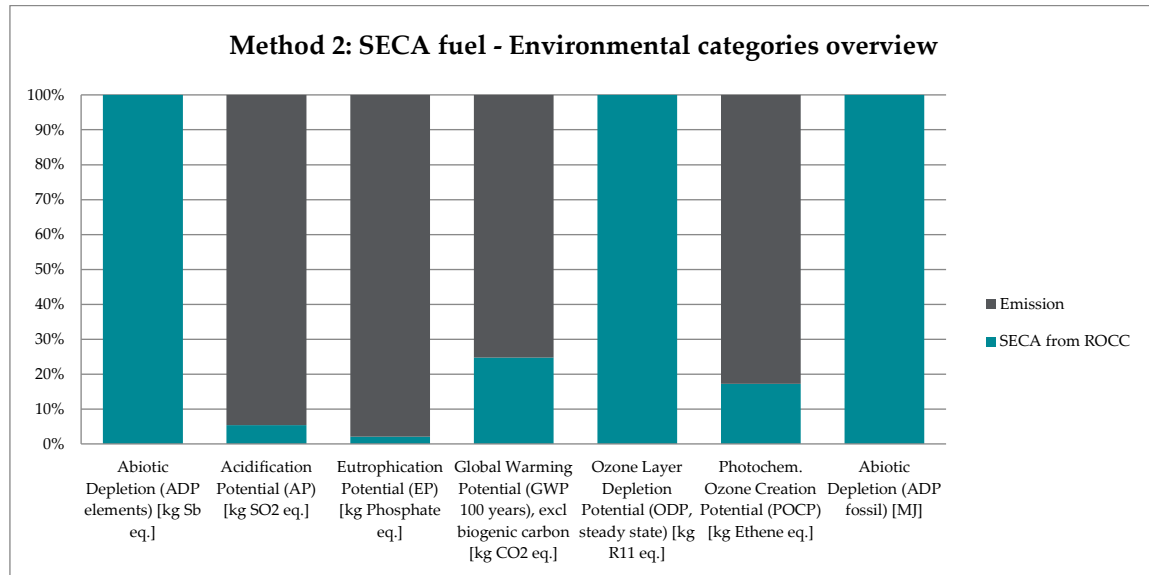


Figure 7.8 Environmental category overview for SECA fuel scenario of Method 2, per functional unit – 1 MJ to propeller

Table 7.11 Environmental impact category overview for SECA fuel scenario of Method 2, per functional unit – 1 MJ to propeller

Impact category	Total	Emission to air	SECA fuel production
Abiotic Depletion (ADP elements) [kg Sb eq.]	4.34E-09	0.00E+00	4.34E-09
Acidification Potential (AP) [kg SO ₂ eq.]	1.55E-03	1.46E-03	8.29E-05
Eutrophication Potential (EP) [kg Phosphate eq.]	3.58E-04	3.49E-04	7.40E-06
Global Warming Potential (GWP 100 years), excl. biogenic carbon [kg CO ₂ eq.]	2.19E-01	1.65E-01	5.42E-02
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1.86E-14	0.00E+00	1.86E-14
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	1.11E-04	9.22E-05	1.91E-05
Abiotic Depletion (ADP fossil) [MJ]	2.50E+00	0.00E+00	2.50E+00

8 Discussion and conclusions

In this study, SECA fuel method 1, SECA fuel method 2, a closed-loop scrubber system, and an open-loop scrubber system are compared and evaluated in a system perspective. For SECA fuel, the sulfur reduction is achieved by desulfurization of the fuel in the refinery at the production of the fuel. Different production processes exist with different quality that will meet the sulfur specification. This is exemplified by method 1 and 2. The data from the SECA fuel include activities from crude oil extraction to the SECA fuel product. No SO_2/SO_3 cleaning is needed. Due to the lighter fuel, some other emissions can also be reduced to some extent such as particles, heavy metals, HC, PAH, NO_x etc; compared to the case where heavy fuel oil is being used outside the SECA areas. The exact emission levels depend on the fuel and on the combustion conditions in the engine. However, no further scrubber cleaning exists.

For the scrubber alternatives, heavy fuel oil is used for the main engine of the ship. This fuel can have a high content of sulfur, such as 2.5 wt.-%, which is mainly converted to SO_2 in the combustion process of the main ship engine and removed from the exhaust gases by the scrubber process to a large extent. In the closed-loop scrubber system, the removed SO_2 is neutralized by NaOH in the scrubber water while in the open-loop scrubber system, the dissolved SO_2 is discharged directly into the sea and neutralized by the alkalinity of the sea water. The neutralization with NaOH is an advantage from an environmental (acidification) point of view but requires an effort for the production of NaOH. The combustion of the heavy fuel oil also forms other pollutants as mentioned above. These are, to some extent, removed by the scrubber process. In the open-loop scrubber system, the scrubber water containing the pollutants are directly discharged to the sea, which means that, in reality, there are no removal effect, only an accelerated transport from air pollution to water pollution preventing the pollutants to reach land areas. The environmental effects on the sea will still remain. In the closed-loop scrubber system, the scrubber water is cleaned in the water treatment system prior to discharge. The pollutants are, in this way, concentrated to a sludge, which will be further treated on shore. The emissions to the environment depends thus very much on the handling and further treatment of the sludge. If the sludge is not treated, the emissions will in principle be the same as for the open-loop system. In the assumed case for this study, the sludge is combusted in a cement kiln and the remaining part will be a part of the cement. Thus, the heavy metals in the heavy fuel oil will end up in concrete. This will significantly slow down the emission rate of the metals, but in a very long time perspective, the metals will leak out.

In Chapter 7, the results from the LCA models of the different emission reduction systems were shown. In this chapter, the results will be compared and analyzed to achieve an overall result. The results are presented separately for each impact category. The SECA fuel case is presented for both method 1 and method 2. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) is shown. The impact of the sludge from the closed-loop scrubber system represents the release of all pollutants in the sludge and do not take into account the use of the sludge in cement/concrete that will slow down the emission rate from the sludge considerably. The following impact categories are shown below in the graphs and presented per MJ to propeller as the functional unit.

- Abiotic Depletion Potential (ADP elements), kg Sb eq./MJ to propeller
- Abiotic Depletion Potential (ADP fossil), MJ/MJ to propeller
- Primary energy resource use, MJ/MJ to propeller (using net calorific values)
- Global Warming Potential (GWP 100), kg CO₂ eq./MJ to propeller
- Acidification Potential (AP), kg SO₂ eq./MJ to propeller
- Eutrophication Potential (EP), kg phosphate eq./MJ to propeller
- Photochemical Ozone Creation Potential (POCP), kg ethene eq./MJ to propeller
- Ozone layer Depletion Potential (ODP), kg R11 eq./MJ to propeller

An important impact from a process or a product is the use of different resources. In this study, three methods are used; ADP elements (kg antimony equivalents), ADP fossil (MJ), and Primary energy resource (in MJ), to estimate and evaluate different types of resources. ADP elements show the primary resource use of abiotic elements and substances such as minerals, ADP fossil shows the primary resource use of fossil fuels and the Primary energy resource use shows the use of non-renewable and renewable fuels in an energy unit (MJ). The results per MJ to propeller from this analysis are shown in Figure 8.1 to Figure 8.3. The results are very much related to the amount and type of materials used in the equipment and for the operation.

As shown in Figure 8.1 (ADP elements), the lowest impact is from the use of SECA fuel method 1 and the highest is from the use of the closed-loop scrubber. The impact emanates mainly from the use of chemicals (material in the chemical and material for its production) and fuel oil (material for its production). For the closed-loop, it is mainly the use of NaOH and water cleaning chemicals that contribute but also the production of the scrubber and the fuel oil (but not the crude oil resource). For the open-loop, it is mainly the scrubber materials and the fuel oil use that contributes. For the SECA fuel, it is mainly the materials used for its production that contributes. However, one shall keep in mind that the SECA fuel process contains much more generic data from databases than the data from the scrubber cases. Deviations can therefore exist due to uncertainties in the LCA datasets.

Figure 8.2 shows the overall fossil primary energy resource use for the entire system divided into production, operation, and End-of-Life. As shown from the figure, the energy use is relatively equal even if the SECA fuel case shows a slightly higher energy use. The difference between SECA fuel method 1 and 2 depends mainly on the use of a residue hydrocracker in method 2 to upgrade a surplus of heavy fuel oil to lighter products.

Figure 8.3 shows the primary energy resource use for the different cases. The main resource is of course the use of crude oil. The SECA fuel method 2 shows relatively high energy use due to the high energy use required for the residue hydrocracker to process HFO. For the closed-loop scrubber case, there are additional energy needs to operate the scrubber system and water cleaning as well as to produce the chemicals needed for the cleaning. For the open-loop scrubber case, there are additional energy needs for the scrubber system and the increased scrubber water flow compared to the closed-loop scrubber case. The energy use for the production of the heavy fuel oil compared to the SECA fuel oil should however be lower. The SECA fuel cases include the fuel use in the engine and the energy for the production of the fuel.

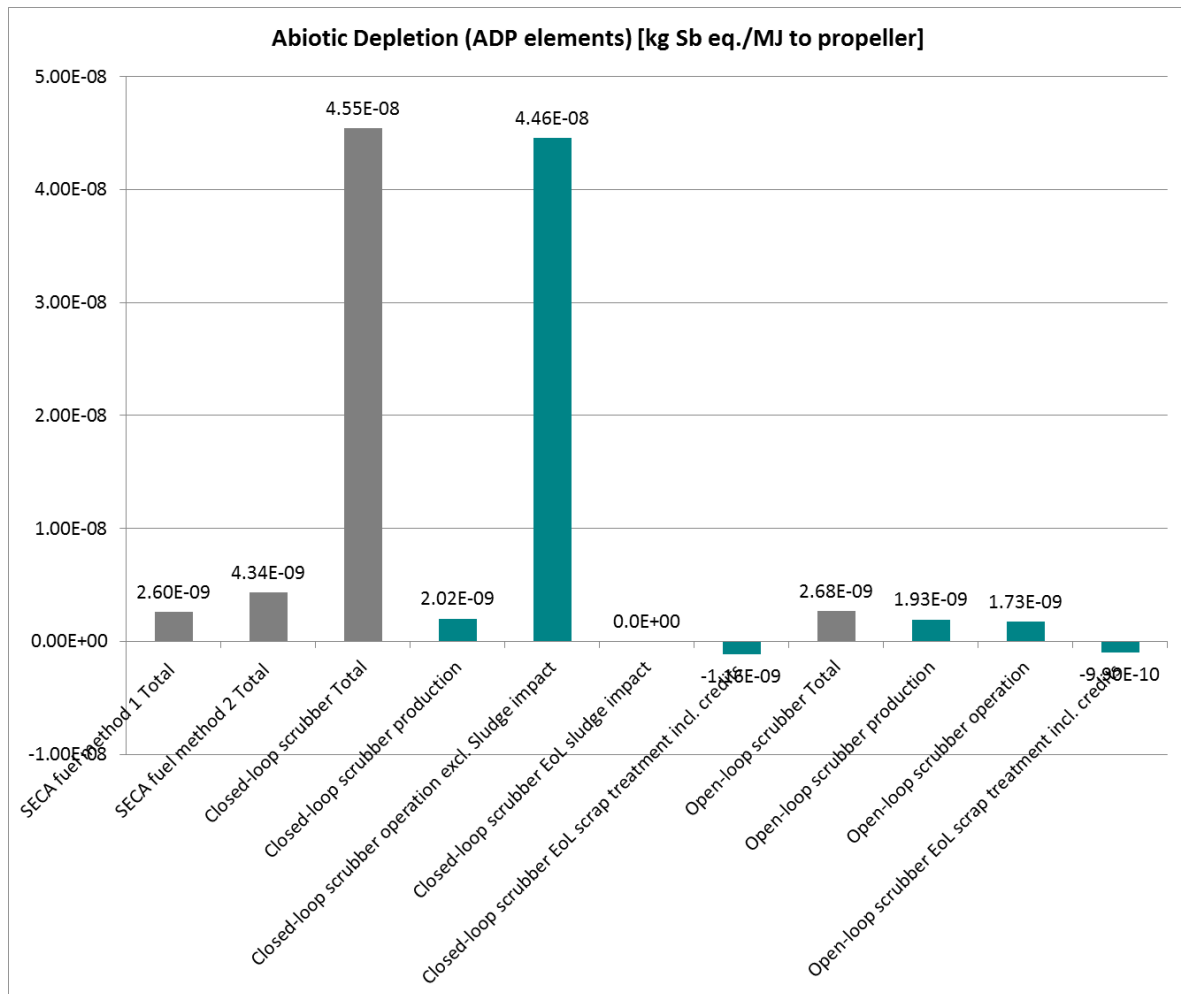


Figure 8.1 Comparison of Abiotic Depletion Potential (ADP elements) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

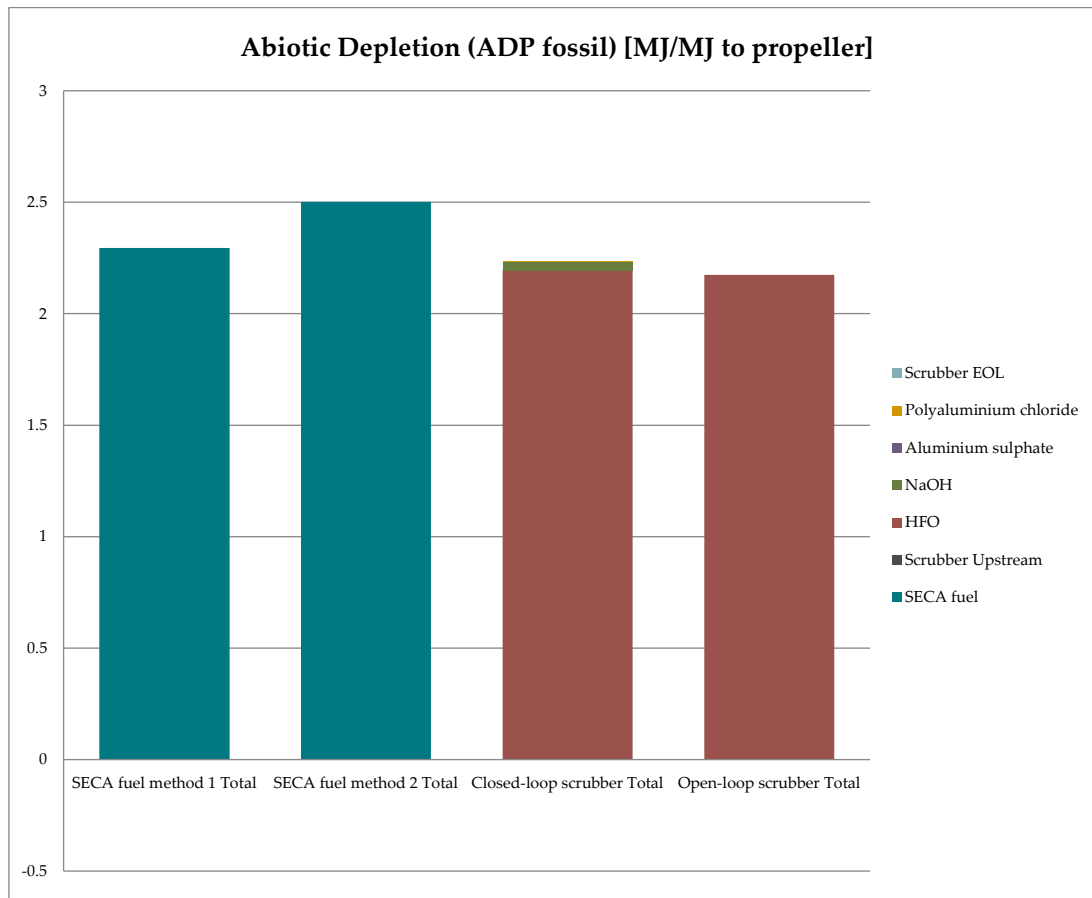


Figure 8.2 Comparison of Abiotic Depletion Potential (ADP fossil) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown.

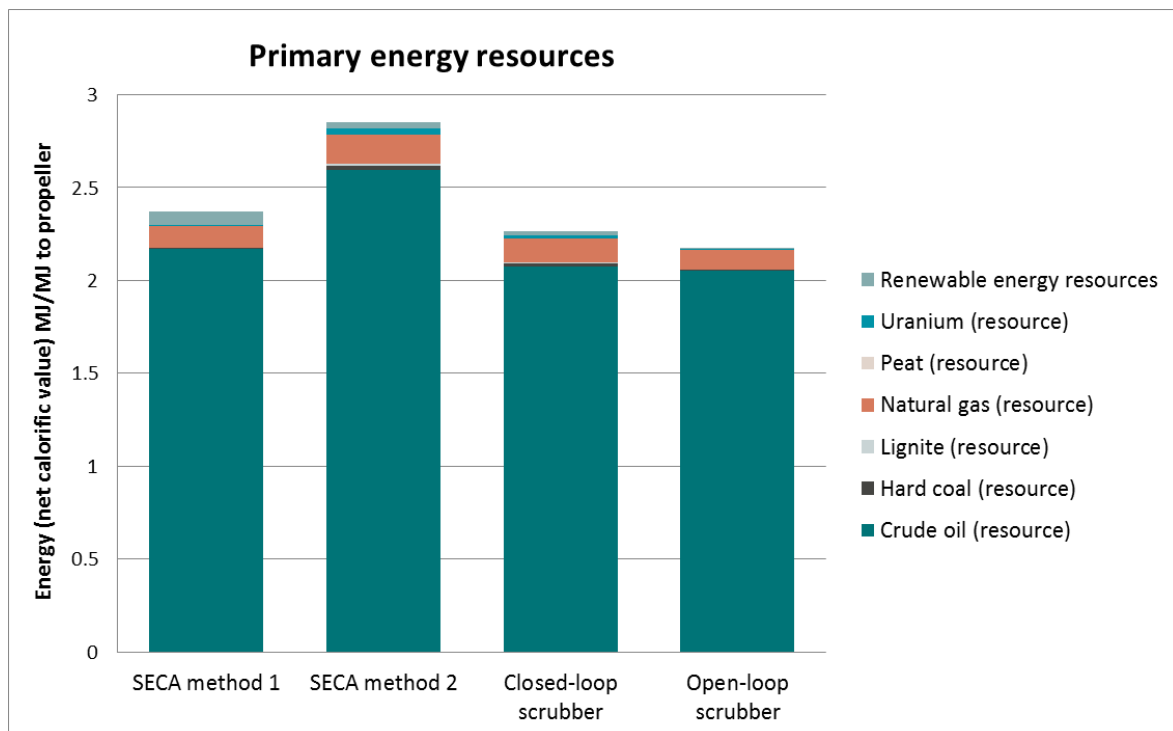


Figure 8.3 Comparison of Primary energy resource use (in MJ) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown.

The Global Warming Potential (GWP) results cover mainly CO₂ from combustion of fossil fuels but also emissions of CH₄ and N₂O. In this case, the combustion of fuel oil is an important aspect. In the SECA fuel case, it covers the combustion in the main engine of the ship and emissions from the fuel production from crude oil extraction to refining to SECA fuel quality. For the scrubber case, it covers the combustion in the main engine of the ship, the emissions from the heavy fuel oil production from crude oil extraction to refining to heavy fuel oil quality, emissions from the production of the chemicals used in the closed-loop scrubber system, and the emission from the extra energy use needed for the entire scrubber process (incl. scrubber water cleaning in the closed-loop and extra scrubber water flow in the open-loop). The GWP results from the different cases are shown in Figure 8.4. As shown in the figure, the GWP results are relatively equal between the different cases even if the SECA fuel alternative (method 2) is slightly higher. This can be explained by the additional use of refinery gas for heating in the residue hydrocracker. GWP emanates also from the operation of the scrubber systems (including the main engine) but less from the scrubber system production or the end-of-life (EoL) parts.

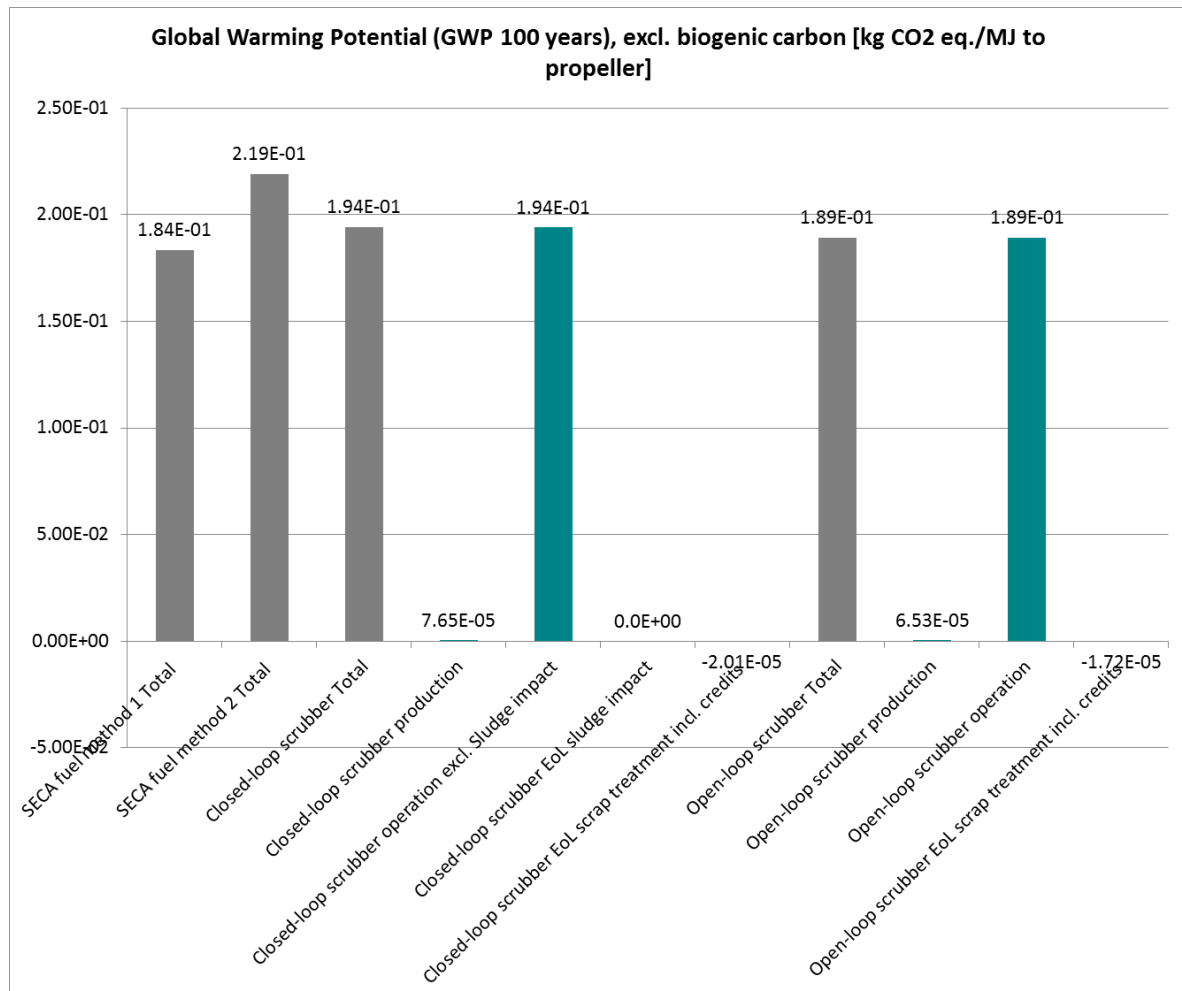


Figure 8.4 Comparison of Global Warming Potential (GWP 100) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

The acidification potential shows a similar pattern as GWP and energy, which is shown in Figure 8.5. The main contributors to acidification are the emissions of SO₂ and NO_x. Both GWP and AP are very much related to the combustion of the fuel oil with a defined emission level of SO₂/SO₃ and with the same type of engine i.e. relatively equal NO_x emissions however, with a difference between heavy fuel oil and SECA fuel. The NO_x emissions are not reduced or changed by the scrubber. The differences in Acidification potential can thus mainly be explained by the differences in energy use.

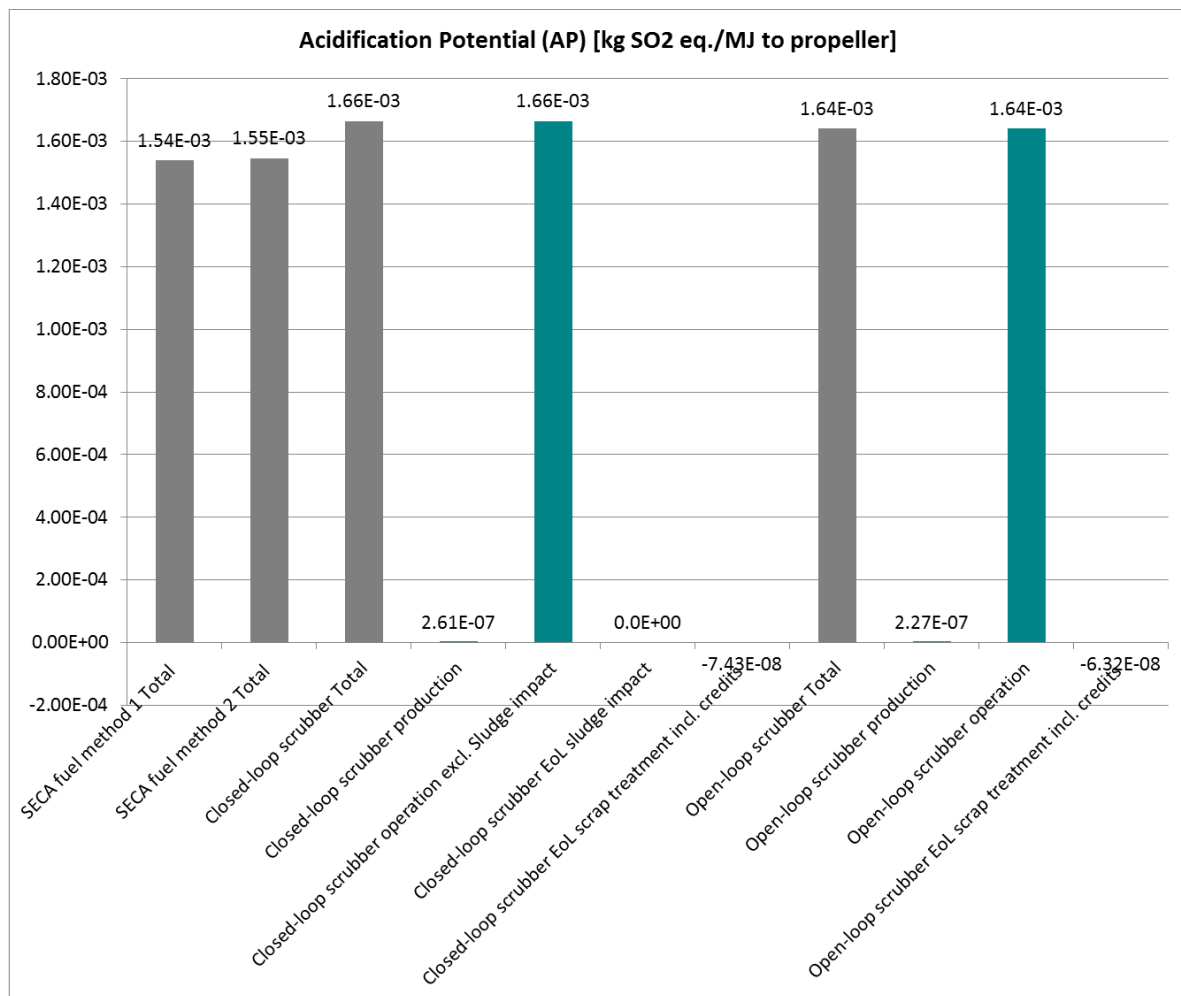


Figure 8.5 Comparison of Acidification Potential (AP) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

Also the eutrophication potential (EP) shows a similar pattern as GWP and AP with a small favor for the SECA fuel, see Figure 8.6. The main contributor to EP is the emission of NO_x. It is still the operation of the scrubber including the main engine that causes the main EP. An explanation to the higher EP values for the scrubber cases can be the higher NO_x emission levels for the heavy fuel oil used in the scrubber cases in combination with the different energy use.

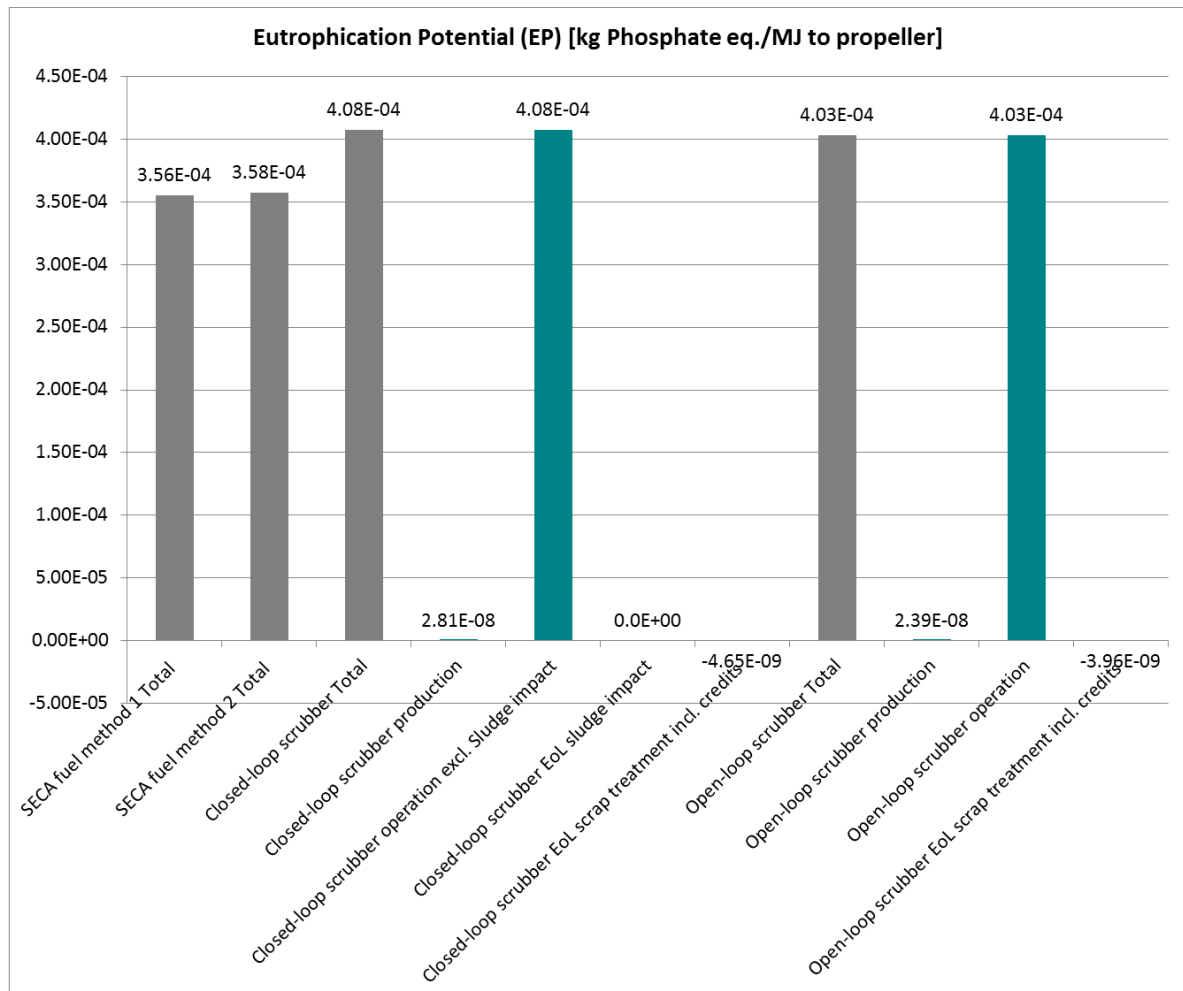


Figure 8.6 Comparison of Eutrophication Potential (EP) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

The Photochemical Ozone Creation Potential (POCP) is formed from hydrocarbons (HC) and NO_x in air, which, by means of sunlight, forms POCP. Both HC and NO_x are formed in the production process to produce the SECA fuel as well as in the combustion of the SECA fuel in the main engine. HC and NO_x emissions are also formed in the production of heavy fuel oil as well as in the combustion of the heavy fuel oil in the main engine and in the extra fuel needed in the main engine to supply the scrubber process with electricity from the generator on the shaft of the main engine to the propeller. Some reduction of HC emissions by the scrubber process can also occur. The net effect of these processes is thus shown the result figure below. As shown in the figure, the POCP values for the three scenarios are relatively equal, see Figure 8.7. However, it is likely to believe that the energy use is the main reason for the variation as the pattern is the same as the variation in energy use.

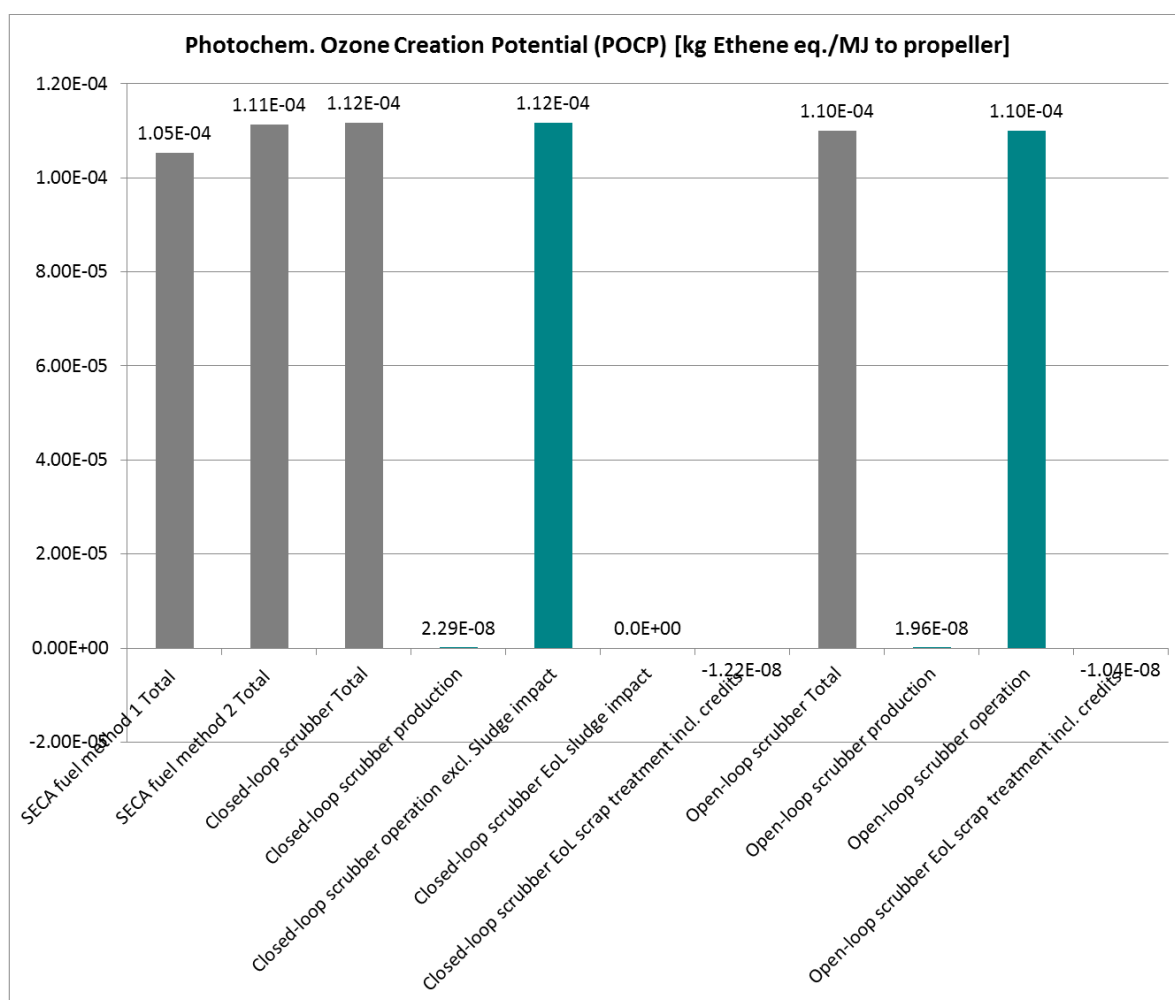


Figure 8.7 Comparison of Photochemical Ozone Creation Potential (POCP) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Negative values come from avoided processes in end-of-life. Grey bars show totals.

The cause of stratospheric Ozone layer Depletion Potential (ODP) is the manufacture of mainly halogen-carbon refrigerants, solvents, and foam-blowing agents (chlorofluorocarbons (CFCs), HCFCs, halons etc.), referred to as ozone-depleting substances (ODS). In the studied cases, the emissions of such chemicals are very low and thus, the ODP levels are also very low for all the cases. Emissions of such chemicals can, for example, occur at some metal production. The results from the analyses are shown in Figure 8.8. Production of aluminium can involve ozone-depleting substances. Aluminium can be used in some of the processes and also as coagulants and flocculants (aluminium sulfate and polyaluminium chloride). This can explain some of the results for the scrubber cases.

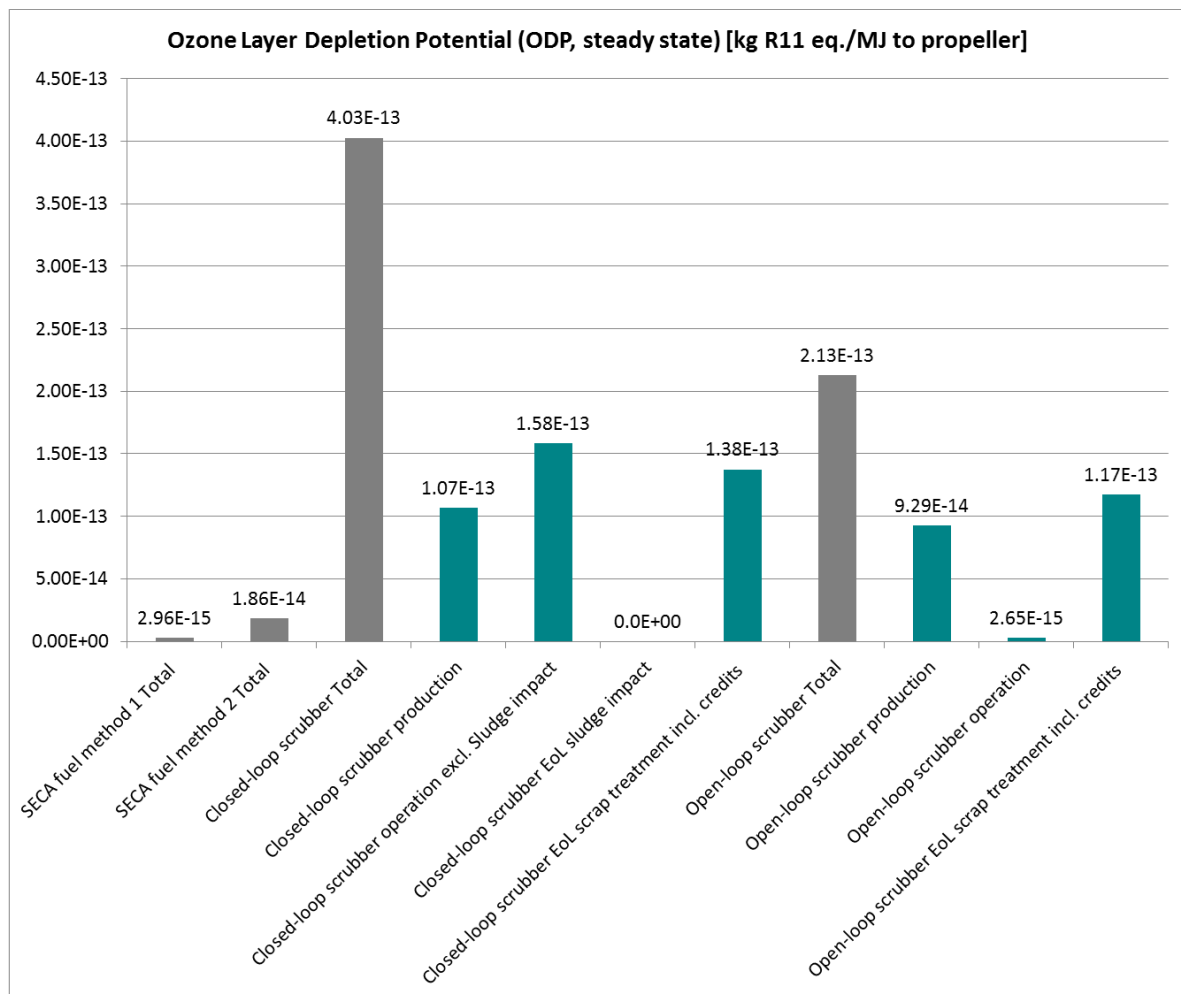


Figure 8.8 Comparison of Ozone layer Depletion Potential (ODP) between the three different cases in the study (SECA fuel, Closed-loop scrubber, and Open-loop scrubber). For the SECA fuel, two different methods are shown. For the scrubber cases, the total impact as well as the different contributing shares (production, operation, and end-of-life) are shown. Grey bars show totals.

Appendix A – Overview presentation of Life Cycle Assessment (LCA)

Environmental life cycle assessment (LCA) is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service (ISO 14040:2006 and 14044:2006).

Environmental inputs and outputs refer to demand for natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transports used at/needed for raw material extraction, production, use and after use (waste management or recycling). LCA is sometimes called a "cradle-to-grave" assessment (figure A1).

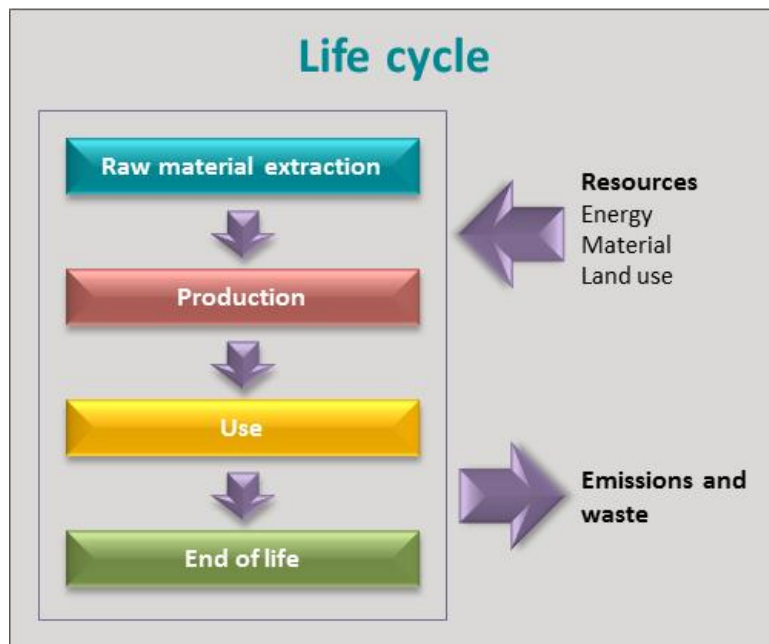


Figure A1: Illustration of the LCA system.

An LCA is divided into four phases. In accordance with the current terminology of the International Organization for Standardization (ISO), the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation (figure A2).

An LCA can be used in many different ways, depending on how the goal and scope are defined. Product development, decision making, indicator identification, and marketing are examples of areas where the information retrieved from an LCA may be valuable.

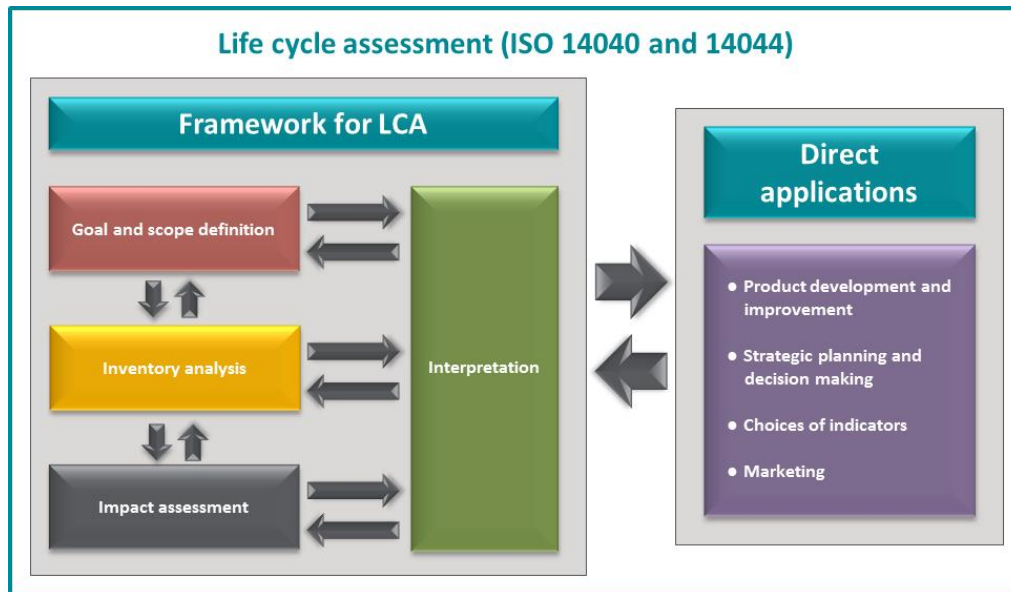


Figure A2: Illustration of the phases of an LCA.

Goal and Scope

In the first phase the purpose of the study is described. This description includes the intended application and audience, and the reasons for carrying out the study. Furthermore, the scope of the study is described. This includes a description of the limitations of the study, the functions of the systems investigated, the functional unit, the systems investigated, the system boundaries, the allocation approaches, the data requirements and data quality requirements, the key assumptions, the impact assessment method, the interpretation method, and the type of reporting.

Inventory analysis

In the inventory analysis, data are collected and interpreted, calculations are made, and the inventory results are calculated and presented. Mass flows and environmental inputs and outputs are calculated and presented.

Impact assessment

In the life cycle impact assessment (LCIA), the production system is examined from an environmental perspective using category indicators. The LCIA also provides information for the interpretation phase.

For comparative assertions, there are four mandatory elements of LCIA:

- Selection of impact categories, category indicators and models,
- Assignment of the LCIA results (classification),
- Calculation of category indicator results (characterization) and
- Data quality analysis.

The following elements are optional:

- Calculating the magnitude of category indicator results relative to a reference value (normalization),
- Grouping and
- Weighting.

Interpretation

The interpretation is the phase where the results are analysed in relation to the goal and scope definition, where conclusions are reached, the limitations of the results are presented, and where recommendations are provided based on the findings of the preceding phases of the LCA.

An LCA is generally an iterative process. The impact assessment helps increasing the knowledge about what environmental inputs and outputs are important. This knowledge can be used in the collection of better data for those inputs and outputs in order to improve the inventory analysis.

The conclusions of the LCA should be compatible to the goals and quality of the study.

Category definition, classification and characterisation

For each impact category i , the reasons why the environmental impact is considered to be an environmental problem are described. The category indicator – the quantified representation of the environmental impact – is defined, and the mechanisms that are modelled in the characterisation are described in brief. The characterisation factor describes the potential contribution to the impact category i from the input or output of substance j per unit mass of j . The total contribution to the impact category from the life cycle, C_i , is calculated as:

$$C_i = \sum E_j \cdot W_{ij}$$

where E_j is the amount of the input or output of substance j .

Global warming

A global climate change is a problem for many reasons. One is that a higher average temperature in the seawater results in flooding of low-lying, often densely populated coastal areas. This effect is aggravated if part of the glacial ice cap in the Antarctic melts. Global warming is likely to result in changes in the weather pattern on a regional scale. These can include increased or reduced precipitation and/or increased frequency of storms. Such changes can have severe effects on natural ecosystems as well as for the food production.

Global warming is caused by increases in the atmospheric concentration of chemical substances that absorb infrared radiation. These substances reduce the energy flow from Earth in a way that is similar to the radiative functions of a glass greenhouse. The category indicator is the degree to which the substances emitted from the system investigated contribute to the increased radiative forcing. The characterisation factor stands for the extent to which an emitted mass unit of a given substance can absorb infrared radiation compared to a mass unit of CO₂. As the degree of persistence of these

substances is different, their global warming potential (GWP) will depend on the time horizon considered, such as 20, 100 and 500 years. In this study, a time horizon of 100 years has been applied. The time scale 100 years is often chosen as a “surveyable” period in LCAs and discussions regarding global warming.

The characterisation of this environmental impact takes into account the substances that contribute directly to the greenhouse effect. The total contribution to the global warming potential from the life cycle is calculated as:

$$GWP = \sum GWP_j \cdot E_j$$

where E_j is the amount of the output j and GWP_j the characterisation factor for this output. The characterisation factor is measured in *g CO₂ equivalents per g of the emitted substance*, and thus, the unit of the category indicator is *g CO₂ equivalents (g CO₂ eq.)*.

Acidification

Acidification stands for the decrease of the pH value in terrestrial and water systems. This is a problem, e.g., because it causes substances in the soil to dissolve and leak into the water systems. These substances include nutrients, which are needed by plants, as well as metals such as aluminium and mercury, which can have toxic effects in the aquatic ecosystems. Reduced pH in the water system also has direct, ecotoxic effects, reducing the number of species that can live in lakes, etc. Emission of acidifying substances also causes damage on human health, and on buildings, statues and other constructions.

The characterisation takes into account the substances that contribute to the acidification of the soil and of lakes. The category indicator is the ability of the emissions from the system investigated to release H⁺ ions. The acidification potential is the ability of 1 mg of a substance to release H⁺ ions compared to that of 1 mg of SO₂.

The substances that contribute most to acidification are SO₂, NO_x, NH₃, HCl and other acids. As stated above, the release of H⁺ will depend on the conditions at the terrestrial or water system where the acid or acid-producing substance is deposited. Most sulphur is emitted as SO₂. It is either deposited as it is or transformed in the air into sulfuric acid, which subsequently will be deposited and will generate two protons, or will react in the air. If SO₂ is deposited, it will be transformed into sulfuric acid in the ecosystem and release two protons per atom of sulphur. In the air, sulfuric acid may react with ammonia to form ammonium sulphates. However, the deposition of ammonium sulphates will generate the same amount of H⁺ as sulfuric acid and ammonia would if they were separately deposited.

The total contribution to the acidification potential from the life cycle is calculated as:

$$AP = \sum AP_j \cdot E_j$$

where E_j is the amount of the output j and AP_j the characterisation factor for this output. The characterisation factors are measured in *mg SO₂-equivalents per g of the emitted substance*, and thus, the category indicator is measured in *mg SO₂-equivalents*.

Eutrophication (nutrient enrichment)

When the nutritional balance in the soil and waters is disturbed, it is called eutrophication (when the amount of nutrition is increased). In aquatic systems, this leads to increased production of biomass, which may lead to oxygen deficiency when it is subsequently decomposed. The oxygen deficiency, in turn, kills organisms that live in or near the bottom of the lakes or coastal waters. It also makes the reproduction of fish more difficult.

In terrestrial systems, deposition of nitrogen compounds leads to increased concentrations of nitrogen, which in turn leads to a change in the growing conditions. The nitrogen may leak into water systems, and cause increased levels of nitrogen in the aquatic systems. The effects in aquatic systems depend on the recipient. Different terrestrial and aquatic systems have different sensitivity to eutrophying and oxygen depleting substances. Phosphorous-containing substances increase biomass production where the availability of phosphorous limits the growth. In other case, biomass production is increased through emissions of N-containing substances. These local variations are not taken into account in this impact assessment.

The category indicator is the potential of the emissions from the system investigated to deplete oxygen in aquatic systems, e.g. through increased biomass production. The potential contribution to eutrophication is in this study expressed as phosphate-equivalents, i.e., the capacity of 1 mg of a substance to favour biomass formation compared to that of 1 mg of phosphate (PO_4^{3-}). Another unit that is used to measure eutrophication NO_x -equivalents. One unit of NO_x -equivalents corresponds to 0.13 g PO_4^{3-} -equivalents.

Oxygen depletion in aquatic systems is caused not only by emissions of nutrients that stimulate the biomass production, but also by direct emissions of organic material that is decomposed in the water. These emissions can be measured in terms of BOD (biological oxygen demand), COD (chemical oxygen demand), or TOC (total organic carbon). They are taken into account in the characterisation of this environmental impact.

The total contribution to the Eutrophication potential from the life cycle is calculated as:

$$EP = \sum EP_j \cdot E_j$$

where E_j is the amount of the output j and EP_j the characterisation factor for this output. The characterisation factors used for eutrophication are measured in *mg PO_4^{3-} -equivalents per mg of the emitted substance*. Thus, the unit of the category indicator is *mg PO_4^{3-} -equivalents*.

Photo-oxidant formation

This impact category reflects the problem of creation of oxidising compounds (oxidants) through photochemical reactions in the air (close to the ground). An oxidant is by definition substances that are able to oxidise I^- (iodide) to I_2 (iodine). The most important oxidant in this context is ozone. The tropospheric concentration of ozone and other oxidants has increased during the last century. The surface ozone (ozone close to the earth's surface) concentration has been doubled in the Northern Hemisphere from the time of pre-industrialisation to today. Surface ozone has toxic effects on humans and vegetation. Smog in large cities is an effect of these kinds of reactions.

The ozone is formed by volatile organic compounds (VOC) and radiation from the sun, under the presence of NO_x . When ozone is created under the influence of solar radiation, NO is gained. This substance must be oxidised back to NO_2 by another molecule than the ozone, in order to get a net

increase of ozone. Peroxy radicals mainly from decomposed VOCs act as oxidising agents. If the background level of NO_x is low, NO_x may be the limiting factor for ozone formation. Where the atmospheric NO_x concentration is high, the concentration of VOCs and, hence peroxy radicals is the limiting factor. The most efficient ozone producers are propene and ethene, but also higher alkenes, aromatics, alkanes and ethers produce ozone.

The impact indicator for photochemical oxidant formation (POCP) is the potential of the emissions from the system investigated to contribute to the creation of oxidising compounds. The equivalent used for this impact category is mg ethene (C₂H₄); the photochemical oxidant creation potential of a substance is a measure of the extent to which a mass unit of the substance forms oxidants compared to the oxidant formation from a mass unit of ethene.

The total POCP of the emissions from the life cycle is calculated as:

$$\text{POCP} = \sum \text{POCP}_j \cdot E_j$$

where E_j is the amount of the output j and POCP_j the characterisation factor for this output. The characterisation factors for photochemical ozone formation are measured in *mg C₂H₄-equivalents per mg of the emitted substance*. Thus, the category indicator is measured in *mg C₂H₄-equivalents*.

Appendix B - Details on data collection

B1: Operation phase data collection

Closed-loop scrubber

Measurement data from the analysis of the closed-loop scrubber system at 75 % engine load and heavy fuel oil as fuel to the main engine.

Table B1 Closed-loop scrubber air emission during operation phase with 75 % engine load. Emissions are calculated per MJ energy to the propeller.

Air emission (at 75 % engine load)	Amount (kg/MJ to propeller)
CO ₂ Specific emission	1.74E-01
CO Specific emission	2.24E-04
HC Specific emission	4.58E-05
NO _x Specific emission	3.10E-03
CH ₄	1.14E-06
PM _{2.5} average	7.35E-05
SO ₂ measured Specific emission	1.69E-05
TC Spec. emission, Dilution	3.25E-05
PAH Spec emission	2.18E-07
SO ₃ Spec emission	2.28E-05
SO ₂ (particulate) Spec emission	5.95E-06

Table B2 Closed-loop scrubber emissions from effluent water to the sea.

Water emission	Amount (kg/l)
benzen	7.20E-10
toluen	4.00E-10
1,4-xylen	5.50E-10
1,2-xylen	4.00E-10
hexachlorbenzen	1.00E-10
acenaftylen	3.60E-10
acenaften	2.10E-09
fluoren	3.20E-09
fenanthren	1.00E-08
anthracen	4.00E-10
fluoranthren	2.20E-10
pyren	5.40E-10
benzo(a)anthracen	2.10E-10
chrysen	3.30E-10
benzo(b)fluoranthren	1.00E-10
benzo(k)fluoranthren	7.00E-11
benz(a)pyren	1.00E-10
benzo(g,h,i)perylene	1.00E-10
indeno(1,2,3-c,d)pyren	1.00E-10
dibenzothiophene	1.50E-09
dimethylnaphthalene	3.00E-08
As	2.00E-08
Cr	9.00E-09
Cu	1.50E-07
Ni	8.30E-07
V	9.80E-06
Al	8.30E-06
S	1.90E-02
Hg	5.20E-12

Table B3 Sludge main composition derived from closed-loop scrubber operation phase.

Sludge composition	Amount (mg/kg)
Aluminium	17 000
Cadmium	<1
Calcium	15 000
Chromium	20
Copper	5
Iron	550
Lead	<1
Magnesium	4700
Nickel	1400
Silicon	12 000
Sodium	21 000
Vanadium	5000
Zinc	150
Sulfur	8200

Open-loop scrubber system

Measurement data from an open-loop scrubber system at 75 % engine load and heavy fuel oil as fuel to the main engine.

Table B3 Open-loop scrubber air emission during operation phase with 75 % engine load. Emissions are calculated per MJ energy to the propeller.

Air emission (at 75 % engine load)	Amount (kg/MJ to propeller)
CO ₂ Specific emission	1.73E-01
CO Specific emission	2.22E-04
HC Specific emission	4.53E-05
NO _x Specific emission	3.07E-03
CH ₄	1.12E-06
PM _{2.5} average	7.28E-05
SO ₂ measured Specific emission	1.67E-05
TC Spec. emission, Dilution	3.22E-05
PAH Spec emission	2.16E-07
SO ₃ Spec emission	2.26E-05
SO ₂ (particulate) Spec emission	5.90E-06

Table B4 Open-loop scrubber emissions from effluent water to the sea.

Water emission	Amount (kg/l)
benzen	4.10E-10
toluen	2.15E-10
xilyen	2.00E-10
1,4-X	2.00E-10
1,2-X	2.00E-10
naftalen	7.40E-09
acenaftylen	1.65E-11
acenaften	2.00E-10
fluoren	1.90E-09
fenanthren	2.65E-09
anthracen	5.40E-11
fluoranthen	3.90E-10
pyren	3.40E-10
b(a)anthr	1.61E-10
chrysen	1.95E-10
b(b)flu	6.75E-11
b(k)flu	2.40E-11
b(a)pyren	1.75E-11
db(ah)anthr	1.30E-11
b(ghi)per	4.00E-11
in(c,d,)pyr	1.34E-11
Al	1.80E-07
S	1.20E-03
V	8.40E-08
Cr	3.10E-08
Ni	3.20E-08
Cu	1.40E-08
Zn	8.20E-08
As	2.40E-09
Cd	5.00E-10
Pb	6.30E-10
Hg	6.50E-12

SECA fuel

Measurement data for air emissions directly from the ship engine at operation with SECA fuel and 75 % engine load.

Table B5 Air emissions from the main engine during operation of the ship at 75 % engine load. Emissions are calculated per MJ energy to the propeller.

Air emission (at 75 % engine load)	Amount (kg/MJ to propeller)
CO ₂ Specific emission	1.66E-01
CO Specific emission	1.47E-04
HC Specific emission	7.25E-05
NO _x Specific emission	2.70E-03
THC Specific emission	7.25E-05
CH ₄ Specific emission	5.45E-07
NMHC Specific emission	7.19E-05
TSP average	3.36E-05
PM _{2.5} average	3.20E-05
SO ₂ Specific emission	1.00E-04
OC Specific emission, Dilution = DT	5.13E-05
EC Specific emission, Dilution = DT	2.66E-06
PAH Spec emission	6.59E-05
SO ₂ (particulate) Spec emission	1.64E-07





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