Trafik analys

Fuels in the Baltic Sea after SECA

PM 2016:12

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Publiceringsdatum: 2016-08-25

Förord

Trafikanalys följer utvecklingen inom sjöfarten efter att kravet på svavelhalten i marint bränsle inom SECA skärptes första januari 2015. Nya bränslen har börjat användas i fartygen för att uppfylla de nya kraven om högst 0,1 viktprocent svavel i bränslet. För att kunna ge möjliga förklaringar till förändringar i sjöfartens utsläpp behöver man känna till vilka bränslen som används, vad de innehåller och vilka utsläpp dessa genererar. Livscykelanalyser inkluderar utsläpp från hela produktionskedjan till slutanvändning. Denna rapport presenterar uppskattningar av bränsleanvändning och fördelning mellan bränsletyper före och efter införandet av svaveldirektivet. Livscykelanalyser visar att utsläppen från marint bränsle förändras med avseende på bland annat koldioxid och partiklar beroende på vilken bränsletyp som används. Trots att direktivet leder till lägre svavelutsläpp kan således andra utsläpp öka.

Datainsamling och analys har utförts av professor Karin Andersson och Dr Selma Brynolf vid institutionen för Sjöfart och marin teknik på Chalmers tekniska högskola. Rapporten har skrivits av Karin Andersson och Selma Brynolf i samarbete med Trafikanalys projektledare Märit Izzo. I projektgruppen har även Krister Sandberg ingått. Vi vill även tacka Transportstyrelsen, Naturvårdsverket och Energimyndigheten för hjälp med datainsamling, faktagranskning och kommentarer.

Östersund i augusti 2016

Brita Saxton

Generaldirektör

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Sammanfattning

Efter att svavelreglerna för marina bränslen trädde i kraft 1 januari 2015 i utsläppskontroll-området i Nordsjön och Östersjön (SECA) har det skett en förändring av fartygens bränsle-användning. Den tillåtna svavelhalten ändrades från 1 viktsprocent till 0,1 procent. Det 1 procentiga bränslet som finns på marknaden är huvudsakligen tjockolja, ”heavy fuel oil” (HFO) som är en restprodukt från raffinaderier. Det 0,1 procentiga bränslet är till stor del destillat som ”marine gas oil” (MGO) eller ”marine diesel oil” (MDO). Efter att regelverket trädde i kraft, har så kallade ”hybridbränslen” (även kallat SECA-bränslen) eller ultra-low sulphur fuel oils (ULSFO) börjat användas i allt högre grad. Det finns även rederier som väljer att konvertera fartygen till att drivas på LNG (flytande naturgas) eller att fortsätta använda HFO med avgasrening, så kallad skrubber.

För att utvärdera effekten av svavelreglerna, även med avseende på förändringar i bränsle-produktion och utsläpp, måste man känna till vilka bränslen som används och vilka emissioner dessa ger upphov till i ett livscykelperspektiv.

Rapporten innehåller två delar där den första syftar till att utreda vilka marina bränslen som används i Östersjön efter 1 januari 2015 i jämförelse med 2014. I den andra delen utvärderas emissionerna relaterade till sjöfartsbränslen i ett livscykelperspektiv när förhållandena förändrats. De emissioner som inkluderas är koldioxid (CO_2), partiklar (PM), svaveloxider(SO_x), metan (CH_4) och kväveoxider (NO_x).

Vid mätningar av svaveloxid i omgivningsluft är det tydligt att dessa har minskat drastiskt efter att regelverket infördes. För att utvärdera påverkan på alla emissioner som uppstår när man övergår till hybridbränsle krävs fler emissionsmätningar och data från raffinaderier. Påverkan på raffinaderiet är inte extremt stor och emissionerna per megajoule bränsle är påtagligt högre från ”tank till propeller” än från ”källa till tank”. Vilken blandning av bränslen som används i SECA påverkar emissionerna på olika sätt. I denna studie dras följande slutsatser om skillnader mellan 2014 och 2015:

- Även om det inte är möjligt att göra en strikt kvantifiering av fördelningen mellan MGO, hybridbränslen, LNG och HFO med skrubber i dag, är det tydligt att för-ändringarna i totala koldioxidutsläpp från en ny bränslefördelning är relativt små och osäkerheten i tillgängliga data är för stor för att man ska kunna dra långtgående slutsatser.
- De totala koldioxidutsläppen kommer att vara mycket större än vad som kan accep-teras för att uppfylla det Europeiska målet om att minska koldioxidutsläppen från sjöfarten med 40 procent till 2050 jämfört med 2005 nivån. Förändrade utsläpp från raffinaderier ändrar inte den bilden i någon påtaglig grad.
- Utsläppen av svaveldioxid har minskat kraftigt.
- Effekten av att använda hybridbränsle i stället för MGO verkar motverka den för-väntade marginella minskningen i partikelemissioner genom att HFO används i mindre grad. Mycket mindre partikelutsläpp fås med LNG eller metanol.
- NO_x emissioner påverkas inte i signifikant grad av att byta från HFO till MGO eller hybridbränsle. De enda bränslen i studien som påverkar detta är LNG och metanol.

Abstract

After the sulphur regulation for marine fuels was entered into force 1st of January 2015 in the North Sea and the Baltic Sea sulphur emission control area, SECA, a change in the kinds of fuels used has occurred. The allowed sulphur content in marine fuels was decreased from 1 per cent to 0.1 per cent by mass. The 1 per cent sulphur fuel available on the market is mainly heavy fuel oils, HFO, which is a residue fraction from refineries. The 0.1 per cent fuels available are primarily distillate fuels like marine gas oil, MGO, or marine diesel oil, MDO. However, after the introduction, a number of "hybrid fuels" (or ECA fuels, or ultra-low sulphur fuel oils, ULSFO), have been introduced to the market. Also, in order to comply with the stricter regulation it is also possible to convert the ship to run on LNG (liquefied natural gas) fuel or to use HFO with abatement equipment, "scrubber".

Besides the sulphur emissions, other environmental effects of the regulations need to be evaluated. Changes in fuel production, the types of fuels used and the emissions in a "well-to-propeller" perspective related to the fuels have to be assessed.

The first part of the report aims at investigating what marine fuels are used in the Baltic Sea after January 1st 2015. The second part evaluates the emissions from marine fuels taking a life cycle perspective. The considered emissions are carbon dioxide (CO_2), particulate matter (PM), sulphur oxides (SO_x), methane (CH_4), and nitrogen oxides (NO_x).

It is clear from measurements in ambient air that the sulphur oxide emissions have decreased significantly since the introduction of the stricter regulation. To assess the other emissions more measurements of exhaust emissions and refinery data are necessary. The impact on emissions from the refinery processes is small. However, the emissions per MJ fuel used are significantly higher from the tank-to-propeller analysis than from the well-to-tank analysis. The mix of fuels used in the SECA area is affecting the emissions in various ways.

- Although a strict quantification of the distribution between MGO, hybrid fuels, LNG and HFO with scrubber is not possible today, it is clear that the changes in total CO_2 emissions caused by the possible fuel mix is quite small, and the uncertainties in data are too large to draw far reaching conclusions from.
- The total emissions of CO_2 from marine fuels will continue to be high and the changes in emissions from refineries will not change this picture to a significant degree.
- The effect of using hybrid fuel instead of MGO seems to counteract the expected minor decrease in particle emissions due to less HFO used. Less particle emissions is obtained by use of LNG or methanol.
- The total emissions of SO_x is significantly reduced.
- The NO_x emissions are not affected significantly change from HFO to MGO or hybrid fuel. The only fuels that affects this are LNG and methanol.

1 Introduction

The increased attention to air emissions from shipping in recent years has resulted in stricter regulations. The International Maritime Organization (IMO), the United Nations agency responsible for the safety and security of shipping and the prevention of marine pollution by ships, has adopted regulations regarding the sulphur content in marine fuels and the emissions of NO_X (IMO, 2013). It is also expected that the PM emissions will be reduced indirectly by these regulations. In addition, the European Commission's white paper "Road-map to a Single European Transport Area", dated 2011, states that CO_2 emissions from maritime transport in the European Union should be reduced by 40 per cent by 2050 compared to 2005 levels (European Commission, 2011).

The global limit on the sulphur content of marine fuels will be reduced significantly to 0.5 per cent sulphur by 2020 or, at the latest, 2025,[1] versus the present cap of 3.5 per cent. This regulation is stricter in certain emission control areas (ECAs). Beginning in 2015, emissions of SO_2 will be limited to the equivalent of 0.1 wt. per cent sulphur in combusted fuel within the sulphur emission control areas (SECAs) in the Baltic Sea, the North Sea, the English Channel, the United States Caribbean Sea and along the coasts of the United States and Canada.

1.1 Background

After the sulphur regulations for marine fuels entering into force 1st of January 2015 in the North Sea and the Baltic Sea sulphur emission control area, SECA, a change in the kinds of fuels used has occurred. The allowed sulphur contents in marine fuels was at that time decreased from 1 per cent to 0.1 per cent by mass. The 1 per cent sulphur fuels on the market are mainly heavy fuel oils, HFO, a residue fraction from refineries. The 0.1 per cent fuels available are to a large degree distillate fuels like marine gas oil, MGO, or marine diesel oil, MDO. These are lighter and less viscous fractions, and usually with lower contents of other contaminants.

The regulation can also be fulfilled by use of an almost sulphur free gaseous fuel, liquid natural gas, LNG. LNG can be used in dual fuel engines which also can be run on HFO, MDO or MGO. Small amounts of diesel oil is used in the dual fuel engines to improve ignition. This solution sets demands on a different solution for fuel tanks, since the fuel is liquid at very low temperature, - 162^{o}C. A technical solution is to remove the sulphur from the exhausts by "scrubbers", a technology that is well proven from land use (Brynolf et al., 2014b).

The change of sulphur contents in the fuel will, as is the intention with the regulation, decrease the emissions of sulphur oxides. It is also envisaged that a "cleaner" fuel will result in less

[1] A review of the availability of fuel oil is to be completed in 2018. If the parties decide that it is impossible for ships to comply, then the standard will postponed until 2025 IMO 2013. *MARPOL ANNEX VI AND NTC 2008 WITH GUIDELINES FOR IMPLEMENTATION,* London, CPI Group (UK) Ltd.The sulphur content in marine fuels in the European Union is reduced to 0.5 per cent by 2020 EUROPEAN COMMISSION 2012. Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels. Journal of the European Union.

particle emissions, an emission that is not regulated today. When the regulation was introduced, it was expected that it would be a large change in fuel use, from HFO to distillates or scrubber installations and also some engine retrofits to LNG. However, after the introduction, a number of "hybrid fuels" (or ECA fuels, or ultra-low sulphur fuel oils, ULSFO), have also entered the market. In this report we will use the term hybrid fuels. These hybrid fuels fulfil the sulphur requirements but are more similar to residual fuels than distillates in terms of viscosity and lubricity. They are also less expensive than distillates. However, hybrid fuels do not belong to a well-defined fuel category, but a trade name for a category of fuel that suits large marine diesel engines and fulfil the sulphur regulation.

In order to assess the environmental effects of the sulphur regulation, also with respect to changes in fuel production in refineries, the fuels used and the emissions related to the fuels have to be known. Avis and Birch (2009) predicted the impacts on the EU refining industry and markets of the regulation and found that carbon dioxide emissions likely will increase.

In 2010, the first decrease of level of fuel sulphur in the SECA (from 1.5 to 1 per cent) was entered into force. Model calculations of the effects on emissions from ships in the Baltic Sea and North Sea found that particle emissions decreased (Jonson et al., 2015). At the same time, however, other positive environmental effects seem to have been counteracted by an increase in transport at that time.

In contrast, (so far) the result of the 2015 regulation in terms of sulphur concentration in the ambient air seems very good. Atmospheric surveillance in Sweden and Denmark show lower concentrations in 2015 than in previous years (Pihl-Karlsson, 2015, Einemo, 2016). The reductions are in the order of 50 per cent or more. The effect on other emissions is not possible to assess from the present monitoring. The expectation that other emissions like particles would decrease when using low sulphur fuel cannot be validated since there are no emission measurements. The predicted effect on emissions and energy use from refineries when producing larger quantities of low sulphur fuel were estimated in early consequence analyses (Dastillung, 2009, Calzado Catalá et al., 2013), but the outcome after the regulation is not evaluated.

1.2 Goal of report

The report comprises two parts. The first part aims to assess the marine fuels used in the Baltic Sea after January 1st 2015 for comparison to 2014. The second part evaluate the emissions from shipping under the changed conditions taking a life cycle perspective on the fuels.

The first part focuses on the use of marine fuels and the production of marine hybrid fuels. The second is an assessment of emissions related to fuels "from well to propeller" before and after the change. The considered emissions are carbon dioxide (CO_2), particulate matter (PM), sulphur oxides (SO_x), methane (CH_4), and nitrogen oxides (NO_x).

1.3 Method

Information on usage of marine fuel, marine fuel sales and fuel quality in the SECA is poor or non-existent. In this study, literature data estimating total fuel consumption by using AIS data have been used as a source. In addition, various sources of information have been used to provide a basis for estimating the distribution between fuel qualities.

The Swedish Transport Agency is the surveying authority for controlling the sulphur content in bunker fuel. Randomized fuel samplings from ships calling Swedish ports are analysed by an accredited laboratory to monitor the fulfilment of the regulation. During 2015 around 400 samples were taken. These results have been available for the study.

The sales of bunker fuel in Sweden are reported to the Swedish Energy Agency (Energimyndigheten) and to the Swedish Chemicals Agency (Kemikalieinspektionen) for use in energy statistics. The Swedish Energy Agency have until now been collecting data in terms of fuel oil (eldningsolja, Eo1 and Eo 2-6) which does not provide details on fuel quality. The sulphur contents is not reported here, which may be due to the fact that this is only an issue for bunker fuel for shipping.

Through the Swedish Shipowner's Association (Svensk Sjöfart) a questionnaire on fuel qualities and quantities used by the members in 2015 was sent out. This reaches only Swedish ship-owners with ships in routes within SECA, but it provides another set of data to combine with the bunker fuel samples.

Environmental indicators for the fuels used in the Baltic Sea after 2015 is calculated using life cycle assessment (LCA). LCA considers the whole life cycle of a product from well to cradle (Figure 1.1). For a more detailed description about the LCA method see for example Baumann and Tillman (2004). The goal of the study decides which type of LCA that is used. The most common division of LCA types in literature is between attributional[2] and consequential[3] studies. Attributional studies explore the system and its causes[4], while consequential studies explore its effects. Attributional LCAs strive to be as complete as possible, accounting for all environmental impacts of a product, while consequential LCAs strive to describe the environmental consequences of alternative courses of action. A consequential LCA addresses questions such as 'What would be the environmental consequence of using Fuel A instead of Fuel B?' while attributional LCA addresses questions such as 'What would be the overall environmental impact of marine transportation with Fuel A?'.

There has been, and still is much debate in the LCA community regarding when the different types should be used (Finnveden et al., 2009).

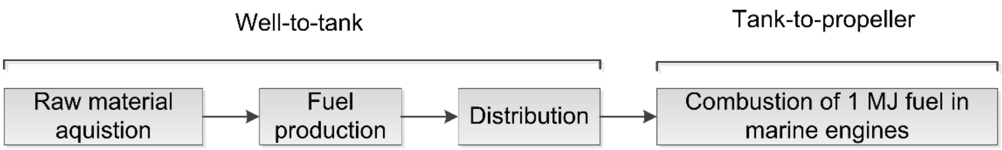

Figure 1.1 A simplified flowchart of the life cycle of marine fuels from raw material acquisition to combustion in marine engines

The LCAs are geographically limited to ship operations in the northern part of Europe but do include the entire fuel cycle, from the raw material extraction to the combustion in marine engines, excluding the production of capital goods (e.g., ships, terminals, exhaust abatement technology, etc.). In a screening LCA by Johnsen and Magerholm-Fet (1998), the fuel life

[2] The term *accounting* is also used, e.g. in BAUMANN, H. & TILLMAN, A.-M. 2004. *The hitchhiker's guide to LCA : an orientation in life cycle assessment methodology and application,* Lund, Studentlitteratur..
[3] The term *change-oriented* is also used, e.g. in ibid..
[4] For example: the economic profit is one of the reasons a system exists; this can therefore be used to motivate an allocation based on economic value in an attribution study TILLMAN, A.-M. 2000. Significance of decision-making for LCA methodology. *Environmental Impact Assessment Review,* 20**,** 113-123..

cycle was shown to be responsible for the largest proportion of the environmental impact associated with a ship's life cycle.

Previous LCAs conducted at Shipping and Marine Technology, Chalmers (Brynolf et al., 2014b, Brynolf et al., 2014a), have been updated and complemented with new data. A first screening LCA of hybrid fuels have also been conducted to complement the previous LCAs for alternatives fulfilling the SECA regulation. The investigated fuels are summarised in Table 1.1.

Table 1.1. Summary of fuels investigated

Abbreviation	Full name	Energy carrier	Primary energy source
HFO+scrubber	Heavy fuel oil with scrubber	Diesel	Crude oil
Hybrid fuels	Fuel oil with <0.1per cent sulphur by mass	Diesel	Crude oil
MGO	Marine gas oil	Diesel	Crude oil
LNG	Liquefied natural gas	Methane	Natural gas
Methanol	Methanol	Methanol	Natural gas

2 Fuels used in the Baltic Sea 2015

The main fuels used in the Baltic Sea are petroleum fuels divided into residual oils, or heavy fuel oils (HFO) and distillate oils (MGO, MDO). HFO usually has a higher sulphur content than 0.1 per cent, but can be used in ships that have installed sulphur dioxide exhaust gas cleaning, scrubber. A category of fuels “in between” HFO and distillates with less than 0.1 per cent sulphur has also come into use. The category is often called “hybrid fuel” or “ECA fuel”.

In general, the marine fuels have a flash point above 60^{o}C for safety reasons. For fuels with lower flash point than 60^{o}C special regulations for use apply (Lloyds Register, 2015b). Low flashpoint fuels are usually more or less sulphur free and offer an opportunity to fulfil the SECA regulation. A change to low flashpoint fuels requires technical modifications to the engine but can be economically attractive as long as the crude oil price is high. The most common low flash point fuel used in the area is LNG, but methanol is also tested.

Marine fuels are standardised in terms of parameters of importance to use in engines, and several standards exist. The ISO 8217 standard is often used but also other standards like the European “International Council on Combustion Engines” (CIMAC), the British Standard BS6843-1:1996 and the American Society for Testing and Materials (ASTM) D-975 (ABS, 2015) are used. The purpose of the standards is not to manage emissions, but there is a need for more details of the fuel in order to assess the environmental performance.

2.1 Description of the fuels used

Heavy oils

The heavy fuel oils (HFO) are what remains after the distillate fuel oils and lighter hydro-carbons are removed in the refinery. These fuel oils are used in production of electric power, vessel bunkering, and various industrial purposes. There are numerous different qualities of heavy fuel oils and one main difference is the viscosity.

Common heavy fuel oils in marine applications are IFO 180 and IFO 380, where the number refers to the viscosity in cSt at 50^{o}C[5] (see Table A.1 in the Appendix). The viscosity when injecting to the engine has to be sufficiently low, normally 10-15 cSt, which is accomplished by heating the fuel. The highest viscosity available on the market is HFO 700. This fuel behaves almost like a solid, and is not very much used.

HFO with less than 1.0 per cent sulphur is referred to as low sulphur heavy fuel oil, LSHFO. These qualities may exist naturally when using low sulphur crude oil (“sweet crude”) but are mainly the result of desulphurisation at the refinery. When the sulphur contents is lower than

[5] The kinematic viscosity describes the movement of a fluid under influence of gravity. The unit of measurement is mm^2/s or cSt, centi Stoke. As comparison, olive oil has a viscosity of around 25 cSt at 50 ^{o}C, fresh water 0.5 cSt.

0.1 per cent the quality is called ultra-low sulphur fuel oil, ULSFO. This fraction is one of the possible hybrid fuel fractions.

Distillates

Marine distillates defined by ISO 8217 are DMX, DMA, DMB and DMC. DMX is a special fuel with low flash point (min 43ºC). The demand for DMC is small due to higher density and more impurities compared to DMB. MDO (marine diesel oil) is a fuel that meets the DMA standard.

ULSD is often used as a name of fuel for land use. The sulphur content varies – in the United States and Canada it is maximised to 0.00015 per cent (15 ppm), in Europe, Australia and New Zealand 10 ppm and in many other countries 50 ppm (ABS, 2015).

Hybrid fuels

Hybrid fuels fulfil the 0.1 per cent sulphur regulations and have similarities both with HFO and distillates. They are often more viscous and have better lubricity than distillates, which is an advantage for use in engine systems designed for HFO. This means that they can replace residual fuel, but need heating and are not suitable for engines that are designed to be running on distillate only. The hybrid fuels may contain solids, aluminium silicate particles called “cat fines”, from catalytic processes in the refinery that have to be removed before use (MAN Diesel & Turbo, 2014). The hybrid fuels are of different composition and they may also cause technical problems if mixed (Lloyds Register Marine, 2014). In spite of needing heating before use, most hybrid fuels have much lower viscosity than HFO, as can be seen in Table 2.1.

Table 2.1 Examples of hybrid fuels.

Refinery	Trade name	Viscosity, cSt at 50 ºC	Flash point, ºC	Reference
St1	RMA 0.1 per cent S	Max 10	Min 60	St1 (2015)
St1	WRD (DMC)	19	>60	St1 (2014)
Exxon Mobil	HDME 50	54	175	Ali (2014)
Exxon Mobil	HDME 50	25-45	Min 70	Lloyds Register Marine (2014)
Exxon Mobil	HDME 50	53,9	>60	ABS (2015)
LUKOIL		16	165	Ali (2014)
LUKOIL	Eco Marine Fuel	65	Min 60	Lloyds Register Marine (2014)
LUKOIL		16	165	ABS (2015)
CEPA		8,8	72	Ali (2014)
CEP SA		8,8	72	ABS (2015)
BP		8,8	70	Ali (2014)
BP	RMD	6-13	Min 60	Lloyds Register Marine (2014)
BP		8,8	>70	ABS (2015)
Phillips 66		8,6	79	Ali (2014)
Phillips 66		8,6	79	ABS (2015)
Chemoil	DMB	10,5	Min 70	Lloyds Register Marine (2014)
Chemoil	Fuel oil	26,3	>60	Lloyds Register Marine (2014)
Shell	ULSFO	10-60	>60	Lloyds Register Marine (2014)
Shell	ULSFO	10-60	>60	ABS (2015)
SK Energy	SK ULSFO	30-40	Min 60	Lloyds Register Marine (2014)

The availability of hybrid fuels is good in the Baltic Sea and North Sea area, with many ports that offer bunkering along the main transport routes. According to Odland (2015) there are at least 21 locations in the SECA from Great Britain to Finland where hybrid fuel is available for bunker. The dominating amount of sea traffic in the Baltic Sea is in the Baltic Proper (south of the Gulf of Bothnia), where also most of the bunker facilities are found.

Low flashpoint fuels

LNG has gained increased importance as a marine fuel because it can comply with the strictest environmental regulations currently in force. It has a sulphur content of only a few ppm, and four-stroke SI and DF engines will comply with the NO_X Tier III regulations[6]. However, one problem associated with the use of LNG is the potential leakage of methane, a stronger greenhouse gas than CO_2.

LNG usually consists of methane, nitrogen and a small proportion of ethane and propane. The use of LNG as a fuel in shipping has earlier been limited to LNG carriers, which use the boil-off gas as fuel in steam turbines, but now also many LNG-fuelled ships are coming into operation (DNV GL, 2014). The LNG-fuelled ships are either equipped with spark-ignited (SI) lean-burn gas engines or dual-fuel (DF) engines. DF engines can run on either LNG or HFO/MGO. When using LNG, a small amount of diesel pilot fuel is injected for ignition.

Examples of ships that operates in the Baltic Sea and are using LNG are passenger ferries, tank and bulk ships. The ferry Viking Grace is operating on LNG in the Baltic Sea and there are more LNG-fuelled ferries and cruise ships being built.

Methanol is the simplest alcohol, an excellent replacement for gasoline, and is used in mixed fuels, but may also achieve a good performance in diesel engines. The use in diesel engines requires an ignition enhancer, which may be a small amount of diesel oil. In all tests performed, methanol shows good combustion properties and energy efficiency as well as low emissions from combustion (Andersson, 2015). The fuel is almost sulphur free and the NO_x emissions measured from converted marine engines are close to or below the Tier III level.

A full scale test of conversion and operation of a RoPax ferry, Stena Germanica, to methanol fuel is in progress with support from the EU Ten-T program. The main objective of the project is to develop the fuel conversion and infrastructure. It includes conversion of engine and fuel supply system on board, bunkering facilities and permit/regulation development.

Alcohol fuels such as methanol has lower energy contents than traditional fuels which is a disadvantage. Given equivalent energy density, space requirements for storing methanol in a tank will be double that of traditional diesel fuels. This has been handled in the Stena conversion by using ballast tanks for fuel storage.

HFO and emission abatement

Fuel with higher sulphur contents than 0.1 per cent may be used together with emission abatement, scrubber (Brynolf et al., 2014b). The scrubber removes the sulphur from the exhausts using water as absorbent. The scrubber may use seawater, which is returned to the sea (open loop scrubber) or water with added chemicals in a closed system (closed loop scrubber). There are also scrubbers that work in both modes (hybrid scrubbers). The scrubber system, independent of mode, will produce waste that has to be left in port where the amount for closed loop operation will be larger (Andersson et al., 2016).

[6] Tier III regulates the NO_x emissions from new ships in the NO_x ECA. In force in the North American ECA and US Caribbean ECA since 2016. There are discussions to implement a NO_x ECA also in the Baltic and North Sea.

2.2 Production of petroleum fuels

Crude oil is extracted from onshore and offshore locations, and the characteristics of the oil vary greatly depending on the location of the oil field and the age of the production site. Typical crude oil contains 84.5 per cent carbon, 13 per cent hydrogen, 1-3 per cent sulphur and less than 1 per cent each of nitrogen, oxygen, metals and salts, but these amounts vary greatly (Aitani, 2004). Crude oil can be transported either by pipeline or by a crude oil carrier from the extraction site to the refineries.

After the removal of contaminants, the crude oil is distilled in atmospheric and vacuum towers to separate the crude into fractions, depending on their differences in boiling temperature. To obtain a larger share of lighter products, the heavier products are usually chemically modified by either thermal or catalytic cracking (Hocking, 2005). Different refinery processes may be used in the production of marine fuels, e.g., atmospheric distillation, vacuum distillation, thermal cracking, catalytic cracking, hydrocracking and coking. The set of refining processes used varies from one refinery to the next, and the feedstock for these processes also varies from one facility to the next and over time.

Gas oils are light, and heavy fractions and blends thereof, from straight-run and cracked origins, have a boiling range between 200 and 350°C. They are predominantly used as automotive diesel fuels and as domestic heating fuels. MGO is also produced from this fraction (Alfke et al., 2007). HFO consists of various mixtures of residual oils from the distilling and conversion processes in the refinery. These products are used as marine bunker fuels, in power stations and in industrial furnaces. The HFOs can be blended with gas oils to adjust the density, viscosity and sulphur content (Alfke et al., 2007).

Hybrid fuels are in this report defined as all fuels that are not distillates but comply with the 0.1 per cent sulphur by mass limit. There are various ways for refineries to produce these types of fuels. Two main options are suggested by Avis and Birch (2009): desulfurizing low sulphur topped crude oil or desulfurizing vacuum gas oils. They also suggest that there may be other possibilities to produce hybrid fuels by blending and desulfurizing different fractions in the refinery. Which options that exists will depend on the refinery configuration. This have also been verified with industry representatives (Tamm, 2016, Reid, 2016).

The hybrid fuel HDME50 produced by ExxonMobil is a hydro-processed vacuum gas oil (Forget, 2016). Another example is residue thickened distillates which are distillates that contains a small amount of residue, this have been introduced by for example Shell and is usually sold as an ISO 8217:2015 RMD80 grade (Forget, 2016). Calzado Catalá et al. (2013) assumes that the 0.1 per cent sulphur fuels in Europe will be produced from vacuum gas oils and middle distillate components. They consider the residual crude fractions produced in EU to be too high in sulphur to be blended into 0.1 per cent sulphur fuels and that the desulphurisation technology only can be used for a small proportion of the crudes processed in the EU.

2.3 Data collection

The total amount of marine fuel used in the Baltic Sea is quite difficult to assess. Bunkering occurs in many different ports and at sea, within and outside the SECA. National fuel statistics are thus not very useful for assessing marine fuel use. If also the fuel quality is to be included, the task becomes even more challenging. It is not relevant to expect that the low sulphur fuel is intended only for use within SECA, since low sulphur fuel is required also when entering many ports outside the SECA, for example in the EU.

Bunkering in Sweden is recorded in terms of energy use by the Swedish Energy Agency. Until now the fuel has been categorized in terms of "heating fuel" (Eldningsolja 1-5) and not in terms of marine qualities. The sulphur content is not recorded in the statistics. For land based use, there are national regulations for sulphur concentration, but for international bunker only the SECA rules are applicable. The Swedish Chemicals Agency (KemI) has the overall responsibility for bunker within Sweden, but does not collect data on fuel quality. The recording of fuel, using bunker receipts by KemI is only done if there is a deviation in fuel delivery reported by the ship-owner to the transport agency (Sohlberg, 2016). The Swedish Transport Agency (Transportstyrelsen) are surveilling the regulations compliance by sampling fuel from ships in ports. In 2015, fuel samples from 400 ships calling Swedish ports have been taken, mainly from ships operating outside the SECA. The total number of calls in the ports in the Baltic sea is very large, in 2006 it was over 379 000 calls recorded (Saurama, 2006) and the traffic has increased since. However, this number includes all calls by ferries, where many routes are short and frequently operated, but the 400 samples taken still represents a very small part of the total ship calls.

A coming European regulation on Monitoring, Reporting and Verification of Carbon Dioxide from Ships (MRV) will enter into force in 2018 and may give a future possibility to monitor the fuel use. The MRV will cover aggregated annual CO_2 emissions at sea and in ports in the EU related to cargo carried and distance travelled, but also the amount and emission factor for each type of fuel consumed in total (Lloyds Register, 2015a).

Fuel use in the Baltic Sea from AIS data

Automated Identification System (AIS)[7] data makes it possible to estimate the total fuel use using transport distance and speed together with recorded IMO numbers of ships where data on engine type and size are available. According to studies made annually for the HELCOM by Johansson and Jalkanen (2015), based on AIS data, the total emissions from all vessels in the Baltic Sea in 2014 were: CO_2 15.0 M tonne, SO_x 81 k tonne and NO_x 320 k tonne. The CO_2 emissions corresponds to 4 750 k tonne of fuel, of which 22 per cent is from auxiliary engines. The distribution of fuel use between ship types is show in Table 2.2.

The total fuel use in 2015 is under assessment, and will be published at the HELCOM Maritime Meeting in September 2016 (Jalkanen, 2016). From Table 2.2 it may be estimated that around 30 per cent of the fuel use can be attributed to RoPax ferries, mainly running on fixed routes all year round, although with large increase in traffic during summer. RoPax ferries also seem to be a segment with large use of hybrid fuel (see Statistics from Swedish Ship-owners below).

[7] AIS is a maritime transponder/receiver system defined by the International Maritime Organization, IMO. AIS operates in the very high frequency, VHF, band. It provides ID, position, course, speed and other ship data.

Table 2.2. Fuel use by different ship categories in 2014. Source: Johansson and Jalkanen (2015)

Ship type	k tonne fuel	TJ*	per cent of total
Ro Pax	1 370	56 170	29
Cruise	160	6 560	3
Passenger ferries	19	779	<1
Tanker	920	37 720	19
Service	17	697	<1
Cargo	760	31 160	16
Container	690	28 290	14
Vehicle carrier	430	17 630	9
Fishing	35	1 435	1
Other ships	130	5 330	3
Unknown	260	10 660	5
Total	**4 791**	**196 431**	**100**

*The energy content is calculated based on an assumed average lower heating value of petroleum fuels of 41 MJ/kg.

Bunker receipts

The Swedish Transport Agency are sampling bunker fuel on ships in Swedish ports for surveillance of regulation compliance. In 2015, a total number of 400 samples were taken. The fuel quality is analysed and described on the bunker receipts. A bunker receipt includes information such as: IMO number, trade name of fuel, supplier, kind of fuel, date, volume or weight bunkered, flash point of the fuel, claimed sulphur concentration, viscosity, density, analysed sulphur contents, port of inspection, port of bunker and flag state.

Around 230 bunker receipts from the sampling in 2015 were included in the investigation. For one month (May) data were recorded for all fuel samples. In addition, data for the available months (all but July, September, October and December) were recorded for the ships using hybrid fuel. The total amount of bunker fuel investigated was 5 200 tonnes, which, if sampling occurs evenly over a year, may be interpreted as 41 k tonne on an annual basis. This is less than 1 per cent of the total marine fuel estimated to be used in the Baltic Sea. The amount of hybrid fuel on annual basis can be extrapolated to 3 k tonne, or around 8 per cent of the total low sulphur fuel. This is an indication that the use of hybrid fuels is low among ships going in and out of the SECA area (or at least among the ships that are selected for inspection)

Survey of Swedish Ship-owners

Since the surveillance data covers the ships passing in and out of the SECA, a questionnaire was distributed by the Swedish Shipowner's Association (Svensk Sjöfart) to RoPaX and tank and bulk carrier owners. In the data from this category there are ships only or mainly operating the SECA. Here, fuel use data for the entire 2015 were provided and over 100 k tonne of liquid fuel, plus 15 k tonne of LNG were reported. This corresponds to about 2-3 per cent of the annual fuel use in the Baltic Sea. In this group, 92 per cent of the liquid fuel was hybrid, the rest MGO or MDO. If also the LNG, in terms of energy content is included, 70 per cent of the fuel is hybrid. Thus, there are indications that the choice of fuel can be expected to be dependent on ship category and use, although the statistical material is very small.

Statistics from the Energy Agency

The Swedish Energy Agency collects data on energy use in different sectors in Sweden. Shipping is included, although the data are recorded in terms of "fuel oil" (eldningsolja, Eo).

The shipping statistics is divided into domestic (Table 2.3) and international (Table 2.4) shipping, where “international” is the most relevant part for the traffic under SECA regulations. The data represents marine fuels sold in Sweden and there are no guarantee that the fuels are used in the Baltic and North Sea. However the statistics gives an indication on the types of fuels used. When summing up domestic and international data for 2014, 80 per cent of the volume were Eo2-6 while 20 per cent were diesel and Eo1. Eo2-6 can be assumed to represent HFO while diesel and Eo1 can be assumed to represent MGO. As is the case for the HELCOM AIS based evaluation, there is not data published for 2015 yet.

Table 2.3 Use of diesel, Eo1 and Eo2-6 for domestic shipping 2006-2014 in 1000 m^3. Source: Swedish Energy Agency (2015).

		2006	2007	2008	2009	2010	2011	2012	2013	2014
Total		142	130	93	147	217	136	76	79	89
-	Diesel	17	17	24	35	36	35	3	4	7
-	Eo1	66	63	26	20	18	19	23	26	30
-	Eo2-6	59	50	42	92	162	82	50	49	51

Table 2.4 Use of diesel, Eo1 and Eo2-6 for international shipping 2006-2014 in 1000 m^3. Source: Swedish Energy Agency (2015).

		2006	2007	2008	2009	2010	2011	2012	2013	2014
Total		2 343	2 355	2 292	2 384	2 211	1 943	1 912	1 809	1 948
-	Diesel and Eo1	169	177	121	102	214	242	282	287	374
-	Eo2-6	2 174	2 178	2 171	2 283	1 997	1 701	1 630	1 522	1 574

Other sources

Veritas Petroleum Services (VPS) suggest that about 89 per cent of the total fuel supplied to meet the 0.1 per cent sulphur limit are distillates and the remaining 11 per cent hybrid fuels (Einemo, 2015). A Swedish bunker delivery company suggest that about 80 per cent of the vessels passing in and out of the North European ECA area using distillate fuels while the rest uses hybrid fuels. For vessels only operating inside the ECA they suggest an almost opposite allocation between distillate and hybrid fuel fractions (Pettersson, 2016). This confirms both the results from the bunker receipts and the survey.

2.4 Scenarios for fuel use in SECA

As discussed above, the information on the fuel use in the Baltic Sea is limited. Even data on the total amount used is not easily available and the estimates differ. When it comes to what kind of fuel is used, the information is very fragmented. However, there are some indications that makes it possible to set up possible scenarios for fuel use. If for example starting with the known total fuel use in 2014, scenarios on what fuel that is used in 2015 can be made, using information from incoming ships leaving bunker receipts together with the survey data. Here, one scenario for 2014 as well as four scenarios for 2015 is developed. The scenarios are summarized in Table 2.5 and the assumptions behind are further described below.

Table 2.5 Fuel use scenarios for 2014 and 2015 in TJ (rounded to nearest 100 TJ due to the uncertainty in the estimates) and per cent of total energy use 2014 in parenthesis.

TJ of fuels used	Scenario for 2014	Scenarios for 2015			
		Base	A) More hybrid fuels	B) More scrubbers	C) More LNG
HFO with 1 per cent S by mass TJ %	157 100 (80)	0	0	0	0
MGO TJ %	39 300 (20)	128 200 (65)	72 200 (37)	99 200 (51)	98 300 (50)
Hybrid fuels TJ %	0	58 100 (30)	118 100 (60)	470 00 (24)	43 800 (22)
HFO with scrubbers TJ %	0	9 200 (5)	5 200 (5)	50 100 (26)	5 200 (5)
LNG TJ %	0	900 (0,5)	900 (0,5)	900 (0,5)	49 100 (25)
Methanol TJ %	0	200 (0,1)	200 (0,1)	200 (0,1)	200 (0,1)
Total TJ	196 400	196 600	196 600	197 400	196 600

For 2014, data on the total amount of fuels used in the Baltic Sea presented in Table 2.2 is used. It is further assumed that 80 per cent of the fuel used were HFO and 20 per cent MGO on an energy basis based on data from Table 2.3 and Table 2.4 (the difference in the energy density, i.e. energy content per volume, between HFO and MGO is not considered).

For 2015 four scenarios are developed, one base scenario and three scenarios that represents cases with more hybrid fuels; more HFO with scrubbers and more LNG, respectively. For all scenarios for 2015, it is assumed that the same amount of energy is used as in 2014 except for the vessels that use scrubbers. The energy use is assumed to increase by 2 per for all vessels using scrubbers.

For the base scenario 2015 the amount HFO in combination with scrubbers, LNG and methanol is estimated to represent 4.7 per cent, 0.5 per cent and 0.1 per cent of the total energy content used in 2014. The use of HFO in combination with scrubbers and LNG is most likely underestimated, while the use of methanol is probably overestimated. For example, data on scrubber installations and orders in July 2014 compiled by EGCSA (Austin, 2015) include 15 cruise ships, 16 container ships, 60 ferries/Ro-Ro ships, 16 tankers, 11 bulk ships and 4 other. In total 122 ships that are most likely operating within the SECA part of the time.

The remaining 95 per cent of the fuels used in the base scenario is divided between MGO and hybrid fuels based on information from incoming ships leaving bunker receipts together with the survey data. For RoPax ships, the dominating category of fuel users in the area, it is assumed that 80 per cent use hybrid fuel. This assumption is based on the survey of Swedish ship-owners where the results show that almost all RoPax ships use hybrid fuels. A hybrid fuel share of 80 per is also assumed for cruise and passenger ships. Furthermore, it is assumed that the hybrid fuel fraction is 10 per cent for the other ship categories in Table 2.2 based on the bunker receipts. As most of these ship categories can be expected to operate both inside and outside the SECA.

In scenario A it was assumed that the share of hybrid fuels were 90 per cent for RoPax, cruise and passenger ships and 50 per cent for the other ship categories. In scenario B it was assumed that 25 per cent of the fuels used were HFO in combination with scrubbers. This resulted in a total use of 26 per cent of HFO with scrubbers when also considering an increase in energy use with 2 per cent. In scenario C it was assumed that 25 per cent of the fuel used was LNG.

In these scenarios the hybrid fuel fraction varies between 20-60 per cent. However, when trying to estimate the share of MGO and hybrid fuels used in 2015 based on the data collected from bunker receipts and Swedish ship-owners a use of 20 – 40 per cent of hybrid fuel seem more likely. Still, use of hybrid fuel in addition to distillates may thus be of importance to the environmental impact from shipping.

3 Environmental indicators for marine fuels

Environmental indicators for the marine fuels used in the Baltic Sea from 2015 are developed using LCA. The main data used in this assessment is summarised in the PhD thesis ”Environmental assessment of present and future marine fuels” by Brynolf (2014). A number of smaller modifications and additional data sources are also used. This data is described in Section 3.1. The life cycle results are presented in Section 3.2 divided on well-to-tank and tank-to-propeller. Section 3.3 in this chapter present the results for some selected ship types, and finally how the SECA regulation affects emissions in a life cycle perspective.

3.1 Data used in the environmental assessment

The main steps considered in the fuel life cycles are raw material extraction, fuel production, fuel distribution (well-to-tank), and fuel combustion in marine engines (tank-to-propeller). For HFO and MGO new data are considered for the raw material extraction and fuel production. For hybrid fuel, new data are added for all steps but using the same data as for MGO regarding the fuel need during distribution. For LNG the fuel combustion stage is updated with new data. For methanol no new data are added and the result are therefore identical to Table 5-1 and 5-2 in Brynolf (2014).

HFO, MGO and hybrid fuel

The data in Brynolf (2014) for HFO and MGO production is based on an attributional LCA approach investigating the question ‘What would be the overall environmental impact of HFO and MGO production?’. If you instead would like to investigate what is the environmental consequences of using HFO with a high sulphur content (>0.1 mass per cent) with a scrubber or a low sulphur marine fuel (MGO or hybrid fuel with <0.1 mass per cent), a consequential LCA approach is needed. The data used in Brynolf (2014) for HFO and MGO production (ELCD core database version II, 2010a, ELCD core database version II, 2010b) are not applicable for that and therefore needs to be exchanged. As this data include both the crude oil extraction and the HFO and MGO production, new data for crude oil extraction is also needed. The new data for crude oil extraction can be seen in Table 3.1.

Table 3.1 Energy use and emissions associated with 1 MJ crude oil extracted (Dones et al., 2007).

Energy use	
Crude oil and natural gas [MJ/MJ crude oil produced]	1,2
Emissions to air **(g/MJ_{fuel})**	
CO_2	4,0
CH_4	0,038
N_2O	-
GHGs[a]	5,1
NO_X	0,028
SO_2	0,060
$PM_{2.5}$	0,0025

[a]The GHG emissions are expressed in CO_2 equivalents calculated from the emissions of CO_2, CH_4 and N_2O using the global warming potentials of 1, 28 and 265 respectively (IPCC, 2013).

When it comes to selecting data that are applicable to the changes made in refineries by the new sulphur regulations for marine fuels in the SECA, it is important to understand how the refineries are affected by the regulations. Refinery energy use increases for heavier crude oil and for increased conversion of residual products into transportation fuels. Bredeson et al. (2010) assessed factors driving refinery CO_2 intensity and found that the most important factor is the hydrogen content in the products relative to the hydrogen content in the crude oil. The increased demand for 0.1 per cent sulphur marine fuels will cause changes in the refinery processes, increasing energy use and emissions. Avis and Birch (2009) and CONCAWE (2009) tried to estimate these changes already before 2015. Unfortunately, there are no similar estimates made, assessing the impact of the actual outcome of the regulation. Another problem is that the data from CONCAWE (2009) and Avis and Birch (2009) only includes energy use and CO_2 emissions.

Data from Avis and Birch (2009) and CONCAWE (2009) is used in this study in order to assess the impact on European refineries by the 0.1per cent sulphur limit in the northern European ECA from 2015. The emissions and energy use from refineries are expected to increase in 2015 and 2020 (or 2025), when the new sulphur regulations come into effect and the demand for low-sulphur fuels increases. The data used to indicate the energy use and CO_2 emissions from HFO, MGO and hybrid fuels are listed in Table 3.2. This data are combined with data from Dones et al. (2007) for emissions and energy use during extraction of crude oils refined in European refineries.

CONCAWE (2009) and Avis and Birch (2009) have a consequential approach investigating how the changed regulation for sulphur content in marine fuels impacts the energy use and CO_2 emissions from the refineries (Figure 3.1). CONCAWE (2009) have developed a model based on linear programming over the refineries in Europe, called the “CONCAWE EU refining model”. This is used to estimate the marginal changes in CO_2 emissions from marine fuels. They have compared the emissions from marine fuels in a case were the sulphur limit remains at 4.5 per cent in 2020 compared to a situation with a 0.1 per cent sulphur limit in the ECAs and a 0.5 per cent sulphur limit globally (Figure 3.1, B). Their results show that decreasing the demand of high sulphur fuels actually increases both energy consumption and emissions and the opposite when increasing the demand for high sulphur fuels, resulting in negative emissions and energy use for high sulphur marine fuels (Table 3.2). The negative emissions associated with a marginal change from low to high sulphur marine fuels estimated by CONCAWE (2009), is probably an overestimation compared to the impact resulting from 1 to 0.1 per cent sulphur in the marine fuel (Figure 3.1, A).

Avis and Birch (2009) have investigated which type of fuels the refineries will choose to produce to meet the 0.1 per cent sulphur marine fuel demand. Four alternatives were investigated (1) to produce 0.1 per cent sulphur heavy fuel oil by desulphurising low sulphur topped crude, (2) use desulphurised vaccum gas oil, (3) to produce marine gas oil and (4) leave the choice open but without allowing residue or vaccum gas oil desulphurisation. Alternative (3) was selected to represent MGO and alternative (2) to hybrid fuel. The increased energy use and CO_2 emissions are shown in Table 3.2.

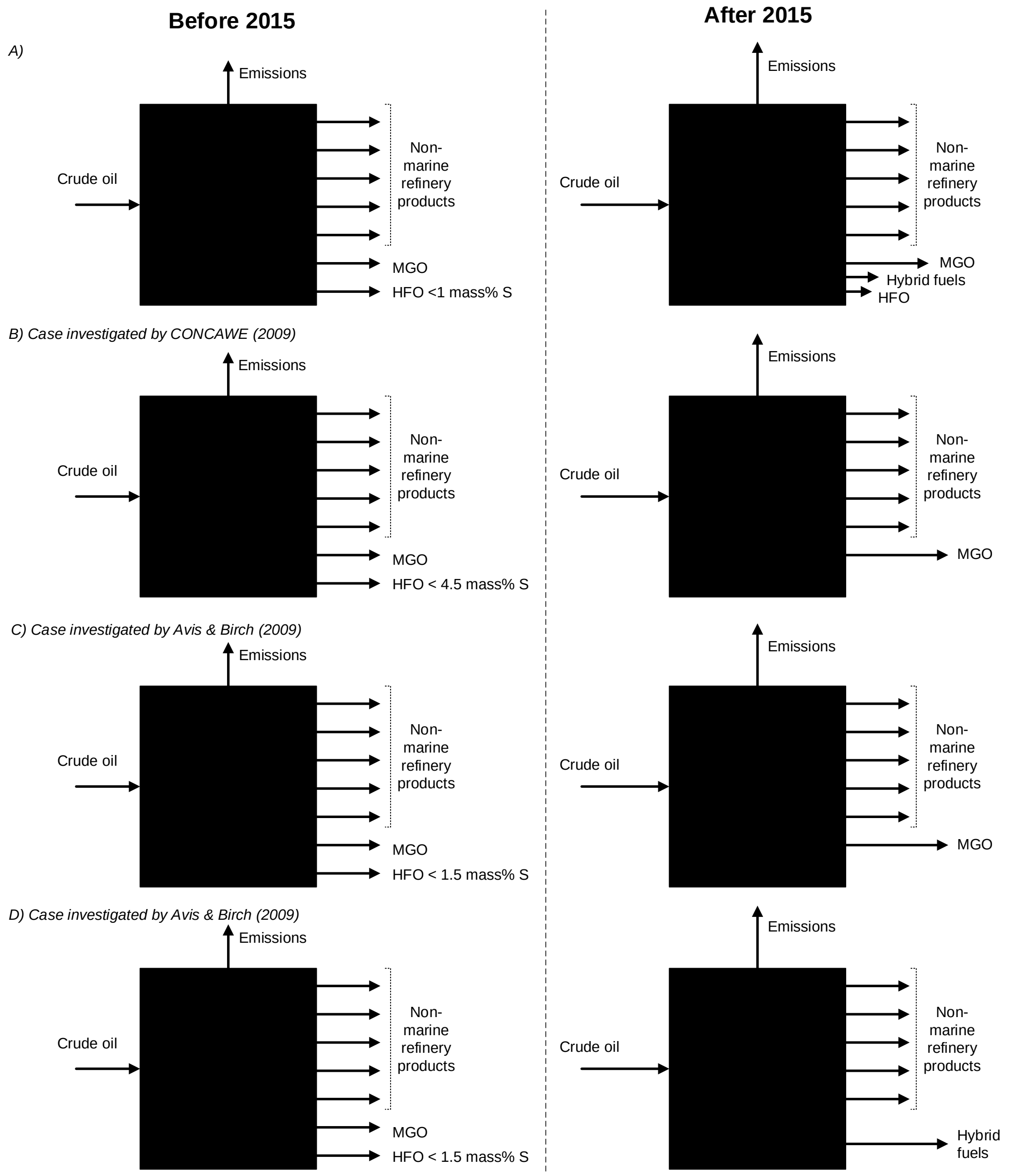

Figure 3.1 Schematics over how the refinery production changes as a consequence of the sulphur regulations in the Baltic Sea and North Sea showing A) "real" changes in the European refineries and B) the changes modelled by CONCAWE (2009) used to model emissions from HFO production, C) the changes modelled by Avis and Birch (2009) used to model emissions from MGO production and D) the changes modelled by Avis and Birch (2009) used to model emissions from hybrid fuel production.

One measurement on a vessel using HFO with 0.48 per cent sulphur and a hybrid fuel with 0.092 per cent sulphur has been made which indicated a reduction in particle mass by about 50 per cent with hybrid fuel. The other emissions except for sulphur dioxide were on the same level as for HFO (Zetterdahl et al., 2016). This is just one measurement made on one type of hybrid fuel and the emission can be expected to vary as the fuel quality differs significantly between the hybrid fuels. However, as this is the only measurement it is used here to indicate emissions from hybrid fuels.

Table 3.2 Indicated marginal change in energy use and CO_2 emissions associated with HFO, MGO and hybrid fuels production after 2015.

Fuels	Change in energy use	Change in CO_2	Scope of the assessment	Source
HFO (>0.1per cent S)	-0,01 MJ_{crude} oil/ MJ_{fuel}	-3,8 g/MJ_{fuel}	Marginal changes in energy and CO_2 emissions associated with high sulphur marine fuel production in 2020 in a scenario with a global cap of 4.5 per cent sulphur	CONCAWE (2009)
MGO	1,1 $MJ_{crude\ oil}$/ MJ_{fuel}	8,0 g/MJ_{fuel}	Estimated increase in CO_2 emission and energy use from European refineries with the implementation of 0.1 per cent sulphur regulation in 2015 compared to 1.5 per cent sulphur level	Avis and Birch (2009)
Hybrid fuels	1,1 MJ_{crude} oil/ MJ_{fuel}	6,6 g/MJ_{fuel}	Estimated increase in CO_2 emission and energy use from European refineries with the implementation of 0.1 per cent sulphur regulation in 2015 compared to 1.5 per cent sulphur level	Avis and Birch (2009)

LNG

Recent on-board measurements from a ship running on liquefied natural gas (LNG) using dual-fuel engines indicates that the slip of methane are only 0.8 per cent at high engine loads and varies between 2.7 - 4.1 per cent for lower engine loads (Anderson et al., 2015). This is for example lower than in previous estimates in Brynolf (2014). The study also suggested very low emissions of particles on a mass basis (0.41 mg/kWh) as well as NO_x emissions of 0.5 g/kWh (Anderson et al., 2015) for an engine load of 71 per cent. The earlier emission factors associated with LNG (Brynolf, 2014) have been modified with the assumption of 1 per cent LNG slip, 2 per cent MGO (by lower heating value) as pilot fuel (instead of 1 per cent), 0.05 mg particles/MJ and 0.07 g NO_x/MJ.

3.2 Environmental indicators

Emissions of CO_2, CH_4, N_2O, NO_X, SO_2 and particles (PM) for fuels used in the North and Baltic Sea per MJ fuel are summarised in Table 3.3 (well-to-tank) and Table 3.4 (tank-to-propeller). The total life cycle emissions per MJ of fuel used can be gained by adding the results from Table 3.3 and Table 3.4 together, which is shown in Table 3.5. It is important to note that the emissions per MJ fuel used are significantly higher from the tank-to-propeller part than from the well-to-tank part.

The emissions should only be seen as indicators of environmental performance since good data is lacking, especially for HFO with scrubber, hybrid fuels and MGO. The fuel associated with lowest overall emissions, including greenhouse gases, are LNG. The alternative with the second lowest CO_2 emissions is HFO with scrubbers with a consequential LCA approach. This is a result of that refineries can reduce their energy use and CO_2 emissions if they do not need to produce marine fuels with a 0.1 per cent sulphur content. This is a result of using a consequential LCA approach and specifically the data from CONCAWE (2009).

The largest difference in emissions between hybrid fuel and HFO are related to the sulphur, making SO_x and particle emissions on a mass basis lower. The total CO_2 emissions from hybrid fuels are higher than for MGO (Table 3.5) even though the refining of hybrid fuels are associated with less CO_2 emissions than MGO (Table 3.3). This is due to the higher carbon content in the hybrid fuel used in this assessment. The carbon content will vary with different types of hybrid fuel and some are probably relatively similar to MGO while others are more similar to HFO. More exhaust emissions measurements are needed on the new hybrid fuel qualities in order to assess their impact on the environment.

Table 3.3 The environmental flows for the evaluated fuels in the base case from well to tank (raw material acquisition, fuel production and distribution) per MJ of fuel used applicable for 2015-2020.

	Consequential LCA approach			Attributional LCA approach				
	HFO with scrubber[a,b]	MGO[b]	Hybrid fuel[b]	HFO 1%S	HFO with scrubber[e]	MGO[c]	LNG[c]	Methanol[c]
CO_2 [g/MJ_{fuel}]	-3,7	12	11	6,7	6,8	7,1	8,3	20
CH_4 [g/MJ_{fuel}]	-3,2E-04	0,041	0,041	0,072	0,073	0,078	0,032	0,011
N_2O [g/MJ_{fuel}]	5,2E-06	5,0E-06	4,9E-06	1,60E-04	1,6E-4	1,7E-4	1,7E-4	2,9E-4
GHGs [g/MJ_{fuel}][d]	-3,7	14,2	12,1	8,8	8,8	9,3	9,2	20,4
NO_X [g/MJ_{fuel}]	0,0021	0,033	0,033	0,021	0,022	0,023	0,0095	0,047
SO_2 [g/MJ_{fuel}]	-4,4E-04	0,065	0,065	0,039	0,039	0,041	0,0012	0,0021
PM_{10} [g/MJ_{fuel}]	8,3E-05	0,0027	0,0028	0,0011	0,0011	0,0011	3,1E-4	5,7E-4

[a]The increased energy use of the scrubber (about 2per cent) is not reflected in these results because this is presented per MJ. [b]Only CO_2 emissions are included from the fuel refinery. [c]Brynolf (2014). [d]The GHG emissions are expressed in CO_2 equivalents calculated from the emissions of CO_2, CH_4 and N_2O using the global warming potentials of 1, 28 and 265 respectively (IPCC, 2013). [e]It is assumed that HFO with scrubber is used during fuel distribution. Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), hybrid fuels (none MGO fuels complying with 0.1 per cent sulphur limit) LNG (liquefied natural gas), methanol (methanol produced from natural gas).

Table 3.4 The environmental flows associated with the fuels under evaluation in the base case during combustion in marine engines per MJ of fuel used.

	HFO[c]	HFO with scrubber[a,c]	MGO[c]	Hybrid fuel	LNG	Methanol[c]
CO_2 [g/MJ_{fuel}]	77	77	73	77	56	69
CH_4 [g/MJ_{fuel}]	4,5E-4	4,5E-04	4,5E-4	4,5E-04	0,16	0
N_2O [g/MJ_{fuel}]	0,0035	0,0035	3,5E-3	0,0035	0	0
GHGs [g/MJfuel]	77,9	77,9	73,9	77,9	60,5	69
NO_X [g/MJ_{fuel}]	1,6	1,6	1,5	1,6	0,070	0,28
SO_2 [g/MJ_{fuel}]	0,69	0,047	0,047	0,047	5,6E-4	0
PM_{10} [g/MJ_{fuel}]	0,093	0,070	0,011	0,046	0,0043	0,0043

[a]The increased energy use of the scrubber (about 2per cent) is not reflected in these results because this is presented per MJ. [b]Only CO_2 emissions are included from the fuel refinery. [c]Brynolf (2014). [d]The GHG emissions are expressed in CO_2 equivalents calculated from the emissions of CO_2, CH_4 and N_2O using the global warming potentials of 1, 28 and 265 respectively (IPCC, 2013). Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), hybrid fuels (none MGO fuels complying with 0.1 per cent sulphur limit) LNG (liquefied natural gas), methanol (methanol produced from natural gas).

Table 3.5 Total life cycle emissions for the evaluated fuels including well-to-tank and tank-to-propeller per MJ of fuel used.

	Consequential LCA approach			Attributional LCA approach				
	HFO with scrubber	MGO	Hybrid fuel	HFO 1%S	HFO with scrubber	MGO	LNG	Methanol
CO_2 [g/MJ_{fuel}]	73	85	88	84	84	80	64	89
CH_4 [g/MJ_{fuel}]	1,3E-04	0,041	0,041	0,072	0,072	0,078	0,19	0,011
N_2O [g/MJ_{fuel}]	3,5E-03	3,5E-03	3,5E-03	3,66E-03	3,7E-03	3,7E-03	1,7E-04	2,9E-04
GHGs [g/MJ_{fuel}][a]	74	88	90	86,7	87	83	70	89
NO_X [g/MJ_{fuel}]	1,6	1,5	1,6	1,6	1,6	1,5	0,080	0,33
SO_2 [g/MJ_{fuel}]	0,047	0,11	0,11	0,729	0,086	0,088	1,8E-03	2,1E-03
PM_{10} [g/MJ_{fuel}]	0,070	0,014	0,049	0,094	0,071	0,012	4,6E-03	4,9E-03

[a]The GHG emissions are expressed in CO2 equivalents calculated from the emissions of CO2, CH4 and N2O using the global warming potentials of 1, 28 and 265 respectively (IPCC, 2013). Abbreviations: HFO (heavy fuel oil), MGO (marine gas oil), hybrid fuels (none MGO fuels complying with 0.1 per cent sulphur limit) LNG (liquefied natural gas), methanol (methanol produced from natural gas).

3.3 Results for different ship categories

The emission factors can be used to estimate the well to propeller emissions per tonne km for different ship types and fuels. The life cycle greenhouse gas emissions and particle emission respectively per tonne cargo transported for two ship categories RoPax (2000-+ GT[8]) and chemical tanker (5000-9999 dwt[9]) are based on the estimated fuel consumption presented in Appendix in Table A.2 and the emissions shown in Table 3.3 and 3.4. The results are shown in Figure 3.2 - Figure 3.5 . A 2 per cent increased energy use when using scrubbers is considered.

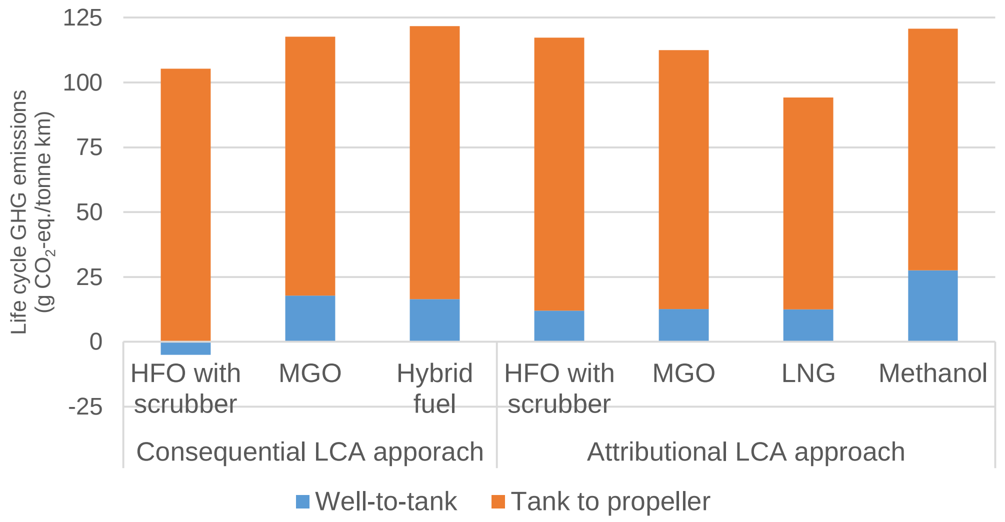

Figure 3.2 The lifecycle greenhouse gas emissions per tonne cargo transported for RoPax (2000 + GT) by the type of fuel used.

[8] Gross tonnage, GT, is a unit less index related to a ship's overall internal volume.
[9] Deadweight tonnage, dwt, is a measure of a vessel's weight carrying capacity, and does not include the weight of the ship itself. It is the sum of the maximum weights of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew.

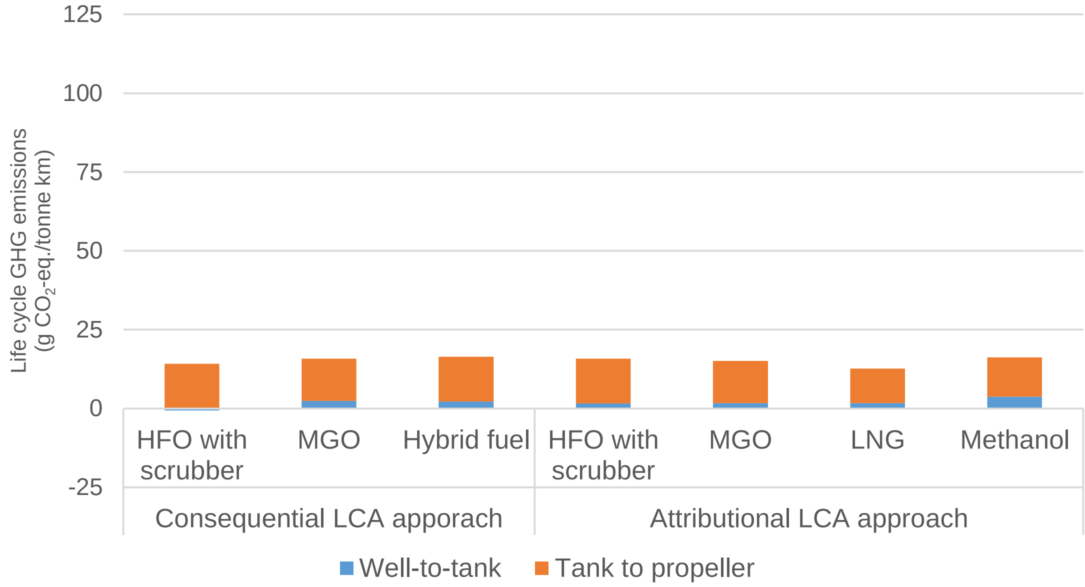

Figure 3.3. The life cycle greenhouse gas emissions per tonne cargo transported for chemical tanker (5000-9999 dwt) by the type of fuel used.

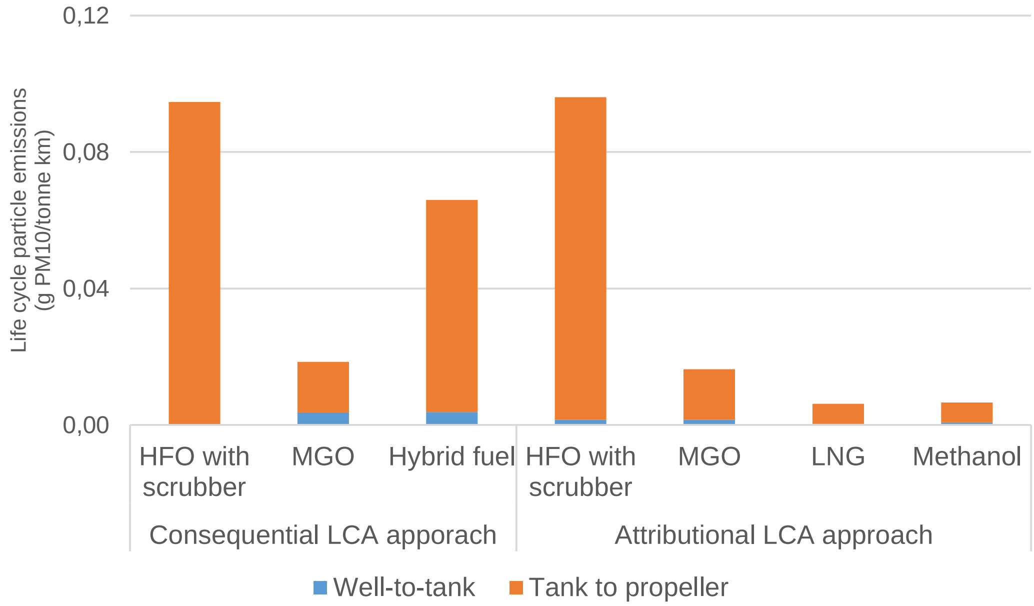

Figure 3.4. The life cycle particle emissions (PM10) per tonne cargo transported for RoPax (2000 + GT) by the type of fuel used.

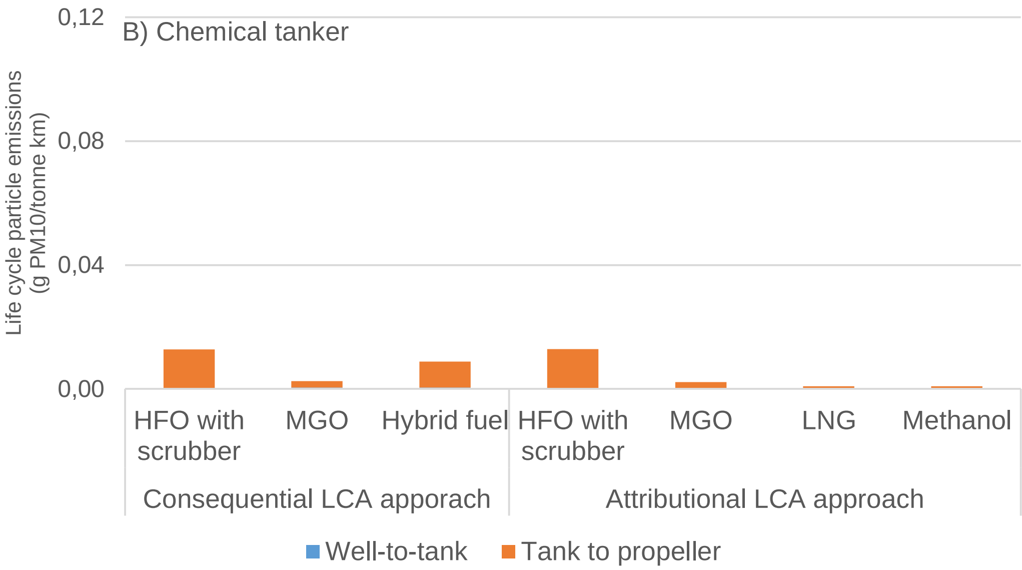

Figure 3.5. The life cycle particle emissions (PM10) per tonne cargo transported for chemical tanker (5000-9999 dwt) by the type of fuel used.

3.4 Estimates of the effect of SECA regulation on life cycle emissions

When using the scenarios presented in Section 2.4 in combination with the attributional data on life cycle emissions in Tables 3.3-3.5 all scenarios were shown to reduce the total emissions (Figure 3.6). Attributional data for the well-to-tank emissions of hybrid fuels were based on the average of HFO and MGO production and transport from Table 3.3.

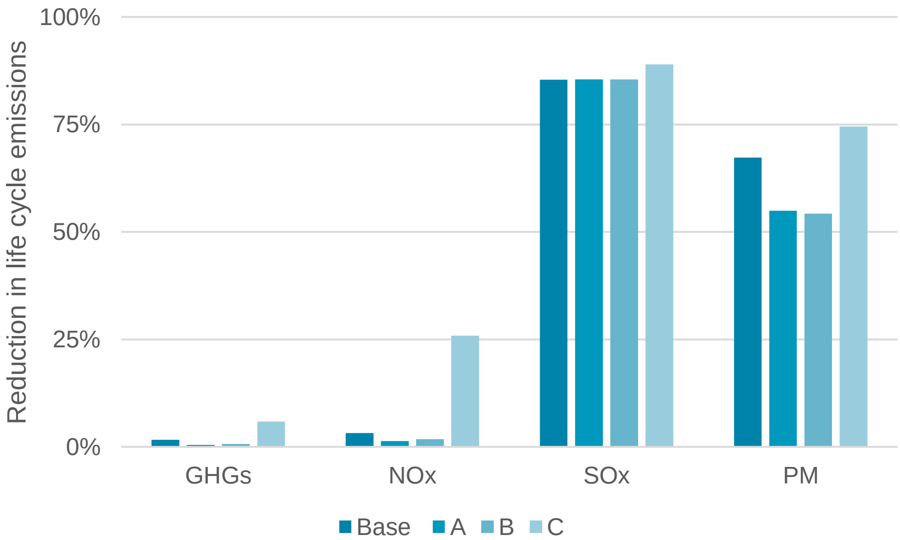

Figure 3.6 Estimated reduction in life cycle emissions in 2015 compared to 2014 for the base scenario, scenario A more hybrid fuels, scenario B more HFO in combination with scrubbers and scenario C more LNG, using attributional LCA data from Tables 3.3-3.5.

Although all scenarios shows a decrease in emissions it should be noted that the attributional data do not consider the increase in energy use and emissions which is the result of producing more low sulphur fuels. This is instead reflected in the consequential data in Table 3.3 and 3.5 which suggests an increase in the emissions for MGO and hybrid fuels. It is not possible to use the consequential data in combination with the scenarios as the consequential data are already considering a change in fuel mix (see Figure 3.1).

The small reduction in GHG emissions shown in Figure 3.4 would most likely result in an increase in GHGs if using a consequential LCA approach. For NO_x it can be seen that it is only scenario C with 25% LNG which results in a large decrease in NO_x emissions. For SO_2 and particle mass the decrease in life cycle emission is substantial.

4 Discussion

An ideal way to assess the life cycle impact of implementing the 0.1per cent sulphur regulations in the SECA area would be to compare the emissions in 2014 and 2015 from the entire fuel life cycle. In order to do this there is a need to first know which types of fuels used and how much of the fuels that are used. Second, data on the life cycle emissions from use of these fuels compared to the previously used fuels are needed. This includes data regarding how emissions changed from the refineries. Emissions from refineries could be estimated with a tool like the "CONCAWE EU refining model" when knowing the exact quantities and qualities of crude oil based fuels used. To get the full picture, data for coming years would also be interesting to study as the fuels used are continuously changing.

The data available on what fuels are used in the Baltic Sea area is not sufficient for a deeper analysis of the total picture of emissions after 1st of January 2015. More comprehensive data will be available when HELCOM update their data for 2015 and still more when the demand for MRV from ships calling European ports is in place in 2018. There is no comprehensive information regarding the use of HFO in combination with scrubbers in the Baltic Sea. However, the use is probably not insignificant as the number of installations and orders for scrubbers was 122 in July 2014 (Austin, 2015). As an example, Finnlines installed exhaust gas scrubbers on 15 ships during 2015 (Finnlines, 2016). There will also probably be more changes in fuels with time. So far only one full year have passed since the regulation came into effect.

It is clear from measurements in ambient air that the sulphur oxide emissions have decreased significantly and that particle emissions have decreased to some extent on a mass basis. To assess the impacts on emissions from using hybrid fuels more measurements of exhaust emissions are necessary. The only measurement made (Zetterdahl et al., 2016) indicated a decrease in particle mass of about 50per cent. However from a health aspect it is also interesting to assess the number of particles. Zetterdahl et al. (2016) did not see the same reduction in particle number as in particle mass with the hybrid fuel assessed.

The data used in the consequential LCA approach do not include other emissions than CO_2. It is applicable for a change when all the demand is for HFO or MGO, while in reality a mix of fuels are used. However the data can be seen as representative of the effect of changes made in refineries even if the magnitude of change is different

Furthermore, there is a number of potential contribution factors that are not considered. For example potential reduction in storage capacity and the indirect emissions of CO_2 to the ocean by sea water scrubbers. Open loop sea water scrubbers discharge the scrubber water in the open sea, thereby indirectly releasing CO_2 to the atmosphere. Approximately 2 moles of CO_2 is formed for every mole of SO_2 released. This would increase the CO_2 emissions from use of scrubbers with approximately 1.5 g/MJ HFO combusted and is not included in the result presented in Tables 3.3-3.5.

Scrubbers, LNG and methanol may reduce the cargo capacity of vessels and thereby increase the fuel consumption. The energy density is higher for LNG than for methanol, but LNG needs to be stored in cryogenic tanks at -162°C (Gullberg and Gahnström, 2011). The cargo capacity was shown to be reduced by 4per cent in LNG retrofit of a feeder container vessel, whereas another retrofit of a tanker vessel did not result in any reduced cargo capacity (Gullberg and Gahnström, 2011). It is also possible that a scrubber will affect the stability of the vessel thereby reducing the cargo capacity. The actual space requirement for scrubbers, LNG and methanol will vary from vessel to vessel and is difficult to estimate.

It is clear that the emissions of SO_2 have decreased since 2015 as well as emissions of particle mass but to a lesser extent. CO_2 emissions are not regulated in the SECA and it is unclear how the life cycle emissions of CO_2 emissions have changed as some fuels show slightly higher CO_2 emissions while others show slightly lower. With the existing data available for a consequential LCA approach, it seems to be quite small differences in CO_2 emissions between MGO and hybrid fuels and a larger difference between using high sulphur HFO with scrubber compared to using MGO or hybrid fuel. However, the most important aspect regarding the CO_2 emissions from the assessed option is that none of these leads to a large reduction. Other resources than crude oil and natural gas will be necessary in the future to reduce the emissions (Brynolf et al., 2014a, Bengtsson et al., 2012).

5 Conclusions

The mix of fuels used in the SECA is affecting the emissions from shipping in various ways.

- Although a strict quantification of the distribution between MGO, hybrid fuels, LNG and HFO with scrubber is not possible today, it is clear that the changes in total CO_2 emissions caused by the possible fuel mix is quite small, and the uncertainties in data is too large to draw far reaching conclusions from this.
- The total emissions of CO_2 from shipping will, for all fossil fuels used, be much larger than is required to fulfil the European goal to decrease CO_2 emissions from shipping with 40per cent by 2050 compared to the 2005 levels. The changes in emissions from refineries will not change this picture to a significant degree.
- The total emissions of SO_x is significantly reduced.
- The effect of using hybrid fuel instead of MGO seems to counteract the expected minor decrease in particle emissions due to less HFO used. Less particle emissions is obtained by the use of LNG or methanol
- The NO_x emissions are not affected to any significant degree by change from HFO to MGO or hybrid fuel. The only fuels that affect NO_x emissions are LNG and methanol.

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Appendix

Appendix 1

In ISO 8217 residual fuels are identified as RMA, RMB, RMD, RME, RMG, and RMK. In the ISO standards there are also subcategories like RME 180, RMF 180, RMH 380 RMK 380 etc. There is also RMB 30 and RMD 80 on the market. Typical properties of some of the most common fuels are summarised in the table.

Table A.1 Summary of marine fuel types. Source: ABS (2015) and Odland (2015).

Fuel type	Viscosity cSt (50 ^{o}C for IFO and 40 ^{o}C for distillates)				Sulphur content per cent		May fulfil SECA limit of 0,1per cent
	min	Max	Typical		Max	Typical	
IFO 180	-	180	-		4,5	1 - 3,5	
IFO 380	-	380	-		4,5	1 - 3,5	
RMB 30	16	30	-			0,05-	x
RMD 80	6	80				0,05-	x
DMB*	-	11	2,6 - 6		2	0,03 - 1,3	x
DMA*	1,5	6	2 - 4		1,5	0,01- 1	x
ULSD*	1,9	4,1	-		0,00015	-	x

*can be called Marine Diesel Fuel Oil, Marine Fuel oil 30, Distillate Marine Diesel (Environment Canada, 2015)

Table A.2 Estimated fuel consumption of some ship types operating in the Baltic Sea. Source: Smith et al. (2014), Buhaug et al. (2009).

Type of ship	*Size*	*Avg. cargo capacity (t)*	*Avg. capacity utilisation (%)(Buhaug et al., 2009)*	*Avg. sea speed (km/h)*	*Avg. fuel consumption, full load (MJ/tonne km)a*	*Avg. fuel consumption, avg. load (MJ/tonne km)b*
RoPax	*0-1999 GT*	*896*	*70*	*16*	*0.60*	*0.86*
RoPax	*2000-+ GT*	*3 459*	*70*	*26*	*0.95*	*1.4*
Chemical tanker	*0-4999 dwt*	*3 937*	*64*	*18*	*0.14*	*0.21*
Chemical tanker	*5000-9999 dwt*	*8 931*	*64*	*20*	*0.12*	*0.18*
Chemical tanker	*10000- dwt*	*17 884*	*64*	*22*	*0.08*	*0.13*
Chemical tanker	*20000-+ dwt*	*42 782*	*64*	*23*	*0.05*	*0.08*
Bulk carrier	*0-9999 dwt*	*5 194*	*60*	*18*	*0.11*	*0.18*
Bulk carrier	*10000- dwt*	*27 366*	*55*	*21*	*0.06*	*0.11*
Bulk carrier	*35000- dwt*	*51 195*	*55*	*23*	*0.04*	*0.08*
Bulk carrier	*60000- dwt*	*76 913*	*55*	*23*	*0.03*	*0.06*
Bulk carrier	*100000- dwt*	*167 167*	*50*	*23*	*0.02*	*0.05*
Bulk carrier	*200000-+ dwt*	*244 150*	*50*	*23*	*0.02*	*0.04*
General cargo	*0-4999 dwt*	*2 405*	*60*	*16*	*0.17*	*0.28*
General cargo	*5000-9999 dwt*	*8 441*	*60*	*19*	*0.12*	*0.20*
General cargo	*10000-+ dwt*	*22 011*	*60*	*22*	*0.08*	*0.14*
Container	*0-999 dwt*	*9 676*	*70*	*23*	*0.15*	*0.21*
Container	*1000-1999 dwt*	*20 723*	*70*	*27*	*0.13*	*0.18*
Container	*2000-2999 dwt*	*35 764*	*70*	*30*	*0.11*	*0.16*
Container	*3000-4999 dwt*	*53 951*	*70*	*31*	*0.12*	*0.17*
Container	*5000-7999 dwt*	*76 981*	*70*	*32*	*0.13*	*0.18*
Container	*8000-11999 dwt*	*108 236*	*70*	*32*	*0.11*	*0.16*
Container	*12000- dwt*	*164 333*	*70*	*31*	*0.08*	*0.12*
Vehicle	*0–3999 dwt*	*9 052*	*70*	*26*	*0.21*	*0.31*
Vehicle	*4000–+ dwt*	*19 721*	*70*	*29*	*0.14*	*0.20*

[a]Assumes an average engine load of 70per cent, [b]Assumes an average engine efficiency of 45per cent.

Trafikanalys är en kunskapsmyndighet för transportpolitiken. Vi analyserar och utvärderar föreslagna och genomförda åtgärder inom transportpolitiken. Vi ansvarar även för officiell statistik inom områdena transporter och kommunikationer. Trafikanalys bildades den 1 april 2010 och har huvudkontor i Stockholm samt kontor i Östersund.

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