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An Environmental Life Cycle Assessment of LNG and HFO as Marine Fuels

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Background

The ongoing climate debate is widespread and the need for change seems inevitable. Emission of greenhouse gases (GHG) contribute to global warming and an increase in temperature of more than 2°C above pre-industrial levels is likely to have major consequences. Although international shipping is the most energy efficient mode of transportation, it is only a modest contributor to the global CO_2 emissions. However, the projected growth in shipping due to an expansion in trade is causing an increased environmental concern. New rules and regulations from the International Maritime Organization (IMO) will come in force in 2015 and because of this; shipowners need to rethink their fuel strategy. Switching from heavy fuel oil (HFO) to natural gas will minimize NO_x and SO_x emissions and comply with the stricter regulations. Lower fuel consumption by increased engine efficiency or switching to natural gas, which has less carbon content, will also reduce CO_2 emissions from shipping. However, the environmental impact of a fuel is not only related to the combustion in the engine, but also to the whole life cycle of the fuel starting at the well. This means that at fuel that seems favorable in the combustion phase, may have large environmental impacts in the upstream process or vice versa.

Overall aim and focus

The overall objective of the master thesis is to compare heavy fuel oil and liquefied natural gas as marine fuels when it comes to their environmental impact in a life cycle perspective. A life cycle assessment (LCA) methodology will be used. The focus will be on the emissions of greenhouse gases, but other investigations such as acidification potential and energy consumption will also be investigated.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide a description of the background to the problem at hand and describe the new regulations that will come in force in 2015. Techniques to fulfill the requirements must also be investigated.*
2. *Describe how the two different fuels, LNG and HFO, are put to use in the shipping industry. Different engine configurations will be central in this part.*
3. *Describe the LCA methodology and define the goal and scope of the study. This will include impact categories, inventory analysis and system boundaries.*
4. *Collect data on every stage of the value chain for both fuels and calculate the total GHG emissions. The result should be presented in a way that allows comparison with other studies.*
5. *Discuss the result from a critical point of view and compare with other studies. Strengths and weaknesses with the study must also be discussed.*

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature. The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: a text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The work shall follow the guidelines given by NTNU for the MSc Thesis work. The work load shall be in accordance with 30 ECTS, corresponding to 100% of one semester.

Supervision

Supervisor: Professor Bjørn Egil Asbjørnslett, IMT

Co-supervisor: Haakon Lindstad, MARITEK

Deadline 10.06.2013

Preface

This master thesis is the final report of the M.Sc. degree at the Norwegian University of Science and Technology (NTNU), Department of Marine Technology. It is written in its entirety by Lars Laugen during the spring of 2013. The topic of this master thesis is a*n environmental life cycle assessment of LNG and HFO as marine fuels,* and this report counts for 30 credits, or 100% of a semester's work load.

The work of this master thesis succeeds the project thesis, written during fall 2012, which was A *study of greenhouse gas emissions from LNG shipping*. The overall aim of this thesis has been to compare liquefied natural gas (LNG) and heavy fuel oil (HFO) as marine fuels when it comes to their environmental performance in a life cycle perspective. It also aims of giving recommendations on how to meet the requirements set by the International Maritime Organization (IMO) regarding emissions of SO_x and NO_x from shipping in the Emissions Controlled Areas (ECAs) from 2015 and 2016.

It was time consuming to get up to date on the topic and the LCA method, so the analysis itself was not finished before April. Finding datasets for the different processes from well-to-propeller was to some extent rather difficult and therefore some simplifications and assumptions had to be made. For the calculations, Excel has primarily been used.

I would like to thank my supervisor at NTNU, Professor Bjørn Egil Asbjørnslett, for advice and feedback during this demanding semester. I would also like to thank Haakon Lindstad, principal advisor at MARINTEK, for guiding me and providing essential information, both for the project- and master thesis.

The assignment has been a great learning experience, providing me with a better understanding on how to approach new subjects and how to perform a pre-study. I have learned more about LNG, environmental solutions for the maritime industry, as well as life cycle assessment techniques. This is a field of both innovative and environmental technology, which I am grateful to have gained insight in.

Trondheim, 10th June 2013

Lars Laugen

Abstract

The maritime transportation industry will face harder requirements from the international community when it comes to environmental issues. The introduction of Emission Control Areas (ECAs) has forced shipowners to rethink their fuel strategy and start looking for other solutions. To address the requirements from the International Maritime Organization (IMO), the shipping industry will either have to change from low quality fuel to more environmental friendly fuels, or introduce reductions techniques to handle their emissions. However, the environmental impact of a fuel is not only related to the combustion in the engine, but also to the whole life cycle starting at the well. This means that at a fuel that seems favorable in the combustion phase, may have large environmental impacts in the upstream process or vice versa.

The overall aim of this thesis has been to compare liquefied natural gas (LNG) and heavy fuel oil (HFO) as marine fuels when it comes to their environmental performance in a life cycle perspective. This has been done by performing a life cycle assessment (LCA). A LCA is a management technique which addresses the environmental aspects and potential environmental impacts throughout a product's life cycle. The selected impact categories for the LCA were global warming potential (GWP), acidification potential and primary energy use.

The case studied was the use of LNG and HFO as marine fuels in passenger ferries out of Rotterdam. The natural gas were assumed to come from Statoil's Melkøya plant in Norway and transported on a LNG carrier to Rotterdam. The HFO were assumed to be extracted as crude oil in the North Sea, transported to a refinery on the west coast and then transported on an oil tanker to Rotterdam. The functional unit of the study was set to transporting one ton cargo one km with a passenger vessel. Allocation issues with the LCA methodology have been solved by using lower heating values (LHV).

The results from the studied case show that LNG is marginally better compared to HFO when it comes to the environmental impact over a life cycle. The total emissions were calculated to be 127 g CO_2-eq/ton km and 130.13 g CO_2/ton km for LNG and HFO respectively. It is also shown that the major contribution to global warming potential is during the combustion of the selected fuels. During this phase, approximately 70% of the total GHG emissions from the whole chain are released. The methane emission for the LNG pathway is eight times higher compared to the HFO pathway and accounts for 20% of the total GHG emissions for LNG. Since most of this is during combustion, it means that the performance of the engines plays a major part in the overall performance of LNG as a marine fuel. A small increase in the methane slip will increase the environmental footprint for LNG consequentially.

For the acidification potential, LNG is the favorable fuel with 92% less emissions than HFO. In addition, LNG as fuel will meet the new regulations from IMO with maximum limit of sulphur in the fuel and the strictest NO_x regulation, Tier III. The total primary energy use was calculated based on LHV, and LNG from Melkøya were found to be the most energy effective fuel with a total life cycle energy use of 1.33 MJ/ton km, while HFO has a lower efficiency with 1.81 MJ/ton km. When the primary energy use is combined with GWP and acidification potential, it becomes clear that not only is LNG more energy efficient, but it also releases less CO_2 and SO_2 equivalents than HFO in a life cycle perspective.

Sammendrag

Den maritime transportnæringen vil møte strengere krav fra det internasjonale samfunnet når det gjelder utslipp fra skip i årene som kommer. Introduseringen av «utslippskontrollområder» (ECAs) har tvunget redere til å se på andre løsninger og andre drivstofftyper for å redusere utslippene. Det er den internasjonale maritime organisasjonen IMO som innfører de nye reglene og rederne har to alternative metoder for å imøtekomme disse; bruke drivstoff som forurenser mindre eller bruke reduksjonsteknikker på skipene. Likevel er det ikke bare under forbrenningen av et drivstoff at utslipp vil forekomme, men gjennom hele livsløpet. Det vil si at et drivstoff som virker fordelaktig under forbrenning på grunn av sitt lave utslipp, kan ha store utslipp under utvinning, transport eller andre ledd tidligere i prosessen. Det kan også være motsatt med lite utslipp oppstrøms, men store under forbrenning.

Det overordnede målet med denne oppgaven har vært å sammenligne flytende naturgass (LNG) og bunkersolje (HFO) når det gjelder påvirkningen på miljøet i et livsløp. Det er gjort ved å utføre en livssyklusanalyse (LCA) som er en metode for å skape et helhetsbilde av hvor stor den totale miljøpåvirkningen er under et produkts livssyklus. Det gjelder fra råvareutvinning, via produksjonsprosesser og bruk til avfallshåndtering, inklusive all transport og all energibruk i mellomleddene. De valgte kategoriene under analysen var potensialet for global oppvarming (GWP), potensialet for forurensing som omdannes til syrer (acidification potential) og energibruk.

Scenarioet som er studert sammenlikner LNG og bunkersolje som blir brukt i en passasjerferge ut fra Rotterdam. Naturgassen som blir brukt kommer fra Statoils anlegg på Melkøya og blir transportert med et spesialfartøy til Rotterdam. Bunkersoljen blir den hentet opp i Nordsjøen før den går via et raffineri på Vestlandet og ned til Rotterdam. Den funksjonelle enheten for oppgaven er satt til transport av ett ton last én kilometer om bord i en passasjerferge. Allokeringsproblemer har prøvd og vært unngått, men nedre varmeverdier (LHV) har blitt brukt da det ikke lot seg gjøre og komme utenom.

Resultatene fra studien viser at LNG er marginalt bedre enn bunkersolje når det kommer til påvirkningen på miljøet gjennom et livsløp. De totale utslippene ble kalkulert til å være 127 gram CO_2-ekvivalenter/tonn km og 130.13 gram CO_2-ekvivalenter/tonn km for henholdsvis LNG og bunkersolje. Det har også vist seg at det er under forbrenningsprosessen mesteparten av drivhusgassutslippene gjøres. Denne «bruksfasen» utgjør omtrent 70% av de totale drivhusgassutslippene for begge drivstofftypene. Metanutslippene fra LNG kjeden er åtte ganger høyere enn for bunkersolje og bidrar til 20% av de totale utslippene for LNG. Siden mesteparten av disse utslippene skjer under forbrenning, vil effektiviteten og utslippsraten til motoren ha en stor innvirkning på prestasjonen til LNG som drivstoff. En liten økning av metanutslippet kan gjøre LNG til et dårligere alternativ enn bukersolje hvis man kun ser på utslipp i CO_2-ekvivalenter.

For utslippet av syredannende stoffer så viser det seg at LNG er det beste alternativet med 92% mindre utslipp av SO_2-ekvivalenter sammenlignet med bunkersolje. I tillegg så vil LNG innfri de nye reglene med maksimalt tillatt sulfurinnhold i drivstoffet og NO_x utslippet vil være lavt nok til innfri Tier III. Det totale energiforbruket ble regnet ut basert på LHV og LNG viste seg å være det beste alternativet her også. Når energiforbruket settes i sammenheng med potensialet for utslipp av drivhusgasser og syreforurensing så er det tydelig at LNG er et langt bedre alternativ enn bunkersolje på bakgrunn av de valgte kategoriene for denne livssyklusanalysen.

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Abbreviations

BOG – Boil of Gas

CH_4 – Methane

CNG – Compressed Natural Gas

CO_2 – Carbon dioxide

ECA – Emission Control Areas

GHG – Greenhouse gases

GWP – Global Warming Potential

HFC – Hydrofluorocarbons

HFO – Heavy fuel oil

ISO – International Organization for Standardization

IMO – International Maritime Organization

IPCC – Intergovernmental Panel on Climate Change (UN's climate panel)

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LNG – Liquefied Natural Gas

MDO – Marine Diesel Oil

MEPC – Marine Environment Protection Committee

MGO – Marine Gas Oil

N_2O – Nitrous oxide

NG – Natural Gas

NO_x – Nitrogen oxide

PM – Particle Matters

SFC – Specific Fuel Consumption

SO_x – Sulfur oxide

TTP – Tank To Propeller

VOC – Volatile Organic Compounds

WTP – Well To Propeller

WTT – Well To Tank

1. Introduction

The ongoing climate debate is widespread and the need for change seems inevitable. Emission of greenhouse gases (GHG) contribute to global warming and an increase in temperature of more than 2°C above pre-industrial levels is likely to have major consequences. Although international shipping is the most energy efficient mode of transportation in order of CO_2 emissions [g CO_2/ton km] compared to rail and road, it is only a modest contributor to the global CO_2 emissions [2]. However, the projected growth in shipping due to an expansion in trade is causing an increased environmental concern.

Today the shipping mode transports 80-90% of the global trade in metric ton and in 2007 maritime transport emitted 1046 million tons of CO_2 according to the International Maritime Organization (IMO) [3]. That represented 3.3% of global greenhouse gas emissions and is expected to increase by 150-250% in 2050 if we do not take action. According to the Intergovernmental Panel on Climate Change (IPCC), estimates show that greenhouse gas emissions need to be reduced by around 50-85% before 2050, compared with current levels, in order to stabilize the temperature. Shipping also contributes to large SO_x and NO_x releases, depending on the fuel and engine type.

By introducing more efficient machinery solutions the fuel consumption will decrease, and the emission levels will consequently be reduced. Switching to alternative fuels is also suggested as a solution to reduce NO_x and SO_x emissions. Lower fuel consumption and switching to fuels with less carbon content will also reduce CO_2 emissions, which is the main GHG when it comes to shipping emissions. However, the environmental impact of a fuel is not only related to the combustion in the engine, but also to the whole life cycle of the fuel starting at the well. This means that at fuel that seems favorable in the combustion phase, may have large environmental impacts in the upstream process or vice versa.

Awareness of the environmental consequences of intensifying international trade has grown within the European Union during the past two decades. Therefore, in more recent years, it has been a lot of research on new fuel options for the maritime sector. The goal is to satisfy the new regulations that will come in force in the ECAs in 2015 and 2016.

1.1 Objectives and structure of the thesis

For evaluating the environmental impact, a Life Cycle Assessment (LCA) is the leading methodology. The method systematically quantifies and assesses environmental impacts during the life cycle of a process, activity or product [4]. Because of the new regulations and lack of research on the topic, the main objective of this master thesis is to compare LNG and HFO as marine fuels when it comes to their environmental impacts, based on a LCA.

The first part of this report describes emissions from shipping with a focus on air quality. In addition, relevant rules and regulations are presented together with engine alternatives for the two fuels. The second part provides an overview of the theoretical framework used in the study. The third part consists of an investigation of the two value chains, data collection and the LCA analysis. Finally the results will be presented with recommendations, conclusion and further work.

2. Emissions from shipping

The world fleet, consisting of more than 100 000 vessels and carries more than 80% of the global trade, only contributes to 3.3% of the global CO_2 emissions [3]. However, some of the cargos that are being carried are potentially dangerous and may have catastrophically consequences if an accident occurs. But it is not only CO_2 emissions, which is considered to be the largest contributor to GHG emissions, that vessels release. The figure below shows emissions and discharges for shipping to air and land.

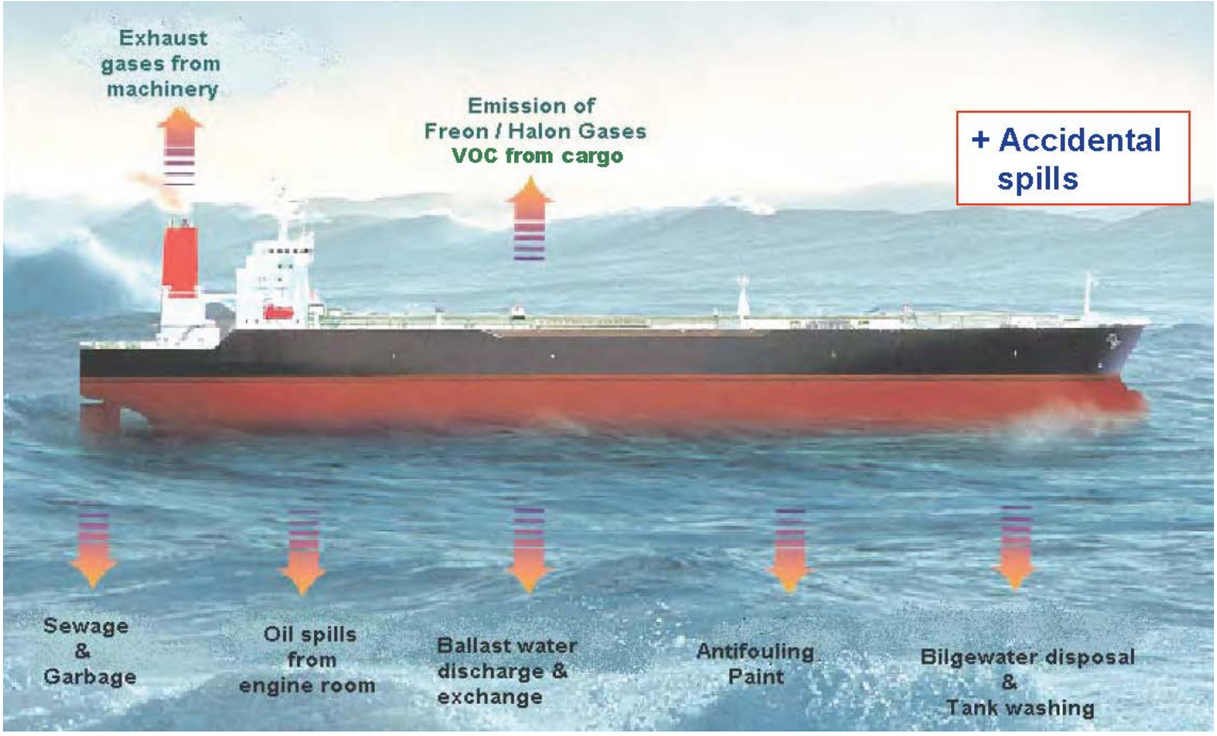


Figure 1 - Emissions from shipping [5]

In the following chapter the focus will be on air emissions, regulations and reduction techniques.

2.1 Emissions to air and greenhouse gases

It is during the combustion that exhaust gases are formed. It happens when fuel is injected into the cylinder where it evaporates and mixes with the air.

The following contribution from shipping to the global emissions were presented by IMO in 2007 [3]:

- 3% CO_2 (3.3% for all shipping, whereas 2.7% from international shipping)
- 4-9% SO_x
- 10-15% NO_x

NO_x is the largest contributor to global emissions from shipping, while SO_x emissions are somewhat lower. The presence of exhaust gases has both locally and global impacts. Impacts on local air quality are mainly linked to pollutions such as NO_x and SO_x, whilst CO_2 have a global impact on the climate. Impact on local air quality is one of the main reasons that IMO has introduced Emission Control Areas (ECAs) which will be described in chapter 2.3

2.1.1 NO_x – Nitrogen oxides

NO_x is the collective term for nitrogenous oxide gases, including NO, NO_2 and other oxides of nitrogen. The most common NO_x, nitrogen dioxide (NO_2), is formed in the ambient air through the oxidation of nitric oxide (NO) and it is a highly reactive gas. The formation of NO_x is a complex process which takes place in the pre-combustion, combustion and post-flame regions [6]. It involves the nitrogen found within the combustion air and nitrogen within the fuel itself. High-temperature combustion processes are the major source of man-made NO_x emissions.

NO_x contributes to eutrophication, ozone and smog formation, acidification of freshwater bodies and increases in levels of toxins that are harmful to fish and other aquatic life. Another impact is acid rain which leads to a decrease in the pH-value of rainwater and damages different ecosystems. It also presents a health threat and may lead to changes in airway responsiveness and lung function. It is also known to cause respiratory problems such as asthma and bronchitis, and damage to lung tissue which will cause premature death [7].

2.1.2 SO_x – Sulphur oxides

Sulphur oxides are formed when fuel is burned in the combustion process. Only fuel that contains sulphur will form SO_x. During the combustion process sulphur dioxide (SO_2) is formed, but also a small fraction of sulphur trioxide (SO_3) is formed when SO_2 oxides.

Marine fuels have traditionally had a high sulphur content compared to fuels used on land. In Europe, shipping make up approximately 4-9% of the SO_x emitted, but this share is expected to grow in the years to come as land based sources reduce their SO_x emissions relatively more than shipping. If the trend continues, shipping will be the single most important source for SO_x emissions in Europe [7].

Sulphur emissions harm the environment through acidification and acid rain, and particularly around coastal areas and ports. Effects on human health are increased airway resistance, wheezing, shortness of breath, lung cancer and asthma [7].

2.1.3 CO_2 – Carbon dioxide

Carbon dioxide (CO_2) is a colorless gas that is produced when carbon is burned. It is produced during the combustion of fossil fuels in main engines, auxiliary engines and boilers. CO_2 emissions from shipping are highly depending on the carbon content of the fuel and the fuel consumption. Therefore the most effective way to reduce emissions is to switch to alternative fuels or more efficient machinery [8].

The greenhouse effect is being increased by release of certain gases and CO_2 accounts for about 85% of GHG released in the US [7]. The second largest source of GHG is methane (CH_4) and comes as a result of agricultural activities. Smaller quantities of stronger GHG and pollutions such as chlorofluorocarbons (CFC), hydrofluorocarbons (HFC) and volatile organic compound (VOC) will also have an effect, but some of them are facing out [5].

2.2 Regulations

The issue of controlling air pollution from ships was discussed in the 1973 MARPOL convention, but it was decided not to include regulations concerning air pollution at the time. There were not enough studies at this field. But between 1972 and 1977, several studies confirmed the hypothesis that air pollutants could travel several thousand kilometers before deposition and damage occurred. This damage includes effects on crops and forests [9].

During the 1980s, concern over air pollution, such as global warming and the depleting of the ozone layer, continued to grow. A group within IMO called the Marine Environment Protection Committee (MEPC) started in the mid-1980s to discuss the issue of air pollution. In 1988, the MEPC agreed to include the issue of air pollution in its work-program following a submission from Norway on the scale of the problem.

The resolution called on the MEPC to prepare a new draft Annex to MARPOL 73/78 on prevention of air pollution. The new draft Annex was developed over the next six years and on 27 September 1997, on the MARPOL convention, the new "1997 Protocol" was added. This included Annex VI titled *"Regulations for the Prevention of Air Pollution from Ships"* [10]. The Annex VI regulation covers the following:

Regulation 12: Ozone depleting substances from refrigerating plants and firefighting equipment
Regulation 13: Nitrogen Oxides (NO_x) from diesel engines
Regulation 14: Sulfur Oxides (SO_x) from diesel engines
Regulation 15: Volatile Organic Compound Emissions from cargo tanks of oil tankers
Regulation 16: Emissions from shipboard Incineration
Regulation 18: Fuel oil quality

MARPOL Annex VI sets limits on NO_x and SO_x emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances. The IMO emission standards for NO_x emissions are commonly referred to as Tier I, II and III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced in 2008. Annex VI amendments was adopted in October 2008 and was then agreed on by 53 countries, representing 81.88% of world tonnage. The revised Annex VI entered into force on 1 July 2010 introduced 3 new things:

1. New fuel quality requirements beginning from July 2010.
2. Tier II and III NO_x emission standards for new engines.
3. Tier I NO_x requirements for existing pre-2000 engines.

In addition, the revised MARPOL Annex VI operates with two geographical definitions: global and emission controlled area (ECA). The limits for NO_x- and SO_x emissions can be seen in figure 3 and 4 in the next chapter.

2.3 Emission Control Area (ECA)

In the years to come maritime transportation will face harder requirements on fuel quality and exhaust emission in some areas of the world. These geographical areas have stricter emission requirements compared to the rest of the world. An emission control area (ECA) can be designed for SO_x and particular matter (PM), or NO_x, or all three types of emissions from ships. The introduction of ECAs is an attempt to address these aspects and to reduce the environmental footprint of the shipping industry in some local areas where the emissions have been more severe [11]. The common denominator for these areas is that they all have major harbors and substantial vessel traffic.

Figure 2 - Existing and future Emission Control Areas (ECAs)

Existing and future Emission Control Areas (ECA):

- Baltic Sea (SO_x, adopted: 1997 / entered into force: 2005)
- North Sea (SO_x, 2005/2006)
- North American ECA, including most of US and Canadian coast (NO_x and SO_x, 2010/2012).
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NO_x and SO_x, 2011/2014).

2.3.1 Regulation 13: Nitrogen oxides (NO_x)

As mentioned previously, the regulation 13 of the 1997 Protocol contains limits for emissions of NO_x from marine diesel engines. Tier I were defined in 1997, while Tier II and Tier III were adopted in October 2008. In the table 1 one can see the requirements to meet the different tiers.

For example, the NO_x emissions of any diesel engine on a ship constructed on or after 1^{st} of January 2011, and have an engine rated speed below 130 RPM, can only have a total weighted emission of 14.4 g/kWh or less to comply with Tier II [12].

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{-0.2}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{-0.23}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016[1]	3.4	$9 \cdot n^{-0.2}$ e.g., 720 rpm – 2.4	2.0

Table 1 - Tier I, II and III limitations [12].

Tier I and Tier II limits are global, while the Tier III is a more massive reduction and is only applied in NO_x Emission Control Areas. The figure below illustrates the limits set by IMO.

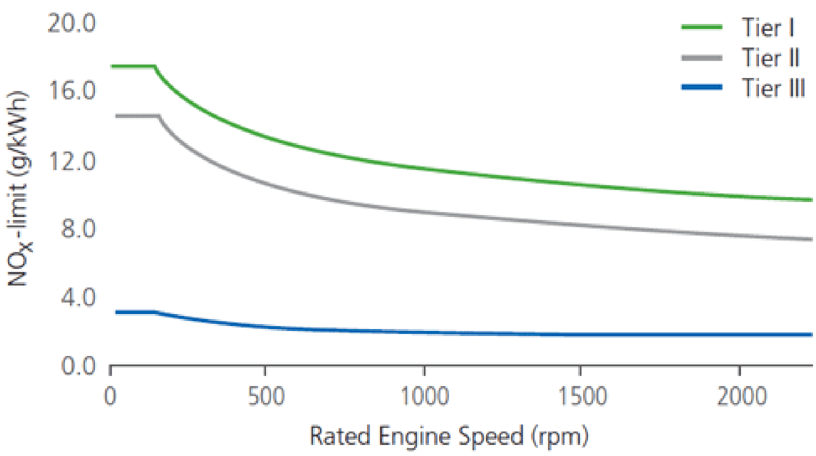


Figure 3 - Tier I, II and III limitations

2.3.2 Regulation 14: Sulphur oxides (SO_x)

The introduction of Sulphur Emission Control Areas (SECA) with a maximum content of 0.1% sulphur allowed in marine fuels from 2015, compared to today's limit on 1 %, will increase the demand for fuel with low sulphur content. For the rest of the world the limit is 3.5% today, but it is planned that stricter regulations will enter into force in 2020. However, if it is demonstrated that the fuel supply of low sulphur fuels are too low, the limit of 0.5% should not be effective before 2025 [13].

Most ships which operate both outside and inside the ECA will therefore have to switch fuel oils to comply with the different limits and regulations. Another alternative is to use various abatement techniques which are the subject for the next chapter.

[1] Subject to a technical review to be concluded during 2013, but this date could be delayed.

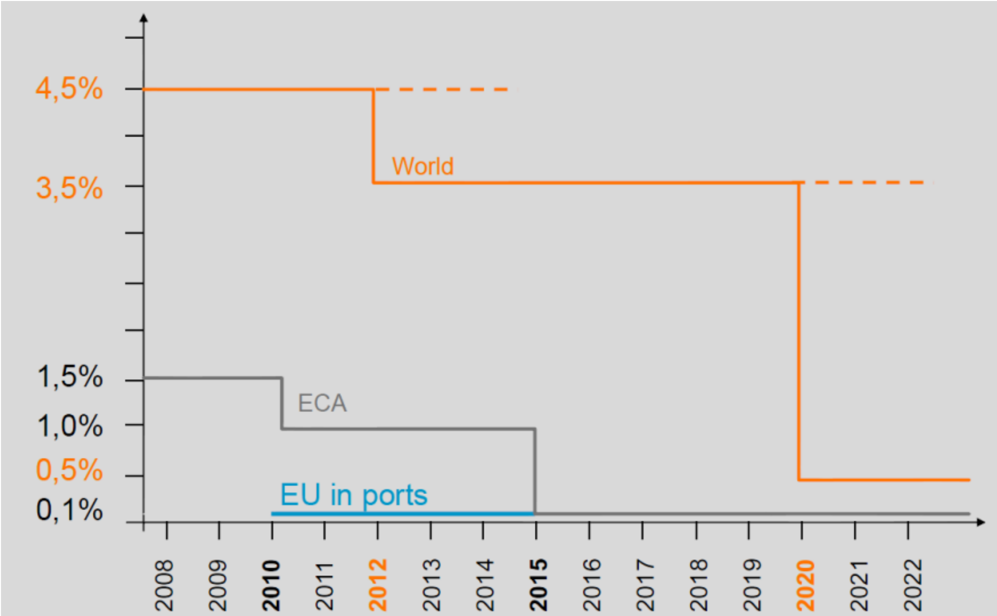


Figure 4 - Sulphur content limitations inside ECA and the rest of the world

2.4 Reduction techniques

Because of the new regulations taking place within the maritime sector, there have been a lot of research and development during the last years considering NO_x, SO_x, PM and CO_2 reduction techniques. To address the requirements from IMO, the shipping industry will either have to change from low quality fuel to more environmental friendly fuels or introduce reductions techniques to handle their emissions. DNV [8] divides the emission reduction measures into four main categories:

1. Technical measures generally aim at either reducing the power requirements to the engines or improving fuel efficiency. These measures tend to have high investment costs since they are linked to the design and building of ships. In general, retrofitting is more expensive compared to applying technical measures in the design and building phase. More efficient engines and devises to capture exhaust emissions are examples of such measures.
2. Alternative fuels and power sources can reduce the use of the more polluting fuels in order to reduce the emissions to air. These measures generally require significant investments upfront, both onboard and in new infrastructure.
3. Operational measures have a focus on reducing emissions to air by changing the operational pattern and maintenance routines. This includes optimized trim and ballasting, hull and propeller cleaning, better engine maintenance and optimized weather routing and scheduling. These measures generally have low investment needs and moderate operating costs, and are closely related to management planning. Many of these measures are attractive for purely economic reasons as well.
4. Structural measures impose changes that are characterized by two or more counterparts in shipping working together to increase efficiency and reduce emissions by altering the way in which they interact. Structural changes are believed to have more reducing potential compared to the above measures, but are generally hard to develop and implement. This could be tailored port berthing instead of using a “first-come, first served” approach.

As mentioned above, switching to an alternative fuel is suggested to comply with the new regulations. Especially liquefied natural gas (LNG) has been predicted to be the *new thing* within maritime fuels. The reason for this can be discussed but the main argument is that LNG is sulphur free and less NO_x is formed during combustion than traditional marine fuels. The reduced NO_x emissions will comply with Tier III limits and can be achieved with both pure gas engines and four-stroke dual-fuel engines, which are typically used on board vessels involved in short sea and coastal shipping. In addition to the SO_x and NO_x reductions, a 20% - 25% reduction in CO_2 emissions is possible due to the lower carbon content of LNG compared to traditional ship fuels. The actual reduction depends on engine type and the range of possible measures for reducing the unwanted release of unused methane [14].

One can see from the measures on the previous page that there is no clear answer to which path one should go to reduce the emissions to air. However, as technology develops and the manufactures gain more knowledge, it is reason to believe that reduction measures both can meet the new regulations and be economically feasible. In the continuation of this thesis, a further look into LNG as fuel will be done. In addition, LNG will be compared to traditional HFO when it comes to emissions.

3. The two different fuel alternatives

In this chapter a brief introduction to both LNG and HFO will be given, in addition to an introduction of the possible engine types for the two fuel alternatives.

3.1 Liquefied natural gas (LNG)

Natural gas is a mixture of various hydrocarbons, consisting of up to 90-95% methane (CH_4). Due to its chemical properties, it emits less CO_2, NO_x and PM compared to any petroleum product during combustion. It also contains zero sulfur, therefore eliminating acid rain contribution from ships [1].

Liquefied natural gas (LNG) is natural gas that has been cooled down to under -163 °C. At that temperature it will reach its atmospheric boiling point, and become a liquid. The volume has been reduced by about 600 times and it is colorless, non-corrosive, odorless and non-toxic [15]. LNG is a clear liquid, much lighter than water, with a density between 430 and 520 kg/dm^3. A mixture of 5-14% of methane gas in air can ignite when in contact with a spark or flame and when LNG is exposed to ambient temperature it vaporizes quickly. The process of turning the gas into a liquid is essential for making natural gas attractive to shipping. One could use pipelines to transport the gas from the production site to the consumer, but when the distance becomes vast, economic aspects takes over.

3.1.1 History of LNG shipping

Godfrey Cabot patented a LNG river barge in 1915 with the intension of freezing meat and transport it up the Mississippi River. This concept did not prove feasible, and 40 years passed before there was interest in the international transport of LNG. In the early 1950s, several groups began studying the feasibility of carrying LNG on rivers by barge and in 1955, Dr. Øyvind Lorentzen designed and patented a methane tanker with DNV's approval. In 1959, the converted vessel, renamed Methane Pioneer, transported the first LNG cargo from Louisiana to the UK. Six more cargoes were similarly transported over the Atlantic Ocean, with the purpose of completing the experimental project, and many expected a rapid expansion with this new technology [1].

Figure 5 - The first LNG tanker- Methane Pioneer

Events moved quickly after the successful trial shipments by the Methane Pioneer. By 1960, negotiations were well advanced toward the conclusion of a 15-year contract with Algeria to ship 100 million cubic feet of gas per day to Great Britain and half that amount to France. The first commercial LNG ships were the Methane Princess and Methane Progress, each with a cargo capacity of 27 400 m^3, making weekly trips from Algeria to Great Britain [16]. Today, there are about 360 LNG carriers over 10 000 m^3 that are in service and close to 80 that are under construction [17].

3.2 Heavy fuel oil (HFO)

Heavy fuel oil (HFO) is a residual oil of high viscosity and density. It is considered to be the dirtiest of the substances that are made in a refinery, but it is also the cheapest. The sulphur content may vary, but low sulphur heavy fuel oil with a content of 1% and less is possible with today's technology. It is made from crude oils in refinery processes, and it is the most common fuel in marine engines with a reported consumption of 257 million tons in 2007. Distillate fuels, accounted only for 23% of the consumption from international shipping according to IMO [3]. IMO also reports that the residual fuels are mainly used for shipping with slow-speed engines. Some selected properties for HFO are listed in the table below are taken from ISO 8217, fourth edition 2010 [18].

Parameter	Unit	Limit	HFO (RMG 380)
Viscosity at 50°C	mm^2/s	Max	380
Density at 15°C	kg/m^3	Max	991
Micro carbon residue	% m/m	Max	18
Ash	% m/m	Max	0.1
Water	% V/V	Max	0.5
Pour point	°C	Max	30
Sulphur content	% m/m	Max	4.5

Table 2 - Selected properties for heavy fuel oil, ISO 8217

3.3 Engines

Marine engines are designed differently and manufactures strive to offer the most energy efficient engines to the shipowners. There are many different types of engines and some run on diesel, other run on gas, some are two-strokes and some are four-strokes. Some engines are designed to run on both gas and diesel, making it more versatile so one can operate on other liquid fuels outside the ECA areas.

3.3.1 Gas engines

Originally the reason for adopting LNG instead of liquid fuel was to reduce emissions of NO_x, SO_x, and PM. In addition the chemical composition of methane is leading to reduced CO_2 emissions. An undesirable feature of LNG fuel is that any gas which is not combusted is a highly potent greenhouse gas, with an effect that may offset the gain from reduced CO_2. In Norway, several passenger ferries and offshore supply vessel have been equipped with gas engines with the aim of reducing the overall emissions, and especially NO_x and SO_x emissions. Most gas engines are either lean-burn gas engines or dual-fuel engines that are based upon diesel technology.

Dual fuel engines are designed to either run on natural gas, light fuel oil (LFO) or HFO and can easily switch between fuels while operating. It is designed to provide the same output regardless of the fuel. When the engine operates in gas mode it utilizes a lean-burn Otto combustion process, and the normal diesel cycle when using LFO or HFO. For the gas cycle, gas is mixed with air before the intake valves. After the compression, the lean air mixture is ignited by a small amount of liquid pilot fuel instead of a spark plug [6]. For the dual fuel engines there have been problems on the methane slip, but engine manufacturers are aware of the problem and there have been a lot of research on overcoming the problem in recent years [19].

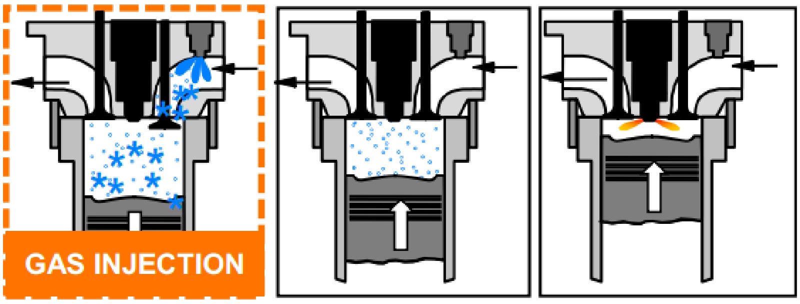


Figure 6 - Engine with dual fuel configuration which meets IMO Tier III

Rolls Royce have designed several spark ignited lean-burn gas engines, and emissions of CO_2 and NO_x are reduced with up to 30 and 90% respectively, compared to diesel, according to the manufacturer [20]. These engines only run on natural gas and have a lower combusting temperature, reducing the NO_x emission dramatically. Pressurized gas, around 4-5 bar, are used in the four-stroke Otto cycle for the combusting phase. The engine has a high efficiency at high load compared to corresponding diesel engines. Because of the low emission of NO_x, these engines meet the Tier III requirements and are therefore attractive as an alternative to the common diesel engine. However, retrofitting is not an option and there have been challenges on the methane slip, which again means that the resulting CO_2 reduction is not necessarily as effective as one could hope for.

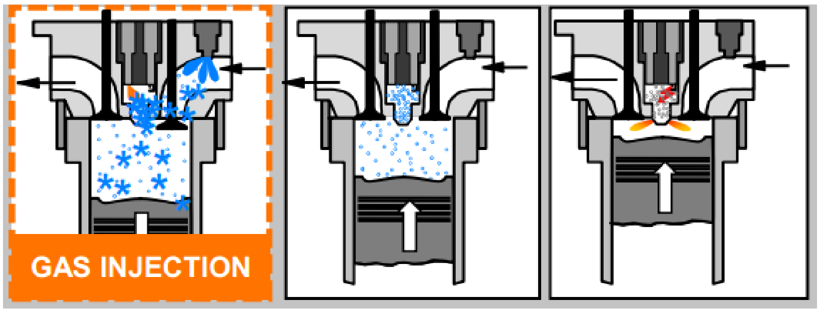


Figure 7 - Engine with spark-ignited gas configuration which meets IMO Tier III, but has no redundancy or HFO flexibility

Another problem that needs to be addressed is the additional space that is required to store LNG. To store LNG one need pressurized tanks with good insulation to keep the gas liquefied. According to Wärtsilä, a LNG system that contains LNG at 10 bar, the tank and additional tank room will require up to 4 times the space compared to HFO [21].

3.3.2 Diesel engines

There are mainly two different diesel engines; two-stroke or four-stroke engines. A two-stroke engine completes a power cycle in only one crankshaft revolution, compared to a four-stroke engines which needs two revolutions. When new vessels are built, the shipowners often tend to choose a two-stroke diesel engine instead of a four stroke diesel engine. A reason for this is that two-stroke engines can burn low grade fuel oil hence reduce running cost on the ship [6]. Furthermore a two-stroke engine often provides a higher power-to-weight-ration compared to a four-stroke engine.

In recent years low -speed two-stroke engine designers have invested heavily to sustain their dominance of the mainstream deep sea propulsion sector formed by tankers, bulk carriers and container ships, and recently extended market opportunities to large twin-screw LNG carriers. New gas engines are slowly introduced in more and more segments of the shipping because of the new and stricter regulations introduced by IMO. NO_x, SO_x, PM and CO_2 are the main emissions related to the use of diesel engines, both two and four-stroke. Some also claim that diesel engines are releasing methane, but in a study done by MARINTEK [22] they said that there is no reason to believe that there is methane in the diesel fuel, and it is unlikely that methane is produced during the combustion.

At the moment, HFO with a sulphur content of 1% is the most common used fuel in the sulphur emission controlled areas. However, when the new regulations will come in force in 2015 the limit is set to 0.1% sulphur content. This is important to have in mind when comparing the two different fuels since HFO could not be used in ECA without the use of exhaust gas abatement techniques, like a scrubber. However, this is not included in this study.

4. Methodology

Life cycle assessment (LCA) is a management technique which addresses the environmental aspects and potential environmental impacts throughout a product's life cycle. The assessment covers all the impacts from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. In a LCA analysis, a product or system is evaluated based on the identification of input and output flows that are responsible for the overall impact. Input flows can be raw material, water or electricity, while output flows can be identified as emission to air, material waste or acidification. When the input and output flows have been identified and quantified, the results can be interpreted. The results can be compared in order to choose the more environmental friendly product, or to show which stage of a product life that is most polluting in order to improve its overall environmental performance.

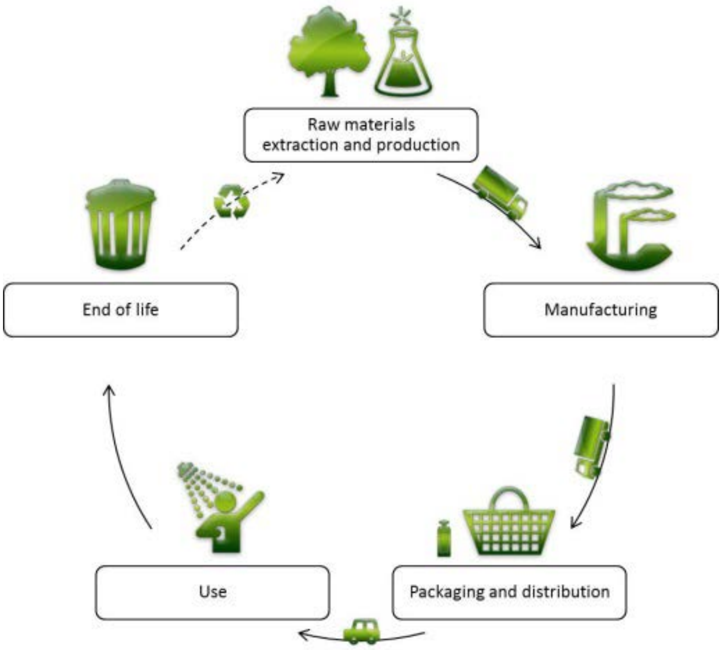


Figure 8 - The processes associated with a product's life cycle

The LCA methodology has its origins in 1970s, and one of the first studies ever performed was done for Coca Cola on the use of plastic versus glass bottles for packing. They wanted to understand the environmental aspects of using plastic bottles instead of the aging glass bottle. To the surprise of many, it turned out that plastic bottles were less polluting than the glass bottles when the whole life cycle was taken into consideration [23]. As a result of this new way of thinking, the scientific community began discussing standardization and in 1984, EMPA published an *Ecological report of packing materials* as step towards today's standards.

The International Organization for Standardization (ISO) has developed two standards for the LCA model, the ISO 14040 and 14044. The ISO 14040 standards are the first standards dealing with LCA methodology and were introduced in 1997. The standard provides the general methodology and describes the principles for a LCA, but does not describe a particular technique for the individual phases of a study [24]. After the first edition of the standard, many updates have been introduced, and now the ISO 14044:2006 are currently used. The standard consists of principles, framework, requirements and guidelines.

The four phases in a LCA is listed below and illustrated in figure 9.

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth can differ considerably depending on the goal of a particular LCA. The life cycle inventory analysis phase (LCI) is the second phase of the LCA and has the purpose of finding superior input-output data. The third phase is the life cycle impact assessment phase (LCIA) which provides additional information to help assess a product or system's LCI results. The fourth and final phase is life cycle interpretation where the results from an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making [24].

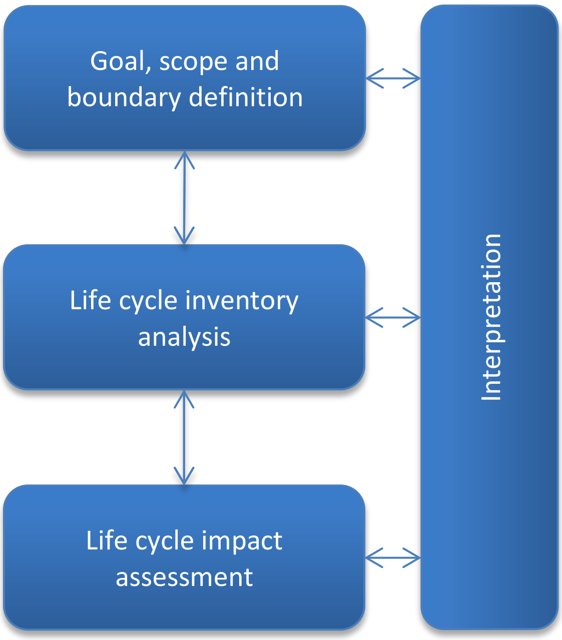


Figure 9 - LCA framework based on ISO standards

4.1 Goal and scope definition

The first stage of LCA is goal and scope definition. The goal and scope of an LCA study should be clearly defined and consistent with the intended applications. It should include the product to be studied and the reasons for carrying out the study [24]. It is important to precisely know the decision makers expectations, so the LCA can be as accurate as possible. One goal of a LCA may be to compare two different products, whilst other studies may aim at determining what stages of the life cycle that contribute the most to global warming. System boundaries shall be clarified so that the right processes are taken into the study. Limitations, data requirements, data quality requirements and assumptions are also identified in the goal and scope definition. The boundaries chosen in the study are defined by the processes that will be included.

The choice of functional unit is important in the specification phase. It must be consistent with the goal and scope of the study and must be measurable. The purpose of a functional unit is to provide a reference to which the input and output data are normalized in a mathematical sense. The functional unit also allows comparison of the results with other LCA analysis, highlighting several aspects of a product or process [25].

All of the factors mentioned above will influence the accuracy of the results and therefore have to be considered in the interpretation phase [25].

4.2 Life cycle inventory (LCI)

The second step of the study is a life cycle inventory (LCI). It is a process of quantifying energy and raw materials requirements, emissions and other requirements or releases for the entire life cycle of a product. This is the most complex part of a LCA analysis and in figure 10 a simplified product system can be seen. In order to quantify these inventory flows, each main process of the product or process should be divided into smaller subsystems [24].

The three steps of the inventory analysis is the following; develop a flow model according to the system boundaries, develop a data collection plan and collect the data and finally evaluate and report the results. A validity check shall be done during collection of data to ensure that the data quality meet the required standards [24]. As one can imagine there are many databases where the required data to calculate the output flows can be found, but it is important to choose what is considered to be the most accurate source. This will in the end influence the quality of the results. However, not all data are easy to obtain. Companies may or may not have precise and accurate information of their factories and plants, but often they choose to keep them private and out of public. In the cases where this happens one has to assume values, try to be as accurate as possible and comment this in the interruption phase of the analysis.

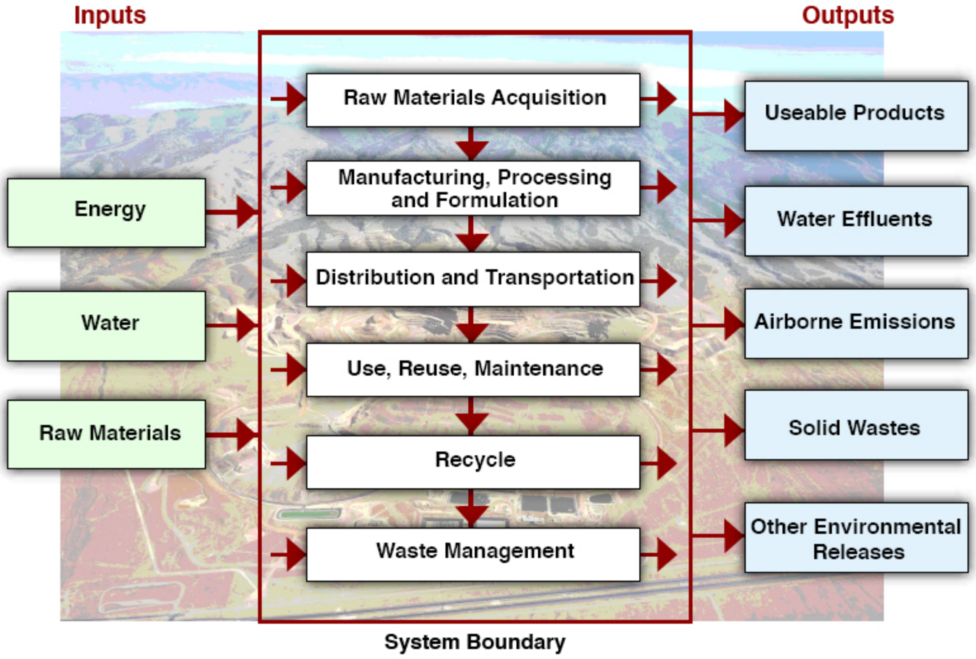


Figure 10 - An example of a simplified product system

4.3 Life cycle impact assessment (LCIA)

Life cycle impact assessment (LCIA) is the third step of a LCA and it is the phase where the aim is to understand and evaluate the magnitude and significance of the potential environmental impacts of a product or process. During this phase, the potential environmental impacts are estimated and classified, characterized, normalized and weighted in order to be interpreted for the next and final stage of the LCA analysis. This step consists of three mandatory elements: selection of impact categories, categories indication and characterization models [24].

The results obtained in the previous LCI phase are analyzed by calculating the contributions of each sub-process to the impact categories stated in the goal and scope definition. To perform an LCIA, several impact categories exist and there are as well many methodologies available to aggregate those impact categories. The choice of these parameters depends on which impacts are included in the study, and this is generally specified by the decision makers [26].

4.4 Interpretation phase

The interpretation phase is the final phase of the LCA. In this phase all the results obtained from the inventory analysis and impact assessment phases of the LCA are collected and evaluated. The results are then summarized and discussed in order to get a final conclusion and to give recommendations to the decision makers. The interpretation must be seen in context with the goal and scope definition and reflect the purpose of the study. It includes the results, the assumptions and limitations associated with the results, and the methodology. The data collection, the data quality assessment and the terms of value choices and expert judgments are also included in the interpretation stage [24]. This phase may also include recommendations for future analysis and studies, but this is not mandatory according to the current regulations [25]. Finally, other aspects aside from the environmental issues can be included to help in the decision making process. This may include economic, social or cultural aspects.

5. Goal, scope and boundaries

In this and the following chapters the methodology will be put to use with a case study. The four major phases in a LCA are described according to ISO standards.

The aim for this study is to evaluate two different fossil fuels for marine transportation when it comes to their environmental impact in a life cycle perspective:

- LNG (fulfill Tier III and SECA 2015)
- HFO with a sulphur content of 1%

5.1 Goal and scope definition

The intended goal for this thesis is to perform a comparative life cycle assessment study, comparing the environmental impact of LNG from the Melkøya plant, in the northern part of Norway, with HFO from the North Sea. Both fuels will be transported to Rotterdam in the Netherlands where it will be used as fuel on a passenger ferry for short sea traffic. Furthermore, a final evaluation shall be completed aiming at giving a recommendation on whether the use of LNG will be environmental friendly compared to HFO in a life cycle perspective. Finally, the results of the case study shall be compared to previous studies. The reason for comparing the two fuel alternatives in passenger ferries is that the technology is proven to work. Several vessels in Norway are equipped with LNG engines, and ferries usually have route based operation and it is therefore easier for them to use LNG, with limited infrastructure.

The growing awareness of climate change and its environmental impact have made the shipping industry rethink their environmental strategy. New rules and regulations that will take affect soon are forcing the industry to come up with better fuel alternatives. However, a fuel that seems favorable in the combustion phase may not be environmental friendly in the previous stages. Therefore it is interesting to perform a LCA on such a traditional fuel as HFO and compare it with, what many describe as the new big thing, LNG. By comparing these two fuel alternatives this study is performing what the LCA community calls a *consequential LCA*. This sort of LCA strives to describe the environmental consequence of alternative course of action, whilst attributional LCAs struggle to be as complete and thorough as possible [27].

The pathways for the two marine fuels are simplified and presented in figure 11.

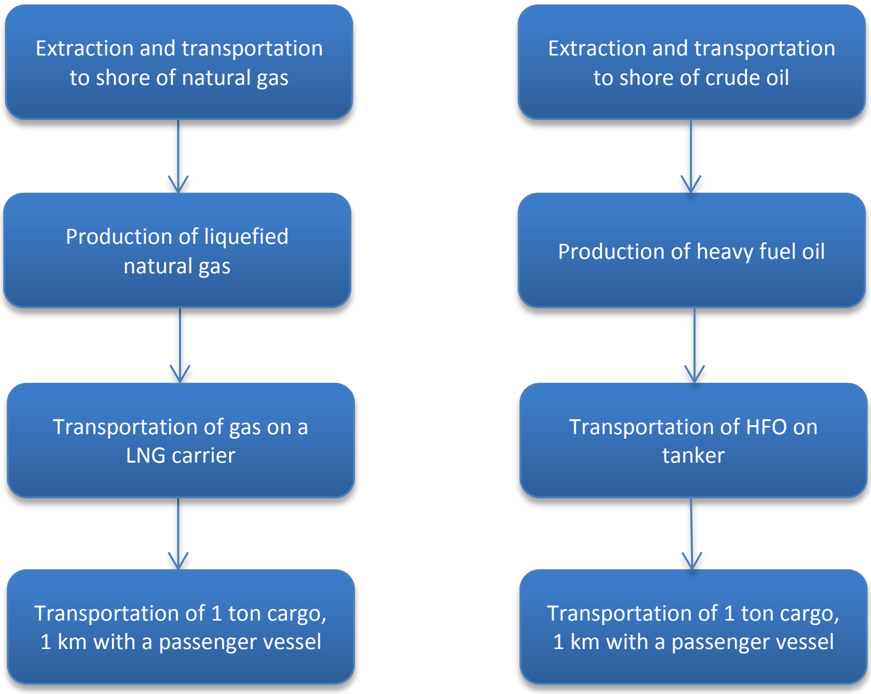


Figure 11 - An overview of the pathways for the two fuels

According to the ISO 14044:2006, the functional unit is defined as *the quantified performance of a product system for use as reference unit.* In other words, it helps quantifying the products and aims at providing a reference between the inputs and outputs. In addition, it allows comparison of results and different products. Here the functional unit must be sufficiently precise to allow the impact assessment of the LNG plant at Melkøya, but wide enough to include the possibility of the environmental assessment of other LNG or HFO pathways. It also needs to be able to compare HFO and LNG as fuel in a way that is logical and can be quantified. The functional unit is therefore set to one ton cargo transported one km with a passenger vessel at normal sea conditions. By using this unit the chance for allocations is low, the results is measurable and in accordance with the objective. The vessel choice was made based on the trend in the ro-pax business where the amount LNG fueled ships are relative higher than in other segments in shipping.

The system boundaries is showed in the figure 12 and includes extraction of raw materials, transportation from offshore to land, production of the fuels, transportation to the market and finally combustion for the transportation of one ton cargo transported one km. Manufacture of capital goods is not included, nor the production of lubrication oil and waste management of oil sludge. The geographical boundaries are set to northern Europe. It is assumed that extraction of crude oil will take place in the North Sea, while natural gas is extracted from the Snøhvit field, 143 km north-west of Melkøya, in the northern part of Norway. Both of the fuels are then transported to Rotterdam harbor in the Netherlands.

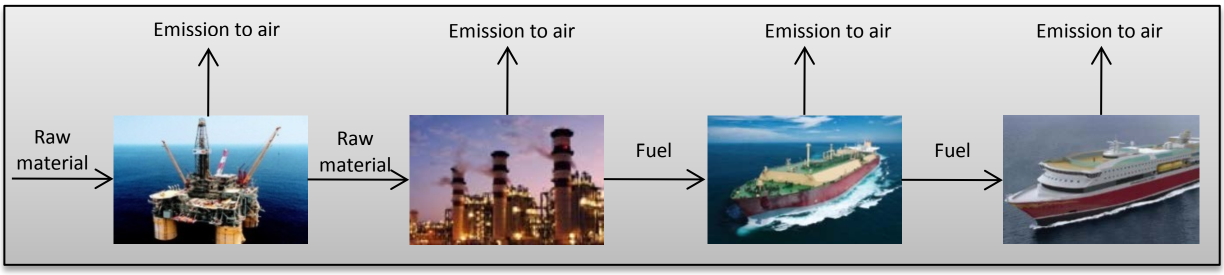


Figure 12 - The selected system boundaries

Allocation procedures are used to partition the environmental burdens of processes which contribute to more than one product system [28]. For example, residual oil is not the only product produced at a refinery. Many products are made and the fraction and type of emissions associated to each component is unknown. Natural gas is produced both in association with crude oil and alone. Allocation procedures are then used in order to quantify the emissions from each component. According to ISO 14044:2006, allocations should wherever possible be avoided by dividing the unit process in sub-processes and collecting the input and output data related to each sub-process. Or one can expand the product system to include the additional functions related to the co-products [24]. A system expansion will lead to more processes being included in the system and are therefore not included in this thesis. Allocation procedures in this analysis are avoided as much as possible. Where it was inevitable, allocation was based on energy content such as lower heating values (LHV). See appendix L for more details.

When it comes to data quality, the most updated data should be collected and used. The data should be relevant for today's conditions and a few years into the future. If it is possible, data from the right geographical area should be used. Where there is no available data, good assumption should be made and argued for. Uncertainty in the assumption will be commented and discussed.

Data used for this study are mainly collected from different databases on the internet and some from relevant books. They are all commented in chapter 6.

5.2 Impact categories

Selection of impact categories is important in order to achieve the intended purpose and goal of the study. However, the ISO standard does not say which categories one should choose so the choice is left with the author.

Since the interesting part of this thesis is to see which of the two selected fuels that is the most environmental friendly, it is natural to look at the carbon footprint. The carbon footprint is defined as the total emissions of greenhouse gases (GHG), expressed in a defined unit. Furthermore, it is of interest to look at the total acidification emissions, not only in the combustion stage. In addition, the total energy use has been chosen to see how much input you would need to complete the functional unit. Therefore, the three selected impact categories will be the following:

Global warming potential (GWP) or climate change potential (CCP)

Global warming potential (GWP), or climate change potential (CCP), is a way of presenting the environmental impact of the greenhouse gases as result of emission to air. Changes in the global average surface-air temperature and their effects, such as storm frequency and intensity, rainfall intensity and frequency of flooding's, are examples of global warming consequences [29]. The potential for each component is based on the environmental impact of the component compared with the impact of CO_2. IPCC has published a global warming potential list for a 100 year period [30]. The data is converted into CO_2 equivalents and covers carbon dioxide, methane (CH_4) and nitrous oxide (N_2O).

Acidification

Acidification potential or SO_2 equivalents is a way of presenting the environmental impact of acidification gasses as a results of emission to air. The potential for each component is based on environmental impact of the component compared with the impact of SO_2 [31]. Examples of acidification gases are ammonia (NH_3), sulphur oxides (SO_x) and nitrogen oxides (NO_x). The emissions are converted into SO_2 equivalents.

Primary energy use

A fuel's energy efficiency is a parameter that can be compared to other fuels and it is chosen in this study because it is easily quantified. It says how much energy you put in compared to what you get out. The unit for this category is MJ and lower heating values are used.

Name	Chemical formula	Global warming potential (GWP), 100 years. (CO_2-eq)	Acidification potential (SO_2-eq)
Carbon dioxide	CO_2	1	-
Methane	CH_4	25	-
Nitrous oxide	N_2O	298	-
Sulphur dioxide	SO_2	-	1
Sulphur oxide	SO_x	-	1
Nitrogen oxide	NO_x	-	0.7

Table 3 – The selected impact categories: global warming and acidification for common greenhouse gases [30] [31].

The primary pollutions that are considered in this study are CO_2, CH_4, N_2O, SO_x and NO_x. In the table above global warming potential (GWP) and acidification potential for the selected pollutions are listed. The characterization factors are taken from the IPCC and the International Marine Contractors Association (IMCA).

As one can see in the table 3, the three first of the pollutions will have impact in the GWP category, whilst the oxides will contribute to the acidification category. Methane and nitrous oxide emissions weigh much more heavily than CO_2 emissions for global warming. As a result of this, methane needs to be multiplied by 25 and nitrous oxide by 298 in order to obtain the CO_2 equivalent for global warming.

It is well known that rising atmospheric CO_2 reduces ocean pH and it will continue to accelerate unless future CO_2 emissions are curbed dramatically. Acidification alters seawater chemical specification and biogeochemical cycles of many elements and compounds, and the potential for marine organisms to adapt to increasing CO_2 are not well known [32]. In this study the effect of CO_2 emissions on the ocean have not been included.

6. Life cycle inventory analysis (LCI)

Life cycle inventory analysis is a quantification of the input and outputs that flows through a system. The inputs are the resources that are needed and the outputs are the desired product, bi-products and waste that is also produced in the same process.

In this chapter the two different value chains will be presented and described in depth. This is to familiarize the reader with the different processes that are included in order to get the final products, LNG and HFO. In addition, the processes, from extraction to combustion, will be described and the relevant data used to calculate the life cycle emissions of both LNG and HFO.

6.1 Extraction of natural gas and crude oil

Extraction, transportation and production of natural gas and crude oil are described in this section. The outputs from these processes are liquefied natural gas and heavy fuel oil. Data used for the each step are also presented together with assumptions and limitations. Figure 13 shows step one of the life cycle for the two fuels.

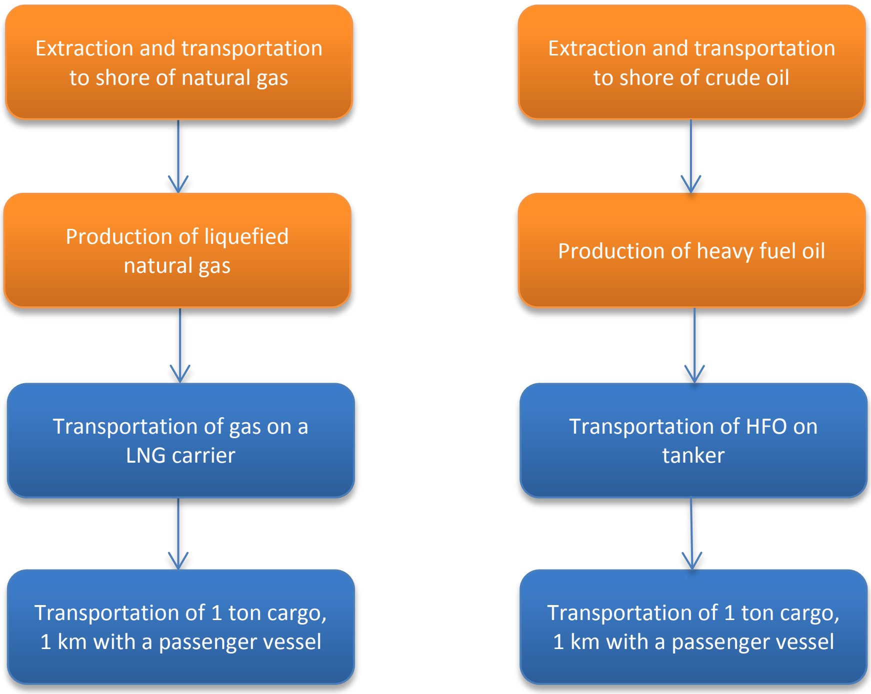


Figure 13 - Extraction and transportation of natural gas and crude oil

The exploration and production of natural gas and oil is very similar, and the two are often found together. In the early days, gas was seen as the poor relation to oil because oil was more valuable. However, oil and gas have some substantial differences, both when it comes to the physical characteristics and the transportation method. Natural gas is considered more difficult to transport than oil, but the extraction from the ocean floor is much easier than for oil, which usually requires an assisted recovery technique such as gas re-injection. This is to increase the pressure in the reservoir to extract as much oil as possible.

6.1.1 Seismic exploration

Before one even can start to extract the hydrocarbons beneath the seabed, one has to find them first. The primary tool for a geophysicist in the search for oil and gas is seismology, which uses sound waves propagating and reflecting through the earth's crust to draw a picture of the underlying geology [1].

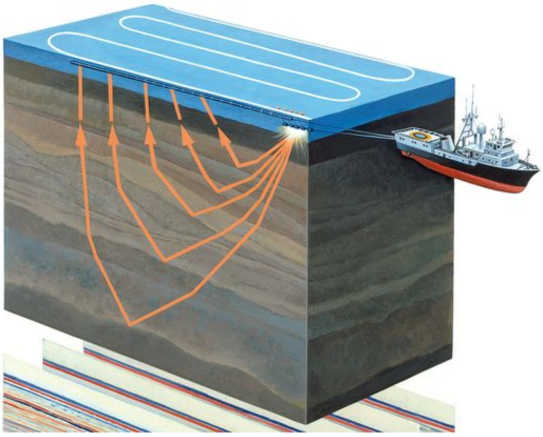


Figure 14 - Marine seismic exploration

After the seismic survey have been completed, geologist study the data collected to see if there are some layers in the seabed that contains hydrocarbons. Seismic data are vital in the identification of potential prospects, but the only way to establish whether a field contains oil or gas is by drilling.

6.1.2 Exploration drilling

To confirm or disprove that there are hydrocarbons under the seabed a wildcat well is drilled. This step is difficult to include in a LCA, because one does not know how many development wells that has to be drilled. Depending on the location and the depth, one can choose between different drilling rigs. In shallow water, rigs can be placed on barges. For slightly deeper water jack-up rigs can be used, but when the depths exceed approximately 400 meter mobile drilling rigs, like Aker Spitsbergen, becomes more attractive. Different types of well logging equipment are lowered down the well bore to get a more detailed picture of the formation than from the seismic data. From acoustics and measurement of natural gamma radiation they will get detailed data about pressure, temperature, porosity, amount of water and where the different layers are located [1]. Rock core samples are brought to the surface for further investigation. Even the mud is analyzed to get as much information as possible. All these factors are valuable for determining the potential productivity of a given formation and to see if the field contains reasonable reserves of oil and gas for commercial extraction.

6.1.3 Production

Once exploration drilling has been completed and it is shown that the field will produce commercial hydrocarbons, development drilling can begin. During the exploration drilling, appraisal wells were also drilled. To start the production the drill string with a drill bit attached is lowered down to the seabed. Then a steel casing is lowered and cement is pumped through the casing and then fills the spacing between the steel pipes' outer diameter and the earth wall. This process goes on with decreasing casing diameter for every section of casing. When all the casing is placed and cemented, a production tube is lowered inside the casing to extract the hydrocarbons [33]. Drilling is well known as a steel intensive industry because of all the casing steel needed to protect the production equipment from the outer earth walls. This step is also difficult to include in a LCA because of the uncertainty of the amount of steel being used.

When the well is completed, the hydrocarbons need to reach the surface. Natural gas is driven by its own pressure and therefore flows into the well on its own. Oil, on the other hand, often requires different recovery techniques to get it up to the platform. In some cases additional treatment must be applied to get the hydrocarbons into the well. Fields which have formations with low permeability or fields that are reaching the end of the normal lifetime can be treated in different ways to improve their production. Fracing is a method were large volumes of water or nitrogen-based foam at high pressure are being pumped into a well so that formations fractures, opening up new pathways [34]. Small particles like sand are often injected together with the other fluids to prevent that the fractures closes. Fields that are treated with these methods are rarely candidates for supplying LNG projects because of the costs of gas development and production [1]. Development of large production fields may require multiple semi-submersibles and the oil and gas industry are continuing to push into deeper waters. Subsea completions allow development with more limited platform requirements and these are Christmas trees on the seabed. Flow lines from each well goes into a central manifold, which then feeds the gas into a pipeline leading to shore, FPSO or a platform above [35].

Refining crude oil

When the crude oil reaches the shore it continues into a refinery. The crude oil can enter the refinery either by pipeline or by a crude oil carrier from the extraction site. As the crude oil comes from the well, it contains hydrocarbon compounds and relatively small amounts of impurities such as oxygen, nitrogen, sulfur, salt and water. The refinery removes any substance from the crude oil that is not a hydrocarbon and then breaks the oil down into various hydrocarbon components [36].

The first step is separating crude oil into different components, called fractions or cuts- groups of hydrocarbons with the same boiling-point range and similar properties. Next it breaks down or rearranges the molecules of some of the separated fractions and separates them again. The final process is to blend the refined hydrocarbons into mixtures that have desirable qualities for certain purposes. The refining process converts almost all of the crude oil into commercial products, including heavy fuel oil. Which processes a refinery use depends on the content and quality of the crude oil it receives, consumer demand and existing plant facilities [37].

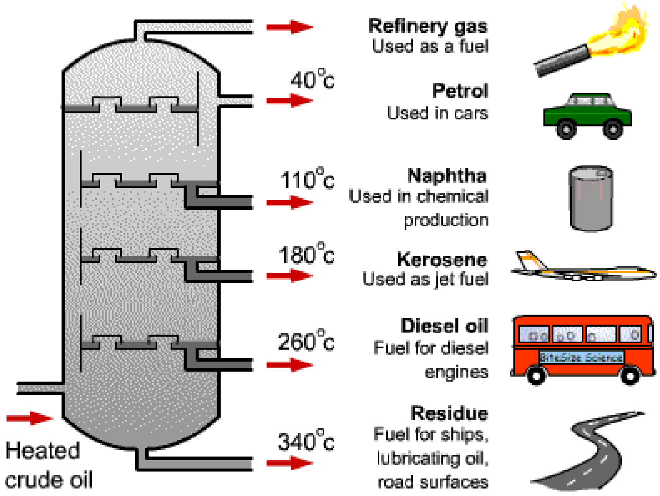


Figure 15 - Heavy fuel oil is a residue with a high boiling point and it is very volatile.

Data used for crude oil exploration and production

The data used for the heavy fuel oil is collected from the European Commission Joint Research Centre on life cycle assessment, called the European reference Life Cycle Database 3.0 (ELCD). The data set covers all relevant process steps over the supply chain of the heavy fuel oil with a good overall data quality. Crude oil mix information is based on official statistical information and the refinery emission data are based on literature and the European Pollutant Emission Register (EPER) [38]. The data represent a cradle to gate inventory and the reference flow is 1 kg HFO.

The data set is from 2003 and is set valid until 2012. However, due to the lack on more recent datasets, this was chosen because it is including extraction, transportation to shore *and* refining of crude oil. Production of vessels used to do seismic surveys is not included because of allocation issues. The HFO is assumed to be transported by pipeline to the harbor. Transportation from harbor to refinery and back is not included. In appendix A the LCI dataset is presented.

Liquefaction of natural gas at Melkøya

Snøhvit is a gas field located 140 km north-west of Hammerfest and was discovered in 1984. The natural gas is extracted from the ocean floor, 250-345 meter below the surface, and then transported 143 km by pipeline to Melkøya LNG plant for liquefaction. The subsea installation is controlled from Melkøya and there is no sign of the production on the surface. There are 20 wells that produce gas from the three reservoirs Snøhvit, Askeladd and Albatross [39].

The Melkøya facility has earned its title as the most energy-efficient plant of its kind in the world, because of its carbon capture and storage procedure [40]. Around half of the CO_2 that it is separated from the natural gas stream is piped back to the field below the ocean floor instead of being released in the atmosphere. This technique is a milestone in carbon capture and storage will serve as a reference project for future natural gas liquefaction plants.

It is two main processes in a liquefaction plant; pretreatment and liquefaction. The first step of the pretreatment process is to remove acid gases, reducing the CO_2 levels to prevent freezing in the main cryogenic exchanger. After that vapor from the previously step is removed along with any traces of mercury to prevent corrosion in the heat exchanger equipment [1]. Then the gas continues into the liquefaction process where the gas is initially cooled to a temperature around -30°C. It then continues to go through the remaining two cycles where the gas finally reaches the liquefaction temperature of -163°C. In the figure below one can see a typical flow diagram for natural gas liquefaction.

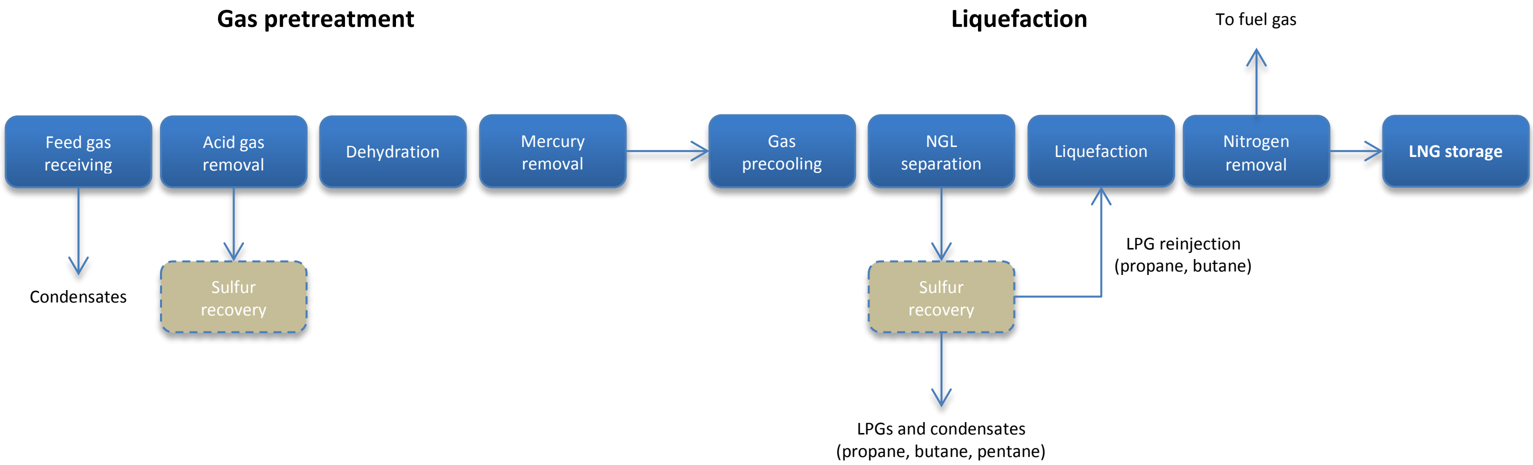


Figure 16 - Natural gas liquefaction flow diagram [1]

LNG is stored and transported as an evaporating cryogen and since tanks cannot have perfect insulation, LNG cargo absorbs heat due to the large temperature difference between the tank and the surroundings. Because of this, boil-off gas (BOG) losses are inevitable and some LNG will evaporate along the supply chain. At the LNG production plant BOG are usually compressed and exported back to the plant fuel system, while it is either flared or sent to the regasification plant at the receiving terminals. The boil-off rate depends on the insulation, design and operating conditions, but according to Hasan et al. 2009, 0.1-0.15% of the full cargo content per day is typical over a 21-day voyage [41].

After the liquefaction process is completed, the LNG is transported and stored in two 125 000 m^3 tanks until it can be transferred to LNG tankers. These membrane storage tanks are similar to the designs found in membrane containment LNG tankers which will be explained in chapter 6.2.

Data used for natural gas exploration and liquefaction

For the extraction and transportation phase of natural gas, data were collected from the Center of Environmental Assessment of Product and Material Systems (CPM) [42]. It is a cradle to gate process and covers exploration, production and transportation to the market, including all main service and support functions for petroleum services in Norway. The system includes production drilling, well steam processing, produced water removal, pressure maintenance, power supply systems and transportation of the natural gas to the main land by pipeline. The construction, operation and final demobilization of the exploration, production, transportation and support facilities are also included. Not included are environmental life cycle data connected to the infinitely varied firms if consumption of oil and gas in their markets. The functional unit on the data set is one mega ton and the data are from 1991. It is rather old, but is still chosen since it represents the region very well. See appendix B for details and calculations.

For the liquefaction process, data were collected from the report *"Well-to-Wheels analysis of future automotive fuels and powertrains in the European context"* [43]. The data is chosen since it is representative for a European context and that data for the Melkøya plant was not available. In addition the data is from 2008 and contains information on CO_2, CH_4 and N_2O which is the three main GWP gases. See appendix C for more details and calculations.

6.2 Transportation

In this section the transportation path for the two fuels will be described. The LNG and HFO are shipped to Rotterdam from Melkøya and the North Sea after the liquefaction and refinery process. This is done by special built vessels with distinctive characteristics.

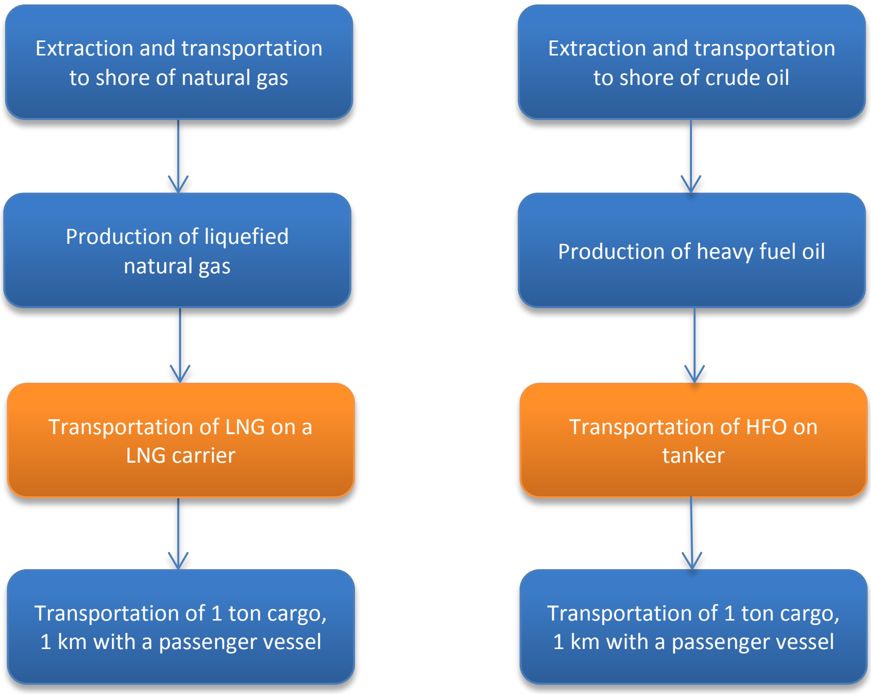


Figure 17 - Transportation of LNG and HFO

LNG shipping

In order to load the LNG on tankers, LNG jetty facilities are designed and constructed. The vessel approaches the jetty with the assistance of three or four tugboats and connects with the jetty. Loading pumps in the facility's storage tanks transfer LNG into the LNG tanker's cargo tanks through a piping system which can withstand the low temperatures. This process normally takes between 12 and 13 hours for a 138 000m^3 LNG tanker [44]. However, if the vessel is "warm", the system and especially the cargo tanks have to be cooled down to a temperature close to that of the LNG which is to be loaded. This additional cool-down process will add another 12 hours to the total loading time [1]. The reasons for this are that if the LNG is pumped directly into warm tanks, the LNG will almost immediately turn into vapor. Another issue that will arise is the damage of the flexibility and strength to the stainless steel if the material is subjected to a very local and rapid cooling, such as a small droplet of LNG comes in contact with a warm tank wall. This is why a normal practice is to leave 5% of the cargo to keep the vessel cold. This is referred to as heel[2] and is often negotiated when LNG vessels are chartered because it directly influences the revenue of the trip and the boil-off rate.

[2] Cargo that is still onboard after unloading.

Today, there are several types of LNG tanks in the market, but the two main types used are the self-supportive Moss-type spherical aluminum tanks, and the membrane-type tanks. In recent years, the trend shows that Moss tanks are less chosen in LNG shipping, since they require more space and a larger vessel per volume capacity compared with membrane tanks. The LNG fleet consisted of 199 tankers in May 2006 and of these, 45% had the Moss design and 51% were constructed with the membrane-type [1].

The spherical tank of the Moss-type is the most recognizable design for LNG tankers. The spherical tanks stick out above the deck and the ships are very characteristic. The hull and tanks are in this design independent. The insulation of the tank is important to maintain the safety against embrittlement. The cold tanks will absorb heat from the hull, and this effect can cause cryogenic embrittlement in the hull steel. The spherical tank is preferable with respect to sloshing. If the tanks are not completely filled up, the motions of the LNG cargo in a membrane tank will cause large motions for the ship as well. The spherical tank minimizes this problem, since the cargo only will follow the boundary of the tank without transferring motions to the ship structure.

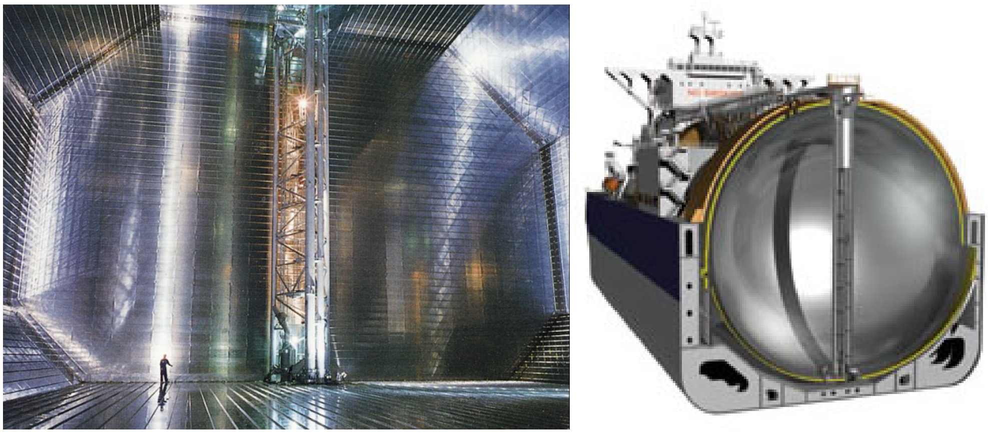


Figure 18 - The two most common LNG tanks; a membrane tank to the left, and a Moss type spherical to the right

When the liquid is loaded onto a ship, it immediately starts to “boil”, or return to vapor form as it warms up by cooling the ship’s containment system and from heat leakages through the tank isolation. The lighter elements, having a higher molecular weight than methane, has a lower boiling points, vaporize first. Nitrogen, although having a higher molecular weight than methane, has a lower boiling point and forms a large part of BOG. The vapor phase of a tank can include up to 50% or more nitrogen in the initial hours after loading, depending on the composition of the LNG. This is important because BOG vapor is used as fuel in the ship’s boiler. In this case, the usable combustible gas is reduced by the nitrogen content and the combustion control system must be designed to take this into account. Evaporation at different rates means that the gas delivered at the end of the voyage has a slightly lower proportion of nitrogen and methane than when loaded and a higher proportion of ethane, propane and butane [15].

Data used for LNG shipping

The scenario in this study is that the vessel Artic Princess will transport LNG from Melkøya to Rotterdam harbor. The distance was calculated using searates.com and the vessel speed was set to 19.5 knots. It is estimated that 50 cargoes of LNG per year will be shipped out from the Melkøya facility and that the annual exports are estimated to be 7.30 billion m^3 of LNG. The harbor of Rotterdam was chosen since it plays a major role in the maritime transportation business in Europe. Emissions from the loading and unloading jettys in Rotterdam and Melkøya have not been modeled. Either has the energy consumption for keeping the natural gas liquefied when stored in the harbor. The vessel is assumed to only use gas as fuel and not diesel on both LNG and ballast transport. It is also assumed that the BOG is 0.15% per day of the cargo and that the heel is 5%. The efficiency is set to 35% and it assumed that the vessel will operate 350 days a year. In addition the NO_x emission is estimated to be 1.2 g/kWh according to Rolls Royce [45]. Specifications on the vessel are listed in the table below and detailed calculation can be found in appendix D.

Arctic Princess	
LNG storage	Moss-type
Size [m^3]	145 000
Engine capacity [kW]	27 600
Service speed [kts]	19,5
Loading/unloading time in harbor [hours]	13
Distance Melkøya-Rotterdam[nm]	1368
Days spent each roundtrip	7
Specific fuel consumption [g/kWh]	218
Utilization when loaded [%]	75.5

Table 4 - Data and route for Artic Princess

The modeled vessel, Arctic Princess, was delivered from Mitsubishi Heavy Industries in January 2006 and was specially designed to carry LNG from Melkøya. The vessel has four tanks with a diameter of 42 meters, has a length of 288 meters and the LNG carried can supply a town with a population of 45 000 with electricity for one year [46].

Figure 19 - The modeled LNG vessel Arctic Princess

Data used for HFO shipping

After the crude oil has been refined, the heavy fuel oil is loaded on an oil tanker and transported to Rotterdam. It is assumed that the refinery is located on the west coast of Norway and that the oil tanker, King Edward, will use 4.5 days on one roundtrip. As for the LNG vessel, the distance has been calculated using searates.com and using Florø terminal as a reference point. King Edward is a smaller vessel and therefore also has a lower service speed compared to the LNG vessel. This has affected the vessel's energy consumption in a favorable way. Because of this, and other reasons, the LNG fueled vessel will use over two times more energy per km. In addition it is assumed that the vessel runs on HFO and has a specific fuel consumption of 250 g/kWh. The NO_x and SO_x emissions are based on data from Rolls Royce and are 12 g/kWh and 4.5 g/kWh respectively. Specifications on the vessel are listed in the table below and detailed calculations can be found in appendix E.

King Edward	
Deadweight [ton]	37 384
Engine capacity [kW]	9 466
Service speed [kts]	14,5
Loading/unloading time in harbor [hours]	10
Distance West coast-Rotterdam[nm]	620
Days spent each roundtrip	4,5
Specific fuel consumption [g/kWh]	250
Utilization when loaded [%]	99

Table 5 - Data and route for King Edward

The modeled vessel for the HFO transportation is the oil tanker King Edward. It was built by Hyundai Mipo Dockyard in 2004 and has length of 182.5 meters. It has 12 oil tanks and is currently trading in UK, North Sea and the Baltic [46].

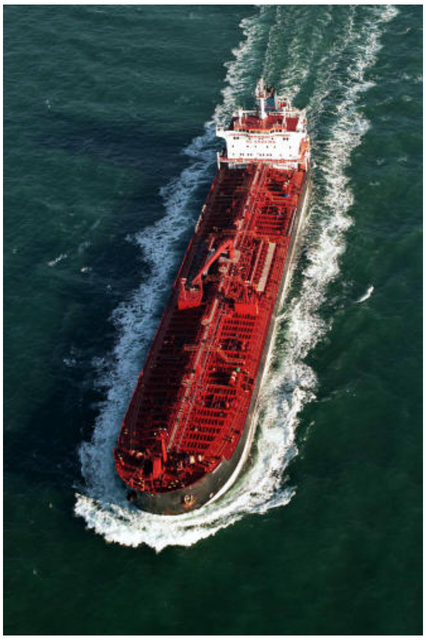


Figure 20 - The modeled oil tanker King Edward

6.3 Short sea shipping out of Rotterdam

When the fuel reaches Rotterdam in the Netherlands it is unloaded and stored in the harbor area. This step is not included in the LCA, neither any possible distance traveled with a bunker ship from the receiving terminal to where the ro-pax is located.

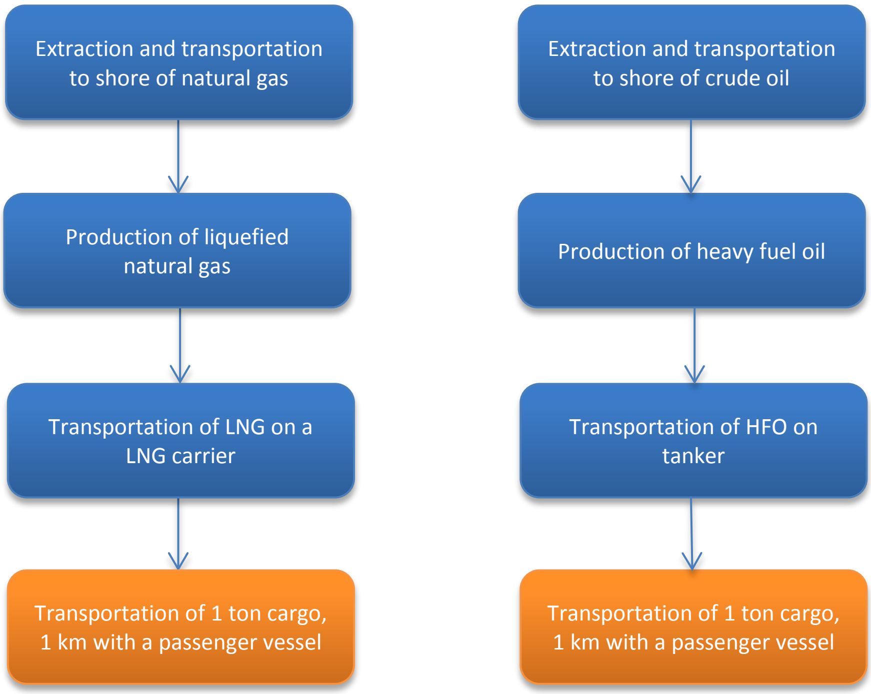


Figure 21 - The final stage of the pathway is the combustion in the ferry engine

In the last stage it is assumed that the marine fuels will be used onboard two ro-pax ferries. The vessel that has been modeled is Fjord Line's new 31 000 gross-ton ferry which will be delivered in august 2013 from Bergen's Fosen yard. The ro-pax will be used as the final link in the life cycle where the two fuels will be used for combustion. As stated previously, the functional unit of the study is to transport one ton cargo one kilometer. However, it could easily have been modeled with any other vessel type like a container-, ro-ro- or offshore vessel.

Data used for ferry transportation

For this trade the new vessel *Stavangerfjord* from Fjord Line will be used with two different engine configurations. For LNG, the original engine configuration which is a Rolls Royce spark-ignited engine will be used and for HFO, a four stroke diesel engine will be used. It assumed the vessel will sail at normal conditions and service speed.

It is calculated that the energy consumption for transporting the reference unit is 0.1752 kWh per ton km for the LNG vessel. This is slightly higher than for the ferry with the HFO configuration. The cargo capacity is lower due to the fact that the LNG tanks require more space. Rolls Royce estimates that LNG configured vessels could require up 2.5-3 times as much space as HFO for the same amount of energy onboard. Wärtsilä operates with 4 times as much space required for LNG compared to HFO. In this study it is assumed to 3 times more bulky. See appendix F and G for more details. Table 6 presents an overview of the two different vessels and which assumptions that form the basis of the calculations.

Vessel details	Stavangerfjord with LNG	Stavangerfjord with HFO
Deadweight [ton]	3 900	3 900
Engine capacity [kW]	22 400	22 400
Length [m]	170	170
Service speed [kts]	21,5	21,5
Pay load	0,7	0,75
Energy consumption [kWh/km]	478	478
Cargo loaded [ton]	2 730	2 925
Specific fuel consumption [g/kWh]	156	250
Transportation efficiency [kWh/ton km]	0.1725	0.1635

Table 6 - LNG vs. HFO ro-pax

The specific fuel consumption (SFC) for the LNG engine was calculated based on a specific energy consumption of 8 MJ/kWh [47] and a lower heating value of 51.3 MJ/kg. These data were derived from a presentation held by Per Magne Einang at MARINTEK [47]. The SFC for the HFO ferry was assumed to be 250 g/kWh. Data provided by Rolls Royce shows that the CO_2 emission is 420 g/kWh for the LNG engine and 600 g/kWh for the HFO engine [45]. Emissions of N_2O were assumed to be 0.4 g/MJ for both fuel alternatives based on figures from the TNO report [48]. As for NO_x and SO_x emissions they were assumed to be the same as for the LNG carrier and oil tanker.

As mentioned previously, methane weigh much more heavily than CO_2 emissions and LNG engines are known for having a rather high methane slip. According to MARINTEKs report *Emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway [22]* the emissions from lean burn gas engines are 3.9 g CH_4/kWh. On the other hand Rolls Royce operates with a lower emission factor of 3 g CH_4/kWh [20]. In this study Rolls Royce's data have been used since they are the engine provider on the new Fjord Line's vessel and that MARINTEKs report is from 2010, and it is therefore likely that the development of gas engines have changed in the past three years.

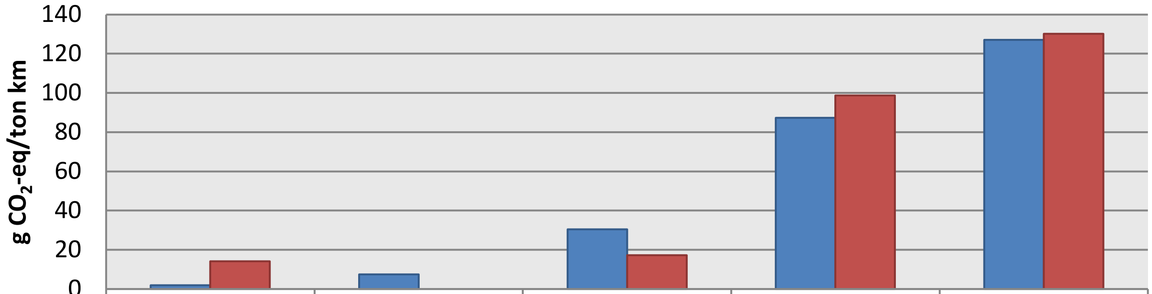
Figure 22 - Fjord Line's new passenger ferry Stavangerfjord

7. Results

In this chapter the results from the study will be presented according to the impact categories defined in chapter 5.2. Additional figures and tables can be found in the appendix H-K.

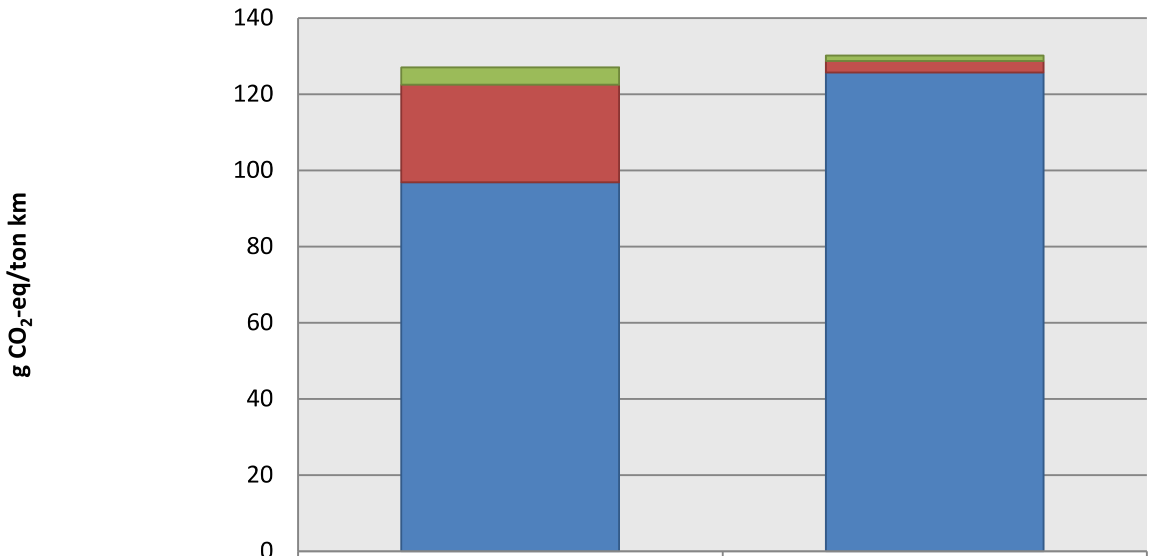
7.1 Global warming potential

In this study it is found that LNG from Melkøya has a lower global warming potential than HFO from the North Sea. With a total GHG emission of 127 g CO_2-eq/ton km, LNG is narrowly better than HFO which has a total of 130.13 g CO_2-eq/ton km. The results are presented in figure 23 and 24.



	Extraction	Liquefaction	Transport	Ferry engine	Total
LNG	1,92	7,48	30,39	87,22	127,00
HFO	14,16	0	17,20	98,76	130,13

Figure 23 - Total well-to-propeller global warming potential for the two compared fuels. The emissions are converted to CO_2 equivalents.



	LNG Melkøya	HFO North Sea
CO2 equivalent of N2O	4,55	1,43
CO2 equivalent of CH4	25,62	3,02
CO2	96,83	125,68

Figure 24 - Global warming potential for the two fuel alternatives divided into three categories; CO_2, CH_4 and N_2O.

Figure 23 shows that LNG as fuels contributes to less CO_2 equivalents than HFO in all phases of the supply chain except from the transportation phase. In that phase it becomes clear that the methane slip from the LNG carrier have substantial impact of the overall picture with an emission rate of 76% more CO_2 equivalents than HFO.

As one can see from figure 24, CO_2 is found to be the greatest contributor to global warming for both of the marine fuels. The "consumption phase" contributes the most to the global warming potential for all of the greenhouse gases, except for nitrous oxide emissions where the transportation stage for HFO pathway emits more. This is illustrated in the table below where the pathways for the two fuels are divided from well-to-propeller (WTP), to well-to-tank (WTT) and tank-to-propeller (TTP). Here it becomes clear that the emissions from the ferry engine are where the main GHG are released during a life cycle.

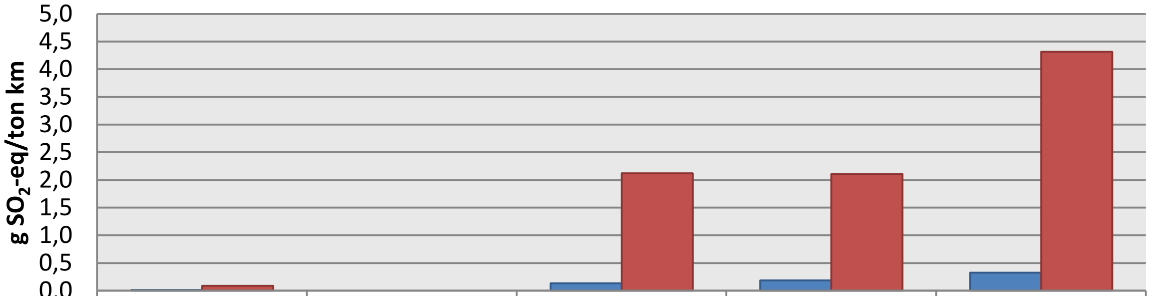
		LNG	HFO
WTT summary			
CO_2	g/ton km	23,27	27,59
CO_2 equivalent of CH_4	g/ton km	12,48	3,02
CO_2 equivalent of N_2O	g/ton km	4,03	0,75
Total WTT	**g/ton km**	**39,78**	**31,37**
TTP summary			
CO_2	g/ton km	73,57	98,09
CO_2 equivalent of CH_4	g/ton km	13,14	0,00
CO_2 equivalent of N_2O	g/ton km	0,52	0,67
Total TTP	**g/ton km**	**87,22**	**98,76**
Total WTP	**g/ton km**	**127,00**	**130,13**

Table 7 - Overview of the well-to-propeller (WTP) GWP for the two fuel pathways. They are divided in well-to-tank (WTT) and tank-to-propeller (TTP) emissions in g CO_2-eq/ton km

The methane emission for the LNG pathway is eight times higher compared to the HFO pathway and accounts for 20% of the total GHG emissions for LNG. This contribution is mainly from the combustion of LNG in the ferry engine and only 5% of the recorded methane emission is from the extraction and liquefaction stage. This means that the performance of the engines plays a major part in the overall performance of LNG as a marine fuel since a small increase in the methane slip will increase the environmental footprint for LNG. As a curiosity it can be seen that if the methane slip from the LNG engine increases with only 12.2%, then HFO will be the most environmental friendly fuel in a life cycle perspective.

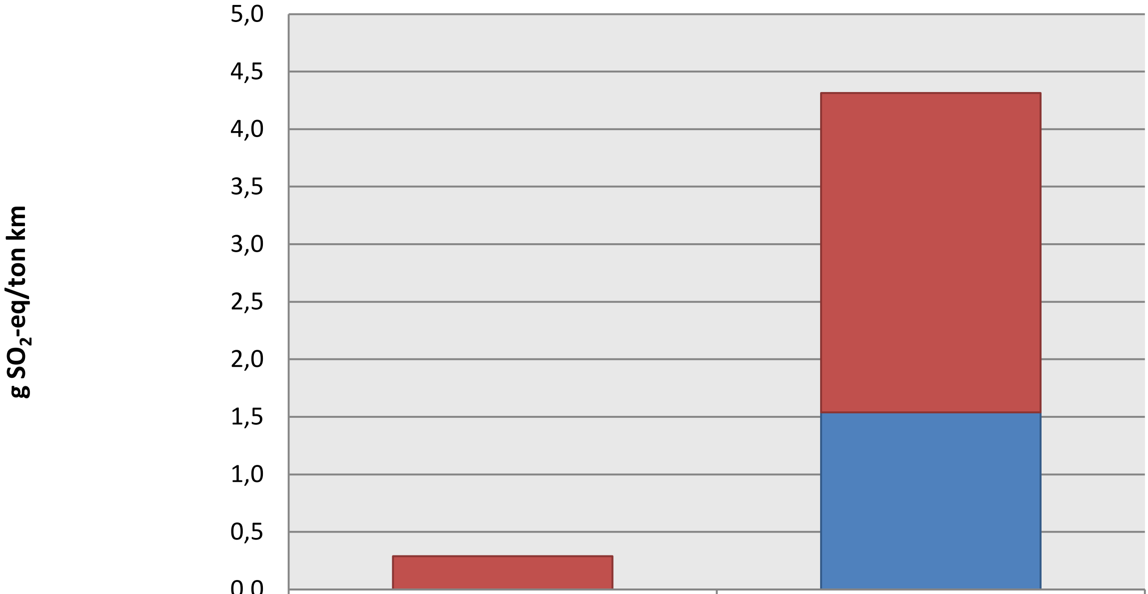
7.2 Acidification potential

For the emissions of NO_x and SO_x it is found that LNG is the most favorable marine fuel with 92% less g SO_2-eq/ton km than the HFO alternative. This can be seen in figure 25 and 26.



	Extraction	Liquefaction	Transport	Ferry engine	Total
LNG	0,008	0	0,132	0,184	0,325
HFO	0,086	0	2,119	2,109	4,315

Figure 25 - Total well-to-propeller acidification emissions for LNG and HFO. The NO_x and SO_x emissions are converted to SO_2 equivalents.



	LNG Melkøya	HFO North Sea
SO2 equivalent of Nox	0,29	2,78
SO2 equivalent of Sox	0,0003	1,54

Figure 26 - Acidification potential for the two fuels divided between the two contributing emissions NO_x and SO_x. The emissions are converted into SO_2 equivalents.

As one can see from figure 26 it is NO_x emissions that contribute the most to the acidification potential for both of the fuels. For the HFO pathway it accounts for almost 64% of the total emissions and this mainly comes from combusting of fuel.

As for the GWP, the table below illustrates the WTP by dividing the acidification potential in WTT and TTP.

		LNG	HFO
WTT summary			
SO_x	g/ton km	0,00027	0,803
SO_2 equivalent of NO_x	g/ton km	0,114	1,402
Total WTT	**g/ton km**	**0,114**	**2,206**
TTP summary			
SO_x	g/ton km	0,000	0,736
SO_2 equivalent of NO_x	g/ton km	0,147	1,373
Total TTP	**g/ton km**	**0,147**	**2,109**
Total WTP	**g/ton km**	**0,261**	**4,315**

Table 8 - Overview of the well-to-propeller (WTP) acidification potential for the two fuel pathways. They are divided in well-to-tank (WTT) and tank-to-propeller (TTP) emissions in g SO_2-eq/ton km

For the LNG pathway it is close to zero SO_x emissions. There is some pollution in the extraction phase but it is minimal. The reason for the low SO_x emissions is that LNG does not contain sulphur compared to HFO which has 1%. The contributing NO_x emissions mainly come from the use phase when the fuel is combusted. With the use of LNG it is found that one will reduce the NO_x emissions with 88% compared to using HFO.

7.3 Primary energy use

The total primary energy use was calculated based on lower heating values as described in chapter 5.2. The values used for the study can be seen in appendix L. Based on these values, LNG from Melkøya were found to be the most energy effective fuel with a total life cycle energy use of 1.33 MJ/ton km, while HFO has a lower efficiency with 1.81 MJ/ton km. When these are combined with the GHG emissions it becomes clear that not only is LNG more energy efficient, but it also releases less CO_2 equivalents than HFO in a life cycle perspective.

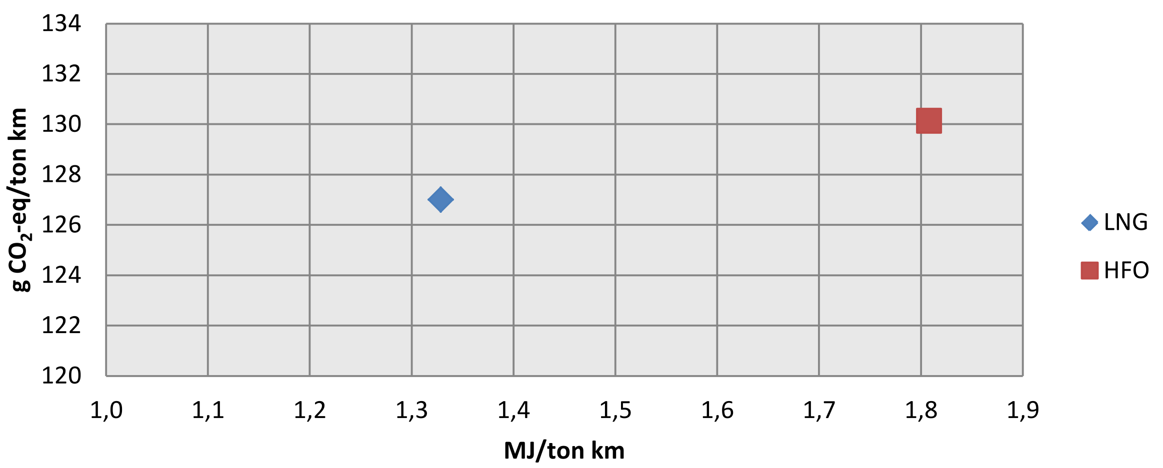


Figure 27 - Primary energy use and global warming potential for the two fuel alternatives.

The total energy consumption is based on the entire pathway for both of the fuels. The energy consumption was first calculated for each step and then summarized to get the total consumption. The energy use was calculated based on each fuel's lower heating value per ton km and the steps can be seen in the figure below. It is primary in the last stage of the pathway that HFO becomes less energy effective than LNG. This is caused by the higher specific fuel consumption for the four stroke diesel engine which is installed in the HFO-driven ro-pax.

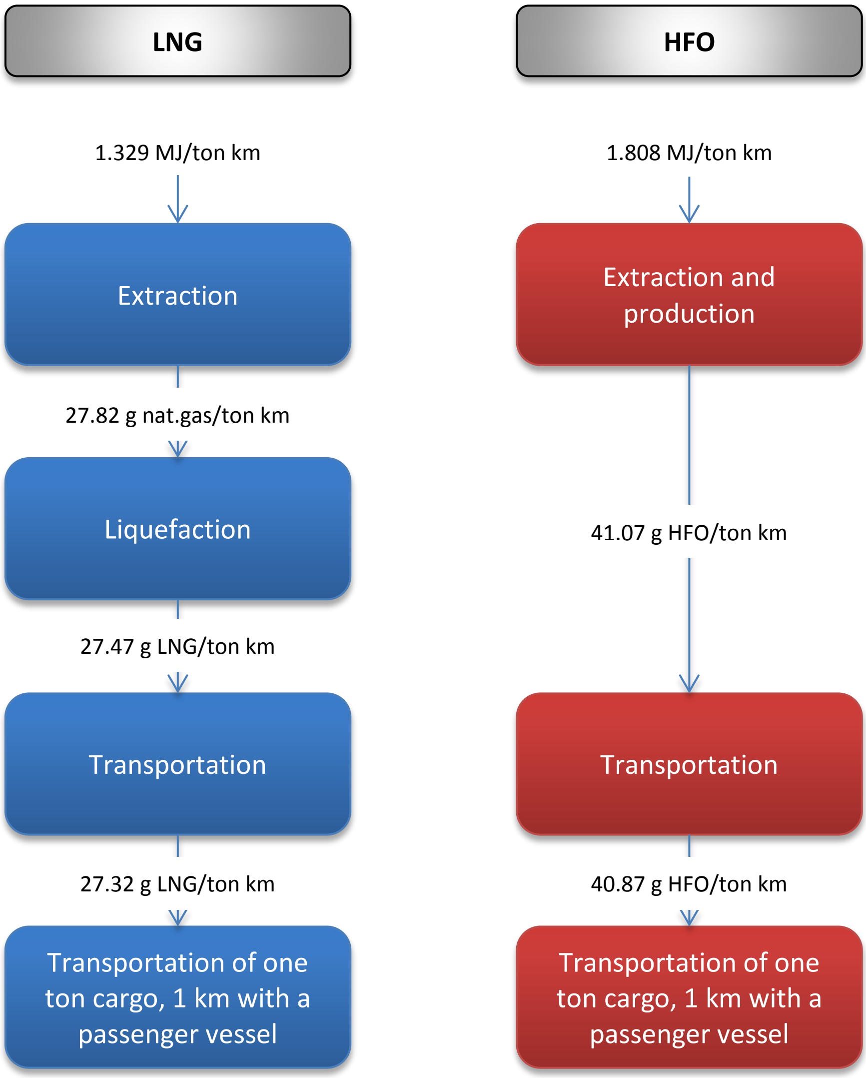


Figure 28 - Summary of the primary energy consumption for the LNG and HFO pathways in gram fuel per ton km.

8. Discussion

In this section, the choices made for both the methodology and data used will be discussed. There are numbers of ways to perform a comparison of two different fuel alternatives and a number of critical choices that will affect the results of a LCA. Therefore it is important to evaluate the robustness of the results and compare them with other studies. This is the fourth and final part of a LCA and choices made previously that have not been dealt with will be discussed in this section.

8.1 Evaluation of data and robustness of the results

In order for data to be reliable is should be relevant for the geographical area for the intended operation, and it should be representative in a certain time perspective. In this study it is strived to obtain the newest and most relevant information for all phases of the two fuel pathways. However, as mentioned previously, some processes are lacking information and therefore assumptions have been made based on the best available information.

This study is very specific on the natural gas extraction phase. I have used Statoil's liquefaction plant on Melkøya as the supplier of natural gas, but precise data for this plant has not been available. It is a new plant and since the data used for natural gas extraction in this study is from 1991, I will assume that it might be outdated. Most likely many things have changed in the way of extracting natural gas in the last 20 years. However, the data set is still believed to be relevant for the geographical area and intended use. The advantage with this data set is that it covers exploration, production and transportation to the market, including all main service and support functions for petroleum services in Norway.

For the liquefaction of natural gas it is assumed to be no emissions of either SO_x or NO_x. Some argue that it might be present in the raw gas that comes from the well, but the quantities are likely to be very low. Edwards et al. [49] also used zero emissions of SO_x and NO_x in his study.

The passenger ferry fueled with LNG was modeled with a spark-ignited engine from Rolls Royce. This is the original engine configuration for Stavangerfjord. Another option would have been to model the vessel with a dual fuel engine, making it more versatile and therefore an easier step for shipowners to take. However, dual fuel engines tend to have slightly lower efficiency but much higher methane slip compared to spark-ignited engines. On the other hand, duel fuel engines can be seen upon as the first step of introducing gas engines in the maritime sector, making the transition to pure gas engines easier. The spark-ignited engine is modeled because of the lower methane slip, more consistent data supplied by the engine manufacturer and that it is easier to model since gas is the only fuel used. As mentioned previously, methane slip can be a game changer when it comes to the environmental friendliness for LNG as fuel. There are slips during the whole supply chain and they are difficult to measure and quantify. The same goes for the engine. In recent years the engine manufacturers have been focused on reducing the SO_x and NO_x emissions, while the awareness of methane slip did not get much attention. This seems to be changing and new engines have less methane production than the earlier gas engines. If this trend continues, and one can reduce the methane emissions to a minimum, LNG as fuel will be very favorable. For the engine using HFO, no specific fuel consumption was found so an estimation of 250 g/kWh was made. This is not an unrealistic number and it could be argued for that the number is too low [19].

Another issue with the LNG ferry is the uncertainty around the extra space requirements for the LNG tanks. It was assumed to require three times more space than the HFO ferry, but how much will that affect the total amount of cargo loaded? In this thesis a payload factor of 75% and 70% for the HFO and LNG configuration, respectively. Ultimately it will make a difference for the amount of energy the vessel will use per ton km.

The data for the energy consumption per ton transported cargo [kJ/ton km] is very uncertain (figure 28). The different processes are assumed to require fuel and lower heating values are used in order to transform it to Joule. The energy consumption are highly dependent on the type of vessel used, sea condition and operation pattern. The modeled passenger ferry could have been an oil tanker, a ro-ro vessel or a military vessel. However, the relative contribution of the different fuel alternatives will not change if the results are calculated with another vessel type or different sea conditions.

Energy used for keeping the natural gas liquid at the Melkøya plant's storage is not included, nor the storage in Rotterdam. This is not included due to lack of information on the insulation of the tanks and the boil-off rate. One can only speculate in how much energy that is being used, but no fossil fuel is burned, only electricity from the power grid. Bunkering of the fuel is not included either, but the relative difference between the two fuel alternatives would most likely be minimal.

The results are assumed to be robust. The global warming potential are of the same magnitude and the difference is minimal. The GWP for LNG could have been less if other modeling choices were made. Another observation is that the largest contribution to GHG is from the combustion phase of both of the fuels, but transportation of the fuel alternatives is also substantial to the overall impact. The next impact category was the acidification potential where LNG proved to be 92% better than HFO. This does not come as a surprise since natural gas does not consist of any sulphur. By using LNG one meets both the sulphur requirements from 2015 and Tier III from 2016. Also for acidification potential it is showed that mainly all the pollution comes from the use phase.

8.2 LCA methodology

As stated in the beginning of this thesis, the methodological choices made in a LCA study should be in accordance with the intended goal of the study. Some choices and assumptions like the functional unit, allocations, boundaries and data chosen may have major impact on the results. The goal of this study has been to compare LNG and HFO when it comes to their environmental impact, but a time horizon has not been set. This could have been done in order for decision makers in the shipping industry to know when one fuel alternative is favorable and when it is not.

The functional unit chosen for this thesis was transport of one ton cargo one km with a passenger vessel at normal sailing conditions. The vessel was modeled as Fjord Line's new vessel Stavangerfjord because of the engine configuration and since it is starting operation the summer 2013. However, all operations related to the operation of the ferry are not included. For example maneuvering in and out of harbor, speed reduction, different operational patterns and berth/bunkering are not part of this study. The reason for not including this is lack of information on the operational pattern. However, it is believed that this may have minimal impact on the overall GHG emissions and that the relative difference between LNG and HFO still will be the same. Another functional unit that was discussed was sailing from Rotterdam in the Netherlands to Hull in UK. This is a current ferry-route and could have been modeled and been presented as an average journey for a passenger vessel. Production of capital goods such as seismic vessels, ports, LNG tanks and other infrastructural items are not included. This should ideally be included in a LCA because it could differentiate the two alternatives, especially when it comes to building of infrastructure.

Another issue that arose during the first stage of the thesis was the modeling of the LNG chain. Is it likely that the whole LNG chain only will use LNG as fuel? If not the vessel transporting LNG from Melkøya to Rotterdam is fueled on LNG, but HFO or marine diesel oil (MDO), it has to have regasification units onboard, increasing the total energy consumption and GHG emissions on each trip. This is an interesting question for further work if bunkering of the different fuels is taken into account. It is most likely in that phase other fuels than the one that are being transported is used.

8.3 Previous studies

There have been several studies related to GHG emissions in the maritime sector in the past and some of them have been for the entire life cycle for a fuel. Some of them are done for or by IMO, whilst others are from different universities around the world. In the following chapters a short presentation of some selected studies will be presented and compared to this study.

8.3.1 Winebrake et al. (2007)

In 2007 Winebrake et al. [50] published a paper called *Energy Use and Emissions from Marine Vessels: A Total Fuel Life Cycle Approach*. The study presents a model called the total energy and emissions analysis for marine systems and it is used to analyze the total life cycle emissions and energy use from "well-to-hull." This is for the entire fuel pathway, including extraction, processing, distribution, and use in vessels, for six fuel pathways: HFO, conventional diesel, low sulphur diesel, compressed natural gas (CNG), Ficher-Tropsch diesel and biodiesel. The model presents results for three case studies using alternative fuels: a passenger ferry, a tanker vessel and a container ship. For the passenger ferry case, conventional diesel is found to have the lowest life cycle emissions of GHG, followed by HFO. Natural gas is calculated to release approximately 3% more GHG than conventional diesel, but it is not comparable with the liquefied natural gas chain which was used in this study. Since it is not comparable with this study it is difficult to say anything about the conflicting results.

8.3.2 Edwards et al. (2011) and Hekkert et al. (2005)

Edwards et al. [49] investigated different fuels relevant to Europe in 2010 and beyond with emphasis on energy use and GHG emissions in a well-to-wheels (WTW) analysis. They investigated several fuels, but the key maritime fuels were compressed natural gas (CNG) and diesel. CNG were found to have the lowest GHG emissions with 145 g CO_2-eq/km from WTW. Hekkert et al [51] compared different fuel chains with a WTW approach in the paper *Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development*. Relevant maritime fuels that were investigated were diesel, LNG and CNG and the reported WTW GHG emissions were 153, 163 and 129 g CO_2-eq/km respectively. Diesel is a very different fuel from HFO so neither here a comparison can be done to the results. However, the magnitude of the emissions is the same, making the results from this study more trustworthy.

8.3.3 Bengtsson et al. (2011)

Bengtsson et al. [52] published a report called *Life cycle assessment of marine fuels, a comparative study of four fossil fuels for marine propulsion* in 2011. This study compares HFO, marine gas oil (MGO), gas-to-liquid (GTL) fuel, and LNG, combined with two exhaust abatement techniques. A life cycle assessment was performed with the necessary steps from extraction of raw material to transportation of one ton cargo one km on a roll-on-roll-off (ro-ro) vessel. Manufacture of capital goods was not included in the study, nor the production of lubrication oil and waste management of oil sludge. It was found that HFO is the most energy efficient fuel while LNG from the North Sea is the fuel with the lowest GWP. The GHG emissions for HFO were 43 g CO_2-eq/ton km, 38 g CO_2-eq/ton km for LNG from the North Sea and 40 g CO_2-eq/ton km for LNG from Qatar. The total energy used for LNG from North Sea was 0.58 MJ/ton km and 0.53 MJ/ton km. The fact that the GWP are highest for HFO is supported by this thesis, but the energy consumption is in this study is found to be lowest for LNG compared to Bengtsson et al. In addition, the magnitude of the results is very different. This is believed to be caused by the choice of functional unit where they used a ro-ro vessel whilst this thesis uses a passenger ferry. A ro-ro vessel will normally have more deadweight compared to a passenger ferry, ultimately driving the emissions down. Nevertheless, both studies found that LNG is the favorable fuel alternative when it comes to GWP and acidification potential. The relevant difference between the two fuels has not changed, only the magnitude of the emissions. This study has also found that the main contributor to GHG is emissions from the use phase. It is also dominating the acidification potential and only small contributions can be traced upstream.

8.4 Advantages and disadvantages with the two fuel alternatives

The results from this study shows that LNG are marginally better than HFO when it comes to GWP, by far better for acidification potential and relatively less energy consuming. It is therefore seen upon as a cleaner fuel than HFO, even though both of them are fossil fuels.

8.4.1 Future fuel prices

Another important aspect that has not been discussed is the economic feasibility for LNG as fuel. LNG and HFO prices tend to be closely related, but recent trends show that LNG is cheaper. Taken into account the lower heating values and the cost of fuels, LNG only cost 60% of HFO if one look at the energy content. The figure below illustrates the different fuel prices over a ten year period from 2001 to 2011.

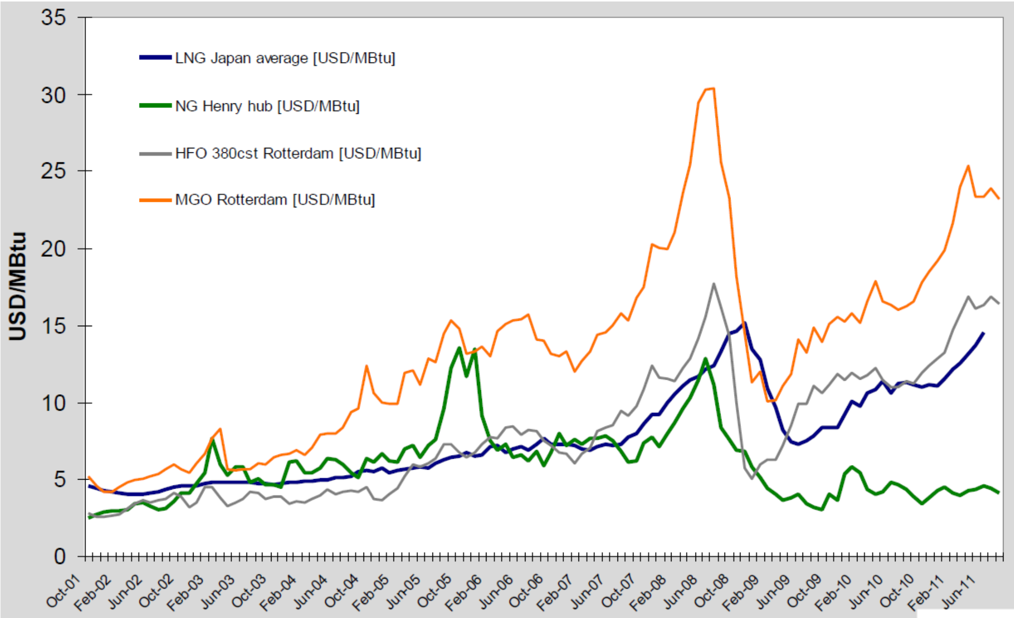


Figure 29 - Fuel prices from 2001 to 2011 [6].

It is not only the purchase price that is interesting when comparing the two fuels. The cost of burning the fuel also needs to be considered because of taxes and exhaust gas cleaning. And then the big question arises; what will the price of LNG and HFO be in the future? No one can see into the future, but various players are trying to predict future fuel prices. In the figure below a forecast from DNV is presented. Here one can see that LNG prices are believed to be kept below HFO and MDO prices from today and towards 2035. This just one forecast and other predictions may say that HFO will be cheapest in the future. There is no right or wrong, but the most important observation is that the choices a ship owner make about a ship today, will adversely impact that ship's economic performance over her life cycle.

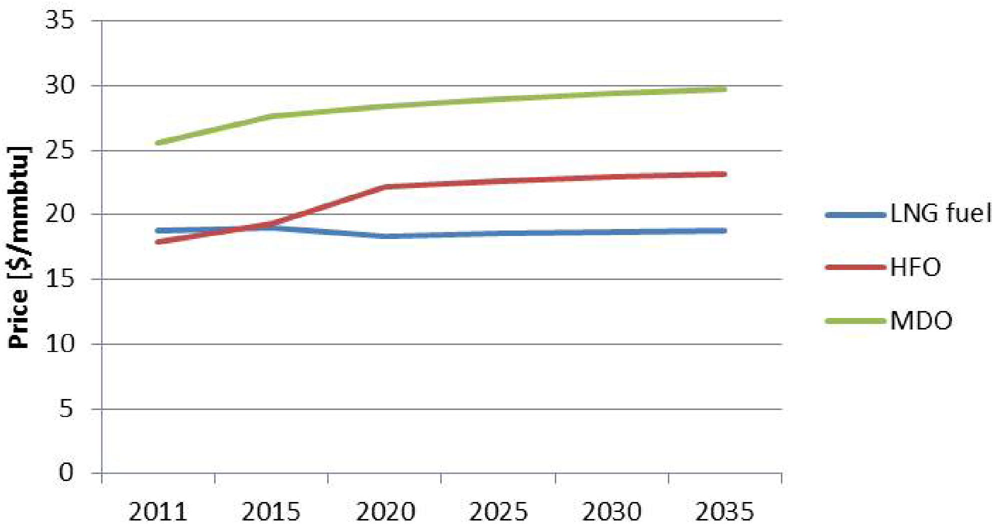


Figure 30 - Predicted future fuel prices for LNG, HFO and MDO [53].

If shipowners decide to equip their vessels with gas engines, are they sure to get fuel if the infrastructure does not yet exist? LNG logistics is therefore a key question for introducing LNG as a marine fuel. LNG storage tanks are needed to keep the natural gas liquid and energy and money needs to be put up front in order to get LNG terminals built. On the other hand, the operational costs of LNG engines are very low and the maintenance needed is minimal compared to machinery running on HFO.

In figure 31 one can see a prediction of the fuel composition from 2013 to 2050. Gasum[3] predicts that LNG will constitute close to 80% of the marine fuels in 2050. This indicates that it is "safe" to equip new vessels with gas engines, if you look at the predicted availably.

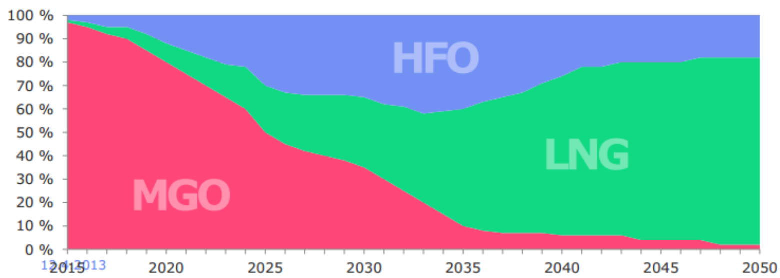


Figure 31 - Gasum's prediction of fuels availability in the future

[3] Gas company from Finland

8.4.2 Pros and cons

Both of the fuels investigated have advantages and disadvantages. LNG has the lowest GWP, but a small leakage of methane along the supply chain could change its position as the most environmental fuel in a life cycle perspective. LNG might be less expensive than HFO in the future, and the predicted availability is positive. However, the best argument for switching to LNG is that vessels will meet the new regulations from IMO; maximum sulphur content and Tier III. On the other hand, HFO could be used inside ECA with abatement technologies and dual fuel engines are maybe a more realistic first step for shipowners.

The bullet points below shows some of the main advantages (left) and disadvantages (right) for LNG as fuel.

- Meets Tier III and SECA requirements
- Cleaner and less pollutive
- Predicted to be cheaper than HFO
- Spills will disappear when in contact with water
- Low hazard
- Low maintenance
- Stored at atmospheric pressure
- More gas reserves than oil

- Infrastructure
- Methane slip
- Skilled and trained crew to operate with LNG as fuel
- Few places to bunker making route scheduling less optimized
- Availability
- Safety equipment
- Extra space required onboard the vessel

The same is done for HFO as fuel with advantages (left) and disadvantages (right).

- Can install a scrubber to fulfill IMO requirements
- Okay to use HFO outside ECA
- Availability
- Can be used with NG in dual fuel engines
- Refineries will most likely continue to produce residual oils

- Does not meet Tier III and SECA requirements
- Oil spills
- Higher maintenance costs than LNG
- High GWP and acidification potential
- Strong localized effects

Figure 32 - A ship owner's many challenges when it comes to the environmental jungle

9. Conclusion

The overall aim for this thesis has been to compare LNG and HFO when it comes to their environmental impact in a life cycle perspective. LNG was assumed to be transported from Melkøya whilst HFO were modeled to come from the North Sea. Both of the fuels were used in a passenger ferry that transported the functional unit, one ton cargo one km, out of Rotterdam. LNG was found to be the most environmental friendly fuel with an overall life cycle emission of 127 g CO_2-eq/ton km compared to HFO's 130.13 g CO_2-eq/ton km. It is also found that the main contributor to the overall environmental impact is during combustion of the fuels. It is also shown that LNG as fuel is significant better when it comes to acidification potential. Here it is proven that one can achieve a 92% reduction of SO_2 equivalents if one chose LNG instead of HFO. It is also demonstrated that the use phase is the major contributor to acidification potential as well.

The results from the GWP analysis are believed to be robust for the scenario chosen, because the potential of the two fuels are in the same order of magnitude. It is also shown that LNG can be even more environmental friendly if the methane slip from the supply chain is reduced. The results from the analysis shows that the potential contribution to acidification from LNG is very low and will fulfill the requirements for sulphur content in fuels and Tier III regulations.

Throughout the work of this thesis it has been several issues with data quality. In some parts of the value chains, very little data is available and therefore older and maybe outdated data had to be used. For further studies, data quality will most certainly raise the level of accuracy of the results. Especially data on emissions of methane over the whole supply chain is interesting when it comes to global warming potential.

On the basis of the results from this study it would be preferable that shipowners would chose LNG as marine fuel in the future, based on the environmental footprint. However, there are areas that still not have been uncovered; methane slip along the supply chain, liquefaction emissions and energy use, and bunkering emissions. This and other issues like time perspective would most certainly be interesting for future studies. Also a comparison between more than two fuels would be favorable in addition to a more thoroughly assessment of future fuel prices.

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11. Appendix

Appendix A - LCI dataset for extraction of crude oil

LCI data:						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	Brown coal	0,0386	MJ	Resource		
Input	Crude oil	41,4382	MJ	Resource		
Input	Hard coal	0,1059	MJ	Resource		
Input	Natural gas	2,3813	MJ	Resource		
Input	Energy from geothermics	0,0010	MJ	Resource		
Input	Energy from hydro power	0,0468	MJ	Resource		
Input	Energy from solar energy	0,0038	MJ	Resource		
Input	Energy from wind power	0,0043	MJ	Resource		
Output	Heavy fuel oil	41,07	g HFO/ton km	Reference flow		
Output	CO_2	11,06	g CO_2/ton km	Emission to air	11,06	
Output	CH_4	0,1209	g CH_4/ton km	Emission to air	3,024	
Output	N_2O	0,00026	g N_2O/ton km	Emission to air	0,076	
Output	NO_x	0,0318	g NO_x/ton km	Emission to air		0,022
Output	SO_x	0,0641	g SO_x/ton km	Emission to air		0,064
				Total g-eq/ton km	**14,16**	**0,086**

Direction	Substance	Quantity	Unit
Input	Brown coal	0,038606	MJ
Input	Crude oil	41,438200	MJ
Input	Hard coal	0,105880	MJ
Input	Natural gas	2,381260	MJ
Input	Energy from geothermic	0,000989673	MJ
Input	Energy from hydro power	0,046790	MJ
Input	Energy from solar energy	0,003832	MJ
Input	Energy from wind power	0,004298	MJ
Output	Heavy fuel oil	1,00	kg
Output	CO_2	0,269304	kg
Output	CH_4	0,002944	kg
Output	N_2O	0,000006	kg
Output	NO_x	0,000774	kg
Output	SO_x	0,001560	kg

Energy use		
c= energy cons.*b	1808,09	kJ/ton km

Appendix B - LCI dataset for extraction of natural gas

LCI data:						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	Diesel	3 663,000	ton	Fuel		
Input	Fuel gas	11 000 008	m^3	Fuel		
Input	Jet fuel	123	ton	Fuel		
Output	Natural gas	27,822	g nat.gas/ton km	Functional unit		
Output	CO_2	1,84	g CO_2/ton km	Emission to air	1,84	
Output	CH_4	0,00259	g CH_4/ ton km	Emission to air	0,065	
Output	N_2O	0,00004	g N_2O/ton km	Emission to air	0,0122	
Output	NO_x	0,0116727	g NO_x/ton km	Emission to air		0,0082
Output	SO_x	0,0002696	g SO_x/ton km	Emission to air		0,0003
				Total g-eq/ton km	**1,92**	**0,008**

Direction	Substance	Quantity	Unit
Input	Diesel	3 663	ton
Input	Fuel gas	11 000 008	m3
Input	Jet fuel	123	ton
Input	Steel	174	ton
Output	CH4	86	ton
Output	CO	83	ton
Output	CO2	61 248	ton
Output	N2O	1,36	ton
Output	Nox	388	ton
Output	SO2	8,96	ton
Output	VOC	817	ton
Output	Crude oil	786 000	ton
Output	Gas	213 000	ton

Energy use		
d= energy cons.*c	**17,05**	**kJ/ton km**

Appendix C - LCI dataset for LNG liquefaction

Liquefaction						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	NG	1,0130	MJ/MJ LNG			
Output	LNG	1	MJ			
Output	CO_2	6,16	g CO_2/ton km	Emission to air	6,16	
Output	CH_4	0,0525	g CH_4/ton km	Emission to air	1,31	
Output	NO_x		g NO_x/ton km	Emission to air		0
Output	SO_x		g SO_2/ton km	Emission to air		0
				Total g-eq/ton km	**7,48**	**0,00**

Inputs		
CO_2 emissions	4,7	g/MJ LNG
CH_4 emissions	0,04	g/MJ LNG
N_2O emissions	0	g/MJ LNG
NO_x emissions	0	
SO_x emissions	0	

Energy use		
c=b*NG use	**27,82**	**g nat.gas/ton km**

Appendix D - LCI dataset for LNG transportation

LCI data:						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	LNG	0,152	g LNG/ton km	Fuel		
Input	LNG	27,466	g LNG/ton km	Product		
Output	LNG	27,466	g LNG/ton km	Reference flow		
Output	CO_2	15,26	g CO_2/ton km	Emission to air	15,26	
Output	CH_4	0,44	g CH_4/ton km	Emission to air	11,11	
Output	N_2O	0,01350	g N_2O/ton km	Emission to air	4,023	
Output	NO_x	0,18882	g NO_X/ton km	Emission to air		0,1322
				Total g-eq/ton km	**30,39**	**0,132**

Dwt	Net payload capacity, ton	Utilization when loaded	Distance per voyage, nm	Speed, kts	Days per voyage	Cargo voyages, a year	Balast voyages, a year	Days at sea, service speed
84 878	64 090	75,5 %	2 737	19,5	6,93	50,50	50,50	140,35

Enginge size,kW	Gram fuel per kwh	Fuel consumption a year, 85%	Cargo in ton each year	Energy equivalent transported, GJ	Ton*nm a year	Ton CO2 emitted	Gram CO2 per ton nm	Gram CO2 per ton km
27 600	218,2	42 998	3 057 728	166 646 156	4 184 102 762	118 246	28,26	15,26

Size	145 000	m3
Max speed	20,89	kts
Service speed	19,5	kts
Speed	19,5	kts
Speed km/h	36,114	km/h
Loading at Melkøya	13	hours
Distance Melkøya-Rotterdam	1368	nm
Unloading in Rotterdam	13	hours
Days spent each roundtrip	6,931	days
Days spent each year	350	days
Roundtrips	50,497	per. year
Total amount transported each year	7 322 103	m3
Total power	27 600	kW
Service speed	19,5	kts
Sea margin/MCR low	0,85	-
Sea margin/MCR high	0,90	-
Spesific fuelconsumption	0,218	kg/kWh
Fuel consumtion per hour low	5118,9	kg/h
Fuel consumtion per hour high	5420,0	kg/h
Fuel spent on each roundtrip low (2736 nm)	851	tons
Fuel spent on each roundtrip high (2736nm)	902	tons
Fuel spent each year low	42 998	tons
Fuel spent each year high	45 528	tons

Energy use		
a*6,12	0,152	g LNG/ton km
b=a+ tilegg	27,466	g LNG/ton km

Appendix E - LCI dataset for HFO transportation

LCI data:						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	HFO	0,205	g HFO/ton km	Fuel		
Input	HFO	41,074	g HFO/ton km	Product		
Output	HFO	41,074	g HFO/ton km	Reference flow		
Output	CO_2	16,53	g CO_2/ton km	Emission to air	16,53	
Output	N_2O	2,27E-03	g N_2O/ton km	Emission to air	6,77E-01	
Output	NO_x	1,972	g NO_x/ton km	Emission to air		1,380
Output	SO_x	0,739	g SO_x/ton km	Emission to air		0,739
				Total g-eq/ton km	**17,20**	**2,12**

Dwt	Net payload capacity, ton	Utilization when loaded	Distance per voyage, nm	Speed, kts	Days per voyage	Cargo voyages, a year	Balast voyages, a year	Days at sea, service speed
37 384	37 010	99 %	1 240	14,45	4,41	79,39	79,39	85,81

Enginge size,kW	Gram fuel per kwh	Fuel consumption a year	Cargo in ton each year	Energy equivalent transported, GJ	Ton*nm a year	Ton CO2 emitted	Gram CO2 per ton nm	Gram CO2 per ton km
9 466	250	16 897	2 938 060	123 692 312	1 821 596 989	55 758	30,61	16,53

Deadweight	37 384	ton
Max speed	15,7	kts
Service speed	14,45	kts
Speed	14,45	kts
Speed km/h	26,7614	km/h
Loading	10	hours
Distance NS-Rotterdam	620	nm
Unloading in Rotterdam	10	hours
Days spent each roundtrip	4,409	days
Days spent each year	350	days
Roundtrips	79,385	per. year
Total power	9466	kW
Service speed	14,45	kts
Sea margin/MCR low	0,85	-
Sea margin/MCR high	0,90	-
Spesific fuelconsumption	0,250	kg/kWh
Fuel consumtion per hour low	2011,5	kg/h
Fuel consumtion per hour high	2129,9	kg/h
Fuel spent on each roundtrip low (1240 nm)	213	tons
Fuel spent on each roundtrip high (1240 nm)	225	tons
Fuel spent each year low	16 897	tons
Fuel spent each year high	17 891	tons

Energy use		
a*2,214	0,205	g HFO/ton km
b=a+ tilegg	41,074	g HFO/ton km

Appendix F - LCI dataset for Ro-pax vessel with LNG as fuel

LCI data:						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	LNG	27,31	g LNG/ton km	Fuel		
Input	Cargo	1	ton/ton km	Functional unit		
Output	Cargo	1	ton/ton km	Functional unit		
Output	CO_2	73,57	g CO2/ton km	Emission to air	73,57	
Output	CH_4	0,525	g CH4/ton km	Emission to air	13,14	
Output	N_2O	0,0017	g N2O/ ton km	Emission to air	0,52	
Output	NO_x	0,26	g Nox/ton km	Emission to air		0,184
				Total g-eq/ton km	**87,22**	**0,184**

Energy use		
a =	**27,315**	**g LNG/ton km**

Stavangerfjord, Passenger/Ro-Ro vessel		
CO2 emission	420	g CO2/kWh
	9 408	kg CO2/h
Speed	21,5	Knots
Speed	39,818	km/h
Engine	22 400	kW
Engine load	85 %	Percent of MCR
Deadweight	3 900	ton
Rotterdam-Hull	210	nm
Duration	10,75	h
Pay load	0,70	-
Energy consumtion	478	kWh/km
Cargo loaded	2 730	ton
Energy consumtion per distance	0,1752	kWh/ton km

Energy use		
Engine size	22 400	kW
Specific energy consumption	8	MJ/kWh
Spesific fuel consumption	0,156	kg LNG/kWh
Vessel energy consumption	0,1752	kWh/ton km
Amount of LNG per. tonne km	27,31	g LNG/ton km

Emissions		
CO2		
Carbon factor	2,75	g CO2/g LNG
Gram CO2 per ton km	75,12	g CO2/ton km
Gram CO2 per ton km	73,57	g CO2/ton km
CH4		
Emission factor	3	g CH4/kWh
Emission factor	0,025	g CH4/g LNG
Gram CH4 per ton km	0,683	g CH4/ton km
Gram CH4 per ton km	0,525	g CH4/ton km
N20		
Emission factor	6,33E-05	g N2O/g LNG
Gram N2O per ton km	1,73E-03	g N2O/ ton km
Nox		
Emission factor	1,2	g Nox/kWh
Gram Nox per ton km	0,210	g Nox/ton km
Sox	0	g Sox/kWh

Appendix G - LCI dataset for Ro-pax vessel with HFO as fuel

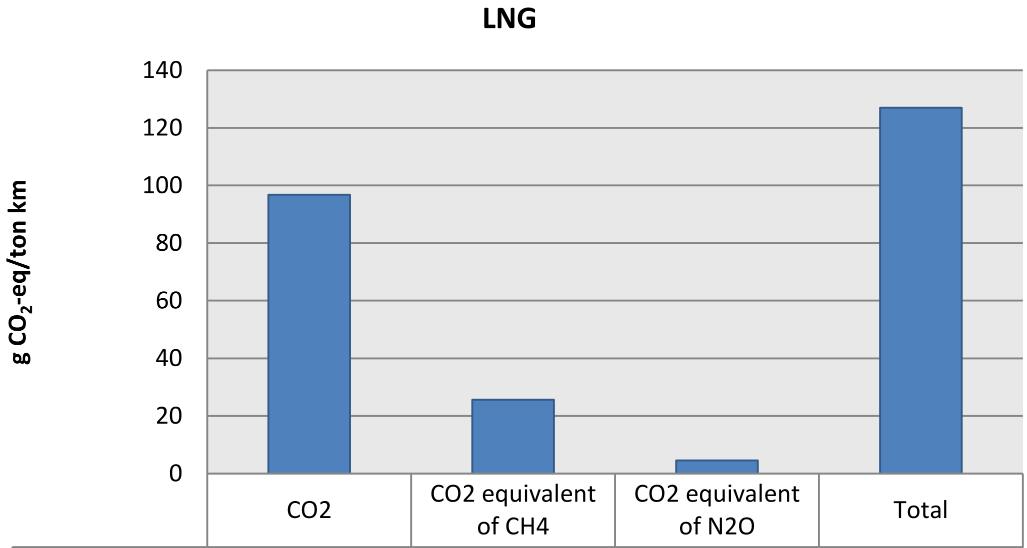
LCI data:						
Direction	Substance	Quantity	Unit	Flow	CO_2-eq	SO_2-eq
Input	HFO	40,87	g HFO/ton km	Fuel		
Input	Cargo	1	ton/ton km	Functional unit		
Output	Cargo	1	ton/ton km	Functional unit		
Output	CO_2	98,09	g CO_2/ton km	Emission to air	98,09	
Output	N_2O	0,00226	g CO_2/ton km	Emission to air	0,674	
Output	NO_x	1,96	g NO_x/ton km	Emission to air		1,373
Output	SO_x	0,7357	g SO_x/ton km	Emission to air		0,736
				Total g-eq/ton km	**98,76**	**2,109**

Energy use		
a =	**40,87**	**g HFO/ton km**

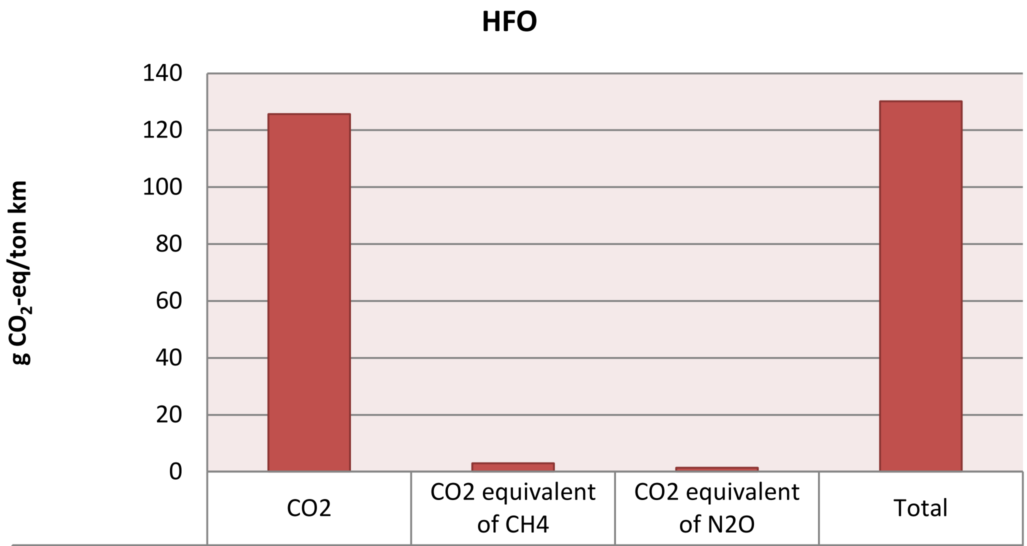
Stavangerfjords sister ship with HFO		
CO2 emission	600	g CO2/kWh
Speed	21,5	Knots
Speed km/h	39,818	km/h
Engine	22 400	kW
Engine load	85 %	Percent of MCR
Deadweight	3 900	ton
Rotterdam-Hull	210	nm
Duration	10,75	h
Load factor	0,90	-
Pay load	0,75	-
Energy consumtion	478	kWh/km
Cargo loaded	2 925	ton
Energy consumtion	0,1635	kWh/ton km

Energy use		
Engine size	22 400	kW
Spesific fuel consumption	0,250	kg HFO/kWh
Vessel energy consumption	0,163	kWh/ton km
Amount of HFO per. tonne km	40,87	g HFO/ton km
Emissions		
CO2		
CO2 emission factor	3,3	g CO2/g HFO
Gram CO2 per ton km	134,87	g CO2/ton km
Gram CO2 per ton km	98,09	g CO2/ton km
N20		
Emission factor	5,53E-05	g N2O/g HFO
Gram N2O per ton km	2,26E-03	g N2O/ ton km
Nox		
Emission factor	12	g Nox/kWh
Gram Nox per ton km	1,962	g Nox/ton km
Sox		
Emission factor	4,5	g Sox/kWh
Gram Sox per ton km	0,736	g Sox/ton km
CH4		
Emission factor	0	g CH4/kWh

Appendix H - Well-to-propeller summary for LNG and HFO

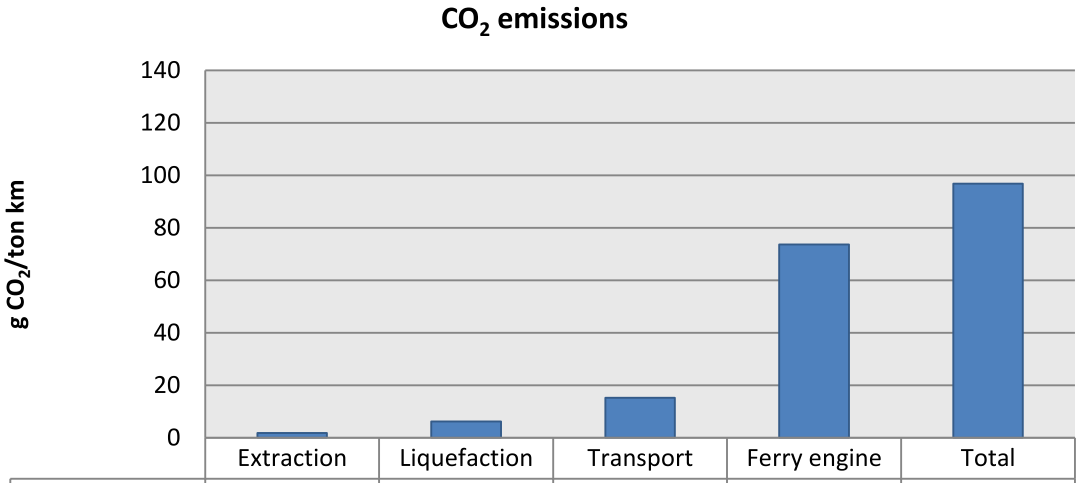


	CO2	CO2 equivalent of CH4	CO2 equivalent of N2O	Total
CO2 emissions	96,83	25,62	4,55	127,00

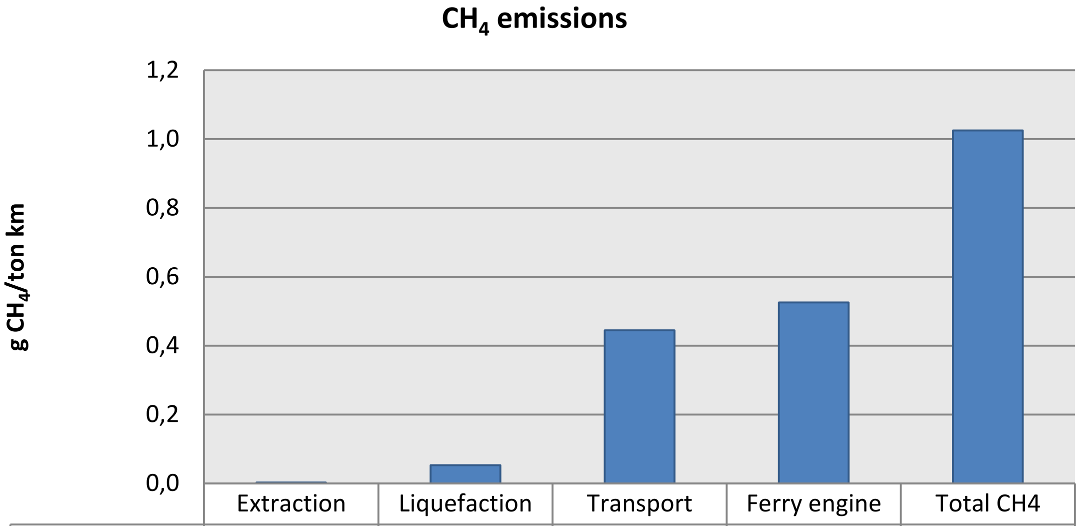


	CO2	CO2 equivalent of CH4	CO2 equivalent of N2O	Total
CO2 emissions	125,68	3,02	1,43	130,13

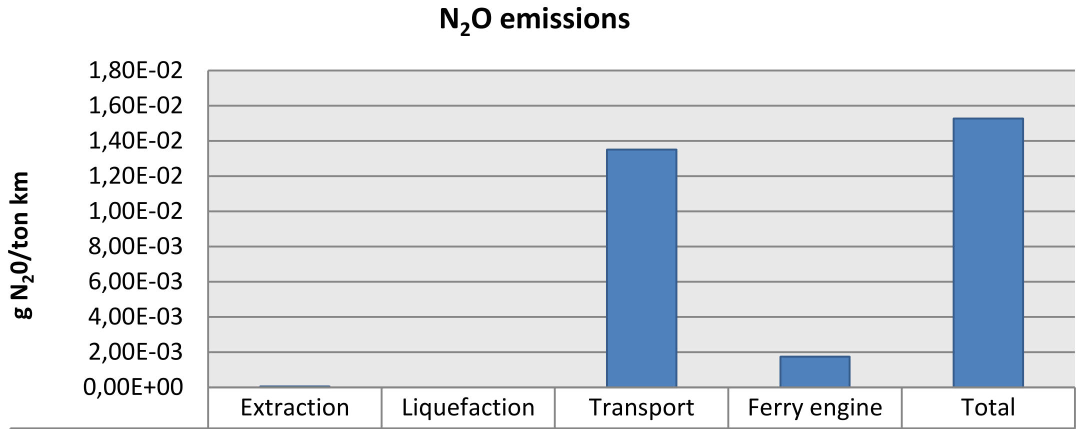
Appendix I - GHG emissions for LNG as fuel



	Extraction	Liquefaction	Transport	Ferry engine	Total
CO2 emissions	1,84	6,16	15,26	73,57	96,83

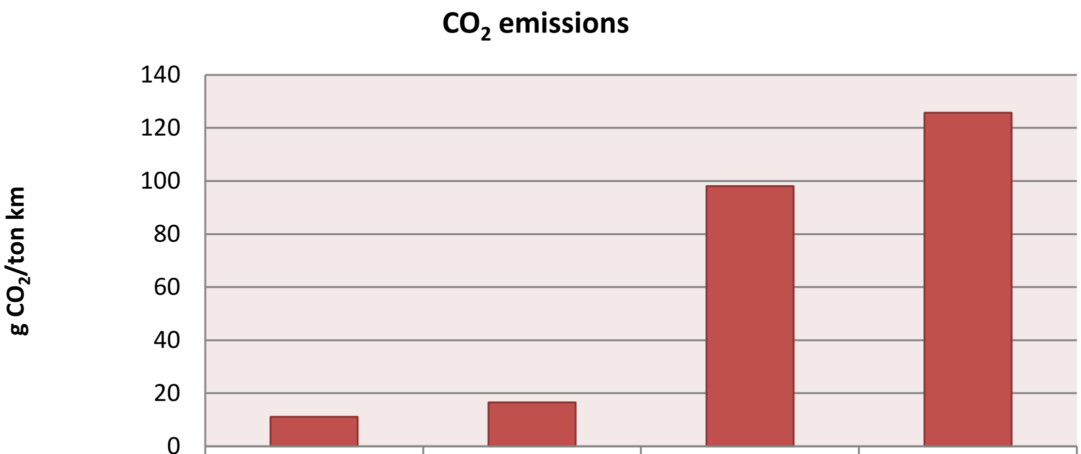


	Extraction	Liquefaction	Transport	Ferry engine	Total CH4
CH4 emissions	0,003	0,05	0,44	0,53	1,02

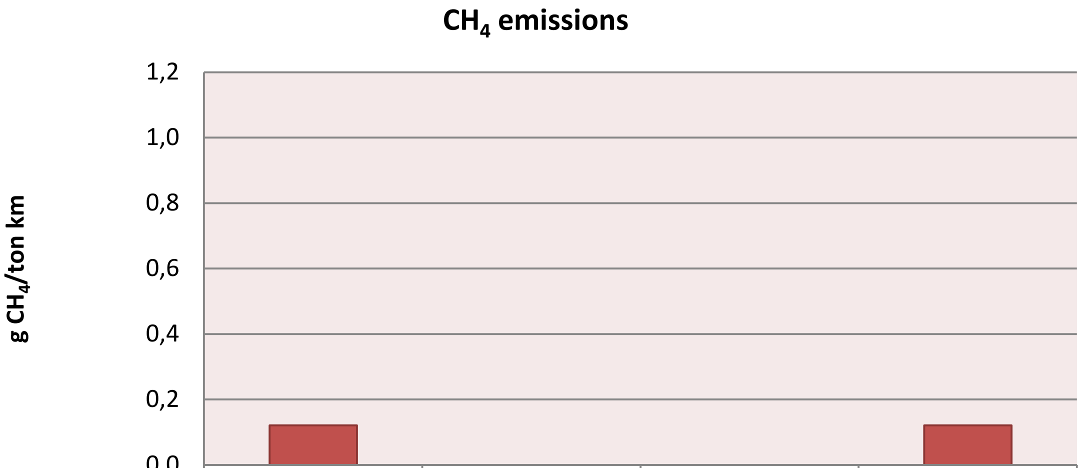


	Extraction	Liquefaction	Transport	Ferry engine	Total
N2O emissions	4,09E-05	0,0E+00	1,35E-02	1,73E-03	1,53E-02

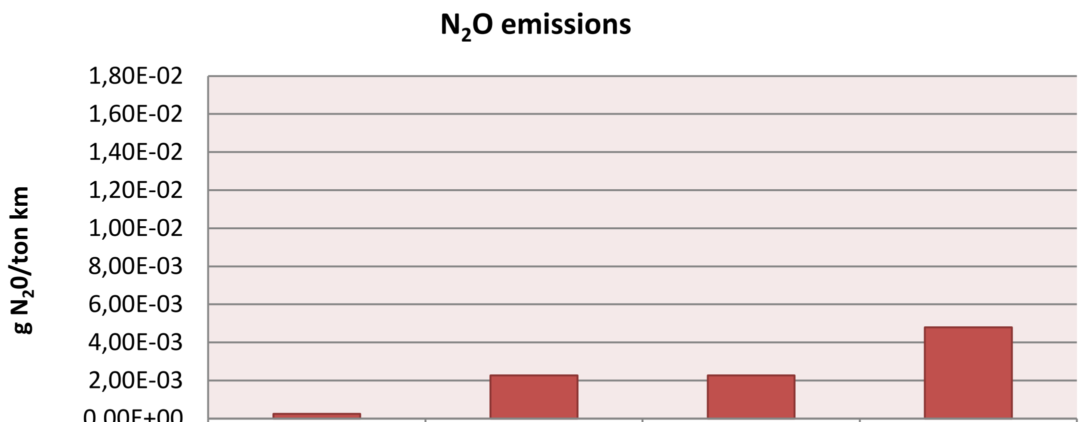
Appendix J - GHG emissions for HFO as fuel



	Extraction	Transport	Ferry engine	Total
CO2 emissions	11,06	16,53	98,09	125,68



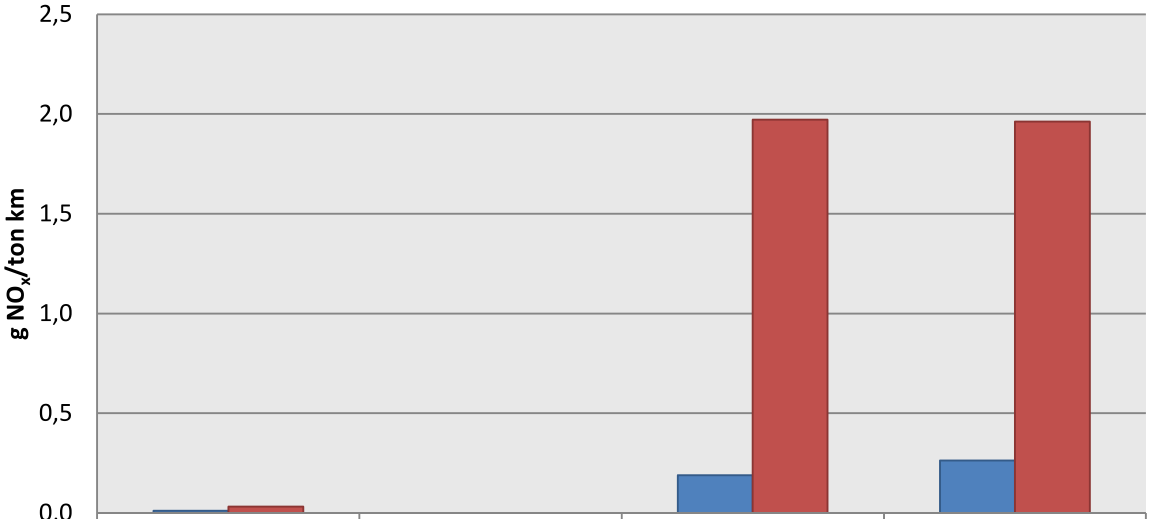
	Extraction	Transport	Ferry engine	Total
CH4 emissions	0,12	0,00	0,00	0,12



	Extraction	Transport	Ferry engine	Total
N2O emissions	2,56E-04	2,27E-03	2,26E-03	4,79E-03

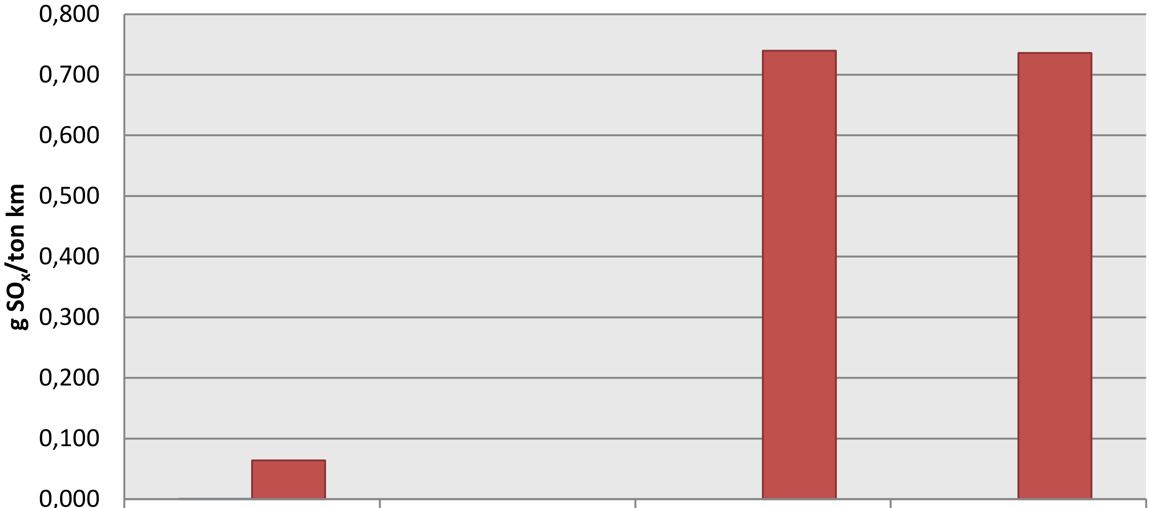
Appendix K - NO_x and SO_x emissions

NO_x emissions



	Extraction	Liquefaction	Transport	Ferry engine
LNG	0,012	0	0,189	0,263
HFO	0,032	0	1,972	1,962

SO_x emissions



	Extraction	Liquefaction	Transport	Ferry engine
LNG	0,00027	0	0	0
HFO	0,064	0	0,739	0,736

Appendix L - Lower heating values

Crude oil	42,69	MJ/kg
Natural gas	47,14	MJ/kg
HFO	41,2	MJ/kg
Diesel	42,7	MJ/kg
Fuel gas	36,8	MJ/m3
Jet fuel	44,1	MJ/kg
LNG	51,3	MJ/kg
Brown coal	11,9	MJ/kg
Hard coal	26,3	MJ/kg

From the Transportation Technology R&D Center:

The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered. The LHV are the useful calorific values in boiler combustion plants and are frequently used in Europe [54].