Master's degree thesis

LOG950 Logistics

An environmental assessment of emission to air from LNG fuel in maritime shipping - Is it a worthwhile investment for the future?

Mona Hustad

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Molde University College
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Preface and acknowledgment

This master thesis is the last assignment in the study program "Master of Science in Logistics." This thesis defines my five years at Molde University College - Specialized University in Logistics, and presents the main results from my work during this period. The thesis has been written in the spring semester 2016, and gives a credit of 30 ECTS.

The whole process writing this master thesis has been a learning process from start to end. It has included interesting ideas, discussions and new knowledge. By researching parts of the environmental assessment of air pollutant for LNG and HFO, I have learned more than I could imagine in the beginning of this process.

I would like to express my deepest gratitude to my supervisor Professor Svein Bråthen for supervising me and giving me good professional guidance throughout the whole process of writing this thesis.

I would also like to thank Awilco AS for giving me good and much appreciated information on the subject of LNG.

Last but not least, I would like to thank to the faculty itself and its staff for giving me five memorable years, both in terms of the academic challenges and the social network I have built.

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Molde, Norway
May 2016

Abstract

This master thesis investigates the environmental assessment of LNG and HFO in order to decide if there is worthwhile for an investment in a new vessel with LNG propulsion. By using the information provided by Awilco, the regulatory framework on air pollutants provided by IMO and earlier studies on the same topic, this thesis had a higher focus on air pollutant emission factors through the chosen life cycle for both the fuels.

A life cycle assessment (LCA) has been performed to be able to compare the environmental impact of the two fuel options. The life cycle stages included in this thesis was extraction, production, transmission and combustion. To be able to present the global warming potential from the two fuels, the emissions, from both of the fuels, is presented in equivalents of both CO_2 and SO_2, which gave interesting findings in the analysis were the differences in the total CO_2 – equivalent in the transmission phase and combustion phase, for both fuels, and in the case of methane slip during the combustion phase. Since methane is considered 25 times heavier than CO_2, such methane slips is very critical for the global warming potential.

By comparing the results from the analysis, one can say there is some advantages by introduce LNG as a fuel compared to HFO when considering the environmental assessment, especially when it comes to SO_x reduction. For Awilco to be able to decide whether or not to invest in LNG technology, there is a need for more research on the subject.

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Abbreviations

AE =	Auxiliary Engine
CCP =	Climate Change Potential
CO_2 =	Carbon Dioxide
EU=	European Union
ECA	Emission Control Area
GHG =	Green House Gases
GWP =	Global Warming Potential
HFO =	Heavy Sulphur Fuel Oil
ICAO =	International Civil Aviation Organization
IMO =	International Maritime Organization
ISO =	International Organization of Standardization
LCA =	Life Cycle Analysis
LCI =	Life Cycle Inventory
LCIA =	Life Cycle Inventory Assessment
LNG =	Liquefied Natural Gas
LSFO=	Low Sulphur Heavy Fuel Oil
MARPOL=	Maritime Pollution (International Convention for the Prevention of Pollution from Ships)
ME =	Main Engine
MDO =	Maritime Diesel Oil
MGO =	Maritime Gas Oil
MMBtu=	Million Metric British Thermal Units
MT=	Metric Ton
NOx =	Nitrogen Oxides
PM=	Particular matter
RO-ROs=	Roll on-Roll off vessels
RPM =	Rounds per minute
SOx =	Sulphur Oxides
TTP =	Tank-to-propeller

USD = United State Dollar

WTP = Well-to-propeller

WTT = Well-to-tank

1.0 Introduction

1.1 Background

The maritime shipping industry sector has increased steadily the last two decades and it plays a significant role in the globalized world economy. Over 90% of world trade is carried out by marine shipping with nearly 90 000 vessels. Like any other transport mode that uses fossil fuels, marine vessels produce a high amount of carbon dioxide emissions that clearly contribute to global climate change. Not just carbon dioxide, marine vessels also produce other pollutants that also contribute to the climate problem. The fuels that the marine vessel burns are also the dirtiest fuel on the market, a fuel that is unrefined.

The "just in time"-age of logistics and global supply chains, where fast and efficient movement of goods is preferred not only to satisfy the customer but also to be economic competitive has become very important within the maritime shipping industry. Ship owners and operators in the shipping market have the last years been more focused on market strategic approaches, combined with capacity utilization in order to balance the economics of transportation by sea. High and volatile bunker prices are two major factors that affecting the shipping industry directly, with fuel prices that fluctuates between 452 USD/MT in Rotterdam to 468 USD/MT in Singapore for HFO (AwilcoAS 2016).

There are not just the economic swings and challenges on a global scale that affects the shipping market. Air pollution emissions from ships are in continuously growth, while the land-based emissions has become more steadily. If the emission from ships does not change, shipping will be one of the biggest single emitter of air pollution in Europe. The challenge of pollution from ships is substantial. Shipping is not only a part of the pollution-problem, but shipping could also be an important part of a solution for the environmental challenge.

To control these challenges, the shipping sector is controlled by some international regulations by the International Maritime Organization (IMO), which are the United

Nations' specialized agency for regulating the shipping industry. The IMO was established in Geneva in 1948, they are responsible for develop and maintain a regulatory framework for shipping to improve maritime safety, the efficiency of shipping and preventing pollution from ships (environmental concerns). The IMO has 171 Member States and three Associate Members.

From 1st of January 2015, the IMOs MARPOL revised regulation regarding pollution to air can into force. This new revised regulation affects marine fuel specifications and which will in turn affect the global market. The new regulation is about a reduction of the maximum sulphur emissions limit for all vessels traveling in Emission Control Areas (Rederi 2013). I. e the new regulation requires that the vessel use low sulphur fuel oil specs in ECA. This new regulation will affect the ship owners and operators trading directly to Europe, it will lower the profit for every port call, as the price for low sulphur fuel oil is more expensive than the regular HFO, e. g for marine gas oil the price is 474 USD/MT in Rotterdam to 550 USD/MT in Singapore (AwilcoAS 2016).

Figure 1: Overview of existing and possible future ECAs (Green4sea 2016).

How to prevent emissions in the best possible way has for a long time been a hot topic in general, and that has not change the last years due to the global warming and the greenhouse gas effect problematic. For the shipping industry, the issue has become more important lately, not only due to regulations, but also to be competitive in the years to come. There have been large investments the last years in trying to make more sustainable ship fuels. Not only from an economical perspective, but also environmental.

1.2 Description of the Awilco-case

Most vessels today use marine residual oil (MDO and HFO) for ship propulsion. HFOs are cost effective, but on the other hand, they produce a high level of NO_x. The interest in new fuels for marine propulsion has increased lately, mainly as a result of stricter environmental regulations. Due to International Maritime Organization (IMO) rules regarding pollution, Liquefied Natural Gas (LNG) has become an interesting option to the marine residual oil for propulsion.

Increased attention to GHG emissions and uncertainty of future oil supply are some of the driving forces for change, as well as requirements on fuel quality and exhaust emissions for marine transportation will be enforced the years to come. This will result in a greater demand in adoption of new technologies and/or fuels in the shipping industry. Awilco has considered an investment of such new technology, which including a MAN dual-fuel engine for LNG propulsion. By now, Awilco has done calculations of the investment cost based on fuel prices, for HFO and LNG, and trading route with respect to the regulations. There is nothing wrong by angle the investment decision in that way, but this investment evaluation will only be from a business point of view and not from a social economical perspective.

There are several fuel alternatives and exhaust abatement technologies, that all has some advantages and disadvantages in relation to the environment and human health. The importance of knowledge of the performance at different system levels and perspective will increase due to increased demand for new technologies and fuels for marine transportation. Ship owners as well as business, administrators and policymakers will be important in the decision-making of different aspects of the fuel choice.

1.3 Company overview: AWILCO AS

Awilco AS is a private ship owning company that was established in 1939. Awilco AS is a wholly owned subsidiary of Awhilhelmsen AS, which is responsible for the technical management of the fleet and holds a valuable and widespread project management competence, which is a part of Awilco´s success. They are located in Oslo, Norway, and their focus is on investment in and operation of shipping and offshore assets. Awilco is also the founder and largest shareholder in Awilco LNG ASA. Awilco LNG ASA owns and operates 156,000 cbm DFDE membrane LNG vessels WillForce and WillPride, and two 125,00 cbm steam Moss type LNG vessels: WilGas and WilEnergy intended for international trade.

The specific trading route used in this thesis is provided by Awilco, and gives an overview of a typical year with trading for one specific VLCC vessel. The trading route for 1 year is approximately 64 000 nautical miles, and the VLCC vessel is attended to operate around 360 days year around, loaded and in ballast. The trading description for this case is as follows:

> **LOADED:** 2 x AG-EAST, AG - LOOP (SUEZ), AG - LOOP, RTM - EAST, ARUBA - SINGAPORE.
> *(2x Arabian Gulf to Far East/Asia)*
> *(Arabian Gulf to New Orleans (via Suez))*
> *(Arabian Gulf to New Orleans (around Africa))*
> *(Rotterdam to East/Asia)*
> *(Aruba (Caribbean) to Singapore) 7500nm*
>
> **BALLAST:** LOOP – ARUBA, LOOP – RTM, 3xEAST – AG.
> *(New Orleans to Aruba (Caribbean))*
> *(New Orleans to Rotterdam)*
> *(3x East to Arabian Gulf)*

1.4 What to investigate

The purpose of this thesis will be to examine the environmental assessment of LNG and HFO, with respect to the regulations. This means that the life cycle of each fuel will be taken into consideration. The focus will be on the emissions of greenhouse gases, but other investigations such as acidification will also be investigated. The emission to sea will not be discussed in this thesis.

The goal for this thesis will be to perform a comparative LCA of the environmental impact of LNG and HFO. Where the main focus will be on the combustion phase of each of the fuels in a MAN 7G80ME-C9-GI engine and a diesel engine. Due to lack of data and time limitations, only the extraction, production and transportation in between processes (only the supply to the end-user) and the combustion process for each fuel will be considered. This thesis use numbers from previously data found in literature and in previously research on the area would be used with some restrictions and assumptions. At the end, a final evaluation will be presented, on whether the use of LNG as propulsion for Awilco will be environmental friendly compared to HFO, in addition the economic perspective over the investment cost will be taken into consideration for the final evaluation in the discussion section.

The reason for comparing these fuels alternatives is several, but the main is that the global maritime industry increasing and the demand to meet the new regulations regarding emissions from maritime shipping are growing. Also, these regulations are expected to become stricter with the new sulphur limits in 2018 or 2020, which will have a huge impact on the industry and especially when using the type of fuel. This growing awareness of climate change and its environmental impact have made the maritime shipping industry rethink their strategies regarding the environment. Overall, a fuel that seems favorable in the combustion stage may not be environmental friendly in the previous phases. In this case, the most important is the combustion phase; since this is a case study where the aim is to investigate whether or not Awilco should invest in LNG. The combustion phase will be the most important from a company point of view. The focus, from the company's side, will be if the fuels fulfill the regulations (Tier III at the moment) and if the investment will be economic favorable based on the regulations today and in the future[1].

In this study, a consequential LCA will be performed to compare the alternative fuels. A consequential LCA strives to describe the environmental consequence of featured action (Aumann 2013). A roughly pathway for the different fuel is presented in figure 7 below.

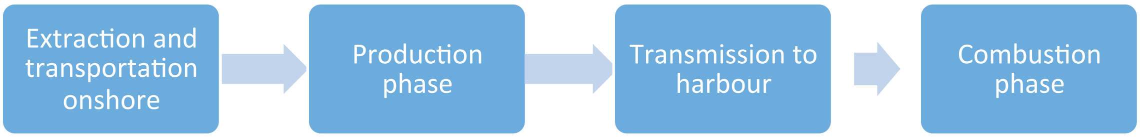

Figure 2: A overview of the chosen phases of the pathway in this research for the different fuels .

The functional unit is the key to make it possible to compare LNG with the other fuels in a way that is logical and quantified. To simplify, the functional unit in this thesis will be to transport one ton cargo one kilometer. Since this is a case study of Awilco´s evaluation on whether or not to invest in a LNG carrier, the functional unit could have been set to the planned yearly route for one VLCC at Awilco presented in section 1.3, but that has been to time consuming regard the short time to do this thesis and the possibility to do mistakes could increase. Therefor the “transportation of one ton cargo for one kilometer” is used as the functional unit, it will give a representative result for the discussion at the end of this thesis.

The selected system boundaries for this research include extraction of raw materials, transportation to land, production of the fuel, transportation to the market and finally the most important one for this thesis, the combustion phase. Based on findings from previously research and the lack of data material for three of the four boundaries, this thesis assume that the extraction of crude oil will take place in the north sea and the natural gas is extracted from Snøhvit field up in northern Norway. An overview of the presented system boundaries is shown in figure 3 below.

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[1] For this particular research there is set a 10years limit.

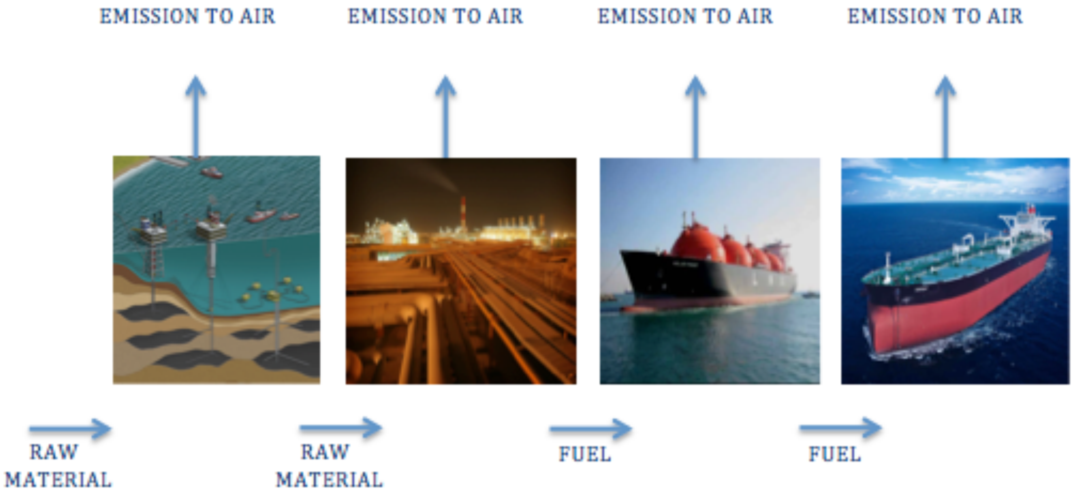


Figure 3: The selected system boundaries for this case study.

In addition, when it comes to the data quality, most of the data is collected from Awilco. The data that was not possible to collect from Awilco is mainly collected from different databases on the Internet and from some other reliable researchers, which will be commented more in depth in chapter 5.0. Where there is no available data, good assumption should be made and argued for.

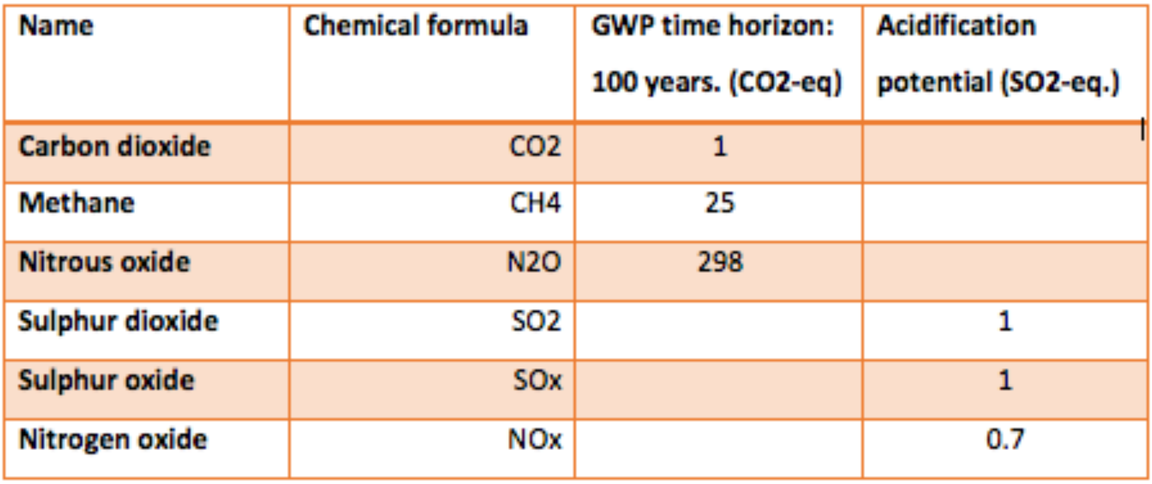
1.5 Impact categories

To achieve the goal of the analysis, selection of impact categories is important. The ISO standards do not specify which categories that are preferred, so the choice is left with the author. For this particular LCA, the interesting part is to see which of the fuel is most environmental friendly when it comes to air pollution, which makes it naturally to look at the greenhouse gas emissions. Global warming potential (GWP) is a way of expressing the environmental impact of the GHG as a result of emission to air. One main example of the consequences from global warming is the change in average surface-air temperature, and the effects of changing weather conditions (intensity, frequency etc.)(McCarthy, Best, and Betts 2010).

There will also be important to look at the acidification potential for each of the fuels. Stricter regulations regarding acidification gasses as result in emission to air has led to the importance. The acidification gases this study will focus on are the impact from SO_x and NO_x.

The United Nations Framework Convention on Climate Change has published a global warming potential list for a period of 100 years, which is the common used time horizon for GWP (EPA). This list is presented in CO_2- equivalents and it covers carbon dioxide, methane and nitrous oxide. It measures how much energy the emissions of one ton gas will absorb over a given time horizon, here 100 years, relative to the emissions of one ton CO_2.

These pollutants are represented by weight factors, which give an indicator on who much impact each of the pollutants has on the global warming potential, as shown in table 1. The United Nations Framework Convention on Climate Change considers that the CO_2 emission is weighted as 1, regardless of the time period because it is used as the reference. Methane emissions is 25, and nitrous oxide is weighted 298, which indicates that both methane emissions and nitrous oxide needs to be multiplied by respective 25 and 298 in order to obtain the CO_2-equivalente for GWP.



Name	Chemical formula	GWP time horizon: 100 years. (CO2-eq)	Acidification potential (SO2-eq.)
Carbon dioxide	CO2	1	
Methane	CH4	25	
Nitrous oxide	N2O	298	
Sulphur dioxide	SO2		1
Sulphur oxide	SOx		1
Nitrogen oxide	NOx		0.7

Table 1: Impact categories (UNFCCC) (EPA)

1.6 Research questions

This section presents the research questions, and the sub-questions.

1.6.1 Research questions

RQ1. Why is LNG considered as a possible fuel alternative in the marine transportation sector?

RQ1.1 When considering the regulatory framework for maritime shipping, what are the advantages and disadvantages of LNG fuel compared to HFO?

RQ1.2 What is the main incentives for Awilco to switch to LNG as propulsion for their vessel?

RQ.1.3 Which is the relevant environmental impacts of HFO and LNG vessels?

RQ2. What are the final recommendations for Awilco regarding investment of a new build VLCC with dual fuel engine?

2.0 Theory review

In this chapter the LCA will be presented as a tool for assessing the environmental impact. In addition, an overview of the pollutants from shipping and the respective regulations will be presented. The first section will briefly describe the framework for conventional LCA, the next sections will go through the emissions from maritime shipping and the regulatory framework that will be important for this thesis.

2.1 Life Cycle Assessment

The increasing focus of the importance to protect the environment, and the possible impacts linked to products, both manufactured and consumed, has arise the interest of better methods to address and understand these impacts. To quantify and evaluate these environmental impact factors of a system that has multiple technical processes, the most commonly used tool is life cycle assessment (Ekvall et al. 2007).

The International Organization for Standardization (ISO) has conducted some standards for the LCA procedure in the ISO 14000 Environmental Management standards. The ISO 14000 consist of different standards for management of the environment, and in ISO 14040 from 2006 you find a definition of LCA; "the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (ISO 2006)." Generally, a LCA can be structured in four phases (ISO 2006):

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

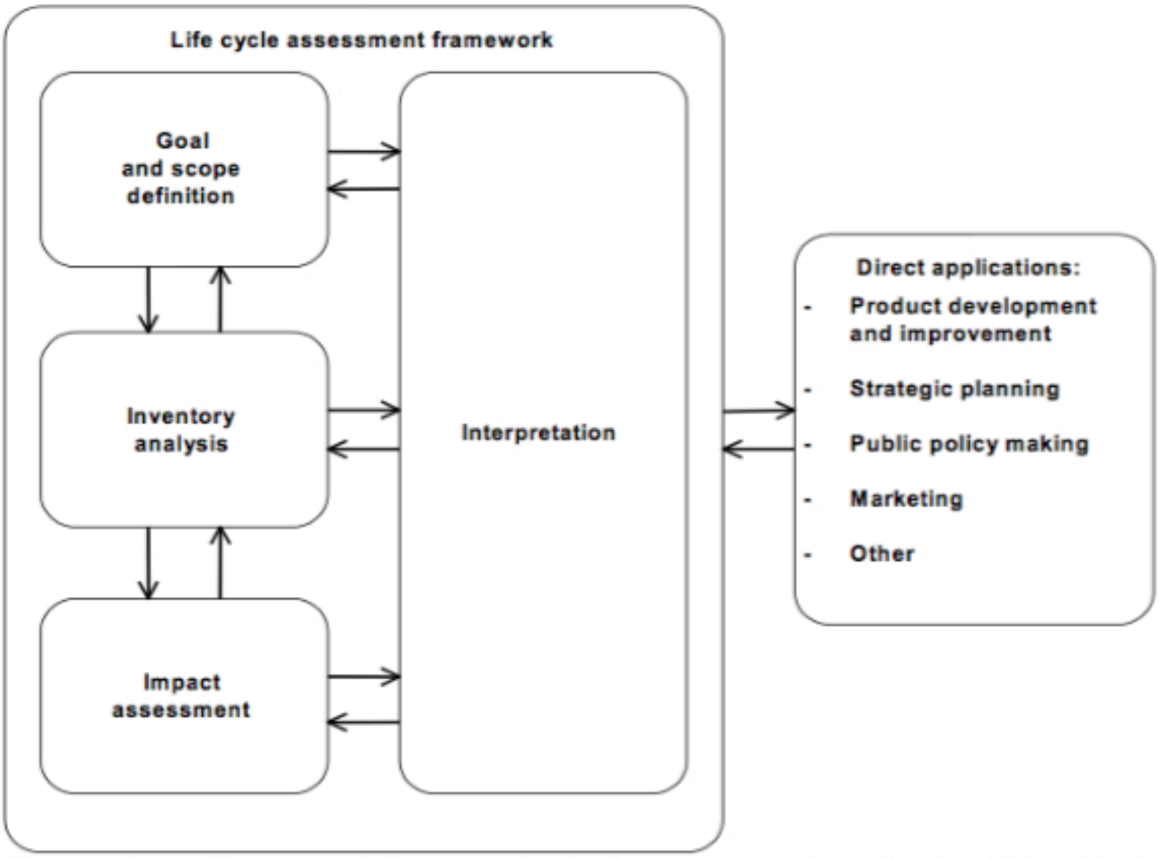
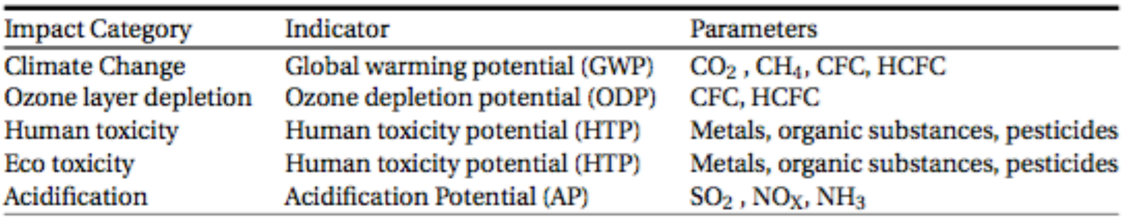


Figure 4: The overall framework of LCA and its applications (Rebitzer et al. 2004).

The first phase provides a description of the product system in terms of the functional unit and the boundaries (Rebitzer et al. 2004). The goal aims to define the objective of the research and the scope definition establishes the main characteristics of the intended research, and it will define wheatear it will a cradle to grave or cradle to gate analysis. When you analyze from a cradle to grave perspective, one take the impact of a product from the beginning of its “life” through the end of its useful life. The cradle to gate analysis consider only the processes up to the delivery of the product, and does not cover the entire life cycle of the product. To be able to quantify the performance of the system that enables a comparison of the alternative goods, services or product, the definition of the functional unit will be important. The first phase intend to include the reasons for carrying out the study, the intended application and the intended audience (Finnveden et al. 2009).

The second phase, the inventory analysis (LCI), defines the product system with boundaries and flow diagrams. Where the flow diagrams shows how the processes that consist in the system are defined by environmental and economic flows. The main focus of LCI is to estimate the consumption of resources and the quantities of emissions caused by a products life cycle i.e. the key task will be to make a model of the system where all the economic flows are transitional steps in a transformation of inputs (resources) and outputs (emissions) from the life cycle of a product with respect to the functional unit (Finnveden et al. 2009). The creation of LCI is the most labor and time intensive stage of a LCA (Finnveden et al. 2009). When using LCA models, the environmental burdens are often calculated per kg or ton of emissions.

The third phase, the impact assessment (LCIA), aims to interpret and collect the data from the LCI, and present the data in an informative way by expressing the environmental flows into environmental impact categories. Where the impact categories are the direct effect on the environment caused by the different pollutant emissions. Figure 2 shows common used impact categories in LCA with the respective indicators and parameter. The impact categories that this thesis will focus on are, climate change and acidification.



Impact Category	Indicator	Parameters
Climate Change	Global warming potential (GWP)	CO_2 , CH_4, CFC, HCFC
Ozone layer depletion	Ozone depletion potential (ODP)	CFC, HCFC
Human toxicity	Human toxicity potential (HTP)	Metals, organic substances, pesticides
Eco toxicity	Human toxicity potential (HTP)	Metals, organic substances, pesticides
Acidification	Acidification Potential (AP)	SO_2 , NO_X, NH_3

Figure 5: Common used impact categories with characterization factors (Øberg 2013).

The interpretation presents recommendations and conclusion based on an evaluation in relation with the goal and scope that is set in the first phase of the LCA. This phase is a bit different from the three others, since the first three phases must be performed consecutively, the interpretation phase could be carried out intermediate to the others. However, in practice, LCA must fulfill three basic criteria; it must be reliable in order of the information and results generated, it must fit into existing information and routines in business to be applicable and at last it must provide quantitative and relevant data and information for the decision makers (Baitz et al. 2012). LCA is considered as an interactive process, and opens the possibility to revising the four phases when it is considered necessary. More on the specific methodology for the LCA will be described in chapter

2.2 Emissions from shipping

LNG as a fuel for propulsion can be analyzed from different angles, e.g. Environmental aspect, safety aspect, physical, economic or other aspects depending on the purpose of the research (Thomson, Corbet, and Winebrake 2015). In this thesis, LNG as a fuel option is analyzed from a business point of view with respect to different perspectives (environmental, physical and economical).

When it comes to physical aspects of fuel decision, factors such as energy density, cost, weight and size of onboard energy storing are important when ship-owners deciding which fuel to choose (EIA 2013). The space available for convey people and freight can be reduced if the fuel need large, heavy and expensive storage. It can also make the vessel operate less efficiently and/or make it too costly too operate, although it is assumed cheaper fuel (EIA 2013). The figure under presents a comparison of energy densities for different transportation fuels in the US. It does not take into account the storage tanks or other equipment that the fuels need, it only presents the energy content per unit volume or weight of the fuels. As shown in the figure, LNG is lighter than diesel, methanol and ethanol, but it have lower densities per unit volume, and will require more space, which lead to bigger and heavier storage tank in the vessel in order to go the same distance.

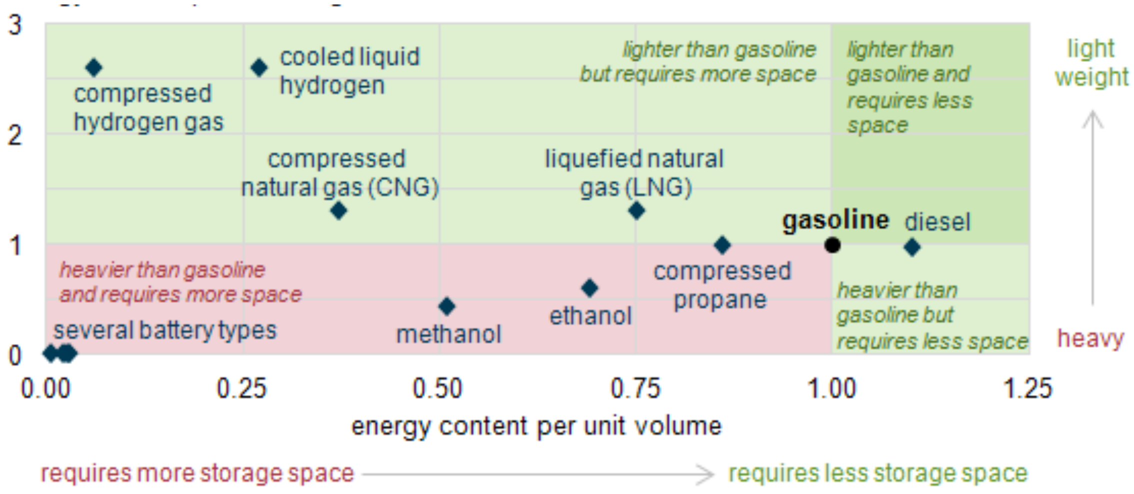


Figure 6: Energy density comparison of several transportation fuels, US Energy Information Administration (EIA 2013).

The use of LNG as a fuel in maritime transportation is less attractive compared to other fuels in the same sector. The relatively low development in infrastructure, especially in the downstream of the supply chain of LNG, is one of the reasons. The diesel technology is more commercially attractive than LNG technology in terms of already existing worldwide fuelling infrastructure, supply and contracting practice in the market, also due to established regulations and new technology on the engines market that has introduced more environmental friendly diesel engines (Johnson 2013). Even though the LNG infrastructure is being built out, it still has some significant gaps in it (Johnson 2013).

One of the main advantages of LNG is the environmental effectiveness compared to traditional oil-based fuels, such as HFOs. This advantage must not be underestimate, since the maritime transport sector represents one of the biggest shares on the global balance of GHG emissions (Stopford 2009).The share of global CO_2 emission is growing in the maritime shipping sector. In Buhaug et al. (2009) report for the International Maritime Organization(IMO), estimated that these emissions was around 3% of all global emissions in 2007, and that these emissions will be double or even triple by 2050 if the situation stays the same. New technology, better operational practices and improved logistics system is some of the key strategies for increasing energy efficiency to abate CO_2 emission from maritime shipping. Where energy efficiency could be defined as the energy used per transported goods and distances (kg of fuel per tonne cargo per km (or nautical mile)).

SO_x, NO_x and PM are all emissions to air that come from the combustion of marine fuels. Emissions to air have potentially ecosystem impacts and negative health effects on the population exposed. One giant container ship can emit nearly the same amount of cancer and asthma-chemicals as 50 millions cars (Vidal 2009). A large ship can generate about 5 000 tons of SO_x pollution in a year. The whole shipping industry is responsible for 18%-30% of all worlds NO_x pollution and about 9% of all SO_x emissions in the worlds (Vidal 2009).

Due to the fact that shipping is becoming a dominant emission source, and have a potential to exceed land-based source, emissions from the maritime sector have been internationally regulated by the IMO.

2.3 Environmental regulations

Kyoto Protocol from 1997 is the international framework agreement targeting 37 industrialized countries and the EU in order to reduce the GHG emissions. It entered into force 16th of February 2005, and address international aviation and maritime transportation by impose direct to the main regulatory bodies such as the IMO and the ICAO to report progress on implementations and measures undertaken to minimize GHG emissions (IMO 2016f).

IMO started their focus on the GHG emissions September 1997 at the International Conference of the Parties to the MARPOL convention. The Protocol of 1997 amend the MARPOL Convention (MARPOL Annex VI) along with the Resolution 8[2] on CO_2 emissions from ships (IMO 2016f). The growing trend in international trade and a still increasing demand for shipping, the environmental aspects in order to stabilize the global climate and addressing the issues of pollution that cause the damage to the environment has become in focus the last decades (IMO 2016c).

MARPOL, the International Convention for the Prevention of Pollution from Ships, includes six annexes which deals with various forms of marine pollution from ships, this thesis will only focus on MARPOL Annex VI regarding the air pollutants contained in ships exhaust gas, that incudes CO_2 emissions as well as sulphur oxides (SO_x – Regulation 14[3]), nitrous oxides (NO_x – Regulation 13[4]) and PM (IMO 2016a).
The MARPOL Annex VI came into force 19th of May 2005. From 1th of July 2010, the revised MARPOL Annex VI entered into force (IMO 2016a). The revised MARPOL Annex VI included significantly reduction globally in emissions of SO_x, NO_x and PM, and also included an introduction of emission control areas to reduce emissions of those air pollutants further in designated sea areas (IMO 2016a). The existing ECAs include the Baltic Sea (SO_x only), the North Sea (SO_x only), North American ECA, which includes most of the US- and Canadian coast (control of NO_x, SO_x and PM) and the US Caribbean ECA, which includes Puerto Rico and the US Virgin Islands (control of NO_x, SO_x and PM) (IMO 2016b).

MARPOL Annex VI regulation 13 for NO_x consists of different standards (Tiers) for controlling the NO_x pollution. These standards is based on the ship construction date, where the actual limit value is determined from the engines rated speed (Azzara, Rutherford, and Wang 2014):

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[2] Resolution 8 is referred to the strategies adopted for the reduction of CO_2 and other atmospheric and marine pollutants (IMO 2016f).

[3] The specific regulation for SO_x pollutant.

[4] The specific regulation for NO_x pollutant.

Tier	Effective Date	NO_x Emission Limit (g/kWh)		
		RPM (n<130)	RPM ($130 \leq n < 2000$)	RPM ($n \geq 2000$)
I	2004	17.0	45,0 x $n^{(-0,2)}$	9.8
II	2011	14.4	44,0 x $n^{(-0,23)}$	7.7
III	2016*	3.4	9,0 x $n^{(-0,2)}$	1.96

Table 2: MARPOL Annex VI NO_x Emission Standards (IMO 2016e).

*In NOx ECA only (Tier II standards apply outside of ECA)

While the Tier III is applied to the specified ships while operating in ECA, outside such areas the Tier II controls apply (IMO 2016e). The NO_x Tier III regarding new buildings will be very interesting for this particular research. Since this case, roughly speaking is about whether or not to invest in a new ship with new technology to meet the standards and regulations.

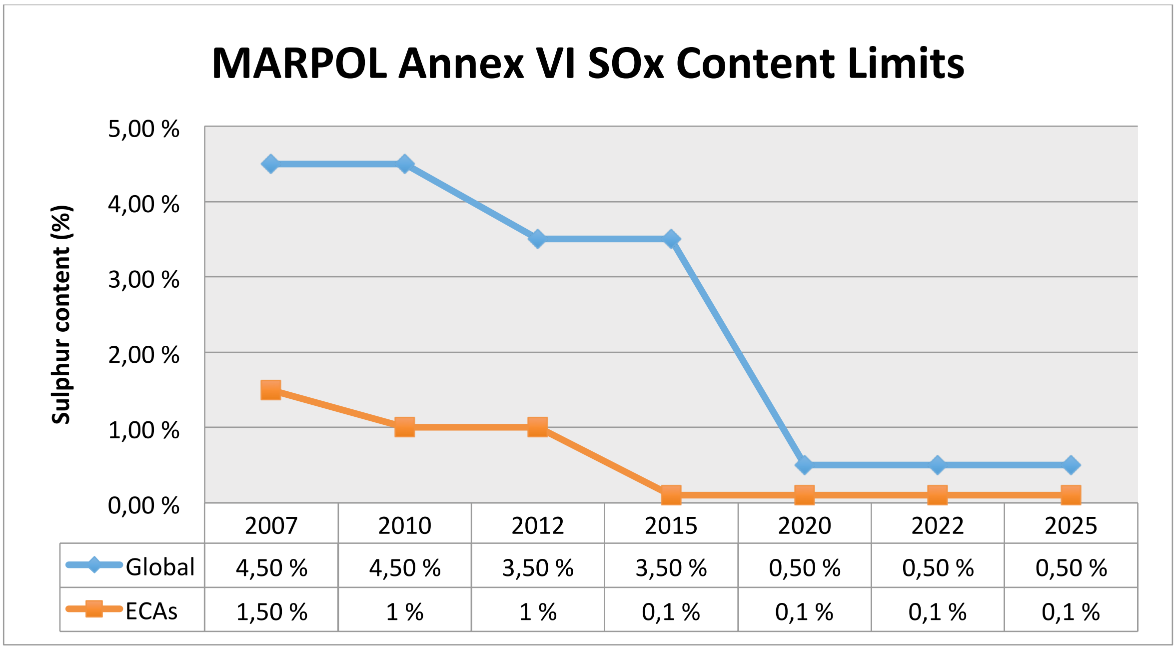


Figure 7: Current and future sulphur limits (DNV 2013).

The increasing focus on both global and local environmental issues, and not to forget the growing realization of the actual pollution burden imposed by shipping, has led to stricter regulations both international and national. Some of these regulations is already implemented, some of them will enter into force in the near future and some are still being developed and impact only in terms of intermediate (DNV 2013). The figure above illustrates the SO_x limits that already exist and the limits that will enter into force by 2020.

The global sulphur cap will be reduced further from the current 3.50% to 0.50% in 2020. Where the limits for the ECA for SO_x and particular matter were reduced to 0.10% from 1th of January 2015 (IMO 2016a). There are some uncertainties about when the global SO_x limit of 0,5% will enter into force, there is a possibility that this will happen in 2020, but the final conclusion will be decided by the review in 2018 (DieselNet 2009).

These SO_x and PM emissions limits applies to all fuel oil, combustion equipment and devices onboard, and therefor include both ME and all AE together with items such boilers and generators (IMO 2016b). For the ECA, it exists special fuel quality provisions. HFO is allowed if it meets the applicable sulphur limits. To meet these sulphur limits, many vessels that run on HFO use fuel switching, scrubbers and any other technological methods as long as they limit SO_x emissions to ≤ 6g/kWh when sailing into ECAs (DieselNet 2009).

There is the sulphur oxide (SO_x) emissions that motivating to replacement of heavy fuel oils with cleaner and lower-sulphur fuels (Corbet and Winebrake 2008). The SO_x is a sort of gas that causes acid rain, and will be damaging in large quantities both for nature and people, especially asthmatics. Most of the ships that uses HFO have to switch to fuel oils with lower sulphur levels to comply with the different limits and regulations within both ECAs and outside ECAs. Another alternative is to use different exhaust abatement techniques, which will be the subject in section 3.4.

The increasing regulatory pressure to improve fuel quality from MARPOL in 2015, push the development of more advanced vessel engine and after-treatment technology for conventional residual and distillate fuelled ships (Lowell and Wang 2013). The industry faces three new realities that are changing marine fuel investment choices. Thomson, Corbet, and Winebrake (2015) mention these three realities in their paper.

The first one is regulation, as mention in the text above, the IMOs MARPOL framework to control specific pollution emissions. The MARPOL Annex VI initiating emissions standards for ships that reduce emissions rates by approximately 80% for both SO_x and NO_x, globally and more than 90% reduction in IMO-designated ECA along European and United States (US) coast (IMO 2016e, 2014, 2013). Through these regulations, vessel operators, engine manufactures and technology providers responded with approaches (e.g. through smokestack controls or fuel switching) to meet the new standards. Local pollution emissions would be lower with natural gas compared to those distillate fuels. An improvement of the engine design on the current engine equal those of distillate fuels may reduce emissions to meet the regulation in MARPOL Annex VI (Thomson, Corbet, and Winebrake 2015). Second factor is price difference between natural gas and high-sulphur fuel oil, where natural gas may support an economic advantage. The growing in infrastructure for natural gas make it more plausible for ships with natural gas to fill fuel (Fullenbaum, Fallon, and Flanagan 2013). These two factors are drivers that highlight an increasing interest in the use of natural gas as a marine fuel.

There are not only positive effects by the increasing use of natural gas in marine sector. And this negatively affects is mention in Thomson, Corbet, and Winebrake (2015) third factor, climate change. IMOs regulations regarding local pollutants such as SO_x and NO_x is not the only concern. During new research, GHG emissions from vessels and international shipping in general, has concluded that there is need for reductions. When the use of natural gas as marine fuel increase, it may affect the greenhouse gas emissions negatively when looking at the whole fuel production and delivery pathway of natural gas. Since natural gas production pathway can be more energy intensive than petroleum's pathways, and possibility of leakage of methane during natural gas extraction and distribution may have huge impacts on the GHG.

3.0 Literature review

This chapter of the thesis presents LNG as fuel alternative, a short presentation of HFO and the different types of engines that is suitable for the fuels. In addition, findings from current literature on the life cycle impacts and climate effects of ships will be presented at the end of this chapter.

3.1 Liquefied natural gas (LNG)

In this thesis Liquefied Natural Gas will be referred to as LNG. About 85-95% of the LNG is methane (CH_4), as well as other hydrocarbons such as ethane (approximately 5%-10%), propane and butane (approximately 5%) (LPG), and some traces of nitrogen (Verbeek et al. 2011). LNG has a lot of the same characteristics as methane; it is colorless, non-corrosive and non-toxic. LNG is a type of gas that is liquefied by cooling it down with temperatures lower than -162 °C (Statoil 2007). During the cooling process, the volume will be reduces by about 600 times, which makes it easy to transport with the aid of pipelines or gas tankers.

Parameter	Value
Boiling point	**– 160ºC to – 162ºC**
Molecular weight	**16 – 19 g/mol**
Density	**425 – 485 kg/m^3**
Specific heat capacity	**2,2 – 3,7 kJ/kg/ ºC**
Viscosity	**0,11 – 0,18 mPa•s**
Higher heat value	**38 – 44 MJ/m^3**

Table 3: Thermo-physical properties of LNG (Dobrota, Lalic, and Komar 2013).

Compared to HFO, LNG has a higher hydrogen-to-carbon ratio, which leads to a lower carbon intensity (kg CO_2/kg fuel). To remove CO_2, hydrogen sulfide, mercury, water, oxygen residue and heavier hydrocarbons, the natural gas is purified. SO_2 emissions from LNG are equal to zero, which means that the fuel does not contain any sulphur. In addition, using LNG as marine fuel will reduce the particular matter (PM) emissions. Due to the fact that LNG in the combustion phase results in less CO_2 compared to conventional fuel combustion, LNG is a winning fuel for marine transportation seen in light of the regulations and the increased climate focus. But there is a negative site about LNG, since the methane slip in the early stage of it life cycle and from the combustion of the fuel, LNGs GHG-gain may be reduced considerably (Verbeek et al. 2011).
In the table below, a typical composition of the LNG are presented in percentage:

Methane (CH_4)	**94,7%**
Ethane (C_2H_6)	**4,8%**
Propane (C_3H_8)	**0,40%**
Butane (C_4H_{10})	**0,06%**
Pentane (C_5H_{12})	**0,01%**
Hexane (C_6H_{14})	**0,01%**
Nitrogen (N_2)	**0,02%**

Table 4: Composition of LNG (%) (Hebeler).

3.1.1 Technical aspects of LNG

The concept of LNG as a marine fuel is still in a start phase, and it will take time to fully optimize its potential. According to Semolinos, Olsen, and Giacosa (2014) there are three phases of development for the LNG. First of these three phases is the development in short sea shipping, and especially in the ECAs, where vessels (new buildings, RO-ROs, existing product tankers etc.) will be forced to reduce its emissions.

When several ships are adopting LNG as propulsion, it will force a development in LNG availability in ports(Semolinos, Olsen, and Giacosa 2014). The second phase is about the deep-sea vessels. For these ships to run on LNG, they must be new-buildings, since retrofitting will be a huge challenge and not least very cost inefficient for the company (Semolinos, Olsen, and Giacosa 2014). Its not unusual that ship operators will test the LNG by ordering few ships, if the testing gives the shipping company and ship owners a positive outcome they will decide to order more vessels that will run on LNG fuel. When it comes to the third phase in Semolinos, Olsen, and Giacosa (2014) article, they consider the future. The third phase is about the development after 2025, when the availability of LNG will be developed further, and LNG will be available at numerous ports in Europe, Asia and North America.

3.1.2 Economical aspects of LNG

LNG compared to other conventional maritime fuels is less related to the oil price, but it could have a significant price margin to conventional maritime fuel. One of the reasons for that could come from the cost-structure of a shipping firm, where the total costs for running is divided into fixed-, variable- and capital costs (Stopford 2009). The fixed costs is represented by the operating cost, the variable cost is the voyage cost. Stopford (2009) presented a shipping cash flow model, showing the revenue- and operating- and capital costs for a shipping company. This model is presented in figure 4 below.

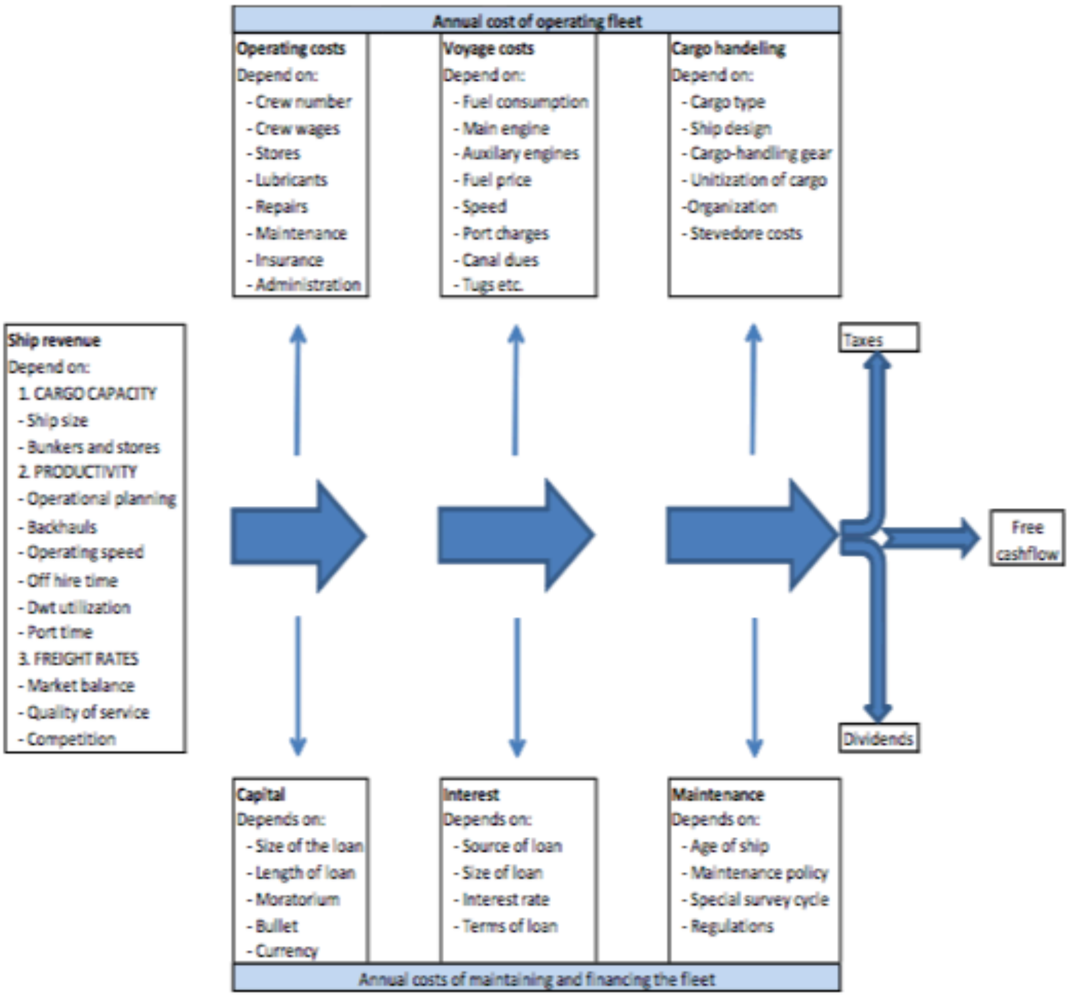
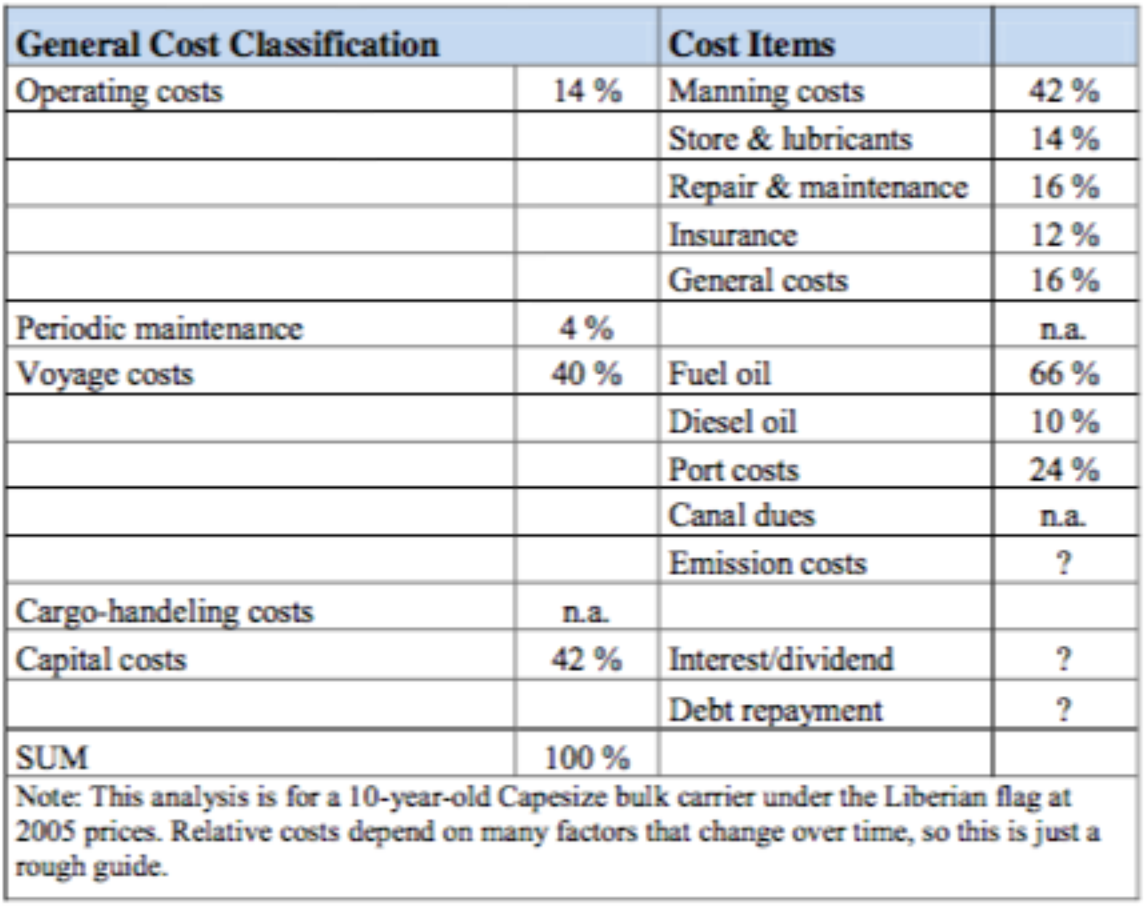


Figure 8: Shipping cash flow (Stopford 2009).

The shipping revenue is shown on the left side of the model, and from this revenue both annual cost of operating the fleet (on top of the model), and annual cost of maintaining and financing the fleet (on the bottom of the model) must be inferred. In addition, it will also be essential to look more specific at the cost structure within a shipping company.

In Stopford (2009) book it is also a cost analysis of the major costs for running a bulk carrier, even though the cost structure differs between ship types this overview is still representative for other ship types. The cost structure is shown in figure 9.



General Cost Classification		Cost Items	
Operating costs	14 %	Manning costs	42 %
		Store & lubricants	14 %
		Repair & maintenance	16 %
		Insurance	12 %
		General costs	16 %
Periodic maintenance	4 %		n.a.
Voyage costs	40 %	Fuel oil	66 %
		Diesel oil	10 %
		Port costs	24 %
		Canal dues	n.a.
		Emission costs	?
Cargo-handeling costs	n.a.		
Capital costs	42 %	Interest/dividend	?
		Debt repayment	?
SUM	100 %		

Note: This analysis is for a 10-year-old Capesize bulk carrier under the Liberian flag at 2005 prices. Relative costs depend on many factors that change over time, so this is just a rough guide.

Figure 9: Cost structure for a bulk carrier (Stopford 2009).

From the figure is clearly that the capital costs related to purchase of a vessel are the largest cost element. Today, the investment cost of a LNG carrier has a higher initial cost compared to vessels without LNG-propulsion. Another important object from this illustration is that the fuel cost is approximately 40% of all voyage cost, and that the voyage cost represents 40%, and in some cases more depending on ship size, of the total cost structure for a vessel. The fact that the fuel cost being one of the main cost drives, the bunker prices will be a key focus when ship-owners deciding the future investment of a ships propulsion alternatives.

LNG propulsion for ships provide opportunities to avoid some of the cost burdens associated with more stringent regulation of air emissions from ships that may be imposed. The chances to utilize these savings are marginal, as capital costs related to the construction of LNG engines are higher compared with conventional engines. The pricing of LNG is depended of several parameters; price index, the distance to LNG source, transportation method and the volume. A typical LNG price will be between the price of HFO and MGO (marine gas oil), but due to the downturn in the oil market, LNG will be more on par with MGO, which applies to the global market.

Burel, Rodolfo, and Zuliani (2013) analyzed in their article the economic upturn of LNG-fuelled vessels, and the results show 15%-20% higher upfront costs, 35% lower operating costs, 25% lower CO_2 emissions and a payback period for installing LNG systems about three years. They also show different scenarios, if the LNG price increases to HFOs price levels, the payback period will arise to five years. In addition, if the price of LNG increases further, up to 120% of HFO price, the payback period will extend to eight years.

Another economic analysis done by Intelligence (2013) upon LNG vessel costs in North America shows a total saving for four type of vessels is different, during a 10 years period. Where the positive payback period is seen for ferries and new build offshore vessels, which indicate that the companies should achieve enough cash flows to deal with high investment costs. On the other hand, the payback after 10 years for tugs and cargo vessels is negative. Reason for this, Intelligence (2013) refers to the fact that tugs and cargo vessels requires less fuel, and that it will be difficult to repay the high enough initial investment costs.

3.1.3 Environmental aspects of LNG

One of the main advantages of LNG is the environmental effectiveness compared to traditional oil-based fuels. In European policies one of the possible measures to reduce the environmental burden of transport operations is to substitute conventional fuel with cleaner alternative fuels, such as natural gas (Arteconi and Polonara 2013). Natural gas as an energy source is emphasized due to its availability to use at a competitive price, with use of already available technology. In addition, natural gas can be highly important for countries that is dependent on oil imports (e.g. several countries in Asia) (Yeh 2007).

Considering the stricter environmental regulations imposed by IMO, researches and the European Commission agrees upon that LNG could be the answer, at least in the medium term. Ship owners that operates in ECA have to comply with a SO_x limit on 0.1%, in addition the stricter control of NO_x emissions that came in force this year (2016), which means that ship builders have to reduce the NO_x emissions to 80% (this will only be valid for Tier III engine standards in ECA. For more see section 2.2). By 2020 (if the regulatory goes ad planned, see more in section 2.2) the sulphur level will be further reduced to 0.5% globally, this making LNG attractive not only within ECA but worldwide as well. The European Commission has issued a draft on a suggestion that consider LNG is a preferred fuel for marine transportation, and requires all European seaports to be able to provide LNG bunker services (Semolinos, Olsen, and Giacosa 2014). Due to strengthen environmental regulations, there are reasons to believe faster LNG penetration in the maritime market, at least within ECA territories.

Acciaro (2014) mention in her research that in order to comply with the new ECA regulations there are three main options. The first is to switch to higher-quality fuel (low in sulphur, also known as distillates), second is to use exhaust abatement technologies (e.g. scrubbers, see section 3.4) or to choose LNG. There is many studies done upon alternative fuels to comply with the regulations, and many of these studies conclude that LNG is the most favorable alternative fuel. Acciaro (2014) points out that LNG can offer substantial reduction in emissions from ships because LNG has a higher hydrogen-to-carbon ration in comparison to HFO; the specific CO_2 emissions will be lower. In addition, LNG does not contain sulphur, which means almost no SO_x emissions and almost no PM emissions.

Acciaro (2014) also mention that LNG can even decrease the operational costs by 35% compared to HFOs. In table 4, the potential reduction of emissions when using LNG fuel in a vessel is presented.

Substance	**Reduction (%)**
CO_2	20% - 30%
SO_x	90% - 100%
NO_x	60% - 80%
PM	70% - 100%

Table 5: Reduction in emission when using LNG fuel (RollsRoyce 2011).

Consider the life cycle of LNG emissions, an estimation of approximately 10% lower total emissions than diesel life cycle emissions is realistic according to Acciaro (2014). When considering the maritime shipping sector there is important to notice that the business is mostly concerned about the last phase of the life cycle, the combustion phase, rather than life cycle emissions in order to comply with the environmental regulatory by IMO. Ship owners also know that LNG does not require any exhaust gas cleaning technology, therefor LNG represents as a cheaper alternative compared with other distillates (Acciaro 2014).

However, there are also a lot of challenges with LNG, and Acciaro (2014) mention some of these challenges: high degree of uncertainty on the differential between the LNG and conventional maritime fuel prices, availability of LNG and the reliability of its supply chain. Due to this, LNG as a fuel for maritime shipping is still in the “new born” phase. It is clear that LNG is the best choice among the other alternative fuels when it comes to its performance regarding the environmental compliance imposed by IMO. Still, there are a lot of challenges that need to be overcome if the usage of LNG as a fuel for ships shall increase.

3.2 Heavy Sulphur fuel oil (HFO)

Heavy sulphur fuel oil, referred to as HFO, is a residual oil with high viscosity and density. It is the cheapest, but also the dirtiest substance of all that are made in a refinery. Approximate 80-85% of the total fuel consumption by the global merchant fleet is HFO (Chryssiakis et al. 2011). The quality of the HFO will be determined by the crude oil grade and the refining process applied. HFO is made of a mixture of residue oils and distillates. HFO remain high in NO_x, SO_x and CO_2 in the exhaust gases, and without any measures, HFO is no longer an alternative fuel to use inside ECA.

HFO is available in almost every harbor in the world, and are traded actively as bunker oil. One distinguishes between different types of HFO based on viscosity, and the best-selling varieties of HFO are called IFO380 and IFO180. The name says something about the viscosity of fuels in centistokes. Both IFO380 and IFO180 contain too much sulfur to fulfill the regulatory without any measures. Since IFO 380 contains more distillate oil than IFO 180, IFO 380 is more expensive.

Industrial Name	Max. Viscosity
Intermediate Fuel Oil 180 (IFO 180)	180 Centistokes
Intermediate Fuel Oil 380 (IFO 380)	380 Centistokes
LS (low Sulphur <1.5%) 180	180 Centistokes
LS (low Sulphur <1.5%) 380	380 Centistokes

Table 6: Most common HFO types (Shippipedia 2011).

3.3 Engines

The most common used engines in todays maritime market is the two-stroke or four-stroke diesel engines. But there are also some vessels that use steam turbines and some high-speed ferries that use gas turbines. Since the demand for gaseous fuels with methane for propulsion on vessels has increased, there have been developed gas engines for these vessels. Fuels with methane as the energy carrier, as LNG, can be used in gas or dual fuel-engines. There is important to notice that there can be some differences in methane content between different qualities of LNG, which may require some engine modification.

3.3.1 Gas engines

As described above, there are two main types of engines for gaseous fuels; spark ignited lean-burn engine and dual-fuel engines. Where spark ignited lean-burn engines can only run on gas. Lean refers to high air-fuel ration, which indicates that extremely lean air-fuel mixes lead to lower combustion temperatures and therefor lower NO_x emissions.

When it comes to the dual-fuel engines, they can run in either gas- or diesel mode. In gas mode this type of engine operates after the traditional Otto cycle principle, the combustion will be triggered by a lean air mixture that ignited by the injection of a small amount of diesel fuel in the combustion chamber. This amount of diesel fuel is approximately no more than +/- 1% of the total fuel based on energy.

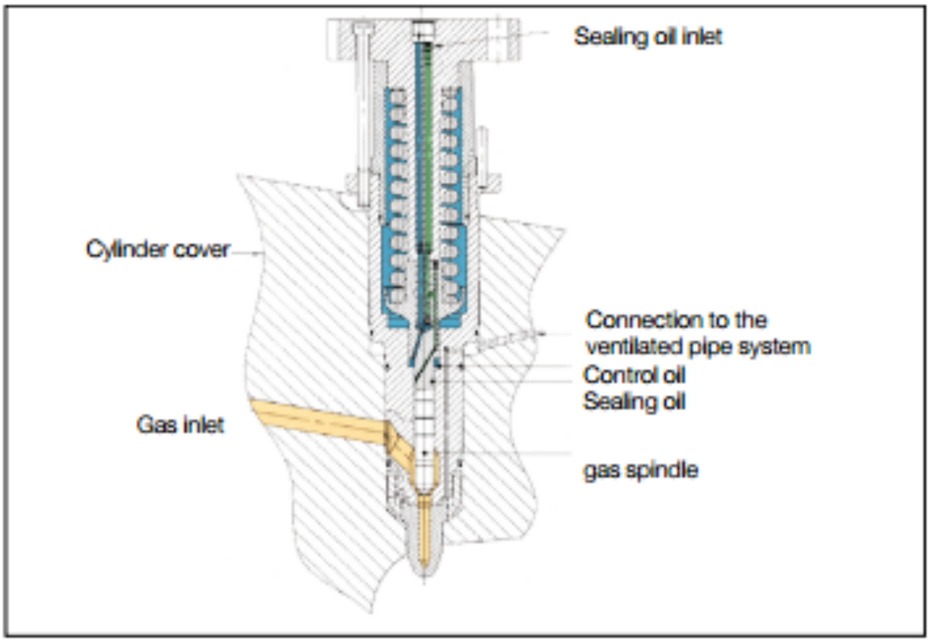


Figure 10: Gas injection valve- ME-GI MAN engine(MAN).

The dual fuel engines have problems with methane slip, but the manufactures of the engines are aware of the problems and there has been a lot research on how to overcome this challenge. When switching to diesel-mode, the engine operates after the normal diesel cycle. MAN engines are one of the manufactures that design dual-fuel engines.

One of their newest dual fuel engines to meet the Tier III is the 7G80ME-C9-GI engine. Where "7" is the number of cylinders, "G" stands for super green ultra long stroke, "80" is the diameter of piston in cm, "ME-C" the engine concept which are for this particular engine electronically controlled, "9" is the mark number and the "GI" stands for gas injection by methane (MAN 2015).

3.3.2 Diesel engines

There are mainly two different diesel engines: two-and four-stroke engines. Where a two-stroke engine works in two strokes, and operates using the diesel cycle. Two-strokes are simpler mechanically than the four-stroke engines, but more complex in the thermodynamic and aerodynamic processes. When a two-stroke engine only need one crankshaft revolution to complete a power cycle, the four-stroke engine need two.

Further, these engines can be split into low speed, medium speed and high-speed engines. Where the low speed typically is a two-stroke engine, medium speed typically a four-stroke engine and the high speed are normally also a four-stroke engine.

Speed type:	**Stroke:**	**RPM/minute:**
High speed	**Four-stroke engine**	**1000 or more**
Medium speed	**Four-stroke engine**	**200 - 1000**
Low speed	**Two-stroke engine**	**200 or less**

Table 7: Types of diesel engines (Andersen 2012).

Where low speed two-stroke engines are the dominating engine type on larger vessels such as tankers, bulk carriers and container ships. Medium speed engines are primary used for propulsion of smaller ships, but they also are found to be on larger ships such as cruise ships. Medium speed engines has an advantage compared with the low speed, the weight-to-power ratio is lower (Andersen 2012).

Generally, NO_x-emissions will be lower for a four-stroke engine compared to a two-stroke engine. Thereby, four-stroke engines will be able to meet the IMOs NO_x regulatory more easily (Andersen 2012).

3.4 Exhaust abatement technologies

Annex VI of the MARPOL Convention allows the after-treatment of exhaust gases as an alternative to low sulphur fuel. In the shipping industry there is very little experience of removing sulphur from exhaust gas on equipment installed in ships compared to energy plants on land. An option is to clean the sulphur from ship exhaust. The principle of a sulphur scrubber is to pass the exhaust gas through seawater; the seawater absorbs the sulphur compounds (and any other impurities, e.g. PM). The sulphur will then be conducted into the sea along with the wash water. By using this method, the effectiveness relies on the "quality" of the seawater, if the water is low in salt, as in the Baltic Sea, a lot more sea water has to be used compared with water that is high on salt like the big oceans.

In addition, if the sulphur scrubber wash water is un-cleaned, it might pose an environmental risk. Also, the wash water will have an adverse impact on the environment especially if the use of scrubbers becomes common, it will have huge impacts on ports and harbors. Therefor, the IMO has conducted some specified criteria's for the quality of the wash water falling into the sea.

There are several possible measures to reduce SO_x emissions, e.g. Scrubbers and fuel switching to low sulphur fuels and number of others options. Since HFO could not be used in ECA without the use of exhaust gas abatement techniques, this thesis consider that a scrubber is installed for the diesel engine.

3.5 Methods used in past studies

3.5.1 LCA

The last couple of years, there have been many publications on the environmental impact of shipping that highlights the big concern of the marine environmental challenges. While the researcher varies their goal and scope of the research, the overall main focus has been on estimating the emission factors (CO_2, SO_x and NO_x) related to consumption of conventional marine fuel.

For methodological framework, many of the previously researchers have used life cycle assessment for estimating and assessing the environmental impacts, e.g. global warming potential. Such LCA can be divided into two main concepts, attributional and consequentional LCA. While attributional LCA includes the full life cycle of a system or product, consequential LCA includes only the processes of the system that will differ between the alternative systems. Different system in this thesis will be the alternative fuels. And different approaches for LCA will be further described in section 4.

Bengtsson, Andersson, and Fridell (2011), Bengtsson, Fridell, and Andersson (2012), Verbeek et al. (2011), are some of the researchers that have used consequential LCA to analyze environmental impact of marine fuels by well-to-propeller method. Such studies examine the environmental impact potential of the different fuel choice across the extraction process, production process, refining process, product and bulk storage, distribution and the consumption of the fuel, and it often excludes the contraction and demolition processes. The result form a WTP study is often presented as a breakdown of the environmental impacts connected to the processes along the whole fuel pathway, from the extraction to the fuel tank and to the operational phase (Chryssiakis and Stahl 2012). This breakdown has some limitations; it does not show how the specific processes through the life cycle influence the results, it only show differences between impacts from consumption phase and production phase impacts, which limits the learning outcome.

Most of the earlier environmental assessment and LCA studies of marine fuels have focused on HFO and LNG. In addition, some of the studies have also included assessment on biofuels, methanol and electricity; since this thesis focus is on if LNG can be a favorable fuel compared to HFO, the findings from this studies will not be included in this section.

Due to the recent focus on GHG emission from maritime shipping activities, and the more tighten restriction and upcoming regulations from IMO on both air and GHGs, WTP studies are relatively new (Bengtsson, Andersson, and Fridell 2011).

4.0 Methodology

In this chapter the LCA will be presented as a tool for assessing the environmental impact. The first section will briefly describe the framework for LCA, as well as different methodology for LCA and the methodology used in this thesis. Section 5.2-5.3 will go more depth into the specific research design for this thesis.

4.1 Different approaches for LCA (LCI)

There exist several different articles and books that describe the LCA methodology; also, the development of the LCA has been substantial. There is no one and only method for a LCA, the different methods differs in scope, certainty and labor intensity etc. Which indicate that they also could provide different results. Therefor, it will be important in this thesis to highlight the limitations and challenges of the chosen method. First, a presentation of the main methods will be presented, and in the next section the limitations and challenges for this particular research will be discussed.

As mention previously (section 5.1) the framework of LCA consist of four different stages; Goal and scope definition, inventory analysis, impact assessment and interpretation. Rebitzer et al. (2004) mention in their article that the focus should be on the inventory analysis, since this stage is typically the most cost and time consuming stage, with possibilities of savings. Assessing the environmental burdens of a product, process or a service can be a daunting task; there have been developed different approaches to LCA. Rebitzer et al. (2004) present three different strategies for the simplification of the inventory analysis. These strategies will depend on the goal and scope of the research, the required level of detail, the acceptable level of uncertainty and the available resources, which are time, human resource, know-how and budget to mention some (Rebitzer et al. 2004). The three different approaches are presented below, starting with the process-based LCA, thereby the input-output LCA and then the hybrid approach to LCA.

Process-based LCA (simplification): A process-based LCA is when the inputs (e.g. Energy resource) and the outputs (e.g. emissions to the environment) are itemized for a given step in the supply chain. This means that all the economic flows, as described in section 5.1, is expressed in form of energy (or material) use (Rebitzer et al. 2004). By applying such cut-offs (excluding processes of the system from the LCI), the success rate will depend on wheatear you cut the processes horizontal or vertical in the flow chart (section 5.1) (Hunt et al. 1998). Hunt et al. (1998) concluded that cutting processes vertical, where data are collected for all relevant stages but in lesser detail, is generally preferable to eliminating processes at any given step. However, the area of simplifying is still in its early ages so there are no general methods that are better and recommended than others. But there consist a specter of specific simplifying methods for specific applications based on previously experience and detailed LCAs. There is also very important to mention that the simplification procedure is a non-linear step-by-step process.

Economic Input-output LCA: This approach has a wider scope compared to the process-based approach. This approach takes the product system, which consist of supply chains, and modeling it by using economic flow databases, which is conducted by statistical agencies of national governments (Hunt et al. 1998, Rebitzer et al. 2004, Hall, Cutler, and Kaufmann 1992). The amount each sector spends on their goods or services produced by other sectors are described financially. To obtain the environmental impact generated, you need to sum up the amount of pollutants emitted or natural resources consumed to produce one unit monetary output of each sector (Rebitzer et al. 2004).

The input-output LCA approach has, along with the process-based approach, some strengths and weakness. Since the input-output LCA consist of a broader system (broader range of sectors involved), it provides greater comprehensiveness. This approach is neither not mathematically different from process-based LCA, but instead they are different in type of data sources, commodity flow units, level of process/commodity detail and the covered life cycle stage. The results from an input-output LCA could be used either for screening purposes or to roughly estimate the overall environmental impacts of services on a regional, national or international level (Rebitzer et al. 2004, Øberg 2013). Considering input-output LCA for this particular research, based on the aim and objectives, the input-output analysis will not hold. There will be a problem of differentiate the potential environmental impact of the different fuel characteristics.

Hybrid LCA: This approach is a combination of the process-based and input-output approach. By combining these two, the analytical benefits can increase and the limitations can be reduced (Suh and Huppes 2002). There are various forms of hybrid LCAs, and some of them are tired hybrid analysis, input-output based hybrid analysis and integrated hybrid analysis (Suh and Huppes 2002). These three different versions of hybrid LCA will be described in short in the following:

Tiered hybrid LCA: Distinguish between the two main systems (process-based and input-output based), and use the results from both of them together. Its done by adding input-output based results that cover far upstream processes to process-based analysis results that cover the near upstream processes (Rebitzer et al. 2004). When setting limits for the system, it must be done with extreme caution to avoid double counting.

Input-output hybrid LCA: aims to selectively disaggregate the aggregated input-output data or create hypothetical new sectors to reduce the uncertainty of economic input-output analysis.

A LCA can be divided into attributional and consequential LCA. In a consequential LCA, the system boundaries are typically defined to include the activities contributing to the environmental consequence of change, regardless if these changes are within or outside the system (Eco-Efficiency 2010). While an attributional LCA is a approach in which inputs and outputs are attributed to the functional unit of the system by linking the unit processes of the system according to a normative rule (Eco-Efficiency 2010).

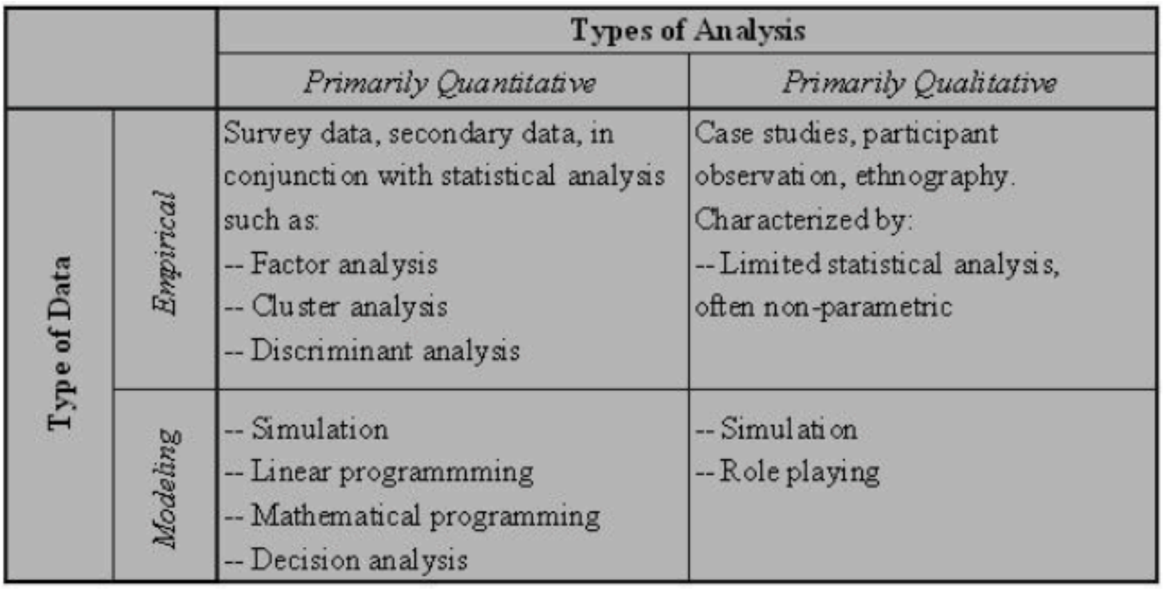
Considering the main goal of this thesis, a consequential process based LCA will be performed, as already stated under section 4.1. The advantages of using a consequential process based analysis is that it include only the processes of the system (fuels) that will differ between the alternative systems (fuels), and is therefor less time consuming and it making it better suited for the comparison of the environmental performance of the marine fuels.

4.2 Case study as research method

A case study could be viewed as a methodology, a type of design in qualitative research, an object of study, or a product of the inquiry (Creswell 2007). It's clear that a case study is most likely a qualitative approach, where the investigator explores a case or multiple cases over time. Yin (1994) mentions an extensively used research method in his book, exploratory case study. This type of case study is used to explore those situations in which the intervention being evaluated has no clear, single set of outcomes (Yin 1994). This thesis explores trade-off between conventional HFO operation vs. new ship with LNG operation, looking upon the environmental assessment of the two different fuels to decide which will be best suitable for the regulations now and in the future.

4.3 Research design

By research design Creswell (2007) refer to the entire process of research from conceptualizing a problem to writing research questions, collect data material, analysis, interpretation and writing the report. The research design is a logical process, that connects the data collected to the research problem and to the final conclusion (Yin 1994). As mention, a case study could be divided into one single case study or multiple cases over time. In this thesis, a single case study is preferred. According to Ellram (1996), research methodologies could be classified into the type of data used and the type of analysis performed. The data can be further divided into two types, empirical- and modeling data (see Figure 1). Where empirical data is in most cases collected from surveys and/or case studies from the real world, and the modeled data is intended for some kind of manipulation in a model, and can be gathered either from the real world or from hypothetical data.



		Types of Analysis	
		Primarily Quantitative	*Primarily Qualitative*
Type of Data	*Empirical*	Survey data, secondary data, in conjunction with statistical analysis such as: -- Factor analysis -- Cluster analysis -- Discriminant analysis	Case studies, participant observation, ethnography. Characterized by: -- Limited statistical analysis, often non-parametric
	Modeling	-- Simulation -- Linear programmming -- Mathematical programming -- Decision analysis	-- Simulation -- Role playing

Figure 11: Basic Research Design (Ellram 1996).

Figure above present the types of data and the types of analysis, which is further divided into empirical- and modeling data, and primarily quantitative- and primarily qualitative analysis. While primarily qualitative analysis focuses most on theory rather than mathematical methods, which the quantitative analysis does. Since this thesis will focus on comparison of different fuel for propulsion with respect to the cost of investing in new technology and the environmental effect of changing fuel for propulsion, the research design preferred is a mix of quantitative analysis and qualitative analysis, put together with an empirical type of data. Since this thesis is a case study, most of it will consist of a qualitative analysis. But case studies can also gather quantitative data (Ellram 1996). The quantitative data analysis in this thesis will therefor be used for the mathematical part of this thesis, when calculating the costs and environmental effect.

4.3.1 Primary and secondary data

In general, primary data is data collected specific to answer the problem. The primary data for this thesis must be able to answer the current state of LNG as a fuel for ships. For this thesis the primary qualitative data has been collected through personal informal interviews by telephone and emails with the shipping company. The interviews has been addressed to the project engineer at the shipping company in order to obtain the most valid opinions and information on technical aspects with LNG as a fuel for ship.

To fully answer the problem in this thesis, there is also a need for secondary data. In Saunders, Lewis, and Thornhill (2009) book, secondary data is described as data include in both quantitative and qualitative data. Secondary data could be raw data or complied data (Saunders, Lewis, and Thornhill 2009). There are several types of secondary data; the three most common is documentary, multiple source and survey. The secondary data in this research will be most documentary data and multiple source data, since I will gather some raw- and compiled data from Awilco AS and also from other companies and earlier research to use for answer my objectives. I will also gather information from the company's website, which all is documentary type of data. In this research, the need for multiple source data will occur when to answer the objectives related to the environment and the regulations. Here I will need government publications and industry statistics and reports. The main advantage behind the use of secondary data is the time advantage.

5.0 Data description and assumptions for the analysis

In this section, the description of the selected life cycle phases for the different fuels will be presented. The data used for extraction and production/refining of HFO will be data collected from secondary sources mainly from European Commission Join Research Center on LCA, which also could be called the European reference Life Cycle Database 3.0 (ELCD 2003). This data set is from 2003 and is set valid until 2012, but due to lack of more up to date dataset, this was chosen because it contains the main data needed for the three phases mention above. It will be important to mention that the transportation from refinery to harbor and backwards will not be included in this analysis. Also the seismic process is not included due to allocation problems.

As stated earlier in this thesis, the main focus in this analysis will be on the combustion phase of each fuel, and the data for this is provided directly from Awilco, both LNG and HFO. The general information on HFO and LNG is based on official statistical information and the data on emissions from the refinery is mainly based on information from previously literature, research and from the European Pollutant Emission Register.

The data used for the LNG extraction and production transmission is based on the database from the Center of Environmental Assessment of Product and Material system(CPM 1991) and the data from Edwards, Larivé, and Beziat (2011) report. This data is representative for a European context, but since there was lack on specific data cover more worldwide this data will be used. Both for the HFO and LNG data that has been collected for this thesis is from a cradle to gate perspective.

Regarding the transmission phase (see figure 2), there was not much information to find. For this phase, this thesis has are used some already calculated factors from previously research to complete the life cycle assessment, see section 5.3. The CO_2-equivalents for each life cycle phases is presented in the Appendix A- D.

5.1 Extraction of LNG and HFO

The extraction of LNG and HFO and the transportation to onshore will be discussed in more depth in this chapter.

The processes of explore and extract LNG and HFO is almost the same for both of the fuels, and in some cases they can be found together. On the other hand, oil and gas have some significant differences when it comes to the handling (transportation e.g.) and their characteristics. When it comes to the transportation of gas, it has some difficulties compared to transportation of oil, but the extraction of gas is then again much easier than extraction of oil, because it often requires gas re-injection to increase the pressure in the reservoir to drag out as much oil as possible from the ocean floor.

The stages before one can confirm or disprove that there are hydrocarbons under the ocean floor is not included in this thesis, mainly because there are no exact data on how many wells that needs to be drilled, and the fact that this thesis do not focus on these stages. In addition, it’s the stages after there has been confirmed hydrocarbons under the seabed and is ready to be extracted that will of importance for this thesis.

5.2 Production/refining

After there has been confirmed hydrocarbons under seabed starts the process of get this hydrocarbons to reach the surface. Where the gas is driven by its own pressure and flows by its own, it is different for the oil. In some cases, it often needs an additional treatment to get it up to the platform.

In the following section the processes of production and refining of gas into LNG and crude oil into HFO will be described.

5.2.1 HFO

After there has been confirmed hydrocarbons under seabed starts the process of get this hydrocarbons to reach the surface. When it comes to the oil, in some cases, it often needs an additional treatment to get it up to the platform. Basically, hydrocarbons are a chain of carbon and hydrogen atoms. An example is that diesel fuel consist on approximately 16 carbons atoms while the gasoline fuel consist of about half as many.

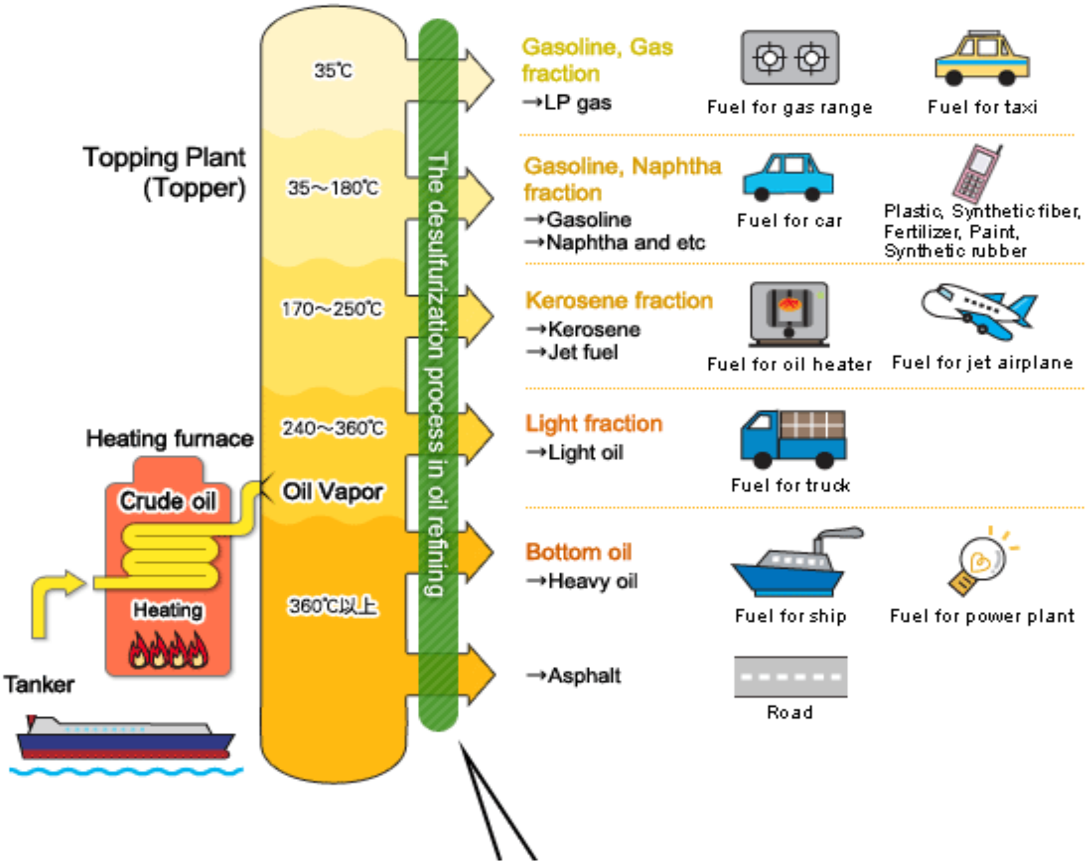
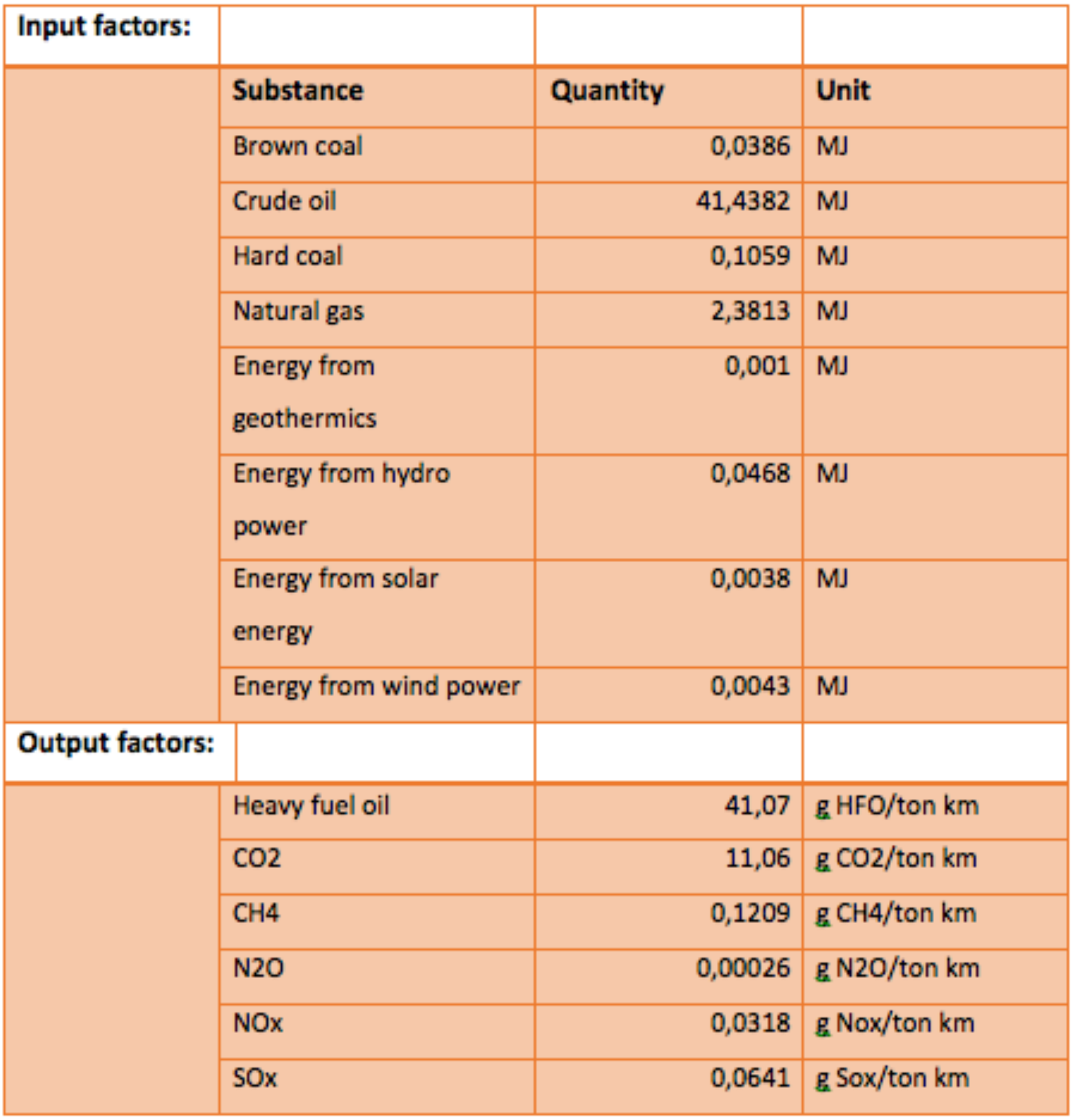


Figure 12: Distillation of crude oil overview.

The refining process starts with cleaning or desalting the crude oil, and then heating it until there are only the residual hydrocarbons that remain in liquid form. The procedure for this process is called “separation”. Where molecules are separated at normal atmospheric pressure, and leave some heavy residuals with many products that contain medium density(Energies 2015). The heavy residuals need to be transferred to another column where they go through another distillation to recover middle distillates like HFO and diesel(Energies 2015).

For the extraction of HFO, this thesis uses a LCI dataset from ELCD (see more in section 5.0), which include some input factors and output factors. These factors are represented in the table below.



Input factors:			
	Substance	**Quantity**	**Unit**
	Brown coal	0,0386	MJ
	Crude oil	41,4382	MJ
	Hard coal	0,1059	MJ
	Natural gas	2,3813	MJ
	Energy from geothermics	0,001	MJ
	Energy from hydro power	0,0468	MJ
	Energy from solar energy	0,0038	MJ
	Energy from wind power	0,0043	MJ
Output factors:			
	Heavy fuel oil	41,07	g HFO/ton km
	CO2	11,06	g CO2/ton km
	CH4	0,1209	g CH4/ton km
	N2O	0,00026	g N2O/ton km
	NOx	0,0318	g Nox/ton km
	SOx	0,0641	g Sox/ton km

Table 8: Data for extraction of crude oil (ELCD 2003)

From the input factors one can see the amount of substance that is that is put in to extract 1 kg HFO, and the pollutants that comes from extracting is presented in the output factor section. The transportation of the HFO to the harbor is assumed to be by pipeline. Transportation from harbor to refinery and back is not included in this dataset. Also the production of vessels used to do seismic surveys is not included due to allocation issues.

5.2.2 LNG

Based on the lack of information from Awilco of where their gas origins from, this thesis use the Snøhvit field as a gas field supply (see section 8.1). The Snøhvit field is located northwest of Hammerfest, Norway. The gas is extracted from the ocean floor about 250-350 meter below the surface, and then transported to land for further liquefaction by a 143 km pipeline (Statoil 2015). The installation is an underwater installation which is designed to be overtrawlable so that neither the installation it self or fishing equipment will damage by meeting.

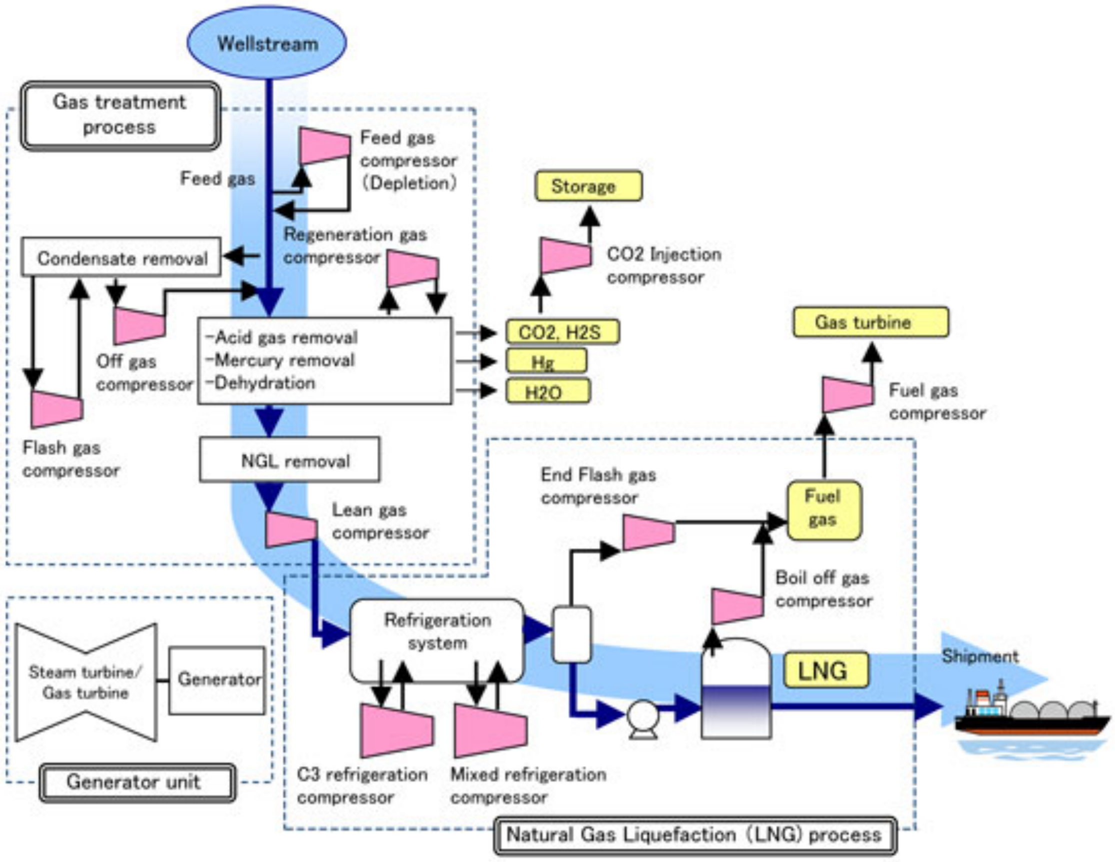
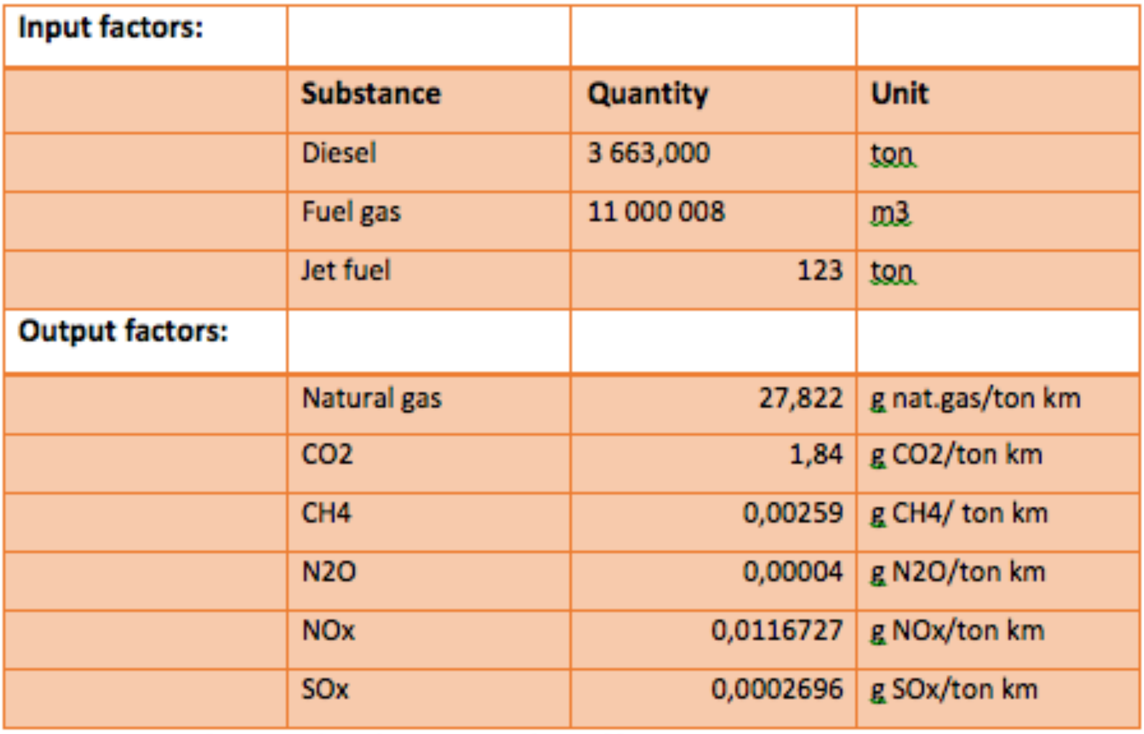


Figure 13: Simplified LNG production process (MHICOMPRESSOR).

The data used for extraction of LNG is based on a LCI dataset from CPM, and include input factors and output factors. This data is presented in table 9. The functional unit of the data set is one mega ton natural gas. This dataset covers the extraction and transportation phase of natural gas in Norway



Input factors:			
	Substance	**Quantity**	**Unit**
	Diesel	3 663,000	ton
	Fuel gas	11 000 008	m3
	Jet fuel	123	ton
Output factors:			
	Natural gas	27,822	g nat.gas/ton km
	CO2	1,84	g CO2/ton km
	CH4	0,00259	g CH4/ ton km
	N2O	0,00004	g N2O/ton km
	NOx	0,0116727	g NOx/ton km
	SOx	0,0002696	g SOx/ton km

Table 9: Dataset for extraction of natural gas (CPM 1991).

In a liquefaction plant, like Snøhvit, there are two main processes when producing the gas. The first one is pretreatment to remove acid gases and to reduce the CO_2 levels to prevent freezing. After this stage, the gas continues to the next process, which is the liquefaction. Here the gas will be cooled down to a temperature approximately around -30 degrees, and then continues to go through the cycle until the gas finally reaches the liquefaction temperature of around -160 to -165 degrees. Then the LNG will be stored in tanks to await transportation. Since there are huge differences in the temperature between the tank of stored LNG and the surroundings, there will occur some boil-off gas. These gases is normally compressed and sent back to the plant fuel system. The total liquefaction process is shown in figure 14.

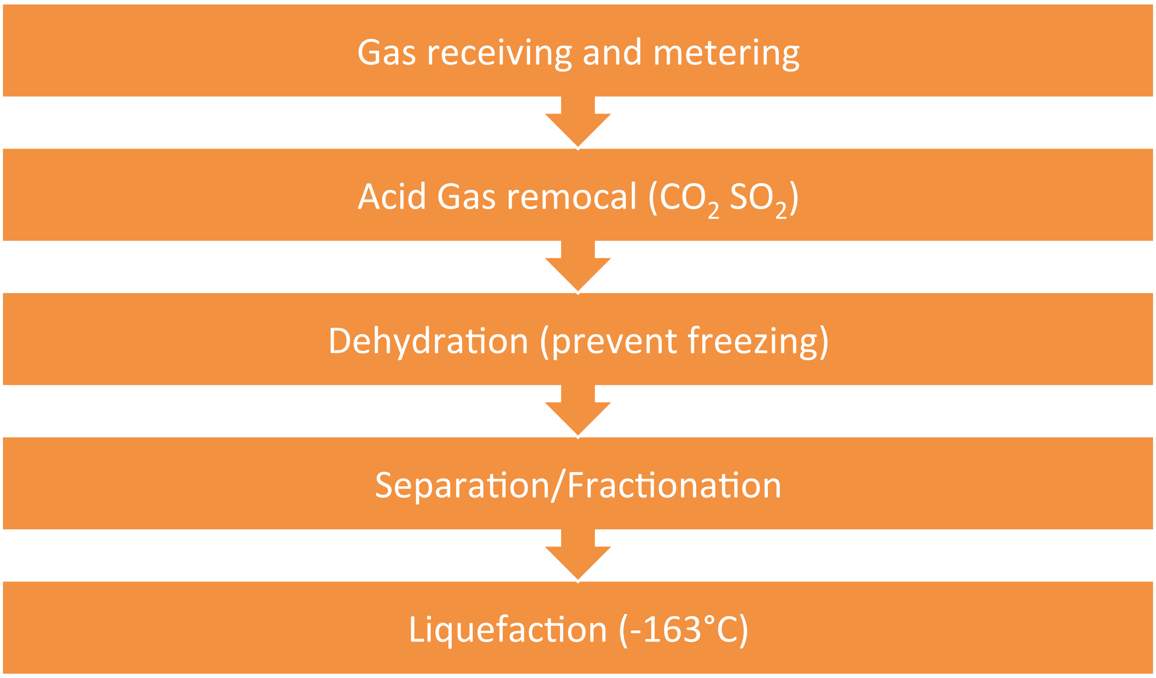
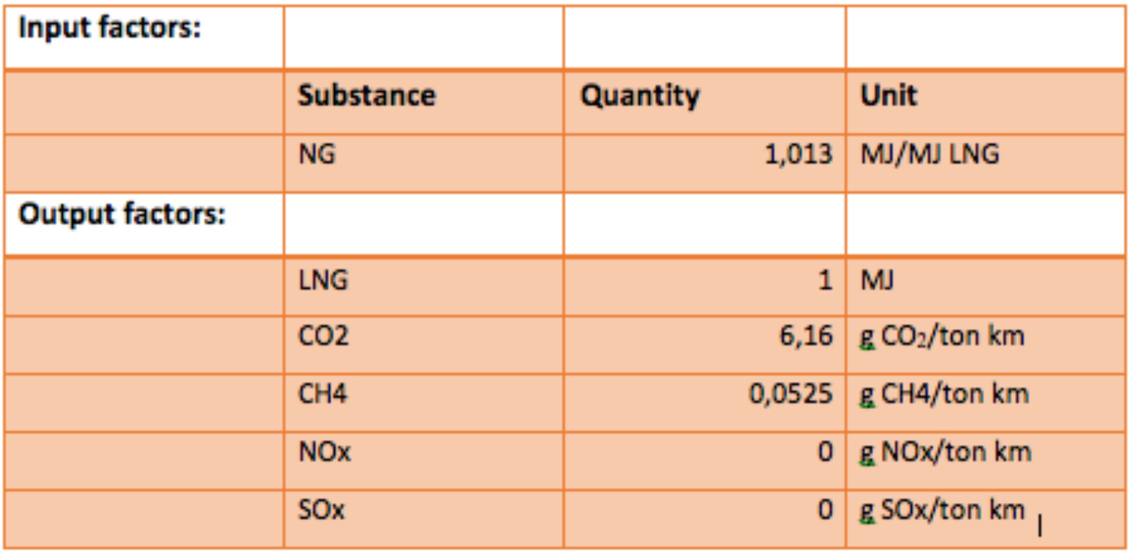


Figure 14: Liquefaction process of LNG.

For the liquefaction process, data were collected from Edwards, Larivé, and Beziat (2011) Well-to-wheels report. The data is chosen since it is representative for a European context, and that there were no available data for the Melkøya plant. The data contains information on CO_2, CH_4 and N_2O, which is the three main GWP gases, and will be useful for the analysis. In table 10 an overview of the input and output factors of liquefaction process are represented.



Input factors:			
	Substance	**Quantity**	**Unit**
	NG	1,013	MJ/MJ LNG
Output factors:			
	LNG	1	MJ
	CO2	6,16	g CO_2/ton km
	CH4	0,0525	g CH4/ton km
	NOx	0	g NOx/ton km
	SOx	0	g SOx/ton km

Table 10: Data set for LNG liquefaction (Edwards, Larivé, and Beziat 2011).

5.3 Transmission of LNG and HFO

The dataset used for HFO- and LNG shipping is provided from Laugen (2013) thesis on LCA of different fuels for marine propulsion. There wasn´t possible this type of data from Awilco, and the fact that there is little specific information on this in public, this data was chosen.

The data consider shipping of LNG from Snøhvit field to Rotterdam and HFO from the North Sea to Rotterdam. Since this thesis already has assumed that the LNG for propulsion of the VLCC origin from Snøhvit field and the HFO used as fuel for the VLCC is extracted from North Sea, this data will give an overall good picture of the transmission phase for the results and discussion part of the thesis.

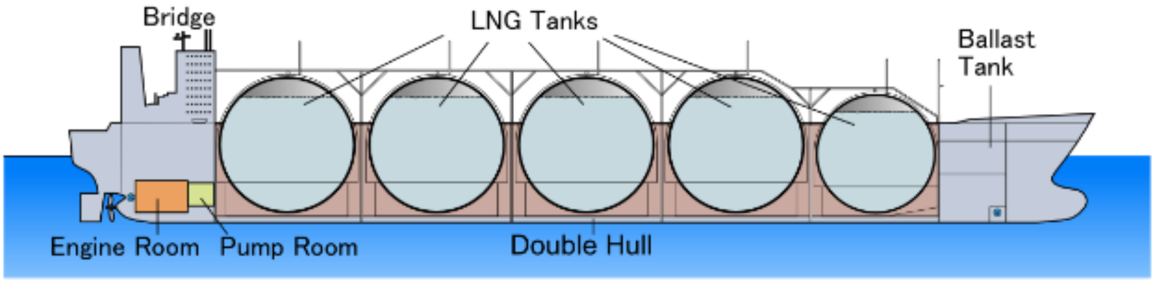


Figure 15: Example of the construction of a LNG-carrier (Shippipedia).

The size of a LNG-carrier could range from small carriers of about 10 000m^3 up to 150 000 m^3 and larger LNG-carriers with ship range up to 230 000m^3. The data on transportation in this thesis will consider a 145 000m^3 LNG-carrier. Due to the applied technology of cargo transport, LNG-carriers belong to a group of ships that is highly specialized (Bortnowska 2010). When transporting LNG there are two main issues that has to be prioritized, ensure cargo cooling and avoid cargo evaporation to the outside atmosphere (boil-off). The amount of boil-off gas will depend on the insulation of the tanks from the environment, with a daily average of 0.15-0.2% boil-off of the gas cargo weight (Bortnowska 2010).

The LNG tanker market consists of four-containment system, but the main types used are the self-supportive Moss-type spherical aluminum tanks and the membrane-type tank. The trend shows that membrane-type compared to Moss-type is preferable; this is most likely because membrane tanks utilize the hull shape more efficiently and has less void space between cargo-tanks and ballast tanks (Moon, Chang, and Lee 2005).

The type of LNG-carrier used in this thesis is a Moss-type and for the transport of HFO there is used a ship with capacity of 12 oil tanks. The modeled vessel for transportation of HFO is the oil tanker King Edward, and are trading in UK, North Sea and the Baltic (Laugen 2013). For more specification on the two different vessels for LNG and HFO transportation see table 11 and 12 below.

LNG storage	Moss-type
Size (m^3)	145 000
Engine capacity (kW)	27 600
Speed (kt)	19,5
Specific fuel consumption (g/kWh)	218
Load factor (%)	75.5

Table 11: Characteristics of the LNG-carrier (Laugen 2013).

Deadweight ton (dwt)	37 384
Engine capacity (kW)	9 466
Speed (kt)	14,5
Specific fuel consumption (g/kWh)	250
Load factor (%)	99

Table 12: Characteristics of the vessel shipping HFO (Laugen 2013).

Further emission data for the transportation scenario of LNG and HFO can be found in appendix D.

5.4 Combustion/use of LNG and HFO

In the last stage of the life cycle, the different fuels will be used on a VLCC to see which one fits the regulatory in a best possible way. The marine fuels will be used onboard a VLCC vessel with two different engine configurations. For LNG propulsion, due to information from Awilco, a dual-fuel engine from MAN, and for HFO a four-stroke diesel engine will be used for the further calculations. There is also assumed that the vessel sails at normal weather conditions and service speed.

The cargo capacity on the vessel will be different between the two fuels, since LNG propulsion systems require more space, the cargo capacity will be lower on a LNG operated vessel than for a vessel with HFO fuel system. Awilco has estimated that a vessel with LNG fuel system will require as much as 2 to 3 times more space than for a HFO fuel system. In the table below an overview of the two different fuels used on a VLCC vessel is presented with the assumption for the further calculations.

Vessel details	VLCC with LNG	VLCC with HFO
Max. Deadweight (ton)	200000	200000
Engine capacity (kW)	28 600	28 600
Length (m)	300	300
Service speed (kt)	15	15
Average amount of load (dwt)	145800	154350
Pay Load	68 %	73 %
Specific fuel consumption (g/kWh)	160,5	192
Transport efficiency (kWh/ton km)	0,223	0,213

Table 13: Vessel details, LNG vs. HFO VLCC.

The reference unit for energy consumption for transportation is calculated to be 0,223-kWh/ton km for the VLCC with LNG propulsion, and 0,213-kWh/ton km for the HFO operating VLCC. The engine used for the HFO propulsion is a medium speed four-stroke engine. Data provided by MAN engines showed that the SPF (g/kWh) for this engine with HFO was 192. The specific fuel consumption for LNG was calculated based on a lower heating value of 48.6 MJ/kg. These data where collected from the Biomass Energy Data Book (Book 2011). Due to lack of emission data from MAN engine manufacturer, this thesis uses Rolls Royce data on emissions, which shows that the CO_2 emissions is 420 g/kWh for a LNG engine and 600 g/kWh for a HFO engine (RollsRoyce 2011).

As mention previously, methane slip weight much more heavily than CO_2 emissions when it comes to the GWP. Methane slip does not occur in diesel cycle mode, but in Otto-cycle mode that represents the dual-fuel engine. World Ports Climate Initiative has concluded that the methane emissions from a dual-fuel engine are 4-8 g CH_4/kWh (WPCI 2013). In MARINTEKs report *Emission factors for CH_4, NO_x, particulates and black carbon for domestic shipping in Norway* they presents for gas burn engine a emission factor of 3.9 g CH_4/kWh (Nielsen and Stenersen 2010). In this thesis 4 g CH_4/kWh is used as the emission factor based on the report from MARINTEK and the WPCI emission factor.

6.0 Analysis and results

In this section the analysis and results from the study will be presented with respect to the chosen impact categories for this study. The results will be presented in two stages, well-to-tank and tank-to-propeller. Reason is that it will help to indicate what can be achieved by using LNG, and the direct emissions from the different fuels, and what may be missed by not considering the whole life cycle.

The four stages that will be analyzed in this thesis is as shown in figure 2; Extraction and transportation onshore – Production phase – Transmission to harbor – Combustion phase. The formula used to convert all GHG emissions to CO_2-equvivalents is following:
$CO_2.eq = GHG \times GWP$[5]

6.1 Comparing the GWP for LNG and HFO

Stated in section 3.1.3, from a business point of view the combustion phase will be most important, and illustrated in figure 17 there is obviously that LNG has a lower GWP than HFO in the combustion phase, with GHG emissions of 88,23 g CO_2-eq/ton km compared to 98.76 g CO_2-eq/ton km. The total GHG emissions for LNG is 127.83 CO_2-eq./ton km, which is little less than the total GHG emissions from the HFO of 129,52 g CO_2-eq/ton km. In all stages, LNG seems to contribute less CO_2-eq. than HFO, except for one phase, and that is the transmission of the fuels.

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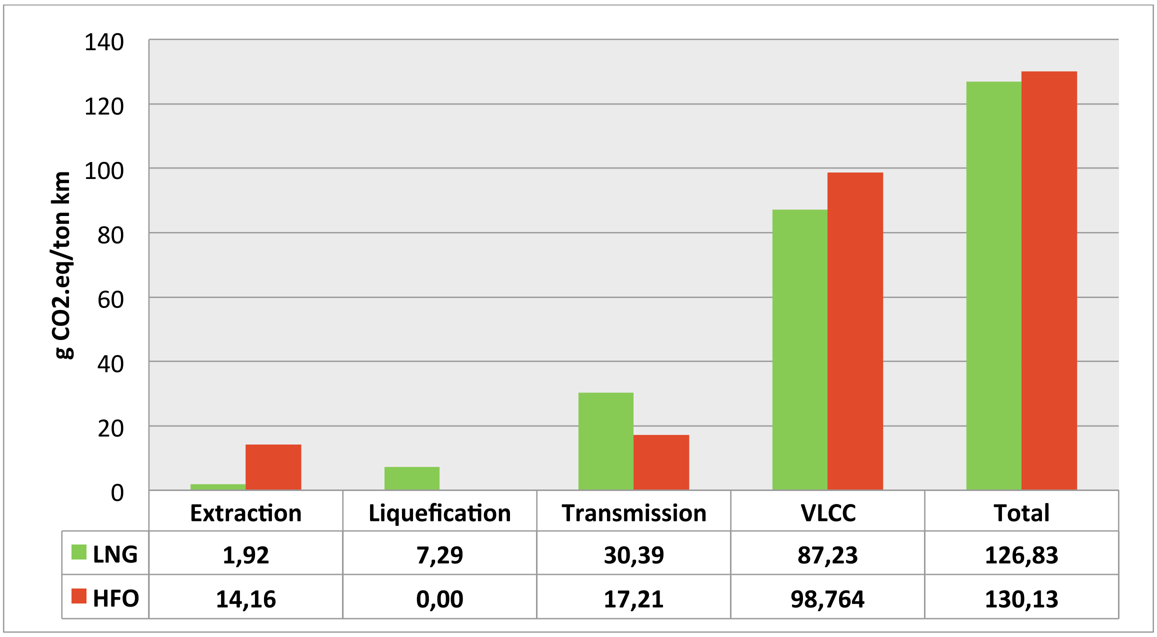
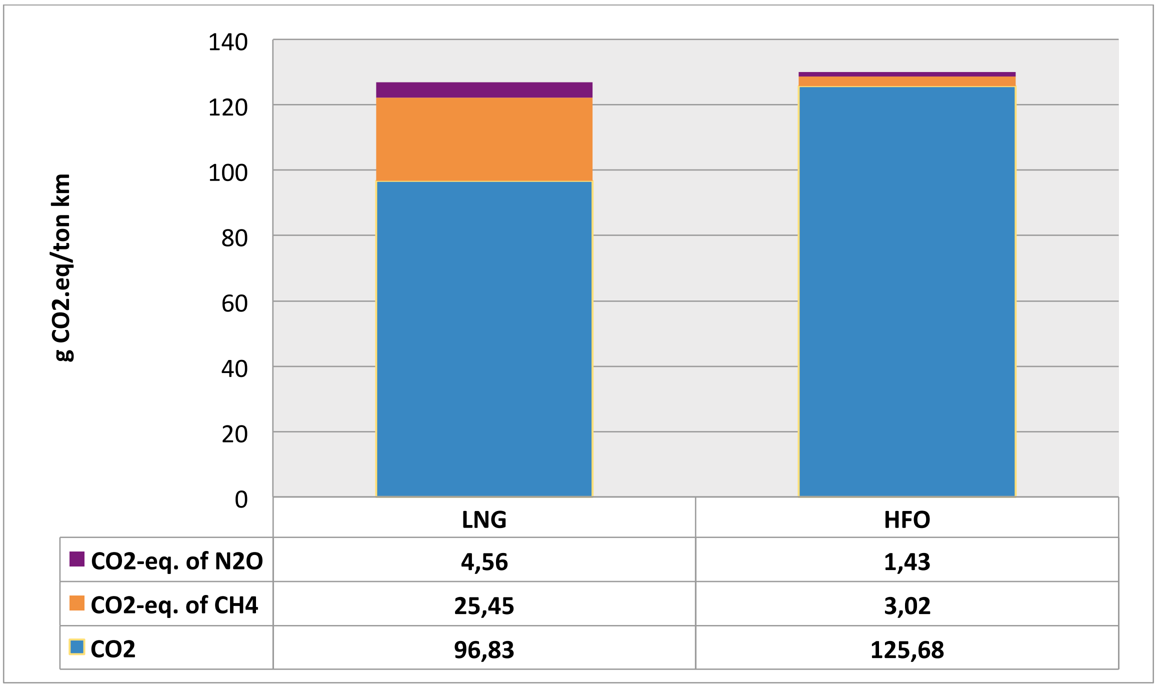
[5] Applies to all calculations of CO_2 equivalents.



	Extraction	Liquefication	Transmission	VLCC	Total
🟩 LNG	1,92	7,29	30,39	87,23	126,83
🟥 HFO	14,16	0,00	17,21	98,764	130,13

Figure 16: Total global warming potential for LNG and HFO. CO_2, CH_4 and N_2O emissions are represented in CO_2 -equivalents.

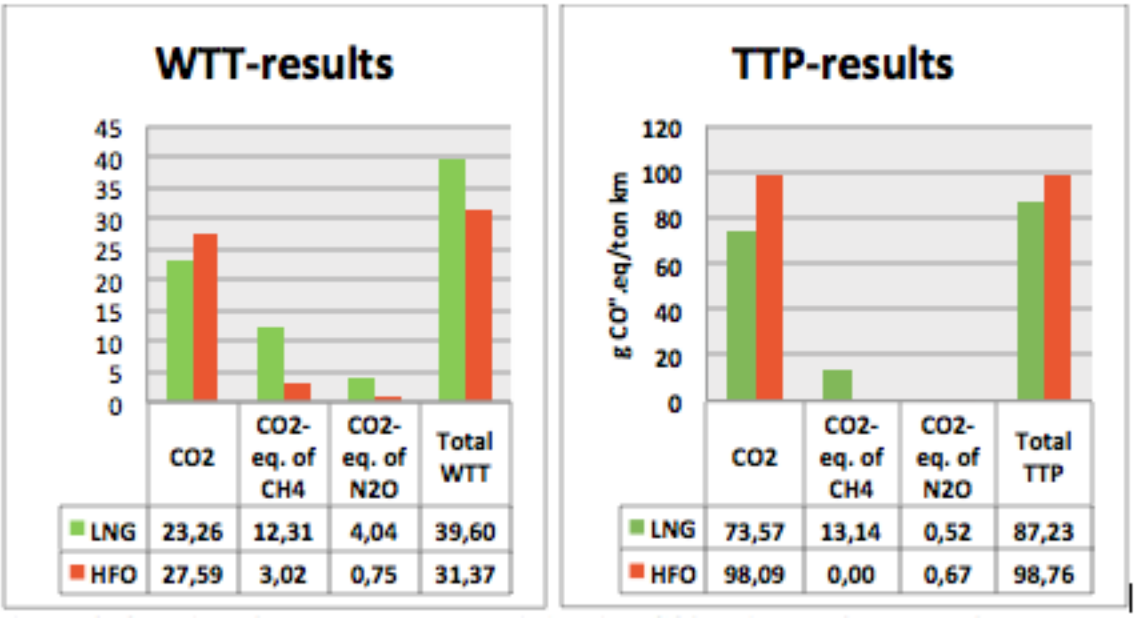
Figure 16 shows that in the transmission phase of the two different fuels, the transmission of LNG contributes almost twice as much GWP than in the transmission phase of HFO. It becomes clearly that the methane slip from the LNG transportation has a huge impact on the overall picture. From figure 18, it shows that the total methane slip from the LNG counts almost 75% more CO_2 equivalents than the methane slip from the HFO.



	LNG	HFO
🟪 CO2-eq. of N2O	4,56	1,43
🟧 CO2-eq. of CH4	25,45	3,02
🟦 CO2	96,83	125,68

Figure 17: GWP for LNG and HFO spitted into N_2O, CH_4 and CO_2.

From the figure 17 one can also see that the CO_2 is the largest contributor to global warming for both LNG and HFO. The consumption, for both of the fuels, contribute most to the GWP for almost all of the greenhouse gases except for N_2O-emissions that emits more in the transportation phase of both LNG and HFO. In figure 19 this is illustrated where the pathway for LNG and HFO are divided in WTT and TTP. In addition one can see that the greatest emissions of GHG is in the combustion phase for both of the fuels, where LNG emits less than HFO. There is also important to notice that in the fuel pathway for LNG and HFO (see figure 19), LNG seems to emit more than HFO. The explanation for this is due to higher emissions from the methane slip during the transportation of the LNG, which is explained above.



	CO2	CO2-eq. of CH4	CO2-eq. of N2O	Total WTT
🟩 LNG	23,26	12,31	4,04	39,60
🟥 HFO	27,59	3,02	0,75	31,37

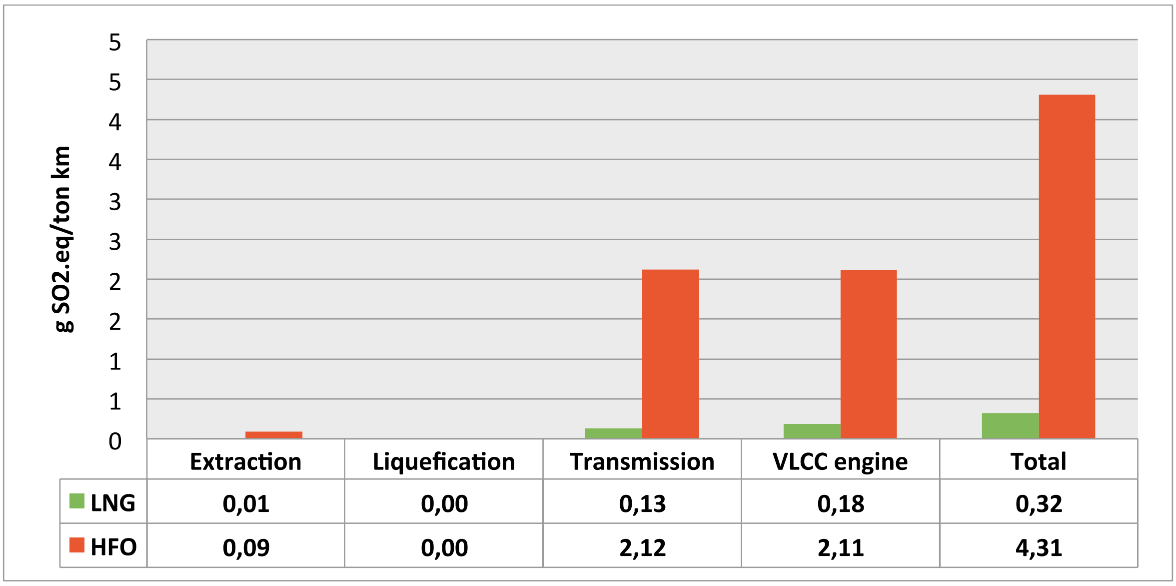
	CO2	CO2-eq. of CH4	CO2-eq. of N2O	Total TTP
🟩 LNG	73,57	13,14	0,52	87,23
🟥 HFO	98,09	0,00	0,67	98,76

Figure 18: Overview of the WTT and TTP emissions in g CO$_2$-eq./ton km for the two fuel pathways.

The methane emission for the total life cycle of LNG counts almost eight times higher than methane emissions in the total life cycle of the HFO. Approximately 20% of the total GHG emissions from LNG are represented by the methane emissions, and this contribution is mainly from the combustion phase of the VLCC and the transmissions phase, only a small amount of the recorded methane emissions originating from the extraction and liquefaction phases of the LNG. Methane slip is 25 times heavier GHG than CO$_2$ per ton, and this could cause that the gain LNG has on the reduction of CO$_2$ will be eaten up by the amount of methane slip from the combustion. According to this, the performance of the VLCC engine will play a major role in the overall performance of the LNG.

6.2 *Comparing the acidification potential for LNG and HFO*

In figure 19 the total acidification potential for LNG and HFO are represented in SO_2-equivalents of SO_x- and NO_x emissions in total.



	Extraction	Liquefication	Transmission	VLCC engine	Total
🟩 LNG	0,01	0,00	0,13	0,18	0,32
🟥 HFO	0,09	0,00	2,12	2,11	4,31

Figure 19: Total acidification emissions for LNG and HFO. The NO_x and SO_x emissions are represented in SO_2-equivalents.

From above one can see that the total acidification potential from LNG is almost 92.5% lower than the acidification potential from HFO. In addition, the combustion phase of LNG is the biggest emitter in the life cycle. For the HFO, there is the transmission phase that has the largest acidification potential in the HFO life cycle with a little higher emission rate than in the combustion phase, only 0,47% larger.

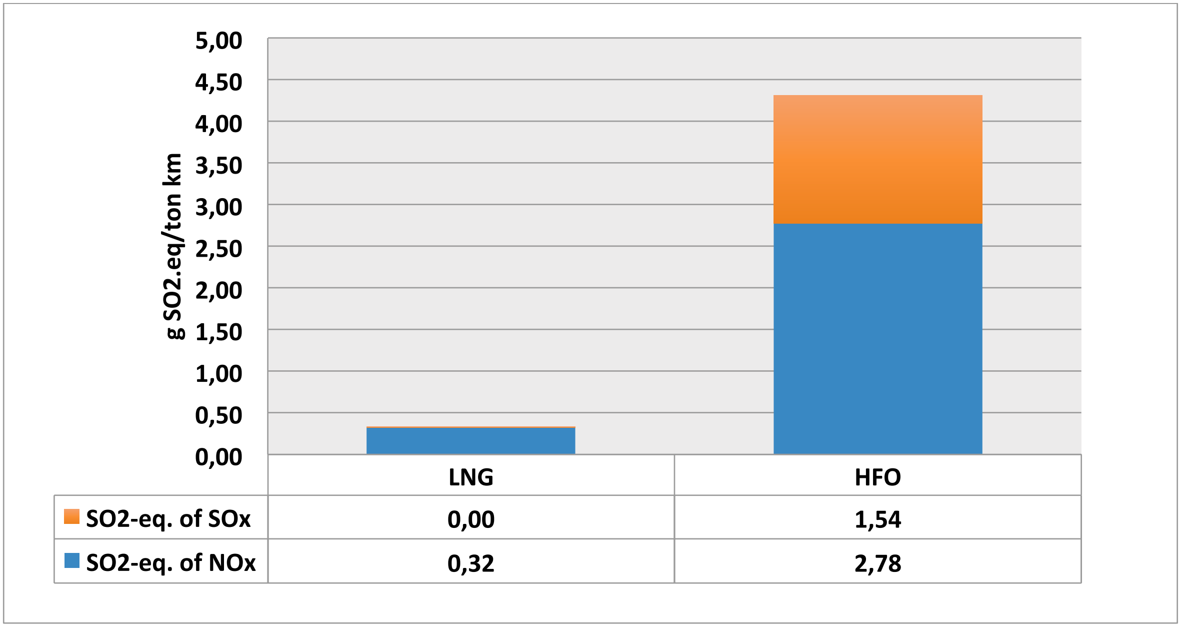


Figure 20: Acidification potential for LNG and HFO presented in SO_2- equivalents of SO_x- and NO_x emissions.

From figure 20, where SO_2 - equivalents is split into SO_x and NO_x, its clear that most of the acidification potential origins from the NO_x emissions for both of the fuels. HFO contains much more acidification potential than LNG; reason for this is that LNG contains zero sulphur content (see table 3 in section 3.1.3) compared to HFO, and has a minimal content of NO_x.

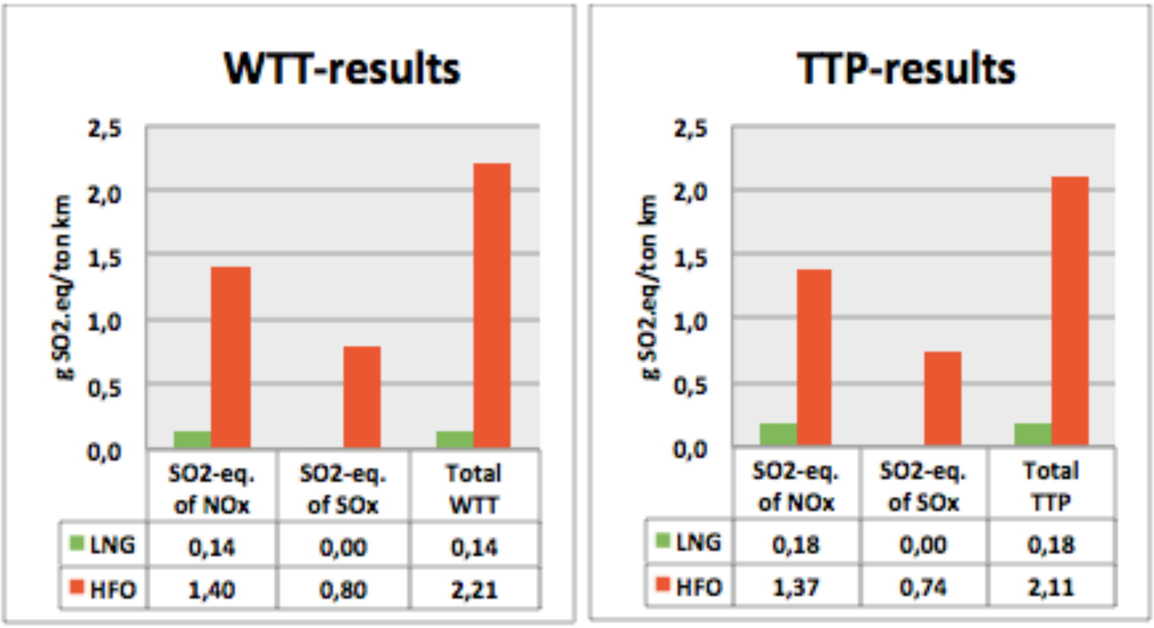


Figure 21: WTT and TTP emissions in g SO_2 equivalents/ ton km of NO_x and SO_x.

From figure 21 one can see that there is the combustion phase of LNG that contribute most of the NO_x emissions. Most of the NO_x emissions from the pathway of LNG, origins from the transportation of the fuel, when the fuel is used. When comparing the combustion phase of LNG and HFO, its found that one can reduce the NO_x emissions with approximately 87%, and 88.5% reduction when looking at the total fuel pathway. This matches the reductions-promises that are presented in section 3.1.3 and table 3 very well.

7.0 Discussion and conclusion

To meet the regulatory for air pollution, now and in the future, LNG as a marine fuel can have huge opportunities. However, its potential will depend on several parameters such as its supply chain, price, policy and market potential to mention a few. It’s clear that LNG main advantage is its ability to reduce air pollutants, especially the NO_x and SO_x.

In this chapter, both the methodology and data used for this thesis will be discussed. To do a comparison of different fuel alternatives there exists numbers of methods and critical choices to make that will all affect the end results of the LCA. In this thesis it is strived to collect the most relevant and newest information for all the chosen phases of the two fuel pathways. As mention previously, some of the processes are lacking in up to date information and therefore assumptions have been made based on the best available information. The extraction pattern of natural gas is very specific in this study, where the chosen supplier of natural gas was set to be at Melkøya plant. It’s a relatively new plant, and up to date data was not available, so in this thesis a dataset from 1991 was chosen. This is a rather old and outdated dataset, many things has changed in the last 25 years when it comes to extracting natural gas. For the geographical area and to use in this thesis, this dataset was believed relevant. The emissions of SO_x and NO_x from liquefaction of natural gas, was assumed to be zero. Some researchers, e.g. Edwards, Larivé, and Beziat (2011) argue that it may be some SO_x and NO_x in the raw gas that comes from the well, but the amount is likely so small, and that in this study is justified to set it equal to zero.

When it comes to the VLCC fueled with LNG, it was assumed, on the basis of information given by Awilco, that this should be equipped with a dual-fuel engine from MAN. Another option could have been to model this VLCC with a spark-ignited engine, but then again it wouldn't have been that versatile. Since a dual-fuel could run on either gas or diesel, which makes that the investment is not as drastic and unilateral, considering the possibility to switch from gas to diesel.

Dual fuel engines can be seen as the lightest step for the ship owners when considering an introduction of gas propulsion for the vessel. On the other hand, a dual fuel engine compared to a spark-ignited engine has a much higher rate of methane slip. When it comes to environmental friendliness for LNG as a fuel, methane slip can be a game changer. Considering the whole supply chain, there will be slip that are difficult to measure and quantify in every stages, and there is no different when it comes to the engine. When engine manufactures have been focusing on reduction of SO_x and NO_x emissions, the methane emissions didn't get that much attention. But there seems to be a change, newer engines have less methane slip than the earliest gas engines. By choosing the newest, which is believed Awilco going to do if they choose to invest, LNG as fuel could be very favorable.

The functional unit for this thesis was transporting one ton cargo one km with a VLCC. All operations related to the operation of the vessel are not included in this study, e.g. maneuvering, reduction of speed and bunkering to mention a few. The reason was the lack of information on these patterns. However, there is no reason to believe that this will have a huge impact on the overall GHG emissions and that the differences in LNG and HFO will not be affected. Another issue is that the production of LNG tanks, ports and other infrastructural items are not included. This should have been included in the LCA to get the total picture of the whole idea of investing in a new vessel. It could have had huge impacts in differentiate the two fuel options, especially when it comes to building infrastructure and the vessel it self. The reason for this is not include is mostly due to time limitations and the capacity, since this is a master thesis with limited available time, but this can be potential idea for further research on this topic.

The GWP is of the same order, and the difference between the LNG fuel and HFO fuel is minimal. If other modeling choices were made, the GWP for the LNG could have been decreased. For both fuels, the largest contribution to GHG origins from the combustion phase, but the transmission of the fuels is also essential to the overall emission results. As mention previously in this thesis, ship owners only care about the emissions from the combustion phase. Another observation is that the acidification potential where improved by 92.5% by using LNG as a fuel compared to HFO. As stated earlier, LNG is not composed with any sulphur, so this result is not a surprise. Also, for the acidification, it showed that the essentially all pollution comes from the combustion phase.

From the analysis one can see that by using LNG as a fuel ship owners encounters both sulphur requirements from Tier II and Tier III. For this particular thesis, there were presented a trading description for the VLCC in the beginning. By looking at that, one can see that most of the trading takes place outside ECA, which means that by the current regulations, Awilco can cope with running on HFO and instead swap to HFO that contain lower sulphur levels when sailing in the ECA. This is just in the short term, when the new regulations on SO_x cap on 0.5% get into force by 2025 (maybe earlier or later, for more see section 2.3) this can be a problem in the future.

To finalize the decisions about Awilco's possibility to invest in LNG propulsion instead of HFO one much look at the different research perspectives. When deciding whether or not to invest in a new vessel with a new type of propulsion to replace the established with, it is important that the new fuel score well on emissions and economy in the first place. In this thesis only the environmental assessments of the different fuels where taken into consideration, and not the economical part of the fuel (fuel price etc.), neither the environmental assessment of the infrastructure of building a new ship or the economical part of the investment. When looking at the life cycle of a fuel, there is also important to notice that the company only is responsible to meet the regulatory for emissions from the combustion phase of the life cycle, since a company do not have responsibility for the emissions in the earlier stage.

From this study, LNG will be the best alternative compared to HFO when considering the environmental assessment, but to give a final decision about if LNG will be a worthwhile investment, the research must be depended even more elaborating on different research perspectives such:

- Current and future fuel prices
- Investment cost
- Infrastructure
- Technical feasibility of the LNG technology

All these issues were not addressed in detail in this thesis, which limiting the LNG potential. Therefor, if an investment should be decided, the preparation for the decision making process for Awilco should include more research, especially on the perspectives listed above.

8.0 Summary

The main goal of this thesis was to investigate the environmental assessment of LNG and HFO, with respect to the regulatory given by IMO, and decide whether or not an investment in LNG propulsion should be done. In order to fulfill this goal and to answer the research question, both an empirical and scientific research was done. The research and the analysis performed in this particular study can be helpful for ship owners to make better environmental decisions in deciding between the two fuels, LNG and HFO.

During the research many assumptions has been made. The availability of newer emissions data has been difficult to collect for the chosen pathway of the two fuels. Many companies for the particular stages in the pathway have been asked, but the response has been negative. Either they did not want to give the data or they did not have the requested data. Because of this, previously research and older data from databases has been used in this thesis where no newer data where able to be obtained. The research problem and questions presented in section 1.3 and 1.6 where answered and analyzed based on the collected data.

The focus on this thesis has been on emissions from the extraction-, production-, liquefaction- and the combustion phase of LNG and HFO. The analysis has been split from a well-to-propeller perspective into a well-to-tank and tank-to-propeller perspective. When comparing the LNG fuel with HFO, the findings from the analysis show that the combustion phase of both fuels is the most polluting when it comes to both greenhouse gases and acidification, but also the transmission to harbor has a huge impact on the total air pollution as well.

On the basis of the results from this thesis, LNG would be a preferable fuel compared to HFO in the future, based on an environmental footprint. However, to make any conclusion on an investment for Awilco based on an environmental footprint, there are areas that still not have been covered; methane slip along the pathway, more specific on the emissions regarding the liquefaction and the energy use. Also, only the environmental footprint for a fuel cannot support such an investment, it will be necessary to look into different perspectives as well.

9.0 Further Research

In this thesis the main goal was to evaluate the situation of the environmental impact from LNG and HFO in order to decide weather or not Awilco should invest in a new vessel with LNG propulsion. As it was mention in the chapter 7.0, additional research and analysis on current and future fuel prices, cost of investment, infrastructure for LNG and the technical feasibility of the LNG technology could bring additional and important value for the decision-making for Awilco.

Further research could also address the environmental assessment of the emissions to sea from both of the fuels, e.g. oil spills and boil-off gas to mention a few, this was not considered in this thesis. Another issue would be to look into a potential government support for LNG technology, NOx founds and investment support for vessels. Finally, another issue for further analysis can be to look at non-conventional fuels that can be competitors to LNG, such as bio-fuels. The total effect and potential of non-conventional fuels within maritime shipping could also be subject for further research.

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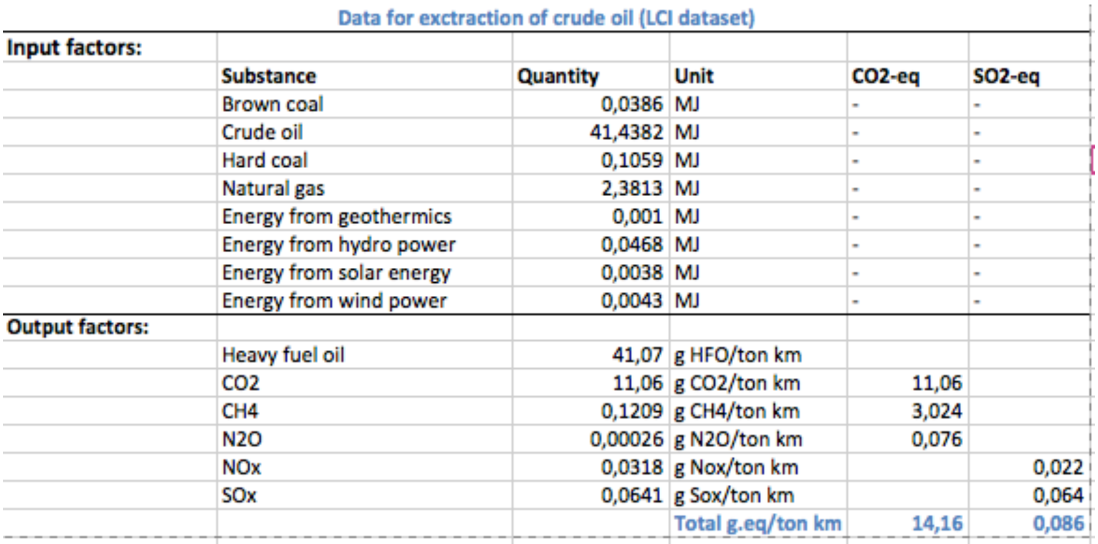
Appendix

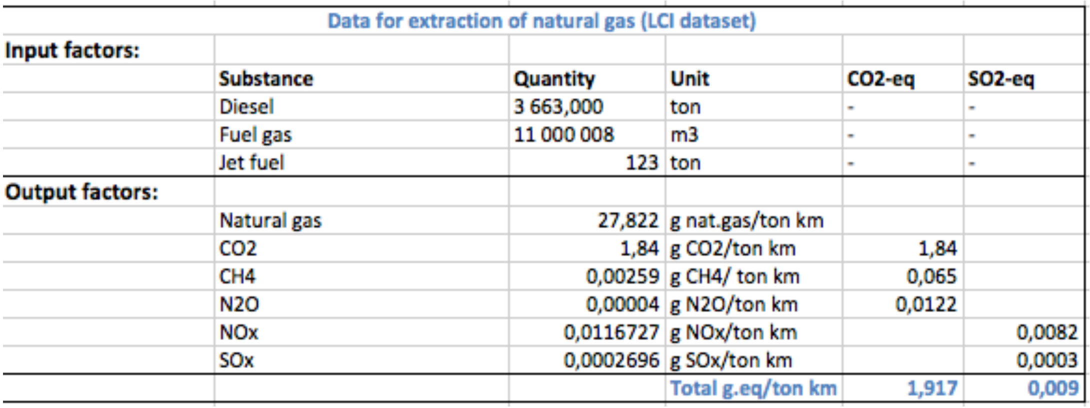
A) LCI dataset for extraction of crude oil.



Data for exctraction of crude oil (LCI dataset)

Input factors:					
	Substance	**Quantity**	**Unit**	**CO2-eq**	**SO2-eq**
	Brown coal	0,0386	MJ	-	-
	Crude oil	41,4382	MJ	-	-
	Hard coal	0,1059	MJ	-	-
	Natural gas	2,3813	MJ	-	-
	Energy from geothermics	0,001	MJ	-	-
	Energy from hydro power	0,0468	MJ	-	-
	Energy from solar energy	0,0038	MJ	-	-
	Energy from wind power	0,0043	MJ	-	-
Output factors:					
	Heavy fuel oil	41,07	g HFO/ton km		
	CO2	11,06	g CO2/ton km	11,06	
	CH4	0,1209	g CH4/ton km	3,024	
	N2O	0,00026	g N2O/ton km	0,076	
	NOx	0,0318	g Nox/ton km		0,022
	SOx	0,0641	g Sox/ton km		0,064
			Total g.eq/ton km	14,16	0,086

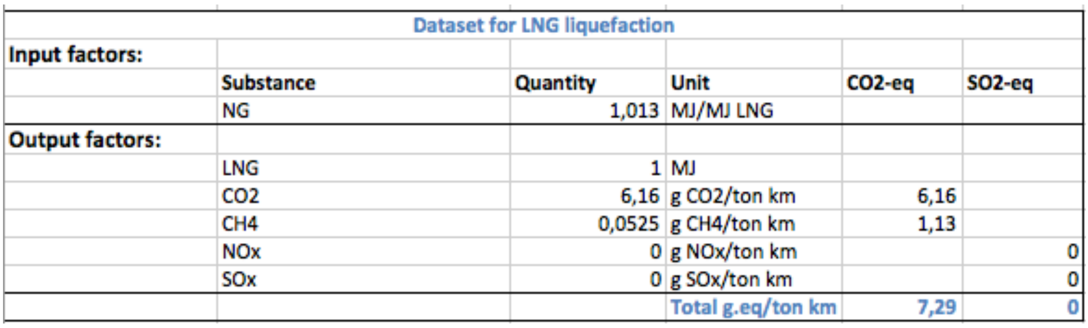
B) LCI dataset for extraction of natural gas



Data for extraction of natural gas (LCI dataset)

Input factors:					
	Substance	**Quantity**	**Unit**	**CO2-eq**	**SO2-eq**
	Diesel	3 663,000	ton	-	-
	Fuel gas	11 000 008	m3	-	-
	Jet fuel	123	ton	-	-
Output factors:					
	Natural gas	27,822	g nat.gas/ton km		
	CO2	1,84	g CO2/ton km	1,84	
	CH4	0,00259	g CH4/ ton km	0,065	
	N2O	0,00004	g N2O/ton km	0,0122	
	NOx	0,0116727	g NOx/ton km		0,0082
	SOx	0,0002696	g SOx/ton km		0,0003
			Total g.eq/ton km	1,917	0,009

C) LCI dataset for liquefaction of natural gas to LNG



Dataset for LNG liquefaction					
Input factors:					
	Substance	**Quantity**	**Unit**	**CO2-eq**	**SO2-eq**
	NG	1,013	MJ/MJ LNG		
Output factors:					
	LNG	1	MJ		
	CO2	6,16	g CO2/ton km	6,16	
	CH4	0,0525	g CH4/ton km	1,13	
	NOx	0	g NOx/ton km		0
	SOx	0	g SOx/ton km		0
			Total g.eq/ton km	7,29	0

D) Emission from transportation

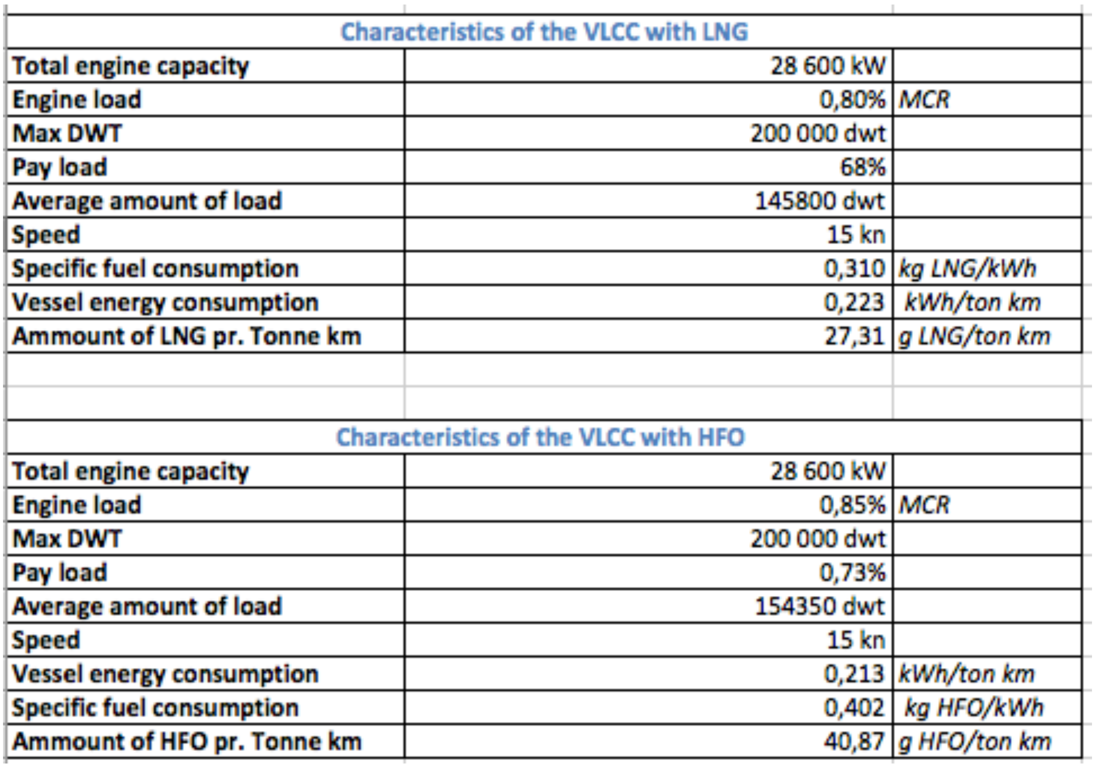
D1) Emission from LNG transportation

Emissions LNG transportation	
CO2 (g CO2/ton km)	15,26
CH4 (g CH4/ton km)	0,44
N20 (g N2O/ton km)	0,0135
NOx (g NOx/ ton km)	0,1888
LNG (g LNG/ton km)	27,47
CO2.eq - g CO2/ton km	15,26
CO2.eq - g CH4/ton km	11,11
CO2.eq - g N2O/ton km	4,02
TOTAL CO2.eq/ton km	**30,39**
SO2.eq - g NOx/ton km	0,13
TOTAL SO2.eq/ton km	**0,13**

D2) Emission from HFO transportation

Emissions HFO transportation	
CO2 (g CO2/ton km)	16,53
SOx (g SOx/ton km)	0,739
N20 (g N2O/ton km)	0,000227
NOx (g NOx/ ton km)	1,972
HFO (g HFO/ton km)	41,07
CO2.eq - g CO2/ton km	16,53
CO2.eq - g N2O/ton km	0,677
TOTAL CO2.eq/ton km	**17,21**
SO2.eq - g NOx/ton km	1,38
SO2.eq - g Sox/ton km	0,739
TOTAL SO2.eq/ton km	**2,119**

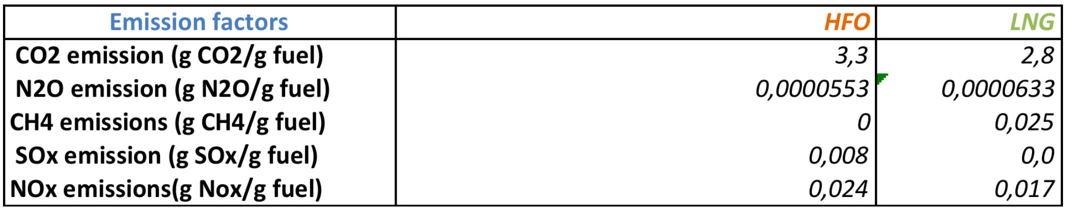
E) Characteristics of VLCC with different fuels (LNG and HFO)



Characteristics of the VLCC with LNG		
Total engine capacity	28 600 kW	
Engine load	0,80%	*MCR*
Max DWT	200 000 dwt	
Pay load	68%	
Average amount of load	145800 dwt	
Speed	15 kn	
Specific fuel consumption	0,310	*kg LNG/kWh*
Vessel energy consumption	0,223	*kWh/ton km*
Ammount of LNG pr. Tonne km	27,31	*g LNG/ton km*

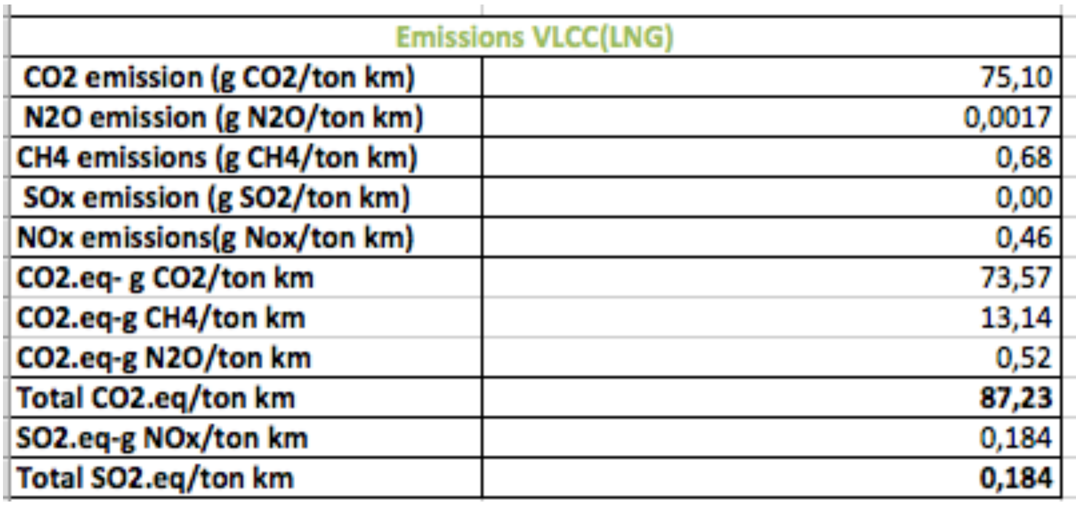
Characteristics of the VLCC with HFO		
Total engine capacity	28 600 kW	
Engine load	0,85%	*MCR*
Max DWT	200 000 dwt	
Pay load	0,73%	
Average amount of load	154350 dwt	
Speed	15 kn	
Vessel energy consumption	0,213	*kWh/ton km*
Specific fuel consumption	0,402	*kg HFO/kWh*
Ammount of HFO pr. Tonne km	40,87	*g HFO/ton km*

F) Emission factors for the different fuels



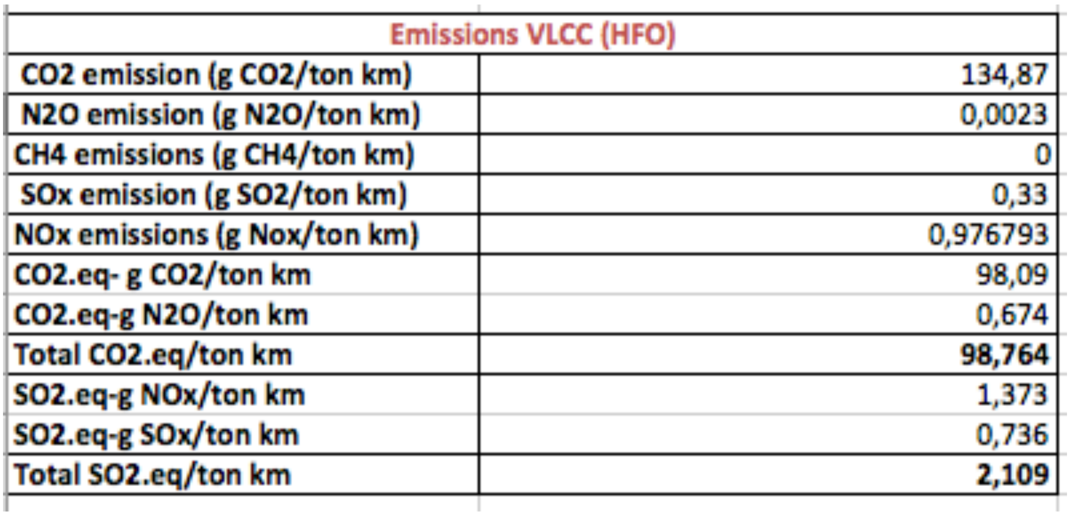
Emission factors	HFO	LNG
CO2 emission (g CO2/g fuel)	3,3	2,8
N2O emission (g N2O/g fuel)	0,0000553	0,0000633
CH4 emissions (g CH4/g fuel)	0	0,025
SOx emission (g SOx/g fuel)	0,008	0,0
NOx emissions(g Nox/g fuel)	0,024	0,017

G) Emissions from VLCC with LNG



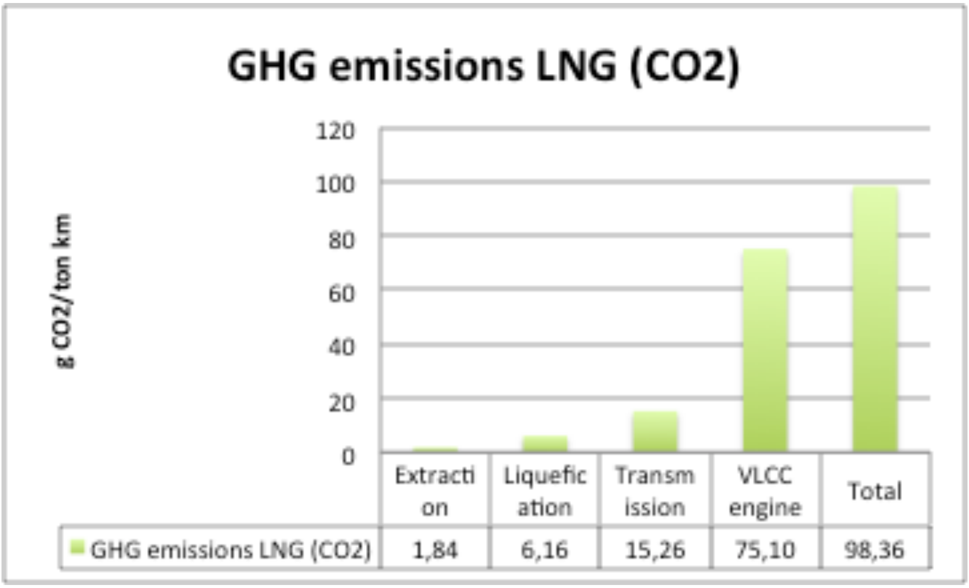
Emissions VLCC(LNG)	
CO2 emission (g CO2/ton km)	75,10
N2O emission (g N2O/ton km)	0,0017
CH4 emissions (g CH4/ton km)	0,68
SOx emission (g SO2/ton km)	0,00
NOx emissions(g Nox/ton km)	0,46
CO2.eq- g CO2/ton km	73,57
CO2.eq-g CH4/ton km	13,14
CO2.eq-g N2O/ton km	0,52
Total CO2.eq/ton km	**87,23**
SO2.eq-g NOx/ton km	0,184
Total SO2.eq/ton km	**0,184**

H) Emissions from VLCC with HFO

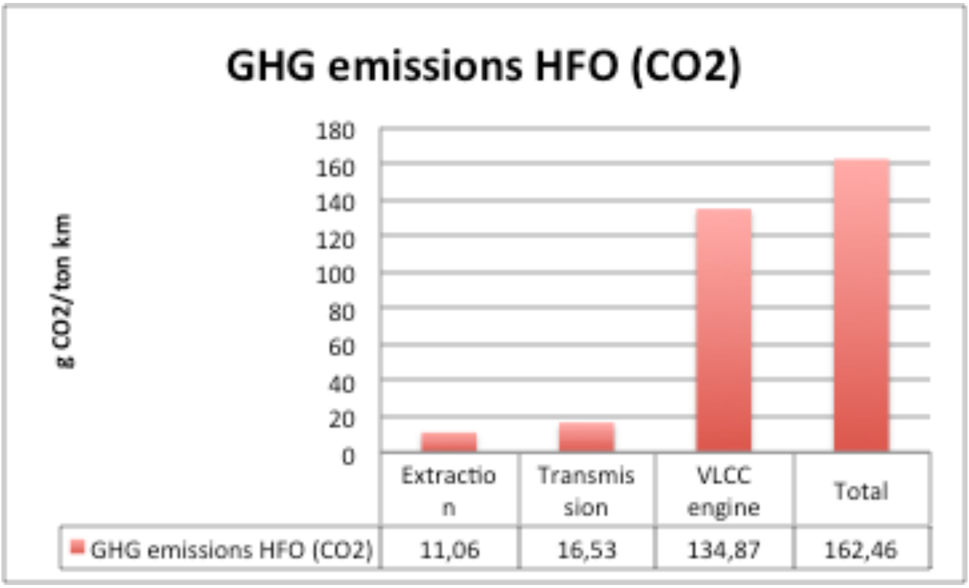


Emissions VLCC (HFO)	
CO2 emission (g CO2/ton km)	134,87
N2O emission (g N2O/ton km)	0,0023
CH4 emissions (g CH4/ton km)	0
SOx emission (g SO2/ton km)	0,33
NOx emissions (g Nox/ton km)	0,976793
CO2.eq- g CO2/ton km	98,09
CO2.eq-g N2O/ton km	0,674
Total CO2.eq/ton km	**98,764**
SO2.eq-g NOx/ton km	1,373
SO2.eq-g SOx/ton km	0,736
Total SO2.eq/ton km	**2,109**

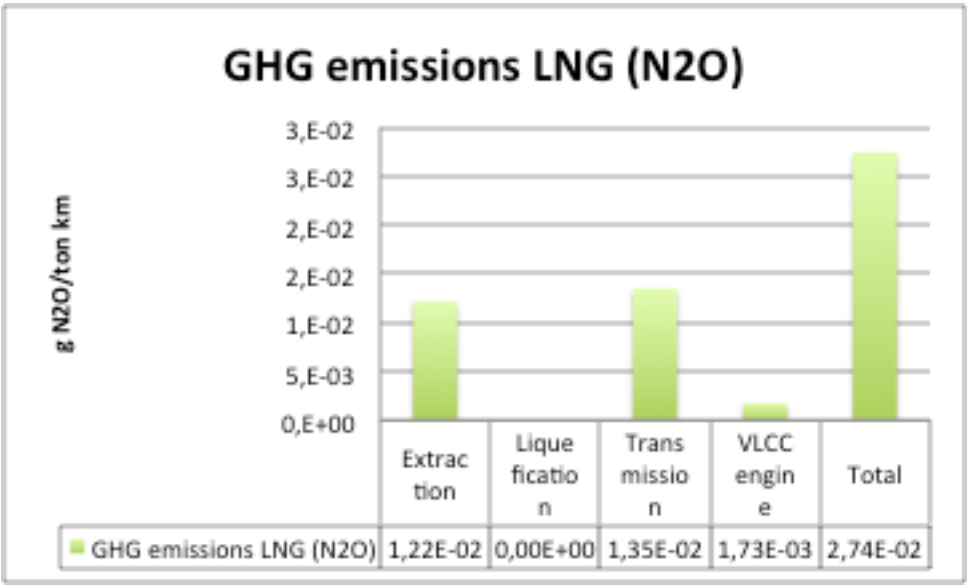
I) CHG emissions, CO2 emissions, from LNG



J) CHG emissions, CO2 emissions, from HFO

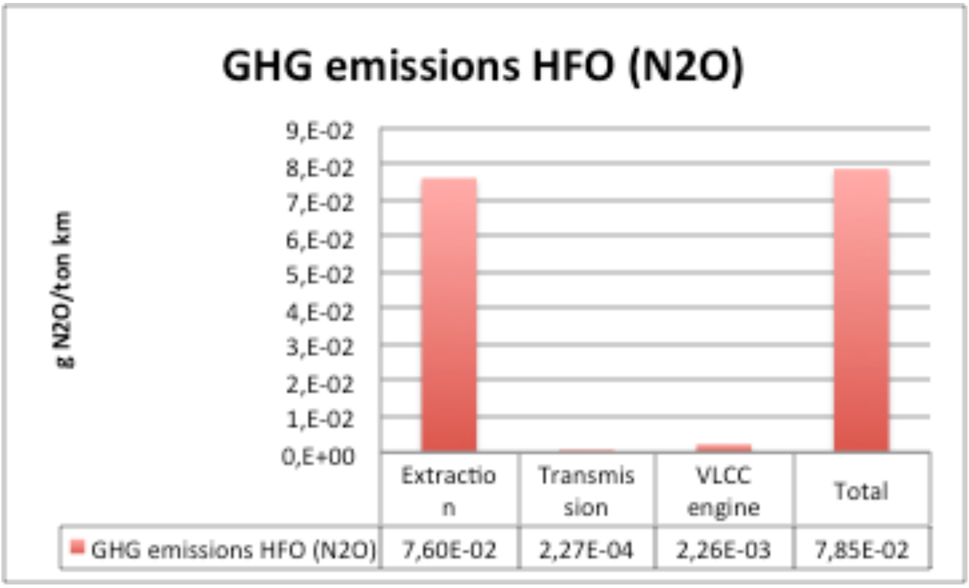


K) CHG emissions, N2O emissions, from LNG



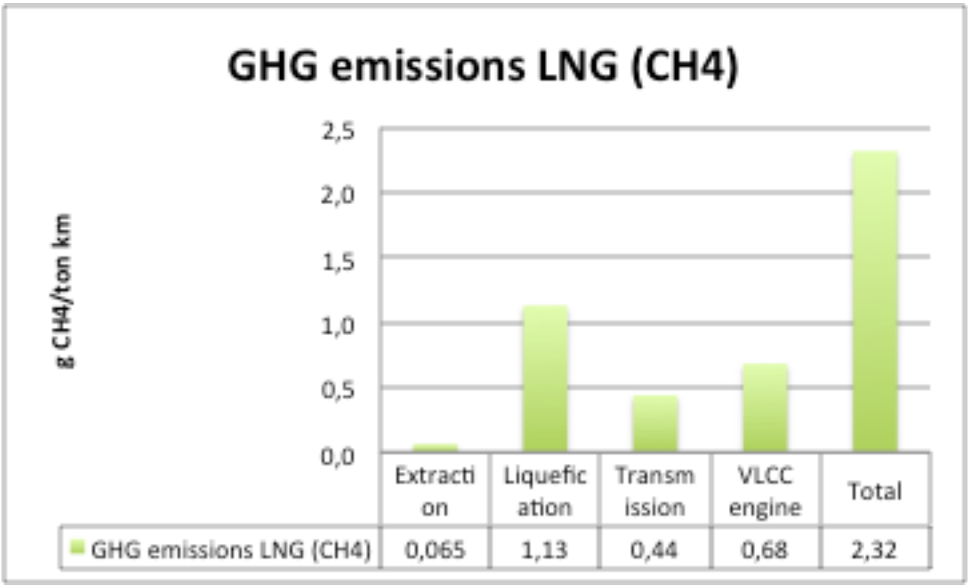
	Extraction	Liquefication	Transmission	VLCC engine	Total
🟩 GHG emissions LNG (N2O)	1,22E-02	0,00E+00	1,35E-02	1,73E-03	2,74E-02

L) CHG emissions, N2O emissions, from HFO

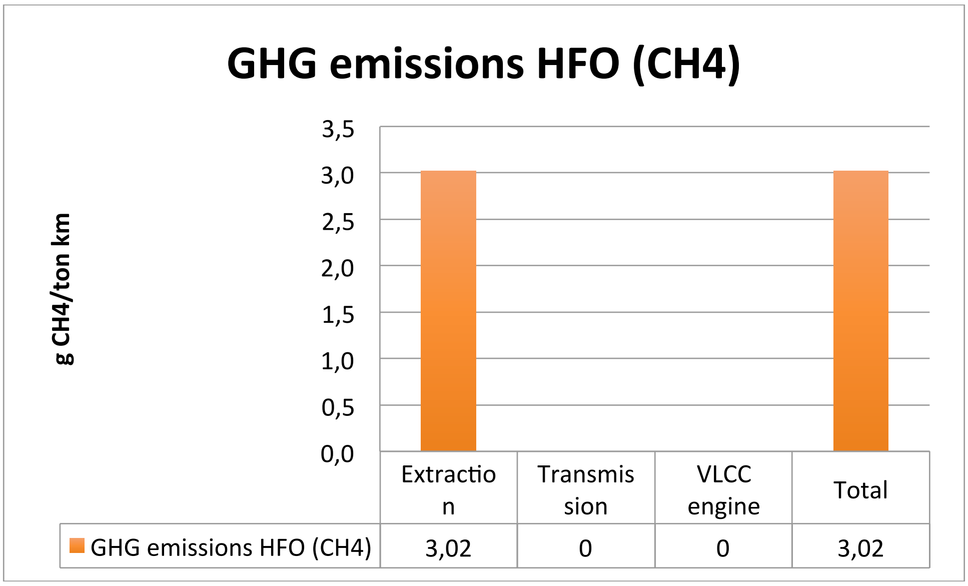


	Extraction	Transmission	VLCC engine	Total
🟥 GHG emissions HFO (N2O)	7,60E-02	2,27E-04	2,26E-03	7,85E-02

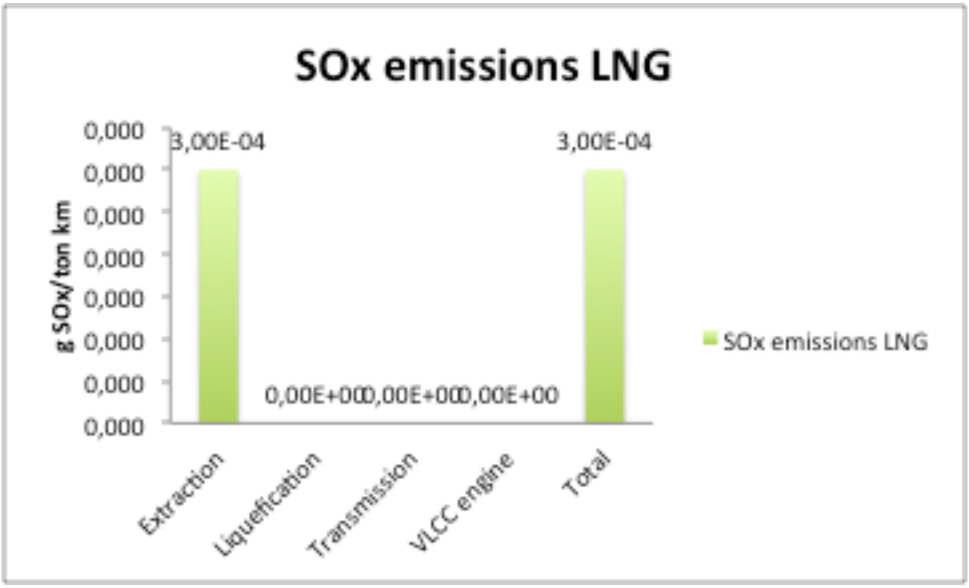
M) CHG emissions, CH4 emissions, from LNG

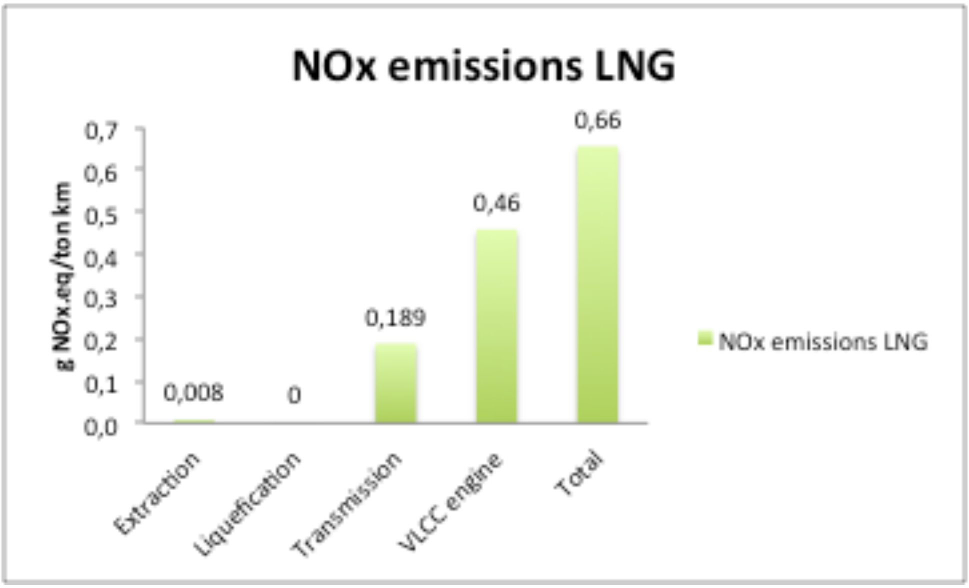


N) CHG emissions, CH4 emissions, from HFO



O) GHG emissions, SO_x and NO_x emissions from LNG





P) GHG emissions, SO_x and NO_x emissions from HFO.