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LNG as fuel on fishing vessels

Assessment of economic feasibility and environmental impact

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Preface

This thesis is written as a completion of the master education and to obtain the degree of Master of Science at Norwegian University of Science and Technology in Trondheim spring of 2018.

The content of this report has been produced in the course of 20 weeks the final semester at department of Marin Technology, and allocates 30 credits in total. The workload have been distributed evenly throughout the semester, with the good help of guidance every other week from supervisor.

My motivation to develop this thesis derives from my interests in environmental issues and the importance of the fishing industry in Norway. One of the main challenges with the thesis, was to establish an interesting objective relevant for the industry today.

I would like to thank my supervisor Svein Aanond Aanondsen (NTNU), for good input and advice on how to handle the problem and objective of the dissertation. I would also like to give my gratitude to Postdoctoral fellow and research scientist Sepideh Jafarzadeh (NTNU, SINTEF), who had some good advice and input on the preliminary project during the fall semester of 2017. There have also been several other contributors from the industry that have dedicated time to answer my questions about various investigated topics.

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Summary

Fisheries have had an important role in the Norwegian economic growth and culture for centuries. While regulatory requirements concerning emission abatement are becoming more demanding, measures aimed at improvement of the environmental profile within the fishing fleet are essential. A transition to more environmentally friendly fuels has been described to be the best measure when the intention is to have a reduction in emissions (Ellingsen and Lønseth, 2005).

The main argument of utilizing natural gas as fuel is the significant reduction of different pollutants, such as carbon dioxide (CO_2), nitrogen oxide (NO_x) and sulfur oxide (SO_x). In this thesis, an evaluation of liquefied natural gas (LNG) as fuel for fishing vessels is conducted. By assessing both the environmental impact and the economic feasibility, LNG is compared to the conventional fuel utilized on fishing vessels today.

An existing trawler using marine gas oil (MGO) as fuel today, is used as a basis for a performed case study. A part of the case is to incorporate the effect when changing the vessel's dimensions, as a result of a more space demanding LNG system.

To evaluate the environmental impact in a complete way, the entire life cycle is assessed using data from previous life cycle assessment (LCA) studies and conversion methods. The vessel using LNG as fuel has a higher required energy consumption, which also have had an impact on the environmental performance. The global warming potential (GWP) for the complete life cycle has been estimated to be approximately the same for LNG and MGO, where methane emissions exhausted during the combustion process for LNG accounts for a large amount of the GWP for LNG. The acidification potential and the eutrophication potential show a decrease of approximately 85% compared to MGO, which indicates a lower impact on terrestrial and freshwater ecosystems. There is, however, uncertainty regarding the conversion methods used to evaluate a product's overall impact on the environment, which makes it challenging to draw a final conclusion as to how environmental friendly LNG really is compared to MGO.

It was found that investment in LNG relative to a conventional energy system, will accumulate savings of 25.4 MNOK over 25 years with the financial support from the NO_x fund. The LNG-fuelled fishing vessel is also exempt from taxes for CO_2 and SO_x, and pays a lower tax rate for NO_x directly to the funding plan. The payback time will be 3-4 years relative to an MGO baseline when all voyage related expenses are assumed to be constant. During the lifetime of the vessel, it was found that the additional profit will on average increase with *0.18 NOK/kg fish* for LNG investment compared to MGO investment. A sensitivity analysis shows that the total cost is highly sensitive towards changes related to tax exemptions and in regards to fuel price dynamics.

Ultimately, regulations are the main driving force for a change to and the adoption of more environmentally friendly technology. Shipowners and important stakeholders make their decisions based on financial gains. As a concluding remark, investing in LNG as fuel can be beneficial considering future regulatory compliance, and will at some level improve a vessel's environmental profile. Based on the findings from the case and current financial benefits, the investment is economically feasible over its anticipated lifetime. However, the vessel used as basis in the case is not representative for all fishing vessels. Furthermore, tax exemptions, fuel costs and other voyage related expenses are not constant, which leads to uncertainty regarding future costs and payback time.

Sammendrag

Fiskeri har i århundrer hatt en viktig rolle for norsk økonomisk vekst og kultur. Regelverk som omhandler krav om utslippsreduksjon blir stadig mer krevende, og dermed er det avgjørende med tiltak som retter seg mot forbedring av miljøprofilen til fiskeflåten. En overgang til mer miljøvennlig drivstoff har blitt beskrevet som det beste tiltaket når intensjonen er å redusere utslippene (Ellingsen and Lønseth, 2005).

Hovedargumentet for å bruke naturgass som drivstoff, er den betydelige reduksjonen av forskjellige forurensende stoffer, for eksempel karbondioksid (CO_2), nitrogenoksid (NO_x) og svoveloksid (SO_x). I denne oppgaven gjennomføres en evaluering av flytende naturgass (LNG) som drivstoff til fiskefartøy. Ved å vurdere både miljøpåvirkning og økonomisk gjennomførbarhet, sammenlignes LNG med det konvensjonelle drivstoffet som brukes på fiskefartøy i dag.

En eksisterende tråler som anvender marine gassolje (MGO) som drivstoff i dag, brukes som grunnlag for en utført casestudie. En del av casestudien er å inkludere effekten av endring i hoveddimensjonene til fartøyet, som følge av et mer krevende LNG-system.

For å kunne evaluere miljøbelastningen på en fullstendig måte, vurderes hele livssyklusen ved hjelp av data fra tidligere livssyklusvurdering (LCA) og konverteringsmetoder. Fartøyet som bruker LNG som drivstoff har et høyere energiforbruk, som videre har påvirket miljøprestasjonen. Det globale oppvarmingspotensialet (GWP) for hele livssyklusen er estimert å være omtrent det samme for LNG og MGO, hvor metanutslipp ved forbrenningsprosessen står for en stor del det estimerte GWP for LNG. Forsuringpotensialet og eutrofieringspotensialet viser en nedgang på rundt 85% sammenlignet med MGO, noe som indikerer en lavere innvirkning på økosystemer. Det er imidlertid en del usikkerhet knyttet til konverteringsmetoder som brukes til å evaluere den samlede påvirkningen på miljøet, noe som gjør det vanskelig å trekke en endelig konklusjon om hvor miljøvennlig LNG virkelig er, sammenlignet med MGO.

Ved investering i LNG i forhold til et konvensjonelt system for fartøyet, vil den samlede besparelsen være på ca. 25.4 MNOK over 25 år ved hjelp av økonomisk støtte fra NOx-fondet. I tillegg er det LNG-drevet fiskefartøyet fritatt fra å betale skatt for CO_2 og SO_x, og betaler en lavere skattesats for NO_x, direkte til fondet. Dette gjør det mulig for en tilbakebetalingstid på 3-4 år i forhold til MGO når alle reiseutgifter antas å være konstant. I løpet av fartøyets levetid, vil den ekstra fortjenesten øke med gjennomsnittlig *0.18 NOK/kg fisk* for LNG-investeringer sammenlignet med MGO-investeringer. En sensitivitetsanalyse viser at den totale kostnaden er svært følsom overfor endringer knyttet til skattefritak og med hensyn til drivstoffprisdynamikk.

Regelverk og miljøkrav er den viktigste drivkraften for endring og bruk av ny og mer miljøvennlig teknologi. Rederier og viktige interessenter tar sin beslutning basert på økonomiske gevinster. Som en avsluttende bemerkning kan investering i LNG som drivstoff være gunstig med tanke på fremtidig regelverk, og vil kunne forbedre fartøyets miljøprofil

en viss grad. Basert på funnene i casen og nåværende økonomiske fordeler, er investeringen økonomisk gjennomførbar i løpet av forventet levetid. Fartøyet som har blitt brukt som eksempel, er imidlertid ikke representativt for alle fiskefartøy. Videre er skattefritak, drivstoffkostnader og andre utgiftet ikke konstante, noe som fører til usikkerhet angående fremtidige kostnader og tilbakebetalingstid.

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Nomenclature

Acronyms

BC = Black carbon
BOG = Boil-off gas
CAD = Computer aided design
CAPEX = Capital expenditure
CCS = Carbon capture and storage technology
CH4 = Methane
CO2 = Carbon dioxide
DME = Dimethyl ether
DTW = Deadweight tonnage
ECA = Emission control area
FC = Fuel cells
GA = General arrangement
GHG = Green house gasses
GT = Gross tonnage
GWP = Global warming potential
H2O = Water
H2S = Hydrogen sulphide
He = Helium
HFO = Heavy fuel oil
ICES = International Council of the Exploration of the Sea
IMO = International maritime organization
LCA = Life cycle assessment
LCC = Life cycle cost
LH2 = Liquid hydrogen
LNG = Liquefied natural gas
LSHFO = Low sulphur heady fuel oil
MDO = Marine diesel oil
MeOH = Methane
MGO = Marine gas oil
N = Nitrogen
N2O = Nitrous oxide
NECA = NOx emission control area
NOx = Nitrogen oxide
NPV = Net present value
ODS = Ozone depleting substances
OPEX = Operating expense
OSV = Offshore supply vessel

PM = Particulate matter
RELH2 = Remewable liquid hydrogen
RORO = Roll-on/roll-off vessel
SBSD = System based ship design
SECA = SOx emission control area
SEEMP = The ship energy efficiency management plan
TFCA = Total fuel-cycle analysis
SOx = Sulphur oxide
VOC = Volatile organic compounds
VOYEX = Voyage related expenditures

Symbols

Δ = Ship volume displacement
ΔP = Effective power
η_D = Propulsive efficiency
η_H = Hull efficiency
η_O = Propeller open water efficiency
η_R = Relative rotational efficiency
η_T = Total efficiency
ρ = Density
B = Ship breadth
b_e = Specific fuel consumption
E = Energy consumption
FC = Fuel consumption
F_N = Froude number
L = Ship length
P_e = Power output
P_E = Effective power
R_t = Net cash flow
R_{Tot} = Total resistance
T = Ship draft
V_S = Ship speed
W_S = Steel weight

Part I

BACKGROUND

Chapter 1

Introduction

1.1 Motivation

Fisheries have played an important role in the Norwegian economic growth and culture. In 2016, it was estimated that Norway was the world's second-largest exporter of seafood with an export value reaching 91.6 billion NOK. Whitefish came second on the list as the most important export product after salmon and trout, with a total value of 13.8 billion NOK in 2016 (Norway Exports, 2017). The export value of aquaculture and fisheries increased by 2.4% in 2017, whereas the future prospect for the seafood industry in Norway appears to be promising (NTB, 2018).

During the last decades, consumers and stakeholders involved in the fishing industry have become more concerned about sustainable aspects. The attention has increased towards how the industry have an impact on the environment; from fishing practices to how the fleet contributes to air pollution. It is demanded more information about the products and to what extent they are sustainable. In order to avoid a decline in the Norwegian market share, it is important for the fisheries to satisfy the demand of stakeholders and value their requirements regarding sustainability matters (Magerholm Fet et al., 2010).

In 2013, the fishing fleet contributed to approximately 10.2% of the total fuel consumption of seagoing traffic in Norwegian waters (DNV-GL, 2015b). By utilizing marine gas oil (MGO) as fuel, the fishing vessels are responsible for large amounts of emitted carbon dioxide (CO_2), regional and local pollutants, such as nitrogen oxide (NO_x), sulphur oxide (SO_x) and particulate matter (PM). Based on calculations from DNV-GL (2015b), the fishing segment is the third most fuel consuming segment in Norwegian waters, after passenger vessels and offshore supply vessels.

In order to deal with the climate change we face today, various measures have been initiated. The regulations are becoming more demanding globally and at national scale, where the Norwegian government have expressed that the fishing fleet have to take part in "The

Green Shift" (Berg, 2017). Some environmental regulations will take effect in the near future, and others are still under development and will have an impact in the intermediate term (Martinsen and Torvanger, 2013).

The average age of the Norwegian fishing fleet is 28 years, which makes it the oldest segment in Norway. Statistics from Fiskeridirektoratet (2017), shows that only 6% of the Norwegian fishing fleet are above 21 meters, where these hold approximately 53% of the total installed power. Considering their size, the vessels are vulnerable to comply with environmental regulations that requires measures to be made in the interest of controlling the exhausted emissions. A vessel's lifetime is considered to be 25 years or more, making the shipowners attentive towards possible future environmental regulations (Wuersig and Chiotopoulos, 2015). Designing and building a vessel without any involvement in possible future regulations can have a large negative impact on the business.

The challenge is to reduce the exhausted emissions and greenhouse gases (GHG) from seagoing traffic in a feasible way in order to comply with the regulations. There are different methods applicable to reduce the emissions. These are for instance optimizing the hull form, by using waste heat to generate electricity on board for cooling, air pollution control devices such as scrubber systems, or by adopting alternative fuels (Utne, 2008).

A report developed by Ellingsen and Lønseth (2005) in conjunction with Sintef, described 16 different measures to reduce the energy consumption and environmental impact from the fishing fleet. The report stated that changes related to propulsion system and energy system will give a great effect compared to other measures. A transition to more environmental friendly energy sources was further described to be the best measure when the intention is to have a reduction in emissions. Alternative energy sources for marine applications can be transition to low or zero-emission technology, such as liquefied natural gas (LNG), batteries, hydrogen in combination with fuel cells, methanol or biofuels.

Today, LNG is a proven and available solution for both new builds and conversion projects. The main argument of using LNG as fuel, is the significant reduction in regional air pollution and GHG when burned, which include emissions such as CO_2, SO_x, NO_x, particulate matter (PM) and black carbon (BC). The future prospects are positive, DNV GL expects that the use and demand of LNG will grow rapidly the next five to ten years (Wuersig and Chiotopoulos, 2015). Whilst the demand for LNG increases, the availability will develop and create an improved supply chain.

Set aside future environmental regulations, financial gains are evidently the decisive factor when it comes to investing in an alternative solution or not. There is still a perception among market actors that the commercial risk of adopting LNG as fuel is high (Wuersig and Chiotopoulos, 2015). Further, the investment costs of a LNG-fuelled vessel have been estimated to be 10-25% higher compared to conventional oil-fuelled vessels (Yoo, 2017). There are however various incentives possible to attain that supports the use of innovative and more environmental friendly solutions, which is fundamental for investing in new technology.

The system for LNG requires more space than a vessel utilizing conventional MGO. Complex circular cryogenic tanks and additional systems occupies large spaces, and gas-fuelled vessels must comply with a number of requirements regarding arrangement and safety on board. The design and construction of a fishing vessel are often made compact filled with heavy gears and machinery, whereas the size of the cargo hold influence income and performance of the vessel.

1.2 Objective

Deriving from the background, the overall objective of the thesis is to evaluate LNG as an alternative fuel compared to the conventional fuel utilized for fishing vessels. The aim is to assess the complete environmental impact and economic feasibility by also incorporate the effect from a more space demanding system for LNG. The approach is further described below.

1.3 Approach

By performing a study case, a comparison between MGO and LNG as fuel on fishing vessels can be addressed. Based on the same mission statement and cargo hold capacity for a vessel, it will be investigated to what degree the fuel storage tanks and additional systems for LNG will have an effect on the main dimensions and hull form. Without any other modifications, an increase in dimensions will increase the resistance of the vessel, which will naturally have an impact on the fuel consumption, cost and environment. As stated, the intention is to assess the environmental impact and economic feasibility by also including the effects of changes in the vessel's dimensions.

Figure 1.1 illustrates three main steps for the case study approach.

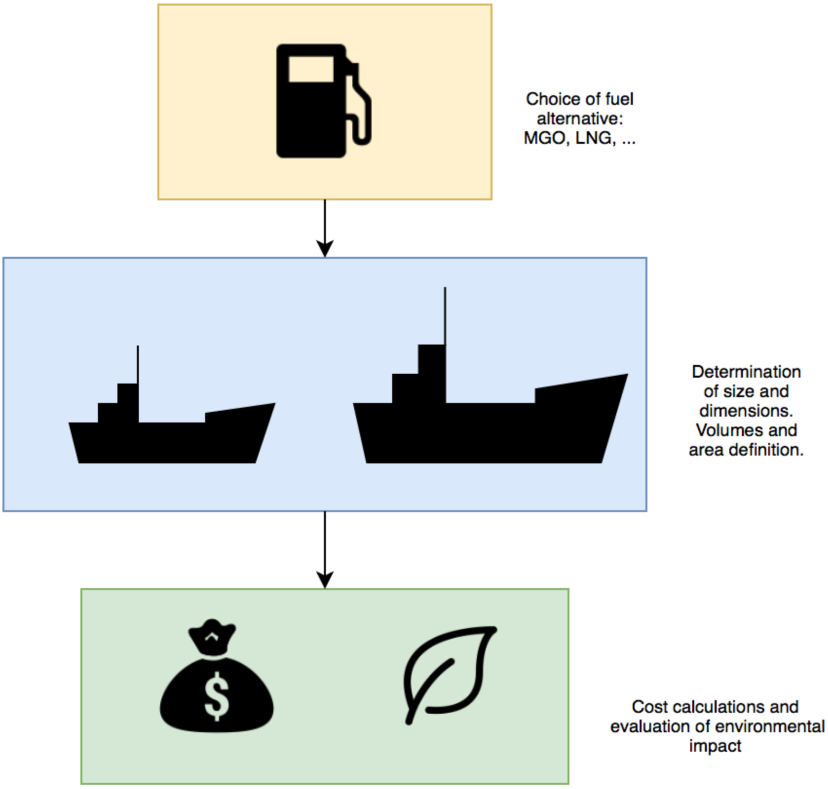


Figure 1.1: Three main steps, illustrating the approach, inputs and outputs.

1.4 Limitations

The thesis is limited to one semester, and therefore ambitious to have evaluated every aspect in a definite way. A task is comprehensive when addressing sustainability matters, in this case the environmental and economic pillars. The social pillar of sustainability will not be evaluated for the most part, causing some limitations where an examination of "the big picture" or the system as a whole is not executed. This will be discussed in the completion of the thesis.

It will be made assumptions and there is room for further work to support the rationale. The assumptions initiated, further improvements and limitations of the thesis are further explained in study case and discussion.

1.5 Structure overview

The report is divided into three parts complete with chapters and sections, covering the background, case study and discussion. The reminder of the thesis will be structured as follows:

Part I Background

This part addresses challenges regarding exhausted emissions of greenhouse gases and regional pollutants. Further, an explanation of how regulations, incentives and other measures have been enforced to control the amount of exhausted emissions. This section will provide the information necessary to understand the motivation of adopting new technologies and implement environmentally friendly measures.

The literature also covers different aspects of the Norwegian fishing fleet. An important part of the thesis is also a definition of the energy efficiency for different fishing vessel segments to understand where environmentally friendly measures can have a great effect.

The advantages and drawbacks regarding both MGO and LNG are assessed. LNG is further elaborated, to understand the complexity of the system and how the different system components and regulations for gas-fuelled vessels will influence the performance of the vessel.

Finally, the methodology of the approach and methods used to perform the following study case is presented.

Part II Case study

Part II contains the assessed case study, presenting the case study selection, system boundaries and approach. It will also address the selection of LNG components for the vessel in the case, changes related to arrangement and how the system will impact main dimensions.

Further, the report gives an overview of the analysis and results of the environmental impact and economic feasibility for the vessels in the case.

Part III Discussion

This part includes a discussion of the results, chosen approach and limitations. It will also include a scenario analysis addressing the influence of fluctuating fuel costs and uncertainty regarding tax exemption and incentives for LNG-fuelled vessels. This leaves the final conclusion and elaboration of further work to be assessed to support the rationale.

Chapter 2

Regulatory Compliance and Emission Abatement

International regulations on exhaust emissions from seagoing traffic are lacking behind the comprehensive regulatory framework for land-based traffic. But the focus on reducing emissions in the maritime sector has become more substantial the last decade. International Maritime Organization (IMO) is one the actors that has enforced regulations to limit the amount of exhausted emissions. MARPOL Annex VI - *Regulations for the Prevention of Air Pollution from Ships*, regulates the emissions of different air pollutants to the atmosphere.

In this section, the major emission components along with their challenges will be introduced. Following, the regulations and measures to control air born emissions are presented, both for present and future execution.

2.1 GHG

The combustion of fossil fuels produces GHG, which are gases that traps heat in the atmosphere. GHGs consist of gases such as CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gasses (EPA, 2016). The different GHGs have a dissimilar effect on the Earth's warming; how the gas is capable of absorbing energy and how long it stays in the atmosphere. The global warming potential (GWP) has been established in order to compare the global warming impact of different GHGs. GWP is described by the amount of CO2-equivalents, where the GWP equals how much impact the given gas will have on the global warming compared to CO_2. For instance, methane is estimated to have a global warming potential factor of 28-36 relative to CO_2 over 100 years (EPA, 2018).

The current degree of warming is presumably caused by human activity and the corresponding increased level of greenhouse gases. Climate change has caused the global temperature to rise approximately 1.1 degrees Celsius since the late 19th century, where the ocean have absorbed much of this increased heat. It has revealed a decline in the extend and thickness in the Artic sea ice, accelerated sea level rise and more intense heat waves. In other words, this can have major consequences for human health and ecosystems if the global temperatures continues to rise (NASA, 2018).

The Kyoto Protocol is a legally binding agreement between nations that decides the amount of GHG emissions the involved industrial countries are liable to reduce. After the renewed protocol in 2012, all parties were committed to reducing their GHG emissions by at least 18% below the 1990 level within 2020. Norway committed to reducing their emissions of GHG equivalent to 30% of the emissions in 1990 (Klima og Forurensningsdirektoratet, 2011). In 2016, the Norwegian GHG emissions for all industries were 3% higher than in 1990. Oil and gas extraction and increased energy supply across the country have been the main sources of the high amount of GHG. The domestic shipping and fishing contributed to 2.9% of the total emissions in 2016 (Statistisk Sentralbyrå, 2018).

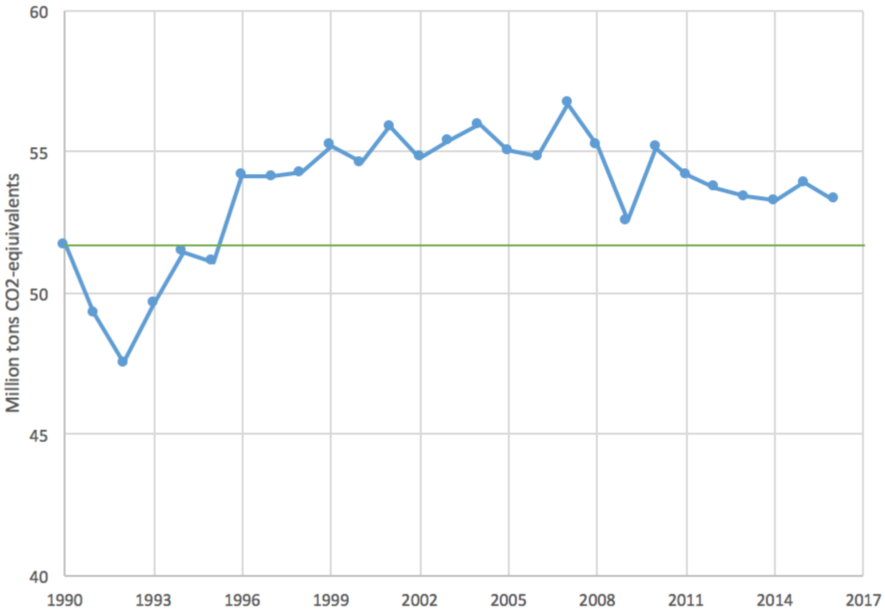


Figure 2.1: Norway's emissions in CO2-equivalents from 1990-2017. Data derives from Statistisk Sentralbyrå (2018)

Figure 2.1 illustrate the increase in exhausted GHG since 1990, but the trend for the recent years also reveals a reduction in emissions. The green line represents the GHG emissions from 1990.

The obligation deriving from the Kyoto protocol means that Norway have a certain allocated emissions quotas for the whole period, from 1. January 2013 to 31. December 2020.

The protocol allows countries to fulfil their obligations by the use of different mechanisms. Norway have the opportunity to obtain quotas when investing in emission-reducing projects, also known as joint implementation. For instance, when the authorities give financial help when investing in projects that can reduce the total exhausted emissions in the country (Klima og Forurensningsdirektoratet, 2011).

Further, MARPOL Annex VI intention is to reduce the GHG emissions by predominantly energy efficiency. This means that it is desirable to use less energy to produce the same amount of service. The Ship Energy Efficiency Management Plan (SEEMP) is mandatory for all ships and is an operational measure to improve energy efficiency of ships in a feasible way (Marpol Annex VI, 2018). Whereas the energy efficiency for fishing vessels can be seen as the amount of fuel used to catch the amount of fish.

2.2 NOx

NO_x is a reactive gas, where the major sources is from high temperature combustion processes, arising from engines or power plants. NO_x emissions can have a negative impact on the environment, and at some level cause harm to forests, fish and animal life. The gas is one of the main contributor to problems regarding air quality in the Nordic region (Martinsen and Torvanger, 2013).

The amendments to MARPOL Annex VI have introduced specified emissions controlled areas (ECAs) where it is aimed to reduce the regional air pollutants, such as NO_x, SO_x, ozone-depleting substances (ODS) and volatile organic compounds (VOC). This will be further explained in Section 2.5. The NO_x emission standard is divided into three tiers, where it sets NO_x emission restrictions based on the time of the ship construction and sailing area. The restrictions presented in Table 2.1 below, applies for marine diesel engines with the rated engine speed between 130-1999 rpm.

Table 2.1: Tier I-III NOx emission limits. n represents speed of engine in rpm (IMO, 2018a).

Regulation	Time of ship construction	NOx limit
Tier I	On or after 1. January 2010	$45xn^{-0.2}g/kWh$
Tier II	On or after 1. January 2011	$44xn^{-0.23}g/kWh$
Tier III	On or after 1. January 2016	$9xn^{-0.2}g/kWh$

Table 2.1 illustrates that Tier III have an even more demanding reduction of NO_x, by approximately 74-76% compared to Tier II. While the Tier III applies to NO_x Emission Control Areas, Tier II holds for rest of the world. For engines with $n < 130$ rpm, a fixed value for NOx limit (g/kWh) of 17.0, 14.4 and 3.4 are established for Tier I, II and III, respectively. This is further illustrated in Figure 2.2.

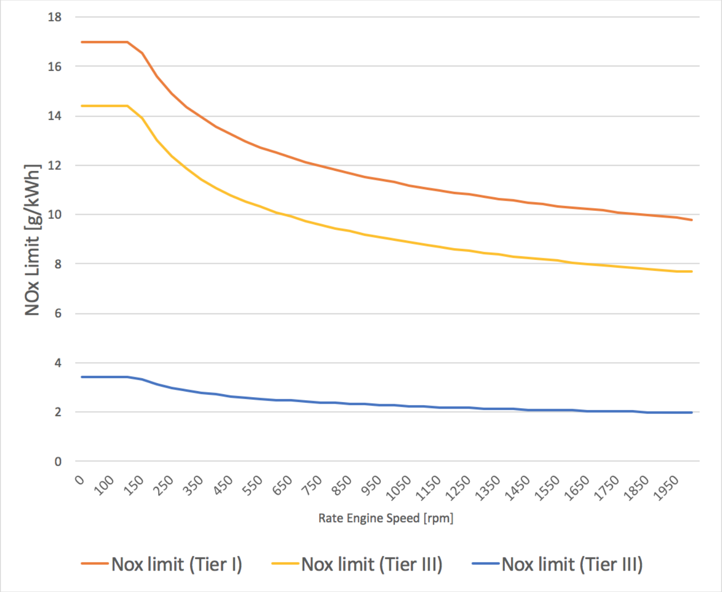


Figure 2.2: Illustration of NOx limits for Tier I-III.

NO_x can be abated by measures which reduce the amount of NO_x during the combustion process or by neutralizing the exhausted gas. Technology such as selective catalytic reduction (SCR) converts the reactive gas into N_2 and water. But one of the most efficient methods is to adopt a main fuel source that gives a cleaner exhaust. This can give a reduction up to 90% dependent on the alternative fuel (Martinsen and Torvanger, 2013).

2.3 SOx

Traditional bunker fuel contains large amounts of sulfur. During the combustion process of the engine, SO_x is caused by the oxidation of the sulfur into SO_2 and SO_3. It can have adverse effects on human health and environment, affect plants and can contribute to acidification of aquatic and terrestrial ecosystems (Martinsen and Torvanger, 2013; Jafarzadeh, 2016).

As stated, MARPOL Annex VI establishes certain SO_x Emission Control Areas (SECAs) with more stringent controls on sulfur emissions (IMO, 2018b). The sulfur content of any fuel oil used on board ships globally or inside an ECA, should not exceed the limits presented in Table 2.2, expressed in terms of % m/m, i.e. by mass. As shown, the restrictions have been subjected to a series of changes and have become more stringent during the last few years. The 2020 global sulfur limit was established when the regulations was was adopted in 2008. However, the new lower global cap have to be reviewed. Dependent on the availability of low sulfur fuel for use by ships, the global requirement can be deferred until 1. January 2025, i.e. 2020* as seen in Table 2.2.

Table 2.2: Overview of SOx limits inside and outside ECAs (IMO, 2018c).

Outside an ECA established to limit SOx and particulate matter emissions	**Inside an ECA established to limit SOx and particulate matter emissions**
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020*	0.10% m/m on and after 1 January 2015

The amount of exhausted SO_x is dependent on the content of sulfur in the applied fuel, and therefore an effective way to reduce the exhausted SO_x is to utilize a low-sulfur fuel. By using alternative fuel with no relevant sulfur content, SO_x can be reduced by 95-100% (Martinsen and Torvanger, 2013). As an alternative, scrubbers can be installed on the vessel to reduce the sulfur emissions which makes it possible to use heavy fuel oil (HFO) and still meet the global requirements, despite of a high sulfur content.

2.4 PM, BC and VOC

Particular matter (PM) and black carbon (BC) does also have negative effect on the environment and therefore desirable to reduce the emissions from the substances. However, the effect of reducing measures is somewhat uncertain. Today, it does not exist any specific regulations regarding PM emissions from shipping. But reduction of PM and BC are associated with the SO_x abatement, which means that the measures deriving from SECA regulations can have an effect. The effect of utilizing alternative fuel types is not well documented, but fuel savings in general can provide valuable reduction and LNG can nearly eliminate the emissions from these substances (Martinsen and Torvanger, 2013).

Vessels does also contribute to emissions of VOC. A reaction between VOC and NO_x can form ground-level ozone which can damage health, vegetation and material.

The Gothenburg protocol, similar to the Kyoto protocol, is one of the agreements that commit countries to various emission reductions. In relation to the Gothenburg protocol, Norway was committed to reduce the national VOC by 30% compared to the level of exhausted VOC in 1990. This target was reached in 2006, and the VOC has been reduced since then due to strict regulations and improved processing (Miljødirektoratet, 2018a,b).

2.5 ECAs

As mentioned before, MAROL Annex VI have established ECA zones for different regional pollutants.

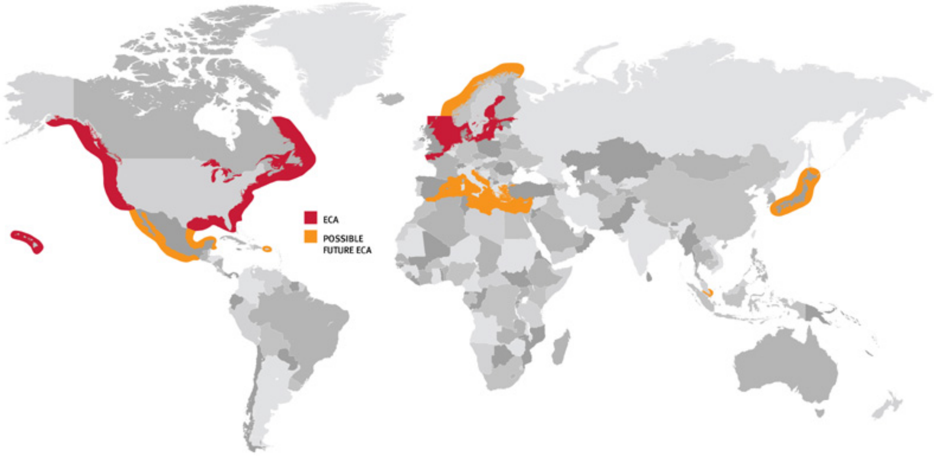


Figure 2.3: Map illustrating ECAs and possible future ECAs. Licensed from: Fuel Trade (2018)

Figure 2.3 is showing that the North sea is the only area within the Norwegian fishing region that is categorized as ECA for the time being. This means that most of the Norwegian fishing fleet only have to comply with the global requirements today. There are no definite plan in expanding the ECAs according to DNV GL and Kystverket. Nevertheless, Figure 2.3 also illustrates possible future ECA zones. The risk is still existent, and it is further reasonable to believe that global demands will reach the same restriction as today's ECA in the near future, which can have an impact on the Barents Sea and important fishing grounds (Yoo, 2017).

2.6 Environmental taxes and funds

In order to comply with the Kyoto protocol mentioned in Section 2.1, the Norwegian government applies CO_2-taxes based on the amount of CO_2 the fuel emits when burned. Taxes also applies for the content of SO_x and NO_x of the fuel. Whilst ocean-going fishing vessels are exempt from CO_2 and SO_x taxes in Norway, the fishing vessels operating in coastal waters (i.e. within 250 nm from shore), are subjected to 0.29 NOK and 0.131 NOK per liter MGO of CO_2 and SO_x, respectively (Finansdepartementet, 2017). This is compared to the general rate of 1.33 NOK per liter fuel for CO_2-taxes. LNG-fuelled fishing vessels are exempt from these taxes regardless of the fishing area (Skatteetaten, 2018a).

As stated, Norway is also part of the Gothenburg Protocol, which is a multi-pollutant protocol that sets emissions ceilings for pollutants, including NO_x. To comply with the protocol, the Norwegian government have established NO_x tax for different sectors. A fishing vessel operating within 250 nm of shore and with a total engine power of 750 kW, is liable to be taxed on NO_x-emissions. This tax rate is 21.94 NOK per kilo of actual emissions of NO_x in 2018 (Skatteetaten, 2018b).

The fishing fleet have the possibility to be involved in the NO_x fund, a fund established to reduce the emitted NO_x. Companies involved in the NO_x fund, contributes with a rate directly to the fund rather than paying NO_x tax to the state. If a vessel adopts a NO_x reducing measure, it can pay a lower rate to the NO_x fund instead of taxes. For the period 2018-2025, the rate of payment to the NO_x fund are 6 NOK per kilo exhausted NO_x for fishing vessels, which have already been showing significant improvements of the environmental profile of the fleet (NHO, 2018).

2.7 Incentives

Utilizing innovative technological solutions which are not yet commercialized, can be demanding both financially and technologically. Incentives in form of economical support are therefore an important drive for stakeholders to make modifications and choose innovative solutions.

Enova is an organization owned by the Ministry of Petroleum and Energy in Norway that provides support and contributes financially to innovative and sustainable projects, which also applies to the fishing fleet in Norway. Their investment is for equipment and for introduction to new technologies on vessels, which is a great motivation to select a more environmental-friendly option. Enova can cover 50% of the project's additional cost, where the additional cost is the cost difference between the green investment and the conventional solution (Enova, 2017).

In addition, involvement in the NO_x fund can be beneficial beyond the lower pay rate for NO_x emissions. The companies associated with the fund can also apply for financial support to invest in new sustainable technology. For instance, the Norwegian NO_x-fund is a significant contributor to various LNG-project that have been developed in Norway. The fund has granted support to more than 1000 applicants for NO_x reducing measures by February 2017. In total, this is approximately 5.5 billion NOK as incentive. These measures are expected to reduce NO_x with 44,000 tonnes (NHO, 2016). The NO_x fund will support the investment by 350 NOK per kilo NOx reduced for gas-fuelled vessels, where the support is limited to 80% of the total additional investment cost (Næringslivets NOx-fond, 2017).

2.8 The impact of climate change on fisheries

As stated, climate change can have major consequences for ecosystems if the global temperature continues to rise, and consequently a significant effect on the fishing industry and fisheries management. According to Seafish (2009), it can lead to the following:

- Changes in the abundance of fisheries, a shift in distribution and changes in productivity.
- Extinction of species.
- Invasion of new species.
- A decline in ocean primary production.
- An increase in ocean acidity.

Increased CO_2-emissions leads to increased absorption of CO_2 in the ocean. This can cause a chemical reaction that cause the pH-value in the ocean to fall and reduce the amount of carbonates. Different species and marine habitats in the sea are sensitive to reduction of the amount of carbonates, and can in the worst case scenario lead to extinction of particular species (Miljødirektoratet, 2013).

It is likely to believe that fishermen have the commercial interest in reducing the CO_2-emissions, considering that CO_2 absorbed in the sea harms the common fishing grounds. However, the issue of environmental pollutions from fisheries is a great example of the *Tragedy of the commons* by Hardin (1968), describing the dilemma where every actor are pursuing their own best interest in a society believing in freedom of the commons. The common environment is shared by the entire world, and therefore challenging to get every actor involved in emission reducing measures requiring a higher cost for the single actor. Investment in the environment by one actor is beneficial for everyone, and not only for the individual actor. Global and national regulatory requirements concerning emission abatement are therefore an essential part of preserving the environment in the best possible way.

Chapter 3

The Norwegian Fishing Industry

The fishing industry remains an important industry in many counties and regions in Norway, whereas the industry is a big part of the global market. In order to assess the feasibility of using alternative fuel, it is beneficial to characterize different aspects of the Norwegian fishing fleet.

3.1 The Norwegian fishing fleet

The fishing fleet is divided into several sizes and segments, determined by their fishing method and equipment. Further, they are characterized between coastal-going and seagoing vessels. This division is predominantly determined by their size, but also partly on their authorized fishing rights. The fleet can also be categorized by whether the vessel fish for bottom fish (such as cod, haddock or pollock) or pelagic fish (such as mackerel and herring). Most of the 5000 fishing vessels sailing in Norwegian waters are small with a length under 15 meters, while only 231 vessels have a length over 28 meters today (Fiskeridirektoratet, 2018a). Although, the vessels ranging over 28 meters accounts for about 81% of the quantity of the caught fish (Fiskeridirektoratet, 2016).

The larger fishing vessels have limited access to fish along the coast, where the largest trawlers must always fish at least 12 nautical miles from the Norwegian baseline (Lovdata, 2008). While the coastal fishing vessels use their quotas when the fish enter the coast to spawn in February to April, the ocean-going vessels will provide income throughout the year by adapting their sailing routes to where the fish is located. The larger vessels often have freezers and factories installed on board, allowing the vessel to sail for a time period up to four to six weeks.

The fishing vessel is a complex system in terms of all of the equipment on board and the functions required. This makes the engineering and technology behind it extremely advanced. For larger vessels, the complex system consist of propulsion and steering machinery, fishing gear, deck, accommodation, freezers, navigation and communication equipment.

As stated by the National Research Council (1991); *"All of the components form the complete engineering and technical system needed to catch, preserve and transport fish."*. Hence, one of the most important main function of a fishing vessel is to catch fish by the help of the designated fishing gear, and this should be done in the most efficient and cost effective way. The catch should further be processed and stored to achieve the highest possible quality. Other important functions is to be able to locate the fish and be a safe working platform for the crew. For these main functions to be intact, different supporting functions have to be provided for the vessel. A supporting function are for instance the energy source or the propulsion system (Ellingsen, 2007).

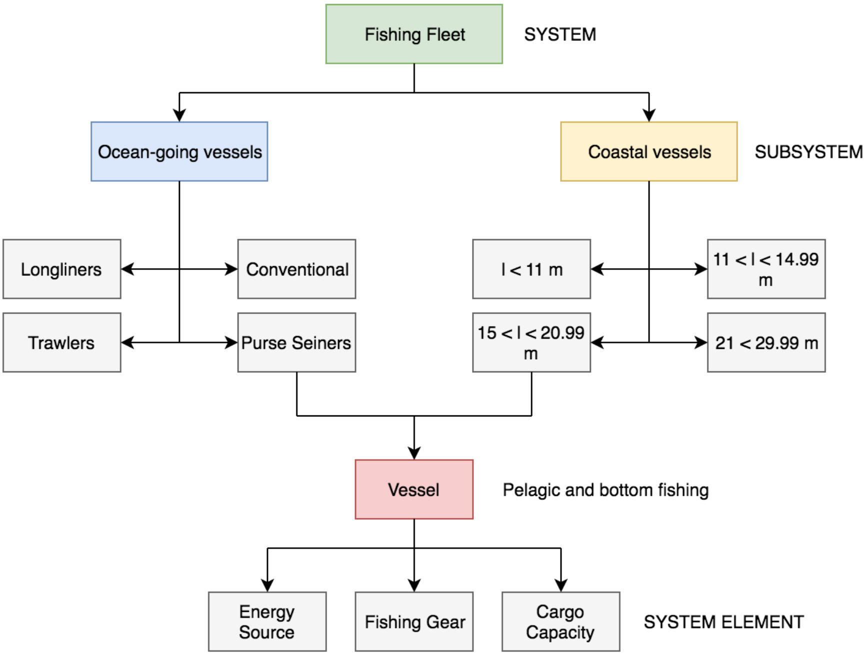


Figure 3.1: Decomposition of the Norwegian fisheries. Based on Utne (2007).

Figure 3.1 illustrates how the fishing fleet can be divided into categories or subsystems dependent on their size and fishing gear. Further, the corresponding system elements are considered as supporting functions for the vessel's performance and main function.

Traditionally, design of fishing vessels are based on empirical methods and are heavily influenced by regional preferences, which creates resistance towards innovative and state-of-art technology.

As stated, the fleet consist of vessels using different fishing methods and gear, processes and stores the fish differently and with individual operational profile. The following study case addresses a trawler, thus a brief explanation of the relevant vessel segment will be given.

3.1.1 Trawlers

There are different types of trawlers, where their common catch technique is by utilizing trawl net. This is a funnel shaped net that is hailed by the vessel under the surface of the water at the required depth to catch the right species (Marine Insights, 2017).

Trawlers are one of the most common designs of fishing vessels. The two main groups of trawling practices are bottom trawling and pelagic trawling. In addition, there are a combination referred to as semi-pelagic trawl. As their name suggest, this depends on the desired fish species located at a certain depth. The size of the trawl nets can vary in a great extent, based on factors such as behaviour of the fish, bottom conditions and engine power of the vessel (Fiskeridirektoratet, 2010).

The trawlers can be characterized in three groups; stern trawler, side trawler and outrigger trawler, where the deck arrangement and equipment is dependent on the relevant group. All trawlers are equipped with trawl winches for handling and storage of the towing warps. Gilson winches, net drums and other auxiliary winches are normally installed to handle the gear and catch. The trawlers range in size, from open boats up to large freezer and factory trawlers which can store and catch fish in the most distant waters. These deep water trawlers are supported with heavy engines that gives sufficient power to haul the trawl at the convenient trawling speed. The factory trawlers usually have the wheelhouse and accommodation placed in the forward part of the vessel. Further, the winches are placed at each side near the stern. The factory is located strategically, below the fishing deck where the catch is hauled in from the stern and delivered to the factory from hatches (FAO,FIIT, 2001).

3.2 Energy efficiency

The operational profile for ocean-going fishing vessels can vary in a great extent for each roundtrip, compared to for instance ferries or cruise ships whereas the sailing route is more or less fixed. Several factors affect the fuel consumption for one roundtrip; such as time spent on heavy operations, weather conditions, duration of the trip and sailing area.

Operations can in general be incredibly energy demanding due to a combination of harsh weather conditions and extensive fishing methods, but also because of energy consuming freezers and heavy machinery on board. Jafarzadeh et al. (2016) examined the energy efficiency of the Norwegian fisheries, based on data from 2003 to 2012. Figure 3.2 shows the results of the statistical characteristics for ten different fishing segments. The energy efficiency for the different segments are fluctuating due to the effect of quota regulations and access to fish.

It was found that the fuel coefficient (kg fuel/kg fish) have in fact decreased from 2003, but shows a great differentiation between some of the fishing segment. The factory trawlers and wet fish trawlers was found to be the least energy efficient segments, with a mean fuel use coefficient of 0.354 and 0.322 kg fuel/kg fish, respectively.

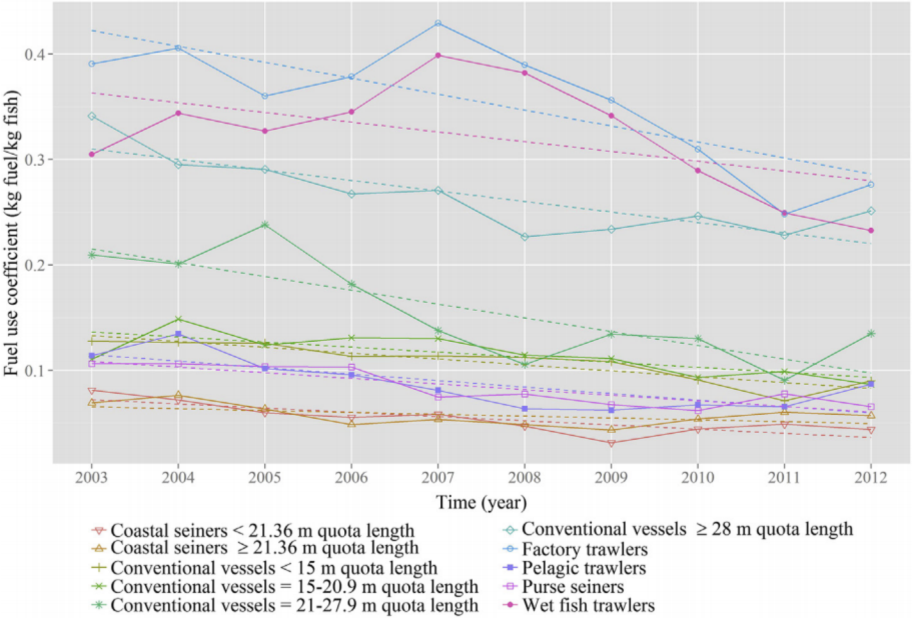


Figure 3.2: Energy efficiency of different segments in the Norwegian fisheries from 2003 to 2012 (Jafarzadeh et al., 2016).

Due to its active fishing gear and excessive transit time to fishing grounds it is apparent that trawlers uses a lot of energy. From the paper *'The next generation stern trawler'* by Enerhaug (2010), it was stated that the cod trawlers accounted for just over one third of the total energy consumption of the entire fishing fleet in Norway. Having in mind that this is based on the entire fleet, and not the percentage. They explained that measures aimed at this part of the fleet can have the greatest effect.

Chapter 4

Energy Sources and Systems

4.1 MGO

This section provides information about the conventional fuel applied on fishing vessels today. MGO is one of the main products for small to medium sized vessels in the Norwegian seagoing traffic, and available along the entire coastline of Norway.

4.1.1 Properties

There are a variety of types and qualities of oil products, or bunkers, which are utilized as fuel on vessels. The fuel is specified by composition, viscosity and sulfur content. MGO is exclusively made out of distillate and not combined with HFO. The sulfur content is usually around 0.05% to 0.10%. By comparison, there is a maximum limit of 0.001% sulfur in automotive diesel and therefore a significant difference between the sulfur content of fuel products used on land and at sea. Unlike HFO or marine diesel oil (MDO), MGO has a low viscosity and can easily be pumped into the engine at temperature around 20 Celsius degrees (Marquard & Bahls, 2015). It will evaporate and mix into the water masses quickly compared to other oils, and the toxicity to marine organisms can be high (DNV GL, 2014).

Table 4.1: Typical value for properties of MGO, presented by Statoil Fuel & Retail Marine AS (2017).

Properties	**Typical value**
Density	855 kg/m3
Sulfur content	0.05 - 0.10 %
Lower heating value	42.8 MJ/kg

MGO have no significant differences in terms of emission factors of CO_2 and NO_x compared to HFO. However, the sulfur content is lower and therefore it results in lower SO_x

emissions. Thus, MGO can be an attractive option for vessels sailing in ECA zones (Marquard & Bahls, 2015). MGO is significantly more expensive than the other conventional fuels such as HFO, which is predominantly used in commercial shipping.

4.1.2 Advantages and drawbacks

Using a conventional marine fuel will be known and familiar for the crew. Hence, the risk of human-errors will be reduced compared to using new alternative solutions if there have not been sufficient training. Utilizing unfamiliar fuel needs knowledge of critical properties, how the system will impact the vessel and expertise regarding operations, such as manoeuvring, maintenance and emergencies.

As for bunkering facilities, there are already several sites in Norway and the infrastructure is well-established with dominant suppliers such as Equinor, Shell and Bergen Bunkers (DNV GL, 2014). Further, the traditional design of the general arrangement for various fishing vessels today, takes the engine room and fuel tanks into consideration. The fuel storage tanks can be stored where there is available space, as opposed to LNG and other alternatives that require circular cryogenic tanks for storage. A transition from the conventional fuel type to new technologies can be seen as challenging for arrangement planning and optimalization.

Even though most of the Norwegian fishing vessels consume a low sulfur fuel, it still contributes to a large amount of exhausted emissions due to a high fuel consumption of the fishing fleet in general.

4.2 LNG

4.2.1 Properties

The main component in natural gas is methane (CH_4), but it can also hold a small percentage of CO_2, nitrogen (N), hydrogen sulphide (H_2S) or helium (He). The composition depends on the geographical location.

LNG is natural gas which is cooled and condensed to liquid form. LNG is produced to enable transportation of gas where pipeline investment are not suitable, in addition to easier storage. The volume is reduced by 600 times of the gas phase volume when cooled down to minus 162 degrees Celsius in atmospheric pressure (Barents Naturgass, 2017). Dependent on the composition, LNG acquire 60-70% of the energy density of diesel in volume. The gas is flammable, but has a high self ignition temperature of approximately 600 Celsius degrees (Martinsen and Torvanger, 2013).

4.2.2 Advantages and drawbacks

Using LNG for marine applications have become more available and is proven to be an acceptable solution for various types of vessels. Central drivers for this development are the emissions regulations, such as MARPOL Annex VI, especially within the ECA zones. It is predicted stable low gas prices compared to oil and diesel, making the fuel attractive for future newbuilds and projects (DNV-GL, 2015a).

As previously stated, the main argument of using LNG as ship fuel is considered the reduction in regional air pollutants and GHG. The exhausted emission reduction can be significant when it comes to CO_2, with approximately 20-25% reduced emissions due to its higher hydrogen to carbon ratio (Lloyd's Register, 2017). $\mathrm{NO_x}$ can be reduced by 85-90% compared to HFO due to a cleaner exhaust, whilst $\mathrm{SO_x}$ can be completely eliminated by using LNG as fuel due to no significant sulfur content (Martinsen and Torvanger, 2013).

There are however some uncertainties regarding the environmental impact and drawbacks when utilizing LNG as fuel. This is particularly related to the leakage of methane, also known as methane slip, which can occur during processing and combustion of the fuel. During leakage, the LNG vaporizes into the atmosphere without any significant direct impact on local ecosystems. However, the environmental impact and global warming potential have been a subject of discussion, where methane has a significant high impact on the total CO2-equivalents relative to other substances, which will have great influence on the GWP and human health. State-of-the-art engines available today can in some degree keep the fugitive methane emissions to a minimum from combustion processes (DNV-GL, 2015a). This will be further elaborated in Section 4.2.4.

4.2.3 LNG on fishing vessels

Various studies that involves LNG on fishing vessels have been conducted and have shown presentable results. A study about alternative propulsion technologies for fishing vessels performed by Altosole et al. (2014), concluded that the use of dual fuel engine with LNG could result in lower emissions and cost savings of as much as 30% for fishing vessels. The report stated that MGO and MDO are expensive fuels, especially for the fishing industry. Further it was described by Altosole et al. (2014): *"The trawler fleet has a high energy consumption rate, around 40% of the total costs (rising with increasing price in fuel). Saving fuel is essential for limiting operational costs and decreasing the carbon footprint of fishing vessels."*

The consortium Alternative Fuels for Fishing vessels did research on three different fishing vessels for the application of natural gas as fuel. In the report it was concluded that for smaller fishing vessels the LNG installation is still too large and complicated. They believed that there are still challenges to face before LNG can be used in a technical and economical feasible way on smaller ships. When the fishing vessel is longer than 50 metres, there might be enough room for the LNG installation. Another important point made was that the rules for all LNG vessels are still derived from large LNG tankers, and that this should be changed to fit dissimilar vessels for other marine operations (Koers & Vaart B.V., 2016).

To this date, there have not been any conversion projects or new-build fishing vessels adopting LNG as fuel in Norway. The reasons for this could be many, but it can be expected that this is due to its space demanding system or that LNG is still in a development stage for different vessel segments, to mention some.

4.2.4 LNG systems

Following, the correlated major system components of LNG are presented.

Gas engine concepts

One can divide gas engines into four different types, where each concept have different effect on efficiency and exhausted emissions. Hence, selected technology will influence the overall environmental effect from the combustion.

The different gas engine concepts have been presented by Sintef (2017), and are explained below.

- Lean-Burn Spark Ignited engines (LBSI-engine), medium-high speed, (0,5-8 MW). Have been used on gas-fuelled passenger/car ferries sailing along the Norwegian coast. But also vessel types such as RORO, Product Tankers and Offshore supply vessels (OSV) have also adopted this type of engine.
- Low pressure Dual-Fuel engines (LPDF-engine), medium speed, 4 stroke (1-18 MW). These engines are dominant for the offshore segment. The main reason for choosing dual-fuel (DF) engine, is the diesel oil as back up fuel and ability to operate on diesel oil.
- Low pressure Dual-Fuel engines (LPDF-engine), slow speed, 2 stroke (5-63 MW). This type has been seen as a prime mover for commercial ships.
- High-pressure Gas Injection (HPDF engine), slow speed, 2-stroke (Above 2,5 MW). This type has not been used to power vessels operating in Norwegian waters, but exist as a good option for larger ships.

Sintef (2017) have stated that the engine and gas system for the ship should be evaluated and adopted based on requirements such as propulsion power, redundancy, flexibility, endurance, operational profile, gas availability and commercial issues.

LBSI-engine and LPDF-engine can both cause methane slip, which means unburned methane is emitted from combustion. As stated, methane cause a higher greenhouse effect than other gases and are of great concern when evaluating gas as fuel. There are two main reasons for methane slip from gas engines (Sintef, 2017):

- Gaps or crevices in the system, causing dead volume in the cylinder unit components. During compression stroke, the gas will be compressed into these crevices instead of being a part of the combustion process. While during expansion stroke, the gas will stream from the crevices. Methane needs a high temperature to ignite, so these methane molecules are to a large extent unburned due to low temperatures during expansion. Design and state-of-the-art technology can help preventing this from happen to a certain degree.

- A incomplete combustion in form of quenching can occur when gas mixture is too lean and cooled down along the cylinder liner. This can be an issue at low load operations. Quenching can be reduced by using a richer mixture, but at the same time this will provide more exhausted emissions of NO_x.

Valve-overlap can also be a cause of methane slip, but new engine designs runs with practically no valve overlap. Hence, this methane slip can be neglected (Sintef, 2017).
The internal combustion engines can in general lose around 30% of their energy through exhaust as heat. The advantage with gas engines, is that it can recover around 10% of the total engine power from wasted exhausted heat into the vessel's waste heat recovery system and can be used as excess power for propulsion systems on board. The sulfur in the exhaust from diesel engines makes it harder to recover the heat due to accumulation of particles (Rolls-Royce, 2018a).

A vessel is dependent on a degree of redundancy while in operation, which means that there have to be some sort of back-up if there is a system failure or if something is damaged. For vessels with conventional diesel engines, it is enough to install one main engine. However, regulations states that gas installations require more components. One gas engine itself is not certified for use in a single-engine configuration. It have to be combined with a PTI or an alternative propulsion system, or by installing an additional gas engine in a separate engine room (CMAC, 2013; IMO, 2015).

Tank types

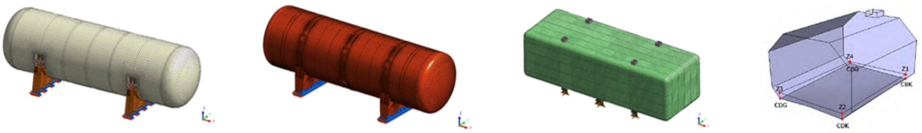
The LNG tank holds the largest investment cost of an LNG fuel system, where the price is predominately dependent on its size. There are some available types of containment systems for LNG, but not every type is feasible for the given conditions on vessels using LNG as fuel (Harperscheidt, 2011).

The containment system is a heavily insulated tank, in order to maintain the LNG is cryogenic temperature under vapor pressure ranging from atmospheric pressure up to 10 barg. Due to large temperature differences between containment and the system's surroundings, the temperature inside the tank can increase and cause boil-off gas (BOG). Unless the BOG is removed, it will gradually build up the pressure inside the tank. It exist two type of tanks handling pressure: pressure tanks and non-pressure tanks. The latter emit BOG to its surroundings to keep an atmospheric pressure, while pressure tanks are designed for increased pressure (Chang, 2017).

The LNG fuel tank must be selected from *Independent Types A, B, or C of the The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)* according to The Interim Guidelines on Safety for Natural Gas Fuelled Engine Installation in Ships (Resolution MSC.285(86)). The independent tank types are self-supporting and does not form part of the vessel's structure. Membrane tank, an integrated and non-self-supporting tank type solution, can also be used for fuel according to the IGC Code.

Table 4.2: Main characteristics of the different tank types (IMO, 2015; WPCI, 2016)

Tank type	Description	Pressure	Pros	Cons
A	Prismatic tank, adjustable to hull shape; full secondary barrier	<0.7 barg	Space-efficient	Boil-off gas handling. More complex fuel system required High costs
B	Prismatic tank, adjustable to hull shape; partial secondary barrier	<0.7 barg	Space-efficient	Boil-off gas handling. More complex fuel system required High costs
	Spherical tank; partial secondary barrier		Reliably proven in LNG carriers	Boil-off gas handling. More complex fuel system required
C	Pressure vessel, cylindrical with dished ends	>2.0 barg	Allow pressure increase. Simple fuel system. Little maintenance Easy installation Lower costs	On board space requirements
Membrane	Integrated tank, structural part of the ship hull; full secondary barrier.	<0.7 barg	Space-efficient	Boil-off gas handling. More complex fuel system required



IMO Type C Single Shell

IMO Type C Double Shell

IMO Type B

Membrane

Figure 4.1: Illustration of different tank types. Retrieved from DSEC (2018)

Table 4.2 explains the difference between tank types presented by the IGC Code. It is stated that tank type A and B need full and partial secondary barrier, respectively. As stated in the IGF code, IMO (2015): *"Secondary barrier is liquid-resisting outer element of a fuel containment system designed to afford temporary containment of any envisaged leakage of liquid fuel through the primary barrier and to prevent the lowering of the temperature of the ship's structure to an unsafe level."*

The risk of leakage is lower for tank type C, and therefore no secondary barrier is needed. Tank type C is often the preferred solution for current designs and are used on both ferries and offshore vessels (WPCI, 2016). The tanks are safe and reliable, and are easier to fabricate and install. Further, tank type C is designed to withstand pressure and are to a high degree insulated, making the system exempt for boil-off gas handling and protects the ship structure from very cold temperatures. Boil-off gas handling requires additional components and subsystems, therefore highly undesirable for compact and largely equipped vessels. A tank type C can hold the boil-off for around 25 days before reaching the maximum allowed tank pressure. Even though tank type C does not have secondary barrier required, it demands 2-4 times more space than conventional tanks with HFO (WPCI, 2016). This is due to the regulations and design restrictions, requiring the tanks to be cylindrical or spherical shaped.

Filling level of the LNG storage tank must also be taken into account. There is a minimum filling level of 5%, due to ensuring that the tank remains in cryogenic condition. In addition, a maximum filling level of about 85-95%, dependent on the design, density of the LNG, system pressure and working area. In regards to the storage capacity of an LNG storage tank, a rule of thumb is a storage capacity of 75% (Koers & Vaart B.V., 2016).

Fuel storage hold space

According to IMO (2015), fuel storage hold space is the space within the ship's structure in which the fuel containment system is located. Often, a tank connection space, also known as a cold box, is located inside this area. Requirements for installing tank connection space are given for smaller vessels with tank type C installed. The tank connection space is the space connected to the tank that surrounds all tank connections, tank valves, vaporizers and process equipment required in an enclosed space.

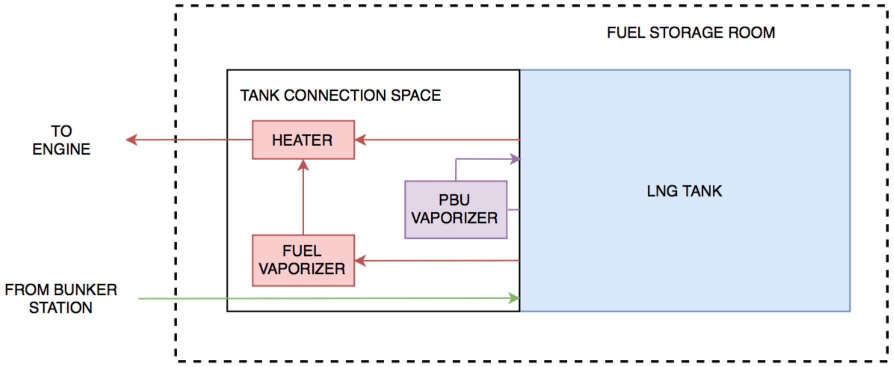


Figure 4.2: System drawing of LNG tank and additional equipment in tank connection space.

Figure 4.2 is a system drawing of the LNG tank and system components in the tank connection space inside the fuel storage hold space. PBU vaporizer is applied to handle pressure build-up inside the tank to keep a constant pressure.

Another component in the system which is not illustrated in the system drawing is the gas regulation unit (GRU) for control and regulation of the gas. The GRU have to be located inside a controlled space with air lock, between the engine and storage tank. It is required one GRU for every gas engine.

Bunker systems

When supplying a vessel with bunkers is known as bunkering. The vessel using LNG as fuel is equipped with two bunker systems, often located port and starboard. The bunker system can be either operated manually or automatically.

4.2.5 Infrastructure

LNG infrastructure represents the equipment and facilities, transport, storage and bunkering related to the supply of natural gas in form of LNG on board vessels for use as fuel.

When providing LNG as fuel to diverse vessel segments and shipping areas, there can be difficulties regarding bunker infrastructure and to make it available wherever it is needed due to the low demand compared to more established fuels. Therefore, it is crucial to locate the LNG infrastructure where it is safe, fast and have a high accessibility for the operators. This is a major task for the actors involved in the small-scale LNG.

There is a difference between small-scale and large-scale LNG facilities. Small-scale LNG are facilities suited to distribute gas directly to the end-users, while large-scale is mainly for international commerce where the gas is filled in designated tankers in large volumes to further be delivered to the end-users.

Large parts of Norway consist of deep fjords and high mountains where access and development of piping for LNG distribution is difficult to achieve. Thus, small-scale LNG distribution have been developed to deliver LNG for different consumers across the country, essentially small LNG plants, small tankers and terminals. This development of small-scale distribution network have made it possible to use LNG as fuel on ships (Energigass Norge, 2015).

Using road tanker is the most common distribution method to end-users of small-scale LNG. By car, LNG can be delivered on any quay in Norway that meets the safety requirements. The delivery station can therefore be very flexible, and LNG can be offered over a large area. The cars can also deliver directly to the ship, thus avoiding the costs for the expensive bunkering terminals at the quay. However, using cars for bunkering also has its limitations. One car can carry around 50 m3 gas, which means several car tankers are needed for vessels equipped with large gas tanks. The bunkering can take up to two hours per vehicle, and there will be additional time spent due to the fact that a new car must be connected. Hence, where bunkering operations occurs frequently and for fuelling tanks above 100 m3, a fixed bunkering terminal provides more efficient and robust supply (Energigass Norge, 2015).

Even though LNG is an established fuel today, it can not compete with HFO or MGO when it comes to accessibility. The market development is still in an early stage, where lack of availability and infrastructure have been identified as an obstacle for further expansion. It requires further development of infrastructure and supply solutions to be as accessible as conventional fuels. Energigass Norge (2015) along with actors involved with supply of gas, have examined the status and development in the LNG market as a fuel for ships in Norway. This report is still just as relevant today. Some of their main findings was that the market for LNG is still small, but given the current market volume, the LNG infrastructure and supply are satisfactory, especially regarding access to small-scale LNG.

4.2.6 Requirements and regulations

It is mandatory for all newbuilds to comply with regulations from classification societies. Adoption of the international code of safety for ships using gases or other low-flashpoint fuels (IGF Code) is required for all ships using gas as fuel (IMO, 2015). The requirements related to the code are intended to minimize the risks as far as reasonably practicable, based on knowledge and technology. DNV-GL have also presents class notations for gas fuelled ships or dual-fuel concepts, which covers every aspect of the installation for vessels with gas as fuel. In regards of this thesis, regulations in relation to arrangement will be aimed attention to.

The IGF Code does not specifically apply for fishing vessels, but refers to cargo and passenger vessels. The regulations are more stringent for passenger vessels, therefore assumed that these regulations will be within the requirements and applicable for the fishing fleet.

Different regulations affect the ship arrangement principles due to hazardous areas and risk of leakage. Compared to a conventional installation, this can lead to several challenges with the arrangement. There are for instance some limitations to LNG tank location, where the tank must be placed:

- Away from engine room and other high fire risk spaces
- Away from ship side
- Away from risks of mechanical damage (cargo operations etc.)

Due to main safety challenges for LNG as fuel, the tanks must have:

- Protection from ship side and bottom (collision and grounding)
- Protection from external fire
- Protection from mechanical impact

(DNV-GL, 2016)

Some of the regulations regarding ship design and arrangement are further illustrated in Table 4.3.

Table 4.3: Regulations regarding arrangement and fire safety. Copy from IMO (2015).

5 SHIP DESIGN AND ARRANGEMENT	
5.3 Regulations – General	
The fuel tank(s) shall be protected from external damage caused by collision or grounding in the following way:	
.1	The fuel tanks shall be located at a minimum distance of B/5 or 11.5 m, whichever is less, measured inboard from the ship side at right angles to the centreline at the level of the summer load line draught; where; B is the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught) (refer to SOLAS regulation II-1/2.8).
.2	The boundaries of each fuel tank shall be taken as the extreme outer longitudinal, transverse and vertical limits of the tank structure including its tank valves.
.3	For independent tanks the protective distance shall be measured to the tank shell (the primary barrier of the tank containment system). For membrane tanks the distance shall be measured to the bulkheads surrounding the tank insulation.
.4	In no case shall the boundary of the fuel tank be located closer to the shell plating or aft terminal of the ship than as follows: .1 For passenger ships: B/10 but in no case less than 0.8 m. However, this distance need not be greater than B/15 or 2 m whichever is less where the shell plating is located inboard of B/5 or 11.5 m, whichever is less, as required by 5.3.3.1.
.5	The lowermost boundary of the fuel tank(s) shall be located above the minimum distance of B/15 or 2.0 m, whichever is less, measured from the moulded line of the bottom shell plating at the centreline.
.7	The fuel tank(s) shall be abaft a transverse plane at 0.08L measured from the forward perpendicular in accordance with SOLAS regulation II-1/8.1 for passenger ships, and abaft the collision bulkhead for cargo ships.
11 FIRE SAFETY	
11.3 Regulations for fire protection	
11.3.3	The space containing fuel containment system shall be separated from the machinery spaces of category A or other rooms with high fire risks. The separation shall be done by a cofferdam of at least 900 mm with insulation of A-60 class. When determining the insulation of the space containing fuel containment system from other spaces with lower fire risks, the fuel containment system shall be considered as a machinery space of category A, in accordance with SOLAS regulation II-2/9. The boundary between spaces containing fuel containment systems shall be either a cofferdam of at least 900 mm or A-60 class division. For type C tanks, the fuel storage hold space may be considered as a cofferdam.

Chapter 5

Methods

The methodical approach will be influenced by both qualitative and quantitative research. The information gathered will provide insights, while at the same time it is necessary to collect measurable data and statistics to formulate facts. The following sections presents the important aspects of the methods applied to assess the study case and analysis.

5.1 Case study

A case study is a research method used to assess the outcome of a real or a hypothetical situation. It is essentially a tool to help encounter the complexities of decisions. The documentation for the following study case is supported by research data as presented in literature review. The aim of literature review is to give a good insight in the LNG system and related aspects, which will further be taken into account when assessing the case.

A case study can be conducted alone or combined with several other research methods, such as quantitative modelling to analyze archival data, qualitative research and experiments (Yin, 2011). There are two main reasons for choosing a case study for a thesis (Denscombe, 2017):

- When developing a case study, it provides a useful platform that allows you to study a situation in a sufficient depth and detail.
- It is a convenient form of research and feasible in terms of the time constraints. Considering a limited time frame for a thesis, a case study can be advantageous.

An instrumental case study is applied to understand more than just a specific case. This is opposed to a intrinsic case study, which is applied when understanding a specific situation or individual. According to Stake (1995), an instrumental case is set as an tool to explore the possibilities beyond the particular case and further to promote an understanding of a specific issue.

Single case study analysis have been seen as incapable of providing external validity and have been criticised concerning researcher subjectivity. This can be conflicting especially when assessing a single instrumental case study. However, the outcome of the case can be analytically generalizable, which means that the results of the study can be compared and seen in context to developed theory. The outcome of the case should expose how it challenges or supports the theory or argument (Yin, 2011). Further, similar to other research methods, it is important to be explicit as possible about the degree of uncertainty (King et al., 1994).

5.2 LCA

Fuels release emissions at various stages in their life cycle, for instance during refining or transportation. Environmental performance of a fuel in a life cycle perspective have to be assessed in order to evaluate the total impact from extraction to combustion.

Life cycle assessment (LCA) is one method among others used to evaluate the environmental impact of a product throughout the complete life cycle, from cradle to grave (Sintef, 2018). LCA is chosen for this thesis because it can be a helping tool to objectively compare different alternatives and make better decisions, where the method quantifies the use of emissions and resources for the entire process.

It is important to emphasise that simplifications are necessary to be made when applying this method and some of the data are widely based on assumptions. Further, there is no standard method applicable for all situations, this is somewhat dependent on the goal of the LCA. A life cycle assessment for fuel can also be named Total fuel-cycle analysis (TFCA). Relative to the definition of LCA, the approach accounts for energy use and emissions along the entire "fuel cycle" (Thomson et al., 2015).

Figure 5.1 shows a simplified illustration of the life cycle of a marine fuel, where release of emissions can occur at every stage, and not just the combustion itself. The first stage is the extraction of raw material and delivery to refinery. The refinement or production stage includes liquefaction in the case of natural gas. The fuel is further transported to the distribution facilities. These three stages can be referred as upstream processes. The downstream processes include the recovery and combustion of the fuel from the vessel.

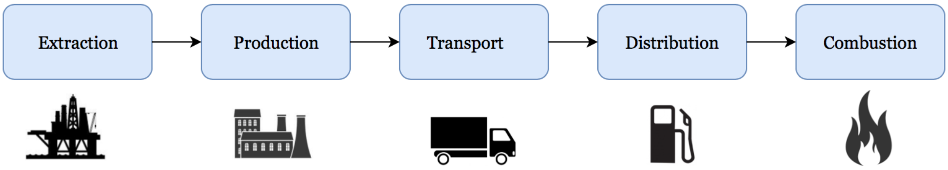


Figure 5.1: Flow diagram of marine fuel life cycle. Based on (Bengtsson et al., 2011)

The results deriving from LCA are often systematically presented for the different environmental categories, where the emissions are grouped in the environmental categories according to their environmental impact. Environmental categories can for instance be greenhouse effect, acidification or ozone depleting substances. Each substance have an allocated factor according to their effect on environment relative to other substances in same category (Goedkoop et al., 2012). As presented earlier, methane is estimated to have a global warming potential factor of 25-36 relative to CO2, thus methane will give a higher environmental impact in the given category.

The major challenge with LCA, in addition to limitations and uncertainty regarding data selection, is the weighting of the endpoint level, i.e between environmental categories and evaluation of the product's total potential environmental impact. This can for instance be the impact on human health and damage to ecosystem quality. This step is somewhat quasi-scientific, where it exist many different weighting methods to be applied. ReCiPe 2008 is one weighting method which can be applied for midpoint and endpoint level, developed by Goedkoop et al. (2012).

Figure 5.2 below, shows a complete evaluation of a product's environmental impact. Often, LCAs only assess the effects from the different environmental categories, i.e. from impact to effect.

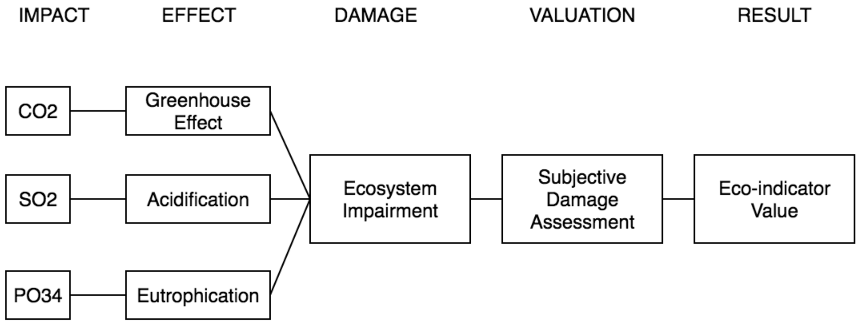


Figure 5.2: Simplified illustration of weighting method approach, Eco-indicator 95, for environmental impact.

5.3 LCC

The life cycle cost (LCC) is the present value of all costs incurred during the lifetime of a project. LCC is an economic analysis used to compare various potential projects in the conceptual phase, when the future revenues are uncertain (Magnussen et al., 2014).

$$LCC = Investment\, cost + Present\, value\, of\, all\, operating\, cost\, during\, lifetime \tag{5.1}$$

The term net present value (NPV) is an important economic term used as a criterion for determine if a project is economically viable (Magnussen et al., 2014). It measures the profit by subtracting the outgoing cash flows from the present values of incoming cash flows during the lifetime. Money spent on a project today, will have a different value in the future, whereas calculation of the NPV will estimate what the future value is worth today. NPV can be used as a suitable approach to find the total LLC when including the value of money in the future (Pohl and Nachtmann, 2007). The description of Equation 5.2 is stated below.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{5.2}$$

where R_t is the net cash flow during the period t. i represents the discount rate, i.e. the return that can be earned per unit of time on an investment with a related risk. Inflation and future uncertainties can be factors causing the future costs and benefits to be discounted to indicate their current value. n stands for the number of years examined.

5.4 Sensitivity analysis

Sensitivity analysis addresses the extent of credibility in the assumptions that have been taken and is used to examine how the results of a study can change if other assumptions are made. Sensitivity analysis is often performed to examine the robustness of the results and understand how sensitive the model is regarding future uncertainties (Chin and Lee, 2008). By changing one or several of the input variables in a financial model, one can determine how this will affect the output and outcome of the results. Scenarios can be created by changing the attributes in the model.

Different sensitivity analysis methods can be applied, whereas this is dependent on the studied system. The analysis can broadly be categorized as either a local or a global method. Local method, also known as one-factor-at-a-time approach, is performed by maintaining all factors constant while changing one variable to determine how this particular input will change the output value. When performing a global sensitivity analysis, several model inputs are changed simultaneously, where the parametric sensitivities are calculated over the whole range for every model input (Saltelli et al., 2000).

There are several benefits by performing a sensitivity analysis. Investors are able to be more perceptive regarding future risks and influence of changes related to different factors. However, when assessing different scenarios, the analysis require a high level of skills and expertise to forecast different plausible changes, especially regarding their probability to occur.

Part II

CASE STUDY

Chapter 6

Case Execution

6.1 Case selection

A case study will be performed to evaluate to what degree the LNG system can influence both the environmental impact and costs over the anticipated lifetime of a fishing vessel. The aim is to increase knowledge for ship owners and other important stakeholders regarding the benefits of utilizing LNG as fuel. The case study will be instrumental, whereas the motivation is to explore the subject and to further indicate how this can be applicable for fishing vessels of other magnitude as well.

This following case is based on an existing fishing vessel that uses MGO as fuel today. This part is conducted by using available data and information. Not all information about the vessel have been easy to provide, which have led to a series of assumptions. These will be further specified in the case.

6.2 System boundaries

For clarification, the system boundaries being studied are made clear as follows. The system being studied consist of environmental, economic and technical aspects of LNG compared to the conventional system on a fishing vessel. The environmental aspects will include the life cycle of the fuel during upstream and downstream processes. The economic aspects will address the major cost elements, covering capital and operational costs in addition to cost benefits. For technical feasibility, the different major components and design consideration will be taken into account, for instance, tank storage space and its positioning in relation to collision distance between tank and hull.

6.3 Case study approach

As stated initially, due to circular cryogenic tanks, additional systems and restrictions regarding arrangement, LNG will take up more space than conventional fuel. Geometric properties such as the volume of the LNG tank and corresponding system, are decisive when determining how the system will impact the hull form. In this case, the catch capacity is considered to be the same independent on the energy source. This will conceivably have an impact on resistance and fuel consumption of the vessel.

By also implementing the impact of changes in hull form when comparing the two fuels, makes the final results more measurable and legitimate. From this, the outcome of using MGO and LNG can be assessed in terms of environmental impact and costs. In order to conduct an evaluation of LNG and MGO in an explicit way, all calculations have been based on a 100% LNG powered vessel.

The approach applied, can be further viewed as the methodology for the case along with a qualitative and quantitative approach, allowing the foundation work to be performed in a structured way. The execution of the case study is listed on the next page, divided into three main steps.

Identification of vessel characteristics

- Elaboration of the characteristics of the existing vessel using MGO as fuel.
- Find a representative operational profile for the existing vessel using available data and regression formulas.
- From the operational profile, find the average amount of fuel (MGO) needed for one roundtrip.

Modification related to LNG system

- Initially, estimate how much fuel MGO corresponds to LNG based on the designated vessel and operational profile.
- Based on previous literature review and reasoning, select the LNG system components, e.g. gas engine and type of LNG storage tank(s), that is considered applicable for the vessel in terms of size and functions.
- Estimate the initial volume of the tank(s) required when including the regulations interpreted in the IGF Code.
- Evaluate the number of tank(s) seen as most sufficient, and arrange the tank(s) in the most space efficient way, by complying with regulations of ship arrangement from the IGF Code.
- Determine how the additional volume for LNG system will affect the main dimensions of the vessel. This leads to adjustments of the vessel's parameters and hull form, which will ultimately influence the resistance of the vessel. This will affect the values found in the initial LNG fuel estimate and adjustment of the storage tanks have to be applied. Hull form, required space for LNG system and amount of fuel consumption will have a mutual impact on one another, generating an optimalization problem regarding space efficiency. Figure 6.1 illustrates this stage.

Evaluation

- Evaluation of the environmental impact of MGO and LNG by assessing the life cycle of the relevant fuel. This will include both the upstream and downstream processes.
- Life cycle cost analysis of LNG investment relative to a baseline MGO investment. This will assess the operational expenses (OPEX), capital expenses (CAPEX) and voyage related expenses (VOYEX) during the lifetime of the vessel.

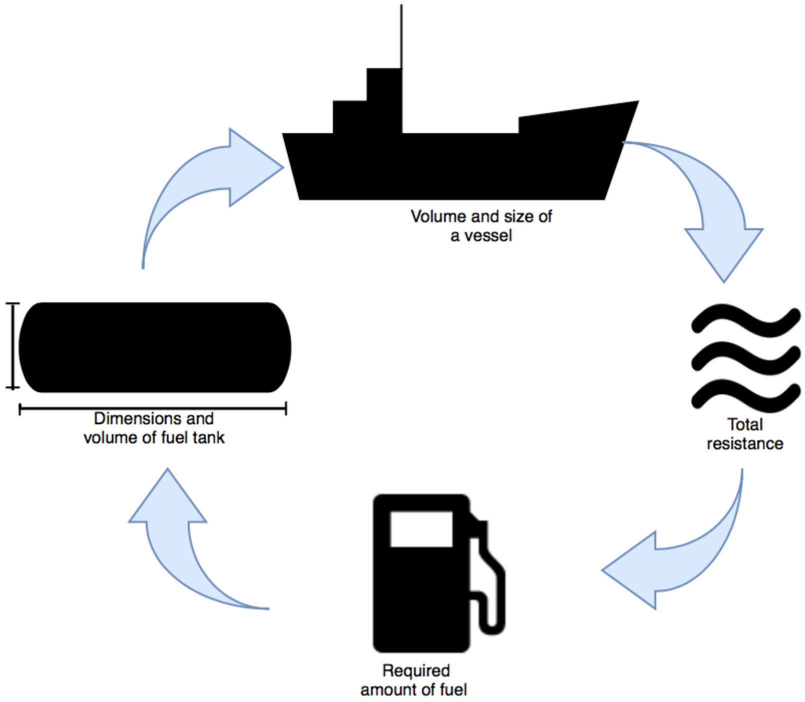


Figure 6.1: Relationship between different elements in the design phase.

Figure 6.1 illustrates how the different elements will have an effect on each other. The volume and size of a vessel will influence the total resistance applied, which again will impact the required amount of fuel or energy consumption. This can have an effect on the dimensions and volume of the fuel storage tank(s). Enlarged storage tank(s) will again influence the required volume of the vessel.

The following presentation of the case does not include every adjustment done when estimating the required fuel consumption. The report will exclusively present the final results for tank size, difference in dimensions for the vessel using MGO and LNG, change in volume and so forth.

6.4 Vessel characteristics

For the case study it is chosen an existing factory trawler with port of registry in Hammerfest, Norway. During large parts of the year, the vessel operates at fishing grounds near Hammerfest and Tromsø. The trawler also have the ability to deliver fresh fish, and therefore it does not stay at sea for a long period of time.

It is important to emphasise that the chosen vessel is not representative for all fishing vessels. As previously mentioned, fishing vessels range is size, fishing method, operational profile and fishing area. The vessel is however chosen for some primary reasons, which are:

- The vessel operates within 250 nm from shore (not fishing in distant waters) with an engine power greater than 750 kW, and therefore liable to NOx, SOx, and CO2 taxes. See Section 2.6. Using LNG as energy source can reduce these costs.
- As previously stated in Section 3.2, cod trawlers and wet fish trawlers have a low energy efficiency compared to other fishing vessel segments. Measures aimed at this part of the fleet can have the greatest total effect.

The vessel is owned by the shipowner Havfisk. They have an annual public report showing an overview of GHG emission from their fleet. This has been an important tool in identifying concrete measures to reduce their GHG emissions (Havfisk, 2015). Due to limited information of data for 2017, further evaluation will be based on data from 2015 as seen in Table 6.1.

Table 6.1: Vessel characteristics for trawler operating in the Norwegian sea (Fiskeridirektoratet, 2018b; Havfisk, 2015).

Characteristics	**Value**
Length overall (m)	39.79
Breadth (m)	10.5
Depth (m)	6.71
Gross tonnage	691
Net tonnage	267
Main engine power (kW)	1840
Design speed (kn)	11-13
Days of operation	340
Roundtrip duration ($\approx days$)	7
MGO consumption in 2015 (m^3)	2014
CO_2-equivalent in 2015 (t)	5526
Total allocated quota in 2015 (t)	7796.55
Total catch in 2015 (t)	5621.00

The values presented in Table 6.1 derives from the actual vessel. Data concerning vessel parameters and performance derives from data presented by Fiskeridirektoratet (2018b). Fuel consumption, total catch and days in operation have been presented by Havfisk (2015).

6.5 Operational profile

The operational profile for the vessel is a decisive factor and will affect the outcome of the specific case, especially considering the size of the gas tank(s). The operational profile will be applied to estimate the average fuel consumption for one roundtrip.

As mentioned in Section 3.2, the operational profile for a fishing vessel can vary for each roundtrip as result of several factors. Hence, the presented operational profile is set as an example to estimate the fuel consumption, and does not define the operational profile for every single roundtrip during the vessel's lifetime. Due to a great variety, the operational profile is somewhat simplified, but will illustrate both the power consumption for propulsion and for powering other facilities on board the vessel such as factory and freezing cargo. In addition, a constant required electrical power of 100kW for other systems on board is included in the estimation of the different modes.

Further, the power output from engine at different modes are based on fundamental calculations. In Equation 6.1, P_e, P_E, η_T, η_D and ΔP are the required power output from engine, effective power, transmission efficiency, propulsive coefficient ($\eta_O \eta_H \eta_R$) and additional power requirement, respectively.

$$P_e = \frac{P_E}{\eta_T \eta_D} + \Delta P \tag{6.1}$$

An overview of the values and parameters used in the case are illustrated in Appendix A1 and A3. The effective power, P_E, have been found by using Equation 6.2, where R_{Tot} is the total resistance and V_S is the speed.

$$P_E = R_{Tot} \times V_S \tag{6.2}$$

R_{Tot} can be estimated by using a resistance prediction method. The Digernes formulae presented as Equation 6.3 is the formula chosen among several other empirical methods, such as Holtrop statistical method or Hollenbachs resistance estimate.

The Digernes formulae is an absolute regression formula formulated at MARINTEK in 1982. Based on experience and tests, the formula shows that the resistance is to a large extent dependent on volume displacement, dimensions and speed (Digernes, 1982).

$$R_{Tot} = a \times (\frac{L_{WL}}{B})^b \times (\frac{B}{T})^c \times \nabla^\delta \times e^{\beta' \times F_n} \tag{6.3}$$

where Table 6.2 and 6.3 shows the coefficient values and range of validity, respectively.

Table 6.2: Coefficient values for Digernes formula.

a	b	c	δ	β'
2.956×10^{-4}	0.802	0.745	1.113	15.605

Table 6.3: Range of validity for Digernes method as defined by Digernes.

$L_{WL}[m]$	$B[m]$	$T[m]$	$\nabla[m^3]$	L_{WL}/B	B/T	F_N
11.9–53.9	3.55–13.6	0.68–5.65	17.6–1376	1.8–4.5	1.9–10.0	0.223–0.494

The Digernes formula is based on fishing vessels in the respective size range, and therefore selected for this case study. Further, the regression coefficient value is R2=0.995, which indicates that the formula is able to almost precisely follow the curvature of the resistance curves for the vessels included in the original dataset (Kleppestø, 2015). The validity of the method can be discussed for new vessel designs, but can be seen as a good estimate and regression formula for this case.

To simplify the case, it is assumed a required fixed energy demand for freezing the fish and covering cargo heat loss. The energy demand is assumed to be approximately 110 kWh/tonnes of fish and the cargo hold requires 0.06 kW/m3 to stay refrigerated. Further, it is assumed that the factory is operational only while trawling.

Figure 6.2 shows the estimated operational profile for the vessel during one roundtrip. The x-axis shows the time in hours spent in one roundtrip, where the time for each operation is places at the intersection between profiles. The y-axis shows both the main engine effect and load for each operation. Here, the first bar illustrates the required output from engine in transit mode, to and from the fishing grounds. Overview of the engine load and effect for the different modes can be viewed in Table 6.5.

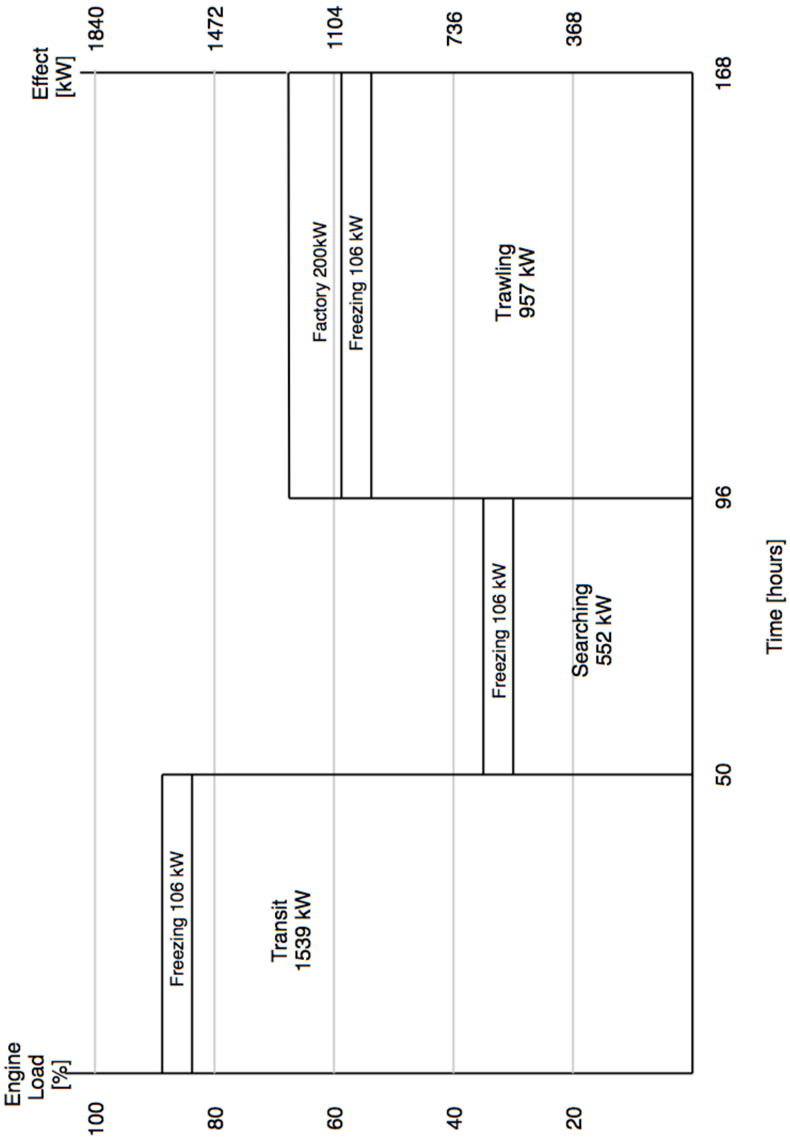


Figure 6.2: Operational profile for the vessel.

6.6 MGO consumption

The operational profile have been defined and the fuel consumption can be found by adding available data as listed in Table 6.4 below. The average specific fuel consumption is used for the entire power range of the operational profile.

Table 6.4: Characteristics of MGO fuel and corresponding engine.

Parameters	**Amount**	**Source**
Marine diesel engine (kW)	1840/1800	MaK (2018)
Average sfc of conventional engine (g/kWh)	170	MaK (2018)
MGO density at 15 C (g/m^3)	855×10^3	Statoil (2008)
Energy content of MGO ($MWh/tonne$)	11.90	Statoil (2008)
Net calorific value, MGO (MJ/kg)	42.8	Statoil (2008)

In Equation 6.4, B, b_e and t stands for fuel consumption, average specific fuel consumption (sfc) and time, respectively. P_e is the power output from engine, as mentioned before. This equation is used to find the consumption of MGO for the different modes based on the previous operational profile for the vessel. The total fuel consumption for one roundtrip is found by adding together the estimate for every mode of the operational profile.

$$B = b_e \times P_e \times t \tag{6.4}$$

The average fuel consumption for one roundtrip is estimated to be approximately 32.92 tonnes of MGO based on the respective operational profile and formulas presented.

Table 6.5: Fuel consumption during different modes for the MGO-fuelled vessel.

Mode	**Fuel use [tonnes]**	**Fuel use [%]**	**Time [Hours]**	**Time [%]**	**Effect [kW]**	**Engine load [%]**
Transit, roundtrip	13.08	39.7	50	29.8	1539.4	83.7
Searching	4.28	13.0	46	27.4	552.0	30.0
Trawling, hauling	9.90	30.1	72	42.9	957.3	52.0
Freezing cargo	3.05	9.3	168	100.0	101.5	5.5
Factory	2.58	7.9	72	42.9	200.0	10.9
Total	32.92	100	168	100.0	1840	100.0

The total fuel consumption per roundtrip corresponds well to what was initially stated by Havfisk (2015) regarding fuel consumption (m^3) for year 2015.

6.7 Initial estimation of LNG consumption

Based on the findings from last section, the required energy consumption (MWh) needed per roundtrip can be found by applying Equation 6.5.

$$E_r(kWh) = \frac{FC_r(m^3) \times \rho(\frac{g}{m^3})}{sfc(\frac{g}{kWh})} \tag{6.5}$$

where E, FC, ρ and sfc are the energy consumption, fuel consumption, density, and specific fuel consumption of the engine, respectively. The subscript r indicates a roundtrip.

When including the values for MGO from last section, it shows that the vessel needs approximately 194 MWh per roundtrip.

Table 6.6: Characteristics of LNG fuel and corresponding engine.

Parameters	Amount	Source
Gas engine power (kW)	1940	Rolls-Royce (2018b)
Average sfc of gas engine (g/kWh)	150	Gilbert et al. (2018)
LNG density at -162 degrees (g/m^3)	452×10^3	Barents Naturgass (2017)
Energy content of LNG ($MWh/tonne$)	13.6	Barents Naturgass (2017)
Net calorific value, LNG (MJ/kg)	48.6	Gilbert et al. (2018)

Table 6.6 shows the average specific fuel consumption for the gas engine, used for the entire power range as for the conventional engine.

Further, Equation 6.5 and the values deriving from Table 6.6, can be used to estimate the initial amount of LNG (m^3) needed, based on the required energy consumption for the vessel. In this stage, the impact from increased dimensions and resistance is not yet considered.

$$FC_r(m^3) = \frac{193.6MWh \times 0.15tonnes/MWh}{0.45tonnes/m^3} = 64.54m^3 \tag{6.6}$$

Equation 6.6 shows that the amount of required LNG is equivalent to 64.5 m3, whereas tank arrangement and necessary safety margin is not included. However, the result can been seen as a good starting point for further assessment and can be used as a comparison to the final result. Calculations and methods can be found in Appendix A5.

6.8 Selection of LNG system components

6.8.1 Gas engine

To evaluate the impact by using LNG as fuel in the most accurate way, there will not be taken into account the possibility of dual fuel solution, i.e. for the vessel to actively switch between using gas or marine diesel. For this case it is therefore chosen a LBSI-engine combined with auxiliary engines that runs on marine diesel oil (MDO) to provide electricity in case of system failure. As described in Section 4.2.4, the vessel is dependent on some sort of redundancy while in operation. In case of system failure, the auxiliary engines can be sufficient enough to bring the vessel back to shore from the fishing grounds, equivalent to a distance of approximately 250 nautical miles. This is a solution that can be beneficial in terms of saving space, considering that the fuel tank(s) for diesel can be easily stored wherever there is available room. The storage tank does not require any considerable room in itself, whereas the fuel is seen as a back-up only intended to be utilized during system failure. As mentioned, the calculations are based on a 100% powered LNG vessel, where it is assumed that the use of MDO is not necessary for the roundtrip, i.e. no system failures.

According to Sintef (2017), a typical LBSI engine will give a NO_x reduction of 85-90% compared to MGO. Further, approximately 25 % reduction in CO_2 and almost eliminate exhausted SO_x and particulates.

6.8.2 Fuel containment system

Three different tank types were described previously in Section 4.2.4. Tank type C is chosen for this design due to its space efficiency and no need for additional components to handle boil-off gas. The vessel is at sea for approximately seven days, which makes the tank type suitable relative to holding the boil-off gas without reaching an excessive pressure.

Due to the complex arrangement on board, it is chosen to have more than one LNG storage tank. One large tank can come in conflict with the logistics on board and the factory deck due to one single tank can result in an extensive diameter. However, more than one tank will increase the costs due to more steel for same volume and will conceivably have extra processing arrangement. This will also produce a higher total footprint than having one single tank with the same capacity. Nevertheless, it is considered to be a better solution in an initial design phase when considering a traditional arrangement of a trawler.

6.9 Tank arrangement

Positioning the tanks can be an optimization task in itself and it will not be considered in a large extend. Although, it will be aimed attention to try to limit the space required for storage tanks and system for LNG.

AutoCAD is used to optimize arrangement of ship compartments and to create design alternatives, in this case used to arrange the storage for fuel supported by the geometric properties such as volume of the tanks.

Tank type C can have a spherical or a cylindrical shape, where the latter can be mounted in a horizontal or vertical direction. To utilize the space on the vessel in the most sufficient way, it is chosen a cylindrical shape mounted below the main deck and factory of the vessel. Based on personal reasoning, this is seen as a good area for the tanks considered the already strategic connection from fishing deck to factory. The tanks are also placed at a location away from the accommodation area, i.e. not directly under the area.

Requirements for stability for fishing vessel is more stringent than for other vessel segment, making the vessels susceptible for regulations when changing in main dimensions, center of gravity and so on. The L/B-ratio, i.e. the relation between length and breadth, for fishing vessel are in several cases lower than for other vessel segments. By positioning the tanks in a longitudinal direction will presumably increase the length of the vessel to a large extent, which will influence the stability without any other modifications. A longitudinal direction of the tanks were further found to be inadequate, creating an unnecessary and impractical void between the tanks and the ship's side.

It was established that positioning the tanks in a transverse direction can be preferable to save space and avoid increasing the length in a great extent. This is done by also expanding the breadth of the vessel, to be certain to fulfil stability requirements and to comply with regulations related to collision distance between tank and hull. This is a somewhat unconventional way to positioning the tanks. M/S Kvitbjørn, a LNG-powered cargo vessel, is an example of a vessel with this tank arrangement.

The final general arrangement with allocated tank arrangement for the vessel can be viewed in Appendix A17 and A18.

6.10 Tank volume and dimensions

From the calculated fuel consumption, the storage tank volume can be found. Table 6.7 shows the different parameters included to find the necessary external volume and dimensions of the tanks arranged in the ship. The values illustrated in the in Table 6.7 and 6.8 derive from the final outcome after implementing new dimensions to the vessel to fit the storage tanks.

The specified fuel volume have increased from 64.5 m^3 deriving from the equation applied to find the initial value, to 70.0 m^3 after including increased resistance and fuel consumption. Further, different margins will been taken into account. Depending on design of tank room it will not be possible to use all LNG in the tank. LNG usage margin of 8%, is a conservative approximation of the LNG that cannot be used and to ensure that the tank remains in cryogenic condition, as mentioned before. The IGF code also state that the cryogenic tanks shall not be filled more than 95% of the total volume. Further, a safety margin of 20% are included.

Table 6.8 shows a more detailed calculations for the tank volume, including the cylindrical shape with dished heads.

Table 6.7: Overview of value and calculations for tank volume and dimensions without Korbbogen tank end volume.

Tank volume calculations		
Properties	Value	Unit
Fuel volume specified	70.0	m^3
Density	451.97	$kg/m3$
Heating value	49.50	MJ/kg
LNG Usage margin	8	$\%$
Safety margin	20	$\%$
Filling margin	95	$\%$
Inner tank volume required	93.10	m^3
No. of tanks	2	$tanks$
Skin thickness	0.112	m
Outer diameter	3.45	m
Simple Calc. (Without Korbbogen Tank End Volume)		
Length	5.92	m
External volume in ship (per tank)	55.33	m^3
Length/diameter	1.72	

Table 6.8: Overview of calculations for tank volume and dimensions with Korbbogen tank end volume.

Calc with Korbbogen Tank End Volume		
Inner diameter	3.23	m
Head radius (r1 = 0.8Di)	2.58	m
Knuckle radius (r2 =0.154Di)	0.50	m
θ	57.61	$\circ$
Head height H1	0.40	m
Knuckle height H2	0.42	m
Length/Diameter	2.09	
Head volume	1.24	m^3
Disc Volume	2.52	m^3
Knuckle Volume	0.64	m^3
Total Internal Volume (both ends)	5.64	m^3
Required Cylinder Volume	87.46	m^3
Required Cylinder Length	5.57	m
Cylinder Length/Diameter	1.62	
Total Tank Length (tank cylinder + cylinder heads)	7.22	m
Total Internal Volume (tank cylinder + cylinder heads)	93.10	m

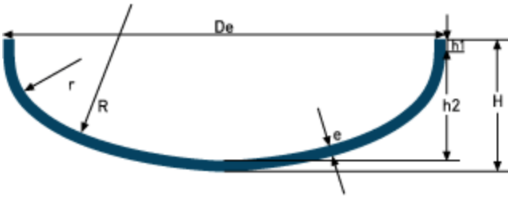


Figure 6.3: Illustration of Korbogen tank end volume (Fondeyur, 2018).

The final main dimensions of the LNG-fuelled vessel after including the required volume for the tanks, are presented in next section.

6.11 Impact on main dimensions

As stated in Section 4.2.6, different regulations affect the ship arrangement due to hazardous areas and risk of leakage. The regulations described in Table 4.3 have been taken into account and have contributed to an increase of the main dimensions of the vessel.

Figure 6.4 illustrates how the regulations as listed in Table 4.3, applies for a LNG tank arranged in longitudinal direction. This shows a section view where B, D are breadth and depth, respectively.

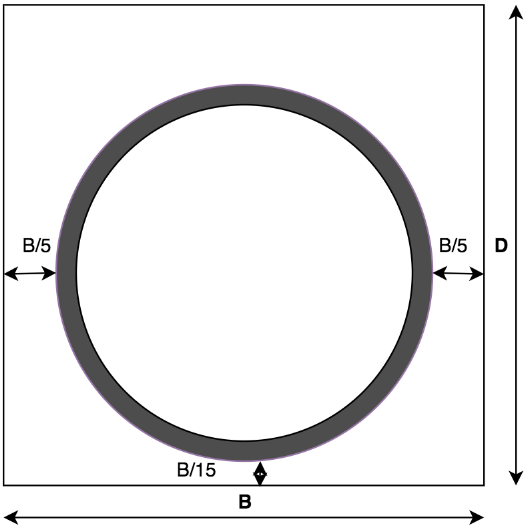


Figure 6.4: Illustration of regulations for LNG tank in longitudinal direction. Based on Jafarzadeh et al. (2017).

The arrangement presented in Figure A17 and A18, shows that the cryogenic tanks are placed midships in transverse direction. The two tanks have an outer diameter of 3.45 meters, with a length of 7.22 meters including the cylinder heads as calculated and illustrated in Table 6.7 and 6.8.

$$B_{new} = L_{tank} + \frac{2 \times B_{new}}{5} \tag{6.7}$$

Equation 6.7 have been used to find the necessary new breadth of the vessel based on regulations stating that the tanks shall be located at a minimum distance of B/5 meters from the ship's side. B_{new} is the required breadth of the LNG-fuelled vessel and L_{tank} is the length of the cryogenic tank.

Table 6.9: Illustration of minimum required distance from ship side, keel and aft terminal for the LNG tanks.

Regulations concerning arrangement of LNG tanks		
Calculated breadth	B new	12.03 m
From ship side	B/5	2.41 m
From keel	B/15	0.80 m
From aft terminal	B/10	1.20 m

As shown in Table 6.9, the calculated new breadth of the vessel is 12.03 meters. From adjustments and tweaking it was found that the new length was 41.06 meters, while having the same required cargo space established in the mission statement.
It was assumed that some of the freezer cargo hold could be placed on factory deck due to an increase in both length and breadth of the vessel. The adjustment have had an influence on the resistance of the vessel, which is calculated by the Digernes formulae. The results of the change in resistance can be viewed in Appendix A6.

6.12 Summary of the findings

Table 6.10 below summarizes to what degree the LNG system and tank volume have influenced the main dimensions of the vessel.

Table 6.10: Overview of the characteristics and distinctions between the MGO-fuelled vessel and LNG-fuelled vessel.

Properties	**MGO**	**LNG**
Density (kg/m^3)	855	450
Net calorific value (MJ/kg)	42.8	48.6
Parameters	**MGO**	**LNG**
Engine power (kW)	1840/1800	1940
Average sfc of engine (g/kWh)	170	150
Vessel Characteristics	**MGO**	**LNG**
Length w.l. (m)	39.79	41.06
Breadth (m)	10.5	12.03
Fuel tank volume specified (m^3)	38.5	70.0
(Tank volume calc.)	(-)	(110.7)
Fuel consumption/roundtrip (tonnes)	32.92	31.39

Figure 6.5 and 6.6 illustrates the difference in general arrangement for the vessel with conventional system and the gas-fuelled trawler. It is important to mention that original GA illustrated here was developed in 1999, and have since then been elongated, thus the drawings does not correspond to the actual dimensions for the vessel today due to modifications. The general arrangement of the gas-fuelled trawler can be viewed in Appendix.

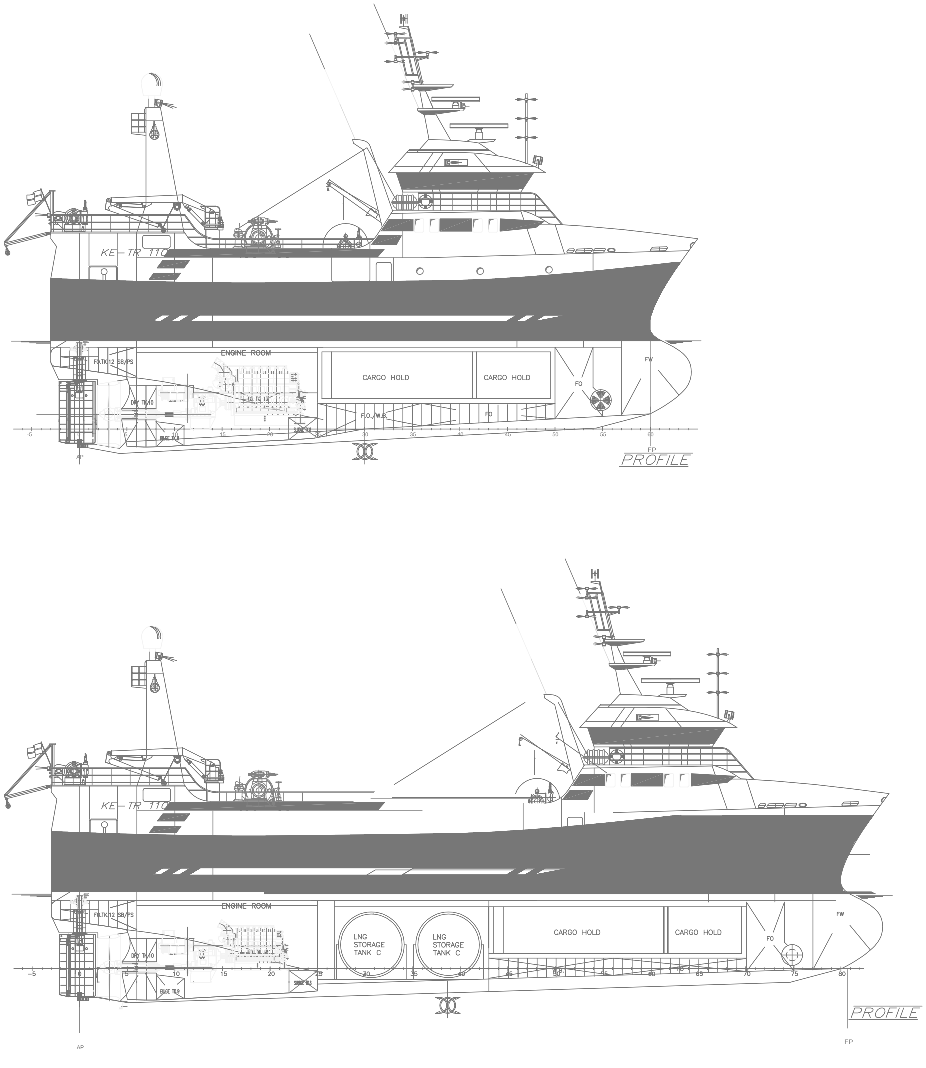


Figure 6.5: Illustration of changes in general arrangement, Profile.

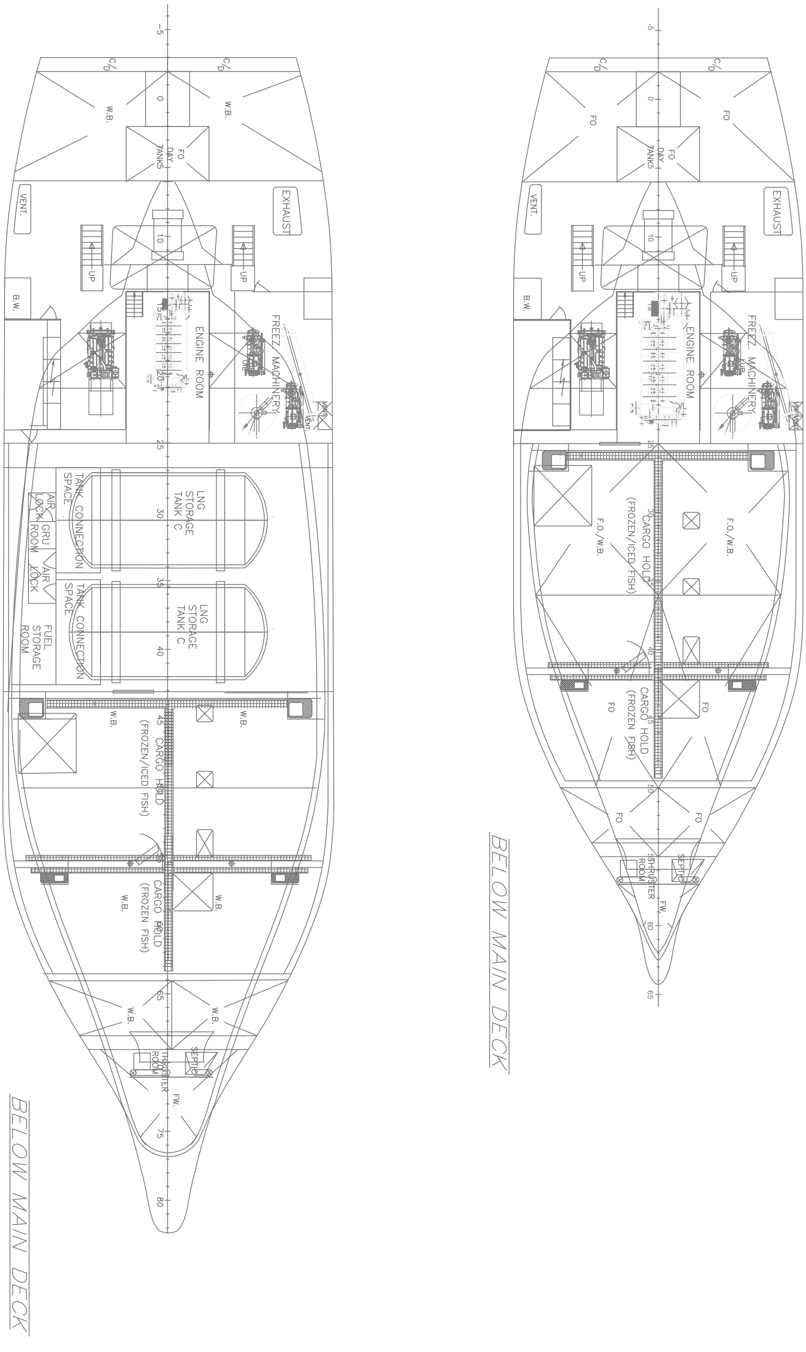


Figure 6.6: Illustration of changes in general arrangement, Below main deck.

Chapter 7

Analysis

7.1 Assessment of environmental impact

As described as the objective, the focus will be aimed at the environmental performance of MGO and LNG. To evaluate the environmental impact in a thorough way, the entire life cycle of the fuel have been assessed.

Section 5.2 described the method for performing an LCA analysis. However, it requires extensive work to collect all the necessary data needed to perform an accurate LCA, where it has in many cases been a complete master thesis in itself. Thus, some simplifications have been done to evaluate the environmental performance of the fuel in an effective and systematic approach.

A comparative LCA of marine fuels have been conducted by Bengtsson et al. (2011). This is a consequential LCA, which means that the aim is to describe the environmental consequences of alternative courses of action. Instead of evaluating all factors that will have an influence on the environment, it focuses on only the parts of the life cycle that differ between the alternative fuels. The system studied includes extraction of raw materials, production and transportation, bunkering, storage and the combustion of fuels during operation as seen on Figure 7.1.

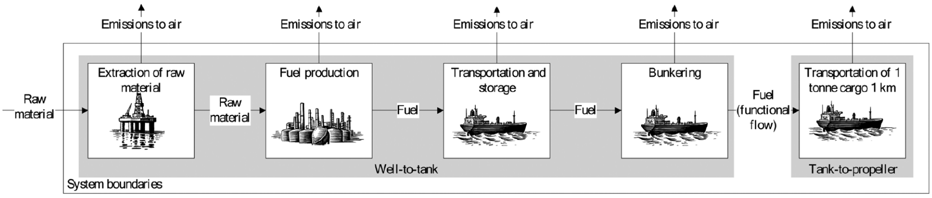


Figure 7.1: Overview of the studied system by Bengtsson et al. (2011).

The LCA by Bengtsson et al. (2011) will be applied as the foundation of the analysis. There are however some adjustments necessary to be made, and not all data are utilized for the purpose of this thesis.

Table 7.2 below, gives an overview of the different emissions factors and their selected weighting at midpoint level. Table 7.1 presents the difference emissions factors for LNG and MGO. These values derives from Bengtsson et al. (2011) and will be used further in the case.

Table 7.1: The emission factors for MGO and LNG. These data derives from Bengtsson et al. (2011) used as baseline for LCA of marine fuels.

Value for following fuels (g/MJ):		
Emissions factors	MGO	LNG
CO2	74	57
CO	0.13	0.28
CH4	0.0005	0.28
NOX	1,5	0.17
NMVOC	0.06	-
N2O	0,004	-
NH3	0.0003	-
PM10	0.034	0.009
SO2	0.05	0

Table 7.2: Overview of weighting of the different emission factors for each impact category. ReCiPe 2008.

Emission factors	Value
GWP	g CO2-equivalent
CO2	1
CH4	25
N2O	298
Acidification pot.	g SO2-equivalent
NO	1.07
NO2	0.7
NOx	0.7
SO2	1
NH3	1.88
Eutrophication pot.	g PO34-equivalent
NO	0.2
NO2	0.13
NOx	0.13
NH3	0.35

The values are not entirely reliable, and there are some sources of uncertainty as for every LCA. The estimated emission factors have been representative for a ro-ro vessel with a given engine type for MGO and LNG, but the values as still seen as comparable for this assessment. The gas engine from the LCA is similar to the chosen LBSI-engine for this case, in terms of reduction of NOx, SOx and CO2 during the combustion process compared to the engine utilizing MGO.

The data represents natural gas from the North Sea. The data are considerably old, but are still chosen because it is a good representation of the region. For the liquefaction process, it is assumed a methane slip of 0.17 % and flaring of 0.25% of the produced LNG. Further, transportation from the North sea are chosen for calculated exhausted emissions during the distribution process. It is assumed that the LNG is transported 10 km with a bunker ship.

A quantified description or a functional unit have to be specified. This represents the function of the studied product or service. As illustrated in Figure 7.1, the functional unit for the specific case by Bengtsson et al. (2011), is the transportation of 1 tonne cargo 1 km for a ro-ro vessel. A fishing vessel has other performance criteria, thus there should be established a functional unit representing this. The functional unit for this case is chosen to be *kilo of fish delivered*.

Table 7.3: Data for one average roundtrip for both vessels

Data, average for one roundtrip:	
Catch (tonnes)	115.7
MGO fuel consumption (tonnes)	32.92
MGO, required energy (MJ)	697104
LNG fuel consumption (tonnes)	31.39
LNG, required energy (MJ)	753408

Table 7.3 summarizes the data used to quantify the environmental impact during the downstream process. The total catch is the same for both vessels. From this, it is calculated that the vessels requires 6.02 MJ/kg fish and 6.51 MJ/kg fish for the MGO-fuelled vessel and LNG-fuelled vessel, respectively. Also, a fuel use coefficient of 0.28 kg fuel/kg fish for the MGO vessel. This can be compared to Figure 3.2, which confirms consistency between estimated fuel use coefficient and previous studies.

The results of the LCA can be viewed in Chapter 8 Results.

7.2 Economic feasibility assessment

The new system should meet requirements, be beneficial in terms of environment and have a reasonable cost over the vessel's anticipated lifetime.

The decision to invest in new technology, such as LNG, is highly dependent on costs and return. The investment costs are undeniably more expensive than for a conventional system. Along with the benefits by investing in green technology regarding incentives and tax deduction, the economic feasibility assessment will explore how an investment will affect the revenue.

Cost estimation and economic assessment of the system is an important part of the thesis, and will be of great importance to the final result. This is also challenging, due to uncertainty regarding price estimation of different components, fluctuating fuel prices and several factors influencing the total cost. For instance, for major fuel consumers there are room for negotiation of prices. This will be further illustrated in Figure 7.3.

I several cases, it may not be necessary to perform a complete LCC analysis (Norsok Standard, 1996). It is chosen to do an estimation of the major cost elements, which is considered to be sufficient enough for this type of task. The main interest is to have more knowledge about the cost differences between using MGO and LNG as fuel. When evaluating the feasibility of a LNG investment, it is chosen to compare the results with the baseline MGO investment. Hence, other lifecycle stages are not considered in this case. The different business categories will be presented in the following subsections, which includes capital expenses (CAPEX), operational expenses (OPEX) and voyage related expenses (VOYEX). Here, the major cost elements will be evaluated, which are listed as follows:

- The cost difference in investment expenses for LNG and MGO.
- The additional cost for an enlarged vessel. This category refers to the study case where new dimensions and volume displacement was found for the vessel to be applicable for LNG system.
- Support from funds and incentives.
- The difference in fuel costs.
- The influence of environmental taxes.

7.2.1 Capital expenses (CAPEX)

As the name suggest, these are costs related to investments, i.e. to buy or rent physical assets.

LNG installation

Previous studies regarding feasibility of LNG-fuelled vessels have mostly been based on large container ships or bulk carriers. This makes the capital expenses difficult to evaluate, also due to the fact that a lot of data is confidential and less accessible. Experience and studies have showed that the investment costs for LNG fuelled vessels are expected to be 10-25 % higher than for a conventional system (Buurma C., 2015). These estimations derives from large ocean going vessels that requires large expensive storage tanks for long distance voyages. This can however be used as an indication for further evaluation.

The capital expenses are higher due to a more expensive propulsion plant, the technology used and procurement considerations, whereas the largest cost driver for all LNG-fuelled vessels are the LNG storage tanks (Schinas and Butler, 2016).

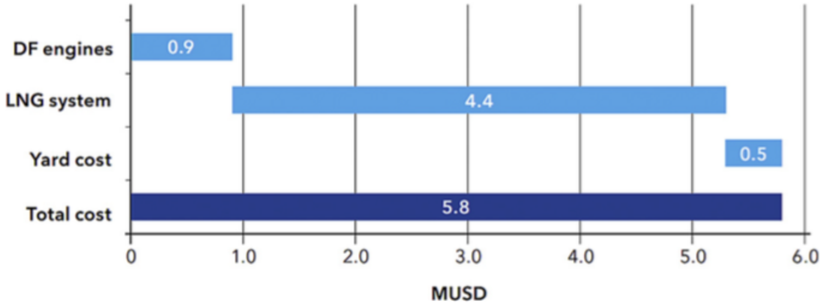


Figure 7.2: Total additional capital costs for LNG-system (DNV-GL, 2014).

Figure 7.2 derives from a case by DNV-GL (2014), which examines the costs for building a dual fuel 50,000 DWT medium range oil tanker. The cost of the LNG system is based on a 1500 m3 tank capacity.

Based on previous studies and information available, it is chosen to make some assumptions regarding the additional capital expenses.

Section 6.4 presented the characteristics of the original vessel using MGO as fuel. It is assumed that a fishing vessel at this size and equipped with new technology, have an estimated new build price of no more than 200 MNOK today. The LNG storage tanks are relative small due to the size of the fishing vessel and operational profile. Accordingly, it is assumed a 15% increase of the total LNG investment cost, which is equivalent to approximately 30 MNOK.

Further, the NOx fund and Enova are both incentives used for economical support to invest in more environmental friendly alternatives. As previously stated, Enova can cover 50% of the project's additional cost, while the NOx fund have a maximum support rate of 80% of the investment or 350 NOK per kg NOx reduced. Only one of the funds can support the investment, and it is assumed that support from the NOx fund may be granted.

Table 7.4: Calculation of NOx reduction and fund support.

NOx fund, Investment incentive	
NOx emitted (kg/ton MGO)	50
Annual NOx emitted MGO (kg)	79944.5
NOx emitted (kg/ton LNG)	5.6
Annual NOx emitted LNG (kg)	8612.8
Annual NOx reduction (kg) (**a**)	71331,7
Support rate (NOK/kg NOx reduced) (**b**)	375
a x b (MNOK)	26.75
Covered by the fund (MNOK)	24

NOx emitted for both MGO and LNG are found from data by Nielsen and Stenersen (2010). This shows a reduction of approximately 89 %, which is acceptable to assume based on several sources.

It is found that the support from the NOx fund exceeds the 80% of the additional cost, and therefore expected that 80% of the investment is covered by the fund, whereas the rest of the cost will be covered by the shipowner.

Additional cost of hull

The additional costs for a larger vessel, i.e. more steel and additional man-hours, is not considered to be covered by any of the funds. To fit the LNG system it was found that it was necessary to increase the size of the vessel, to avoid reducing the catch capacity. An appropriate estimation of the additional cost of the steel structure can be difficult to achieve. It depends on factors such as steel costs when built, amount of man-hours or if the production is outsourced.

First, steel weight calculations can be found by using a fundamental calculation formula, in this case the following equation from statistical analysis regression (d'Almeida, 2009):

$$W_S = k1 \times L_S^{k2} \times B^{k3} \times D^{k4} \tag{7.1}$$

In Equation 7.1, the coefficients $k1$, $k2$, $k3$ and $k4$ are characteristics for a vessel type deriving from statistical regression analysis. Due to lack of data for fishing vessels, the values are obtained from general cargo vessels. The values for the coefficients are listed on the next page.

Table 7.5: Coefficient values.

k1	*k2*	*k3*	*k4*
0.0313	1.675	0.850	0.280

From Equation 7.1, it was found that the steel weight increased by approximately 50.2 tonnes with LNG investment due to an increase in dimensions. This includes plates, stiffeners and beams.

By establishing a 'unit costs per ton of steel installed', one can multiply the unit costs by the steel weight. Already established regression formulas is not applicable to use on smaller fishing vessels, but according to Magnussen et al. (2014), a value from 15000-35000 NOK can be applied. When all costs associated with the building of the hull, such as man-hours, steel costs and processing, it is estimated a price of 32200 NOK per tonne of steel. This is equivalent to 1.62 MNOK of additional cost.

7.2.2 Operational expenses (OPEX)

Operational expenses are costs related to operations incurred during the entire lifetime of the vessel, for instance maintenance, salaries and any cost related to administrative expenses.

The fuel storage and piping systems for a LNG-fuelled vessel are more complicated than for a conventional system. It is possible to think that maintenance costs are much higher for LNG fuelled vessels, but previous studies and experience have showed that implementation of LNG technology does not necessarily increase the operational costs in a great extent (Schinas and Butler, 2016). Therefore, it is chosen to evaluate the OPEX, i.e. crewing, maintenance and repair, as negligible for this case study.

For the purpose of the thesis, the competitiveness of the LNG-fuelled vessel is mainly determined by the capital expenses (CAPEX) and voyage related expenses (VOYEX).

7.2.3 Voyage related expenses (VOYEX)

Fuel price

Different factors can affect the fuel price, such as demand and supply, world economic growth and taxes. Historical data shows that the price is very fluctuating, and therefore difficult to predict and will lead to some uncertainty.

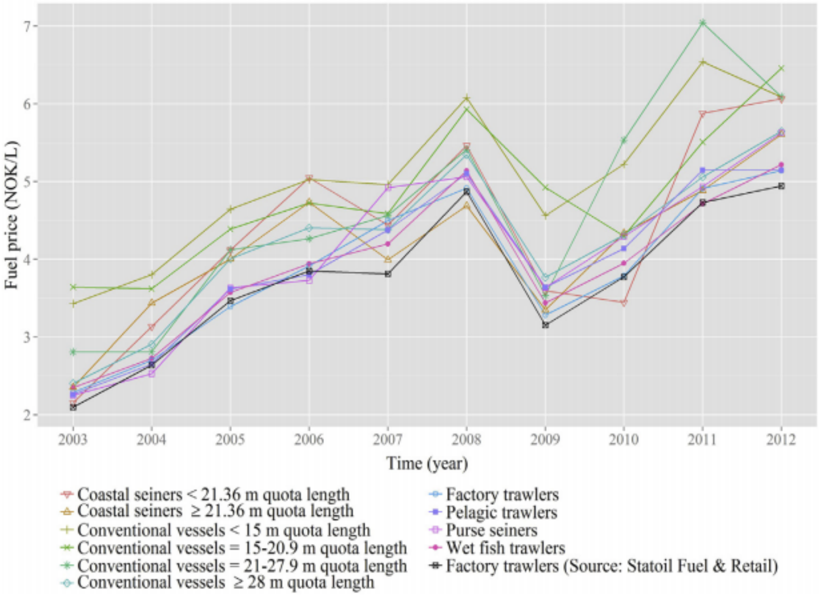


Figure 7.3: Fuel prices for different fishing segments (Jafarzadeh et al., 2016).

Figure 7.3 illustrated by Jafarzadeh et al. (2016), shows the fuel prices incurred in the Norwegian fisheries from 2003-2012 for different fishing segments. The price derives from data provided by Directorate of Fisheries, which included fuel prices for various vessels in different fleet segments and average fuel prices from Statoil Fuel & Retail. This shows that the prices are fluctuating, and major consumers such as factory trawlers have the opportunity to negotiate and pay lower fuel prices.

DNV-GL (2018) have estimated the fuel price based on historical internal data. As end of March 2018, MGO with 0.1 % sulphur, cost approximately 15.1 \$/mmBTU or 610 \$/ton. This is equivalent to 4.15 NOK per liter MGO. Compared to Figure 7.3 showing the prices from 2003 to 2012, and following estimated price for LNG, this can be evaluated as a suitable fuel price estimate.

There are currently no mature market for bid and quote pricing for LNG as for MGO, which makes the comparison even more complex. There are many prerequisites behind an LNG price, some of them are mentioned below.

- First, the pricing mechanism and which index is controlling (e.g. TTF or GasOil) combined with contractual assumptions (spot price versus binding agreement between actors).
- Delivery method, distance to end-users and cost of distribution to a ship. As stated in Section 4.2.5, the total price also depends on whether it is small-scale or large-scale LNG distribution. The volume per bunkering is also a decisive factor.
- The quality of the LNG gas mixture. This varies and is dependent on the natural gas reservoir and facilities used for liquefaction and storage (Schinas and Butler, 2016).
- The technology used throughout the entire value chain, from natural gas (NG) transportation, liquefaction process and quality of delivery to end-users (Schinas and Butler, 2016).

In order to simplify the case, the price indication will be based on deliveries in Stavanger. As of March 2018, the price were around 4300 NOK/tonne of LNG, which is equivalent to 1.94 NOK/liter (Skangas, 2018). It is assumed that this cost is based on the entire value chain, and consist of liquefaction and distribution of the LNG.

Table 7.6: Cost of MGO and LNG as of March 2018.

Fuel type	Cost [NOK/ton]	Cost [NOK/liter]	Source
MGO (0.1 % S)	4849.5	4.15	DNV-GL (2018)
LNG	4300.0	1.94	Skangas (2018)

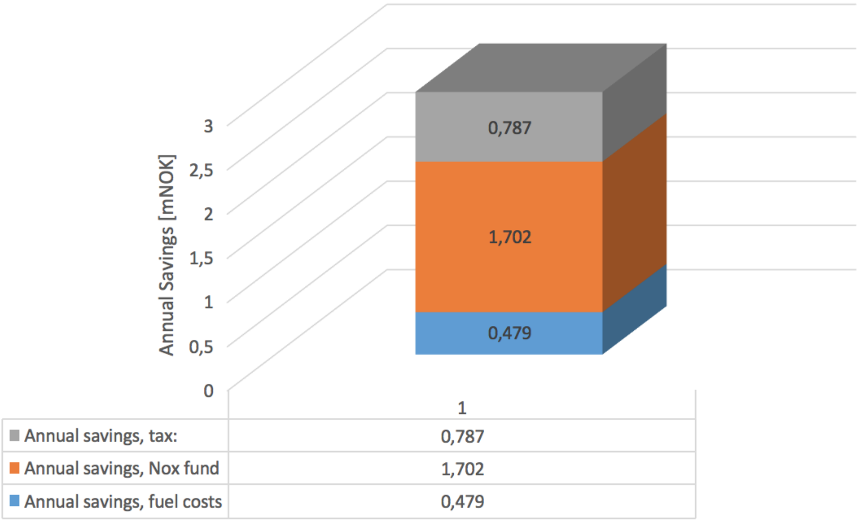
Environmental taxes and support

For the case it is assumed that the environmental tax and fund rates explained in Section 2 are constant during the lifetime of the vessel.

Table 7.7: Examination of annual fuel cost and taxes.

MGO		**LNG**	
Fuel consumption per year [tonnes]	1598.89	Fuel consumption per year [tonnes]	1538.00
Fuel consumption per year [liter]	1870047	Fuel consumption per year [liter]	3417778
Fuel cost [NOK/ton MGO]	4849.5	Fuel cost [NOK/ton LNG]	4300.0
Fuel cost per year [MNOK]	7.75	Fuel cost per year [MNOK]	6.61
Annual savings, fuel costs [MNOK]: 0.48			
Environmental taxes and fund			
NOx tax rate [NOK/kg NOx]	21.94	NOx fund payment [NOK/kg NOx]	6.00
Emitted NOx [kg/ton MGO]	50	Emitted NOx [kg/ton LNG]	5.6
NOx emitted per year [kg]	79944.5	NOx emitted per year [kg]	8612.8
Annual NOx tax [MNOK]	1.75	Annual NOx fund payment [NOK]	0.052
Annual savings, NOx fund [MNOK]: 1.702			
CO2-tax rate [NOK/liter fuel]	0.29	*LNG-fuelled fishing vessels are exempt from paying CO2-tax and SOx-tax.*	
Annual CO2-tax [mNOK]	0.54	-	
SOx-tax rate [NOK/liter fuel]	0.131	*LNG-fuelled fishing vessels are exempt from paying CO2-tax.*	
Annual SOx-tax [MNOK]	0.24	-	
Annual savings, CO2 and SOx taxes [MNOK]: 0.787			
Annual savings, total [MNOK]: 2.969			

Table 7.7 summarises the total annual savings by using LNG fuel for the specific vessel in the case. As stated, the LNG-fuelled vessel is exempt from paying CO2 and SOx taxes, which has been proven to be a significant incentive to choose alternative fuels.



	1
■ Annual savings, tax:	0,787
■ Annual savings, Nox fund	1,702
■ Annual savings, fuel costs	0,479

Figure 7.4: Illustration of savings regarding taxes, NOx fund and fuel costs when adopting LNG as fuel.

The final results of the economic feasibility and LCC are presented in Chapter 8 Results.

Chapter 8

Results

8.1 Environmental impact

The assessment of the environmental impact have given the following results. Table 8.1 presents the environmental categories for the upstream and downstream process, where the exhausted emissions have been weighted at midpoint level according to their environmental impact. The results is also illustrated in the following pages. It has been chosen not to give an quantified estimation and weighting of the environmental impact at endpoint level. This will however, be further elaborated in Part II Discussion.

Table 8.1: Summary of the results from the LCA for both upstream and downstream processes.

	GPW (g CO2-eq./kg fish)	Acidification pot. (g SO2-eq./kg fish)	Eutrophication pot. (g PO43-eq./kg fish)
MGO, total	**430.995**	**6.0235**	**1.031**
Well-to-Tank	46.734	0.311	0.014
Tank-to-propeller	384.260	5.712	1.018
LNG, total	**431.791**	**0.913**	**0.149**
Well-to-tank	54.821	0.228	0.013
Tank-to-propeller	376.897	0.685	0.137

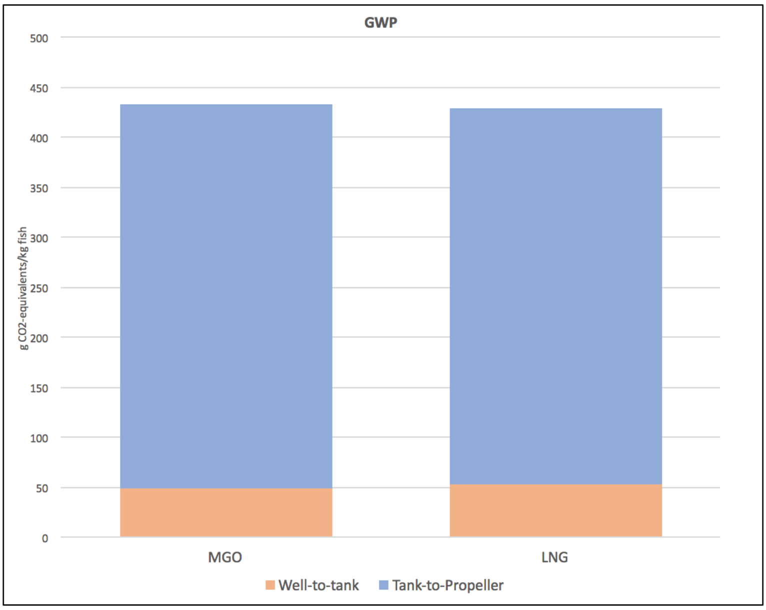


Figure 8.1: Life cycle global warming potential of the investigated fuels.

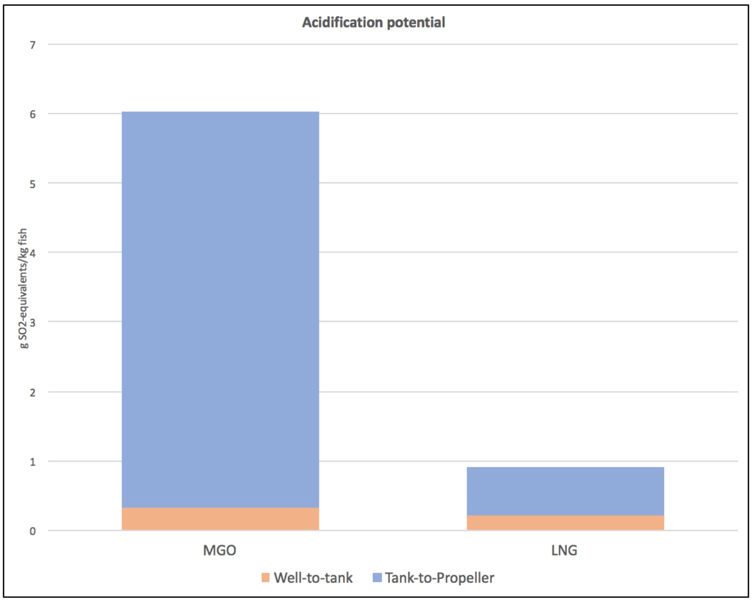


Figure 8.2: Life cycle acidification potentials of the investigated fuels.

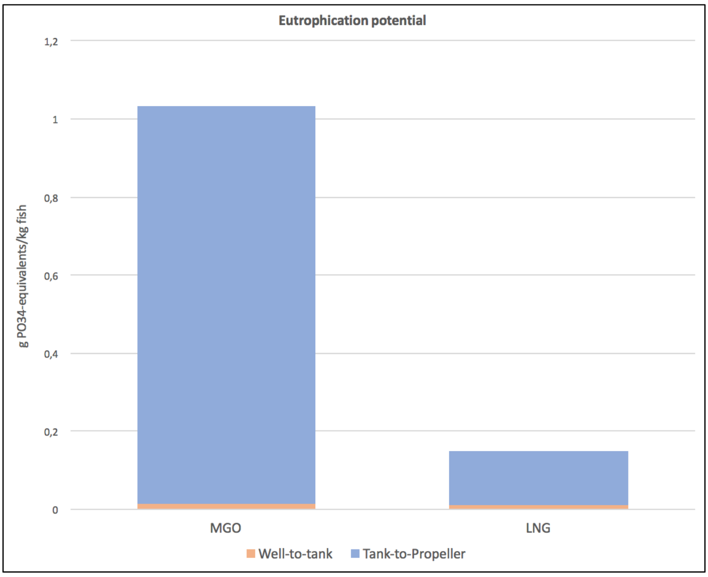


Figure 8.3: Life cycle eutrophication potential of the investigated fuels.

Figure 8.1 shows an almost equal estimated GWP for the two fuels for the case. The largest proportion of CO2-equivalents derives from the downstream process for both fuels. Figure 8.4 shows the results of the contribution of the different emissions species of the CO2-equivalents.

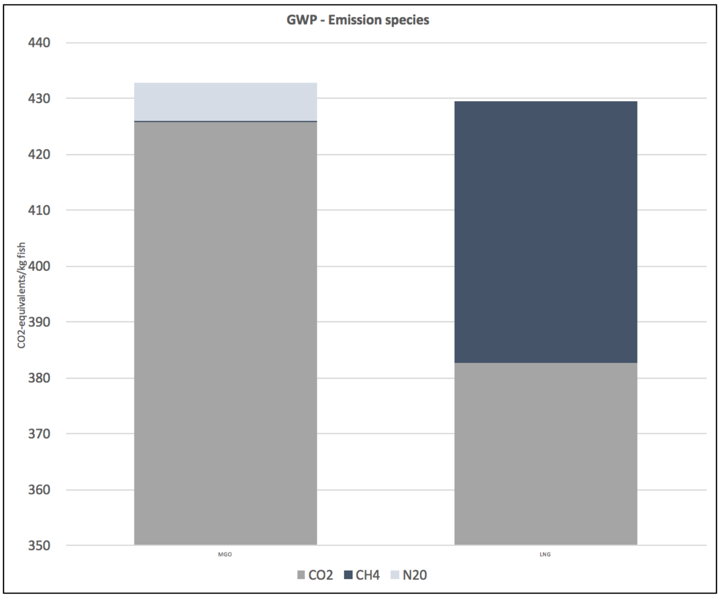


Figure 8.4: GWP of upstream and downstream process, distinguished between the contribution to the overall CO2-equivalents of the different emissions species.

Figure 8.4 shows the distribution of the substances, i.e emission species, for the GWP for both upstream and downstream processes. This is based on the GWP factors as listed in Table 8.2, along with the corresponding distribution of the emissions.

Table 8.2: GWP Factor and emission distribution of emissions.

Substance	GWP Factor	MGO (g CO2-eq.)	LNG (g CO2-eq.)
CO2	1	425.87	382.60
CH4	25	0.072	46.98
N20	298	6.860	0.00

The acidification potential and eutrophication potential for the complete life cycle of LNG have decreased by approximately 85% compared to MGO.

8.2 Economic feasibility

The analysis presented an evaluation of the costs of a LNG investment relative to MGO for the vessel. The main costs are incurred initially, and some are incurred in the future, such as taxes and fuel costs. As stated, the value of money changes over the lifetime of the vessel, whereas using the NPV technique can be an approach to evaluate the LCC of the investment.

Equation 5.2 illustrated how the NPV was being calculated for a project. Below, the equation is adapted to this case when evaluating the differences for LNG and MGO.

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{8.1}$$

In equation 8.1, B_t and C_t represent the benefits and costs, respectively, of an LNG-fuel investment at time t compared to the conventional vessel. n stands for the number of years examined and i is the discount rate as explained before.

The capital costs include the extra cost in investing in the LNG-system. Having included a safety margin, it is assumed that the extra investment will increase the costs by 15%, which is equivalent to 30 mNOK. These investment costs are incurred when the vessel is build, i.e. t=0. The operational expenses are described as negligible for this case and will not be taken into account when calculating the NPV. The costs related to voyage expenses, i.e. fuel price and tax exemption, are beneficial, whereas the cost for an LNG-fuelled vessel is less than the corresponding values for the conventional vessel. As for the investment support from the NOx fund, it is assumed that this is granted the first year in operation, i.e. t=1.

The discount rate, i, can be difficult to evaluate in this case. More uncertainty regarding future cash flow will increase in the discount rate. For the case study, the discount rate is set as i=7%. The number of years accounted for, will be the assumed lifetime of the vessel, which equals 25 years. Further it is calculated that 80% of the investment is covered by the NOx fund, which equals 24 MNOK.

$$\begin{aligned} NPV = (-1.62)(-30) + 24 \times \frac{1}{(1+0.07)^1} \\ +(0.48+0.79+1.70) \times \frac{(1+0.1)^{25}-1}{0.07(1+0.07)^{25}} = 25.4MNOK \end{aligned} \tag{8.2}$$

Equation 8.2 includes the investment cost and corresponding support from the NOx-fund. The annual savings from fuel cost, NOx fund and savings regarding exemption from taxes during the lifetime of the vessel are further included.

If investing in the LNG-fuelled fishing vessel instead of conventional system, with a 7% discount rate, 25.4 mNOK accrues over 25 years. With involvement of the NOx fund, the LNG investment is economically more beneficial and the additional costs will have a payback time of 3-4 years.

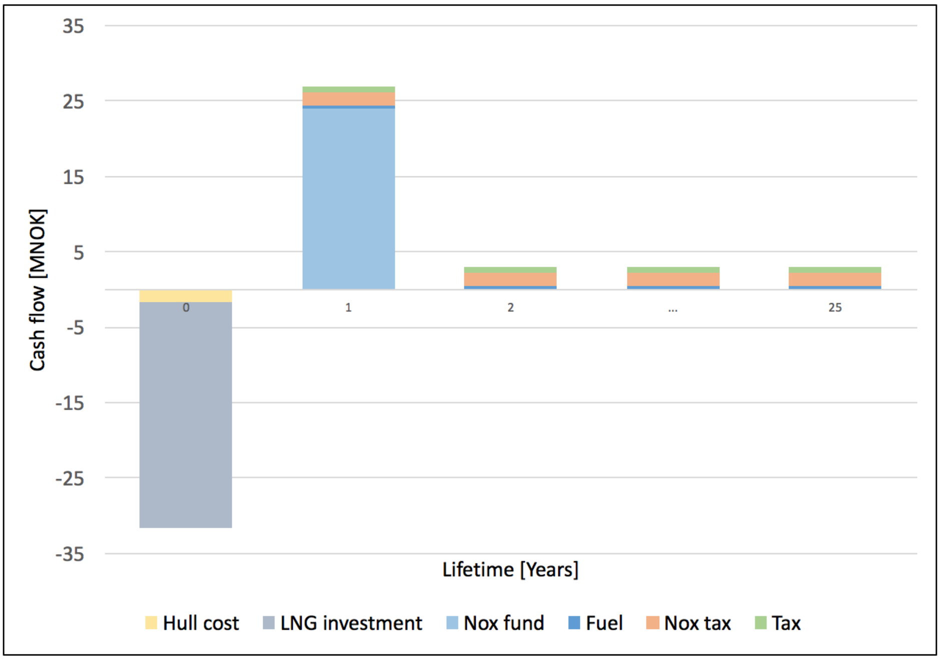


Figure 8.5: Cash flow for the LNG investment compared to MGO investment during the predicted lifetime of the fishing vessel.

As stated, the annual cargo amount is equivalent for both vessels every year. With the same cargo capacity, it is interesting to estimate the difference in yield, i.e. the increased profit (NOK/kg fish), by investing in LNG.

The increased profit can be calculated by dividing the annual additional return (NOK) in average, with the amount of fish (tonnes) the vessel is expected to carry in the course of one year.

$$\frac{F}{C} = \frac{\text{Additional annual return}[NOK]}{\text{Cargo per year}[tonnes]} = \frac{1016223}{5621} = 180.8NOK/tonne \tag{8.3}$$

From the calculations on the NPV and Equation 8.3, the additional return can on average increase with 0.18 NOK/kg fish for LNG investment compared to an MGO investment.

Part III

DISCUSSION

Chapter 9

Discussion and Limitations

9.1 Uncertainty regarding economic assessment

9.1.1 Calculating the NPV

NPV was used for the LCC analysis, generated a fundamental overview of the major costs differences. When calculating the NPV, several assumptions were made and there are some uncertainties regarding the elements in the NPV formulae.

The discount rate i, is set as 0.7 and assumed constant during the lifetime of the vessel. This amount is critical for the result of the NPV and at the same time very difficult to establish without great insights and knowledge about future economic and risks. However, a value between 5-7% is considered decent, where 10% can be evaluated as too conservative for vessels. Further, the lifetime of the vessel t is unknown. Considering that the average age of the fleet is 28 years today, it can be expected that the lifetime of this vessel may be prolonged compared to what was first assumed, i.e. longer than 25 years.

9.1.2 Sensitivity analysis

The fuel prices were assumed to be constant during the lifetime of the vessel. As previously stated, the fuel prices are fluctuating, and the future prices are highly uncertain. The fuel costs are challenging to predict, but different price projections should be applied to evaluate the risks. It should be mentioned that there is a positive correlation between natural gas and oil prices, an increase in oil prices may influence the natural gas supply, and consequently the gas prices. Natural gas and crude oil, in this case MGO, have had a historically stable relationship, although in some periods the prices have appeared to be decoupled (Villar and Joutz, 2006).

Further, benefits such as tax exemption are not necessarily constant during the lifetime of the vessel. A sensitivity analysis assessing different scenarios can be applied to predict how the total cost of the vessel will be affected by possible future regulations or fuel prices. Four different scenarios are presented relative to the baseline with established fuel price and tax exemption in the case. A 20% higher/lower fuel cost relative to the central price level have been taken into account. High gas price versus low MGO price, and vica versa, is not considered as a plausible scenario and therefore not assessed.

It is chosen to evaluate fuel price and tax regulations separately, to get a better overview of how different changes in variables will affect the outcome of the NPV. Probability distribution regarding the different scenarios is beyond the scope of the thesis and candidate's expertise, thus this have not been established. In *Scenario 1*, the fuel prices are the same as the baseline, but liable to pay the same taxes as for a vessel utilizing conventional fuel.

Table 9.1: Presentation of scenarios with price level and tax regulations.

Scenario Name	LNG price level	MGO price level	Tax regulations
Baseline	Central	Central	Exempt from tax, pays to NOx fund.
Scenario 1	Central	Central	No tax exemption.
Scenario 2	High	Central	Exempt from tax, pays to NOx fund.
Scenario 3	Central	Low	Exempt from tax, pays to NOx fund.
Scenario 4	Low	Central	Exempt from tax, pays to NOx fund.

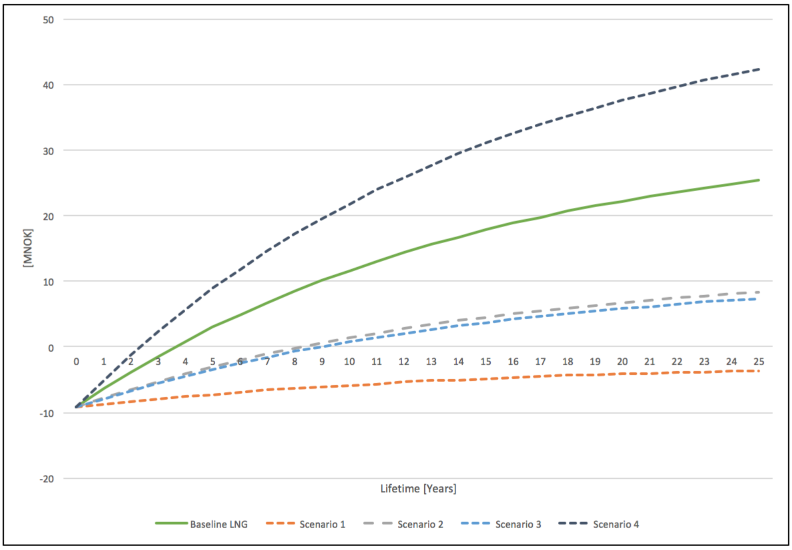


Figure 9.1: Modelled scenarios when including future uncertainty regarding fuel price and tax exemption.

Table 9.2: NPV for different scenarios.

Scenario Name	NPV in MNOK	Payback period in years
Baseline	25.4	3-4
Scenario 1	-3.6	-
Scenario 2	8.4	8-9
Scenario 3	7.4	9
Scenario 4	42.3	2-3

Table 9.2 shows the relative NPV of the LNG investment compared to MGO investment. The LNG investment is feasible in scenarios with a positive NPV.

The analysis shows that the NPV is highly sensitive towards changes regarding tax exemptions as illustrated for *Scenario 1*. Despite central fuel costs, it will not be profitable to invest in the LNG system if the vessel is liable to the same taxes as an MGO investment during the entire lifetime. The analysis is also sensitive towards fuel price dynamics, whereas the probability of changes related to fuel price are more likely, if not inevitable.

9.2 Review of environmental impact

The interpretation of the LCA contributes to uncertainties regarding the specific case study assessed. There are several factors influencing the exhausted emissions during upstream and downstream processes. The LCA contains former data for the upstream process, which may not be as applicable or relevant today.

From the results if was found that the GWP was almost equivalent for MGO and LNG in the case. As stated in Section 2.1, methane has a stronger GWP than CO2, which constitute a lot of the proportion of the CO2-equivalent of LNG.

Considering that the main component in natural gas is methane, and due to the fact that methane slip can occur during upstream process and operation, a significant amount of emitted CH4 in the LCA will have a great influence on the result. Small leakages can cancel out the beneficial effect of the GWPs. However, the methane slip during operation is highly dependent on the gas engine and is in several cases difficult to quantify. Further, the changes related to the main dimensions of the vessel have had some effect on the result for the downstream process. It can be difficult to measure these changes, but compared to the results deriving from the case by Bengtsson et al. (2011), it shows an estimated increase of the GWP of approximately 9% for LNG in this case, which have resulted in almost identical GWP for MGO and LNG.

The results show the environmental impact at midpoint level. The GWP have a considerable higher value compared to acidification- and eutrophication potential. The midpoint to endpoint conversion factor developed by Goedkoop et al. (2012), ReCiPe 2008, is illustrated in Table 9.3 below.

Table 9.3: Midpoint to endpoint conversion factor. Retrieved from: Goedkoop et al. (2012), ReCiPe 2016.

Midpoint to endpoint conversion factor	Unit	Hierarchic
Human health		
Global warming - Human health	DALY/kg CO2-eq.	9.28E-07
Terrestrial ecosystems		
Global Warming - Terrestrial ecosystems	Species.year/kg CO2-eq.	2.80E-09
Acidification - Terrestrial ecosystems	Species.year/kg SO2-eq.	2.12E-07
Freshwater ecosystems		
Global warming - Freshwater ecosystems	Species.year/kg CO2-eq.	7.65E-14
Eutrophication - Freshwater ecosystems	Species.year/kg P to freshwater-eq.	6.10E-07

As stated, the endpoint value will not be assessed in a quantitative approach due to large variety between different weighting methods. This conversion method is one of many LCA weighting methods, and therefore not a standard way to establish a conclusion regarding the total impact. It can, however, be discussed qualitatively. From Table 9.3, each of the environmental category assessed, dominates and have a prominently higher impact on either human health or ecosystems.

Utilizing LNG as fuel will evidently reduce the exhausted emissions of SO_x, NO_x and CO_2, as a result of the properties of natural gas. LNG has a lower impact on terrestrial ecosystems and freshwater ecosystems. The GWP have had an influence on these categories, but the level of impact still appears to be low compared to MGO. However, when evaluating the impact on human health, the methane slip from the combustion process will evidently almost override the benefits of adopting LNG relative to a conventional system according to this conversion method at endpoint level.

9.3 Regulatory framework

The requirements for gas-fuelled vessels are mainly an adaption from bulk transport of LNG at sea. The regulations for gas fuelled vessels can be seen as too stringent when applied for other vessel segments (Koers & Vaart B.V., 2016). In Norway, the focus have primarily been on affordable solutions and environmental friendly alternatives for platform supply vessels (PSV's).

The IGF Code for application of gas as fuel shows some high safety aspects. It is assumed that this is due to the focus that the gas fuelled vessels can be applicable offshore, and therefore a high risk involved. This can for instance be when there is operations near oil rigs. For commercial shipping and fisheries the case will be somewhat different, and there should be balance with prevailing risks to give the alternative fuel a better possibility to be adapted.

The IGF Code and regulations for gas-fuelled vessels are intended for cargo and passenger vessels, and not for fishing vessels by definition. Due to this, there is some uncertainty when it comes to what regulations to comply with. The requirements differs for cargo- and passenger vessels, mainly due to the difference in the degree of trained personnel on board. The regulations states that all seafarers on board gas-fuelled ships shall have completed training to be capable to perform their responsibilities and duties. It is considered that this will apply for all personnel on a fishing vessel, as well. Therefore, it is conceivable that a fishing vessel is more or less similar to a cargo vessel. However, to be certain to comply with the regulations, it was decided to follow the regulations for a passenger vessel. This decision can have an effect on the end results and the space required for LNG, but it was assumed that these are minimum.

Further, stability have not been calculated for the vessel. The main dimensions and the center of gravity of the vessel will both have an influence on stability. The stability criterion for fishing vessels are significant, due to several loading conditions for one single roundtrip. It has, however, not been made several changes that will influence the center of gravity in a high degree and the vessel is originally equipped with water ballast tanks to avoid trim at different loading conditions. By using some of the fuel tanks on the original vessel for water ballast can be efficient to retain the stability. The breadth has increased in line with the length of the vessel to keep the vessel stable at all times, but also due to regulations regarding the distance from tanks to the ship side.

It is also important to mention that own interpretation have been used to understand the rules regarding arrangement of the tanks and the general arrangement of the fishing vessel. This can have led to sources of errors, thus some deviations which are inconsistent with the given regulations. But assumptions made are considered to not affect the end results to a large extent.

9.4 Sustainability - Social pillar

Sustainability consists of the three pillars; economic, environmental and social. A sustainable system is dependent on all pillars, whereas one weak pillar can make the system as a whole unsustainable (Chopra and Meindl, 2007). While the economic and environmental pillar regarding LNG as fuel have been assessed, an evaluation of the social pillar is not part of the final result, primarily because it is challenging to quantify. The social pillar can be seen as for instance work environment and risk involved processing and utilizing LNG. There are up till now, no well-established statistics regarding the risk of utilizing LNG as fuel other than for LNG carriers.

The perception stakeholders, consumers and others have of utilizing LNG as fuel can be seen in context with the social aspect. Great attention and recognition from influential enterprises such as DNV GL, supports the idea of utilizing the alternative fuel and increases the social value.

As for the risk related to LNG systems, an inexperienced crew that is unfamiliar with a gas-fuelled vessel can more frequently cause human errors. Further, there have to be taken safety measures when it comes to the risk of explosion in case of gas leakage. The crew have to familiarize themselves with new monitoring and safety systems. With no natural odour, it can be very difficult for the personnel to detect small gas leakage, therefore it is essential that methane detectors are located in the area where the gas is stored or transferred (DNV GL, 2018).

With sufficient training and safety measures, which are already indicated to be more than satisfactory according to the regulatory framework, nothing suggests that utilizing LNG is less desirable than conventional system when it comes to the social pillar of sustainability. It can however, increase the operational costs due to more expenses regarding training of personnel, which have been neglected in the previous economic analysis.

9.5 Alternative energy sources

It is important to emphasize that LNG as fuel is not the singular option when investing in green technology, and not necessarily the best alternative when evaluating different fuels. As of today, there are different alternatives that can be proven to be sustainable options in the future. However, when addressing availability of the fuel, energy sources such as methanol (CH_3OH) and hydrogen (H) does not perform well. LNG already have a satisfying infrastructure, and can be available along the Norwegian coastline in small-scale. Availability and usability are two important determining factors for actors when investing in unconventional systems.

Methanol will however be beneficial in regards to space efficiency. Methanol does not require large cryogenic tanks to cool it under a specific pressure and is flexible in terms of where to store the fuel, similar to MGO. A way to remove the CO2 emissions can be done by producing methanol from biomass. But there have been done limited research and developing projects for this production method (Øberg, 2013). Further, it has been shown that the interests and investment is higher for LNG than methanol in Norway today, which is a decisive factor and is not assumed to change in the nearest future.

Batteries can be applicable for the coastal fleet, where the distance to the fishing grounds are short. It can be considered as a good alternative, mainly because electricity does not lead to direct emissions when in operation, leads to less vibration and noise. The use of an electric motor based on energy from battery is limited today due to low energy density in the batteries. The main question is how rapidly the technology develops, and when batteries can replace the energy sources on large ocean going vessels requiring extensive power and duration. It can, however, be utilized to optimize energy consumption on board large fishing vessels, thus contribute to lower the emissions (Thompson S., Stakeholder, 2017).

The intention with the thesis is to evaluate a greener alternative that can be applicable in near future, where infrastructure, technical solutions and economic feasibility makes it possible to implement.

Chapter 10

Conclusion and Further work

The findings have been discussed in the previous chapter, whereas this chapter summarizes the conclusion for the thesis and further work to be conducted to support the rationale.

The objective for the thesis was to increase knowledge regarding the financial and environmental aspects of utilizing LNG as fuel, but also to explore the technical solutions and how it affects the vessel's performance overall. This have been evaluated by performing a case study.

Investing in LNG as fuel can be beneficial for a fishing vessel to improve the environmental profile in regards to emitted regional pollutants such as NO_x and SO_x, as several studies have shown. It has, however, only given a small decrease in emitted greenhouse gases, mostly due to methane leakage during the combustion process. The vessel using LNG as fuel has a higher required energy consumption, which again have influenced the environmental performance. It has been concluded that the impact on human health will evidently be similar for LNG and MGO, according to the weighting method discussed.

Regulations are the main driving force for a change to and the adoption of more environmental friendly technology. The focus is largely aimed at the reduction in the regional pollutants. As stated initially, it is reasonable to believe that global demands will reach the same restrictions as today's ECAs. Hence, LNG with a naturally low sulfur content and cleaner exhaust is a good option, regardless.

As a result of the incentives and tax exemptions that can be obtained today, the investment is beneficial for the fishing vessel. In the context of an ageing fishing fleet, incentives for replacing the oldest vessels can be important to accelerate the effects of a new regulatory system. However, tax exemptions, fuel costs and other voyage related expenses are not deemed to be constant, which leads to uncertainty regarding future costs and payback time.

The vessel studied is not representative for every fishing vessel. The vessel was chosen due to two primary reasons; it operates within 250 nm from shore and is part of the segments that acquire a low energy efficiency in general. Fishing vessels operating in distance waters will not have the same outcome, considering that these vessels are nevertheless exempt from CO_2 and SO_x taxes in Norway. Thus, it is limited how the conclusion will indicate the outcome for vessels of other magnitude, e.g. large ocean-going trawlers, in terms of financial gains. The LNG fuel price is however predicted to be at a low and stable range, which indicates that this can be an attractive solution overall. A different appealing solution could be to have a conventional system with MGO in addition to SCR technology which can reduce the NOx of 50–95% according to measurements collected by the Norwegian NO_x fund (Martinsen and Torvanger, 2013). This measure will give the investors the opportunity to be a part of the NOx fund. This can potentially be a better solution, also in terms of less complex systems and the vessel can still meet the requirements in the future.

Assumptions made and uncertainty regarding future costs are some of the elements that should be reevaluated and studied further. As stated, the thesis is limited to one semester, gathering and analysing sufficient data can be time consuming. The case study have in some ways raised more questions, such as how this will be applicable for fishing vessels of other magnitude and how to cope with the list of uncertainties that have been encountered.

Further work concerns more thorough analysis and data collection of both the environmental and economical aspects. Future work which can be interesting and to support the rationale are listed as follows:

- Evaluation of dual-fuel solution, utilizing LNG combined with MGO can be of interest. This combination could potentially save space and be cost-effective (Altosole et al., 2014). Dual-fuel solution has not been evaluated due to the objective and approach of the thesis, where the aim was to compare the two fuels.
- Other fishing vessel segments with different fishing methods and gear can be explored in order to support the validity of the findings. An evaluation of LNG for other fishing vessels can increase knowledge about how the LNG-system affect other traditional fishing vessel's arrangements, and whether or not the impact on main dimensions and hull form will be significantly less.
- An LCA of the complete vessels, i.e. environmental impact of ship construction, ship operation and ship scrapping in addition to the respective fuel assessed. The environmental performance of the vessel is however assumed to be mostly affected by the fuel utilized, where additional hull structures and systems do not make a large impact overall.

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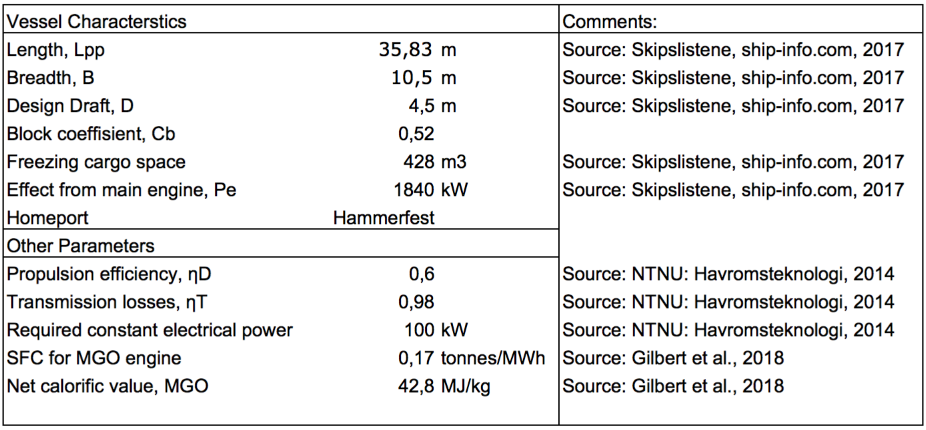
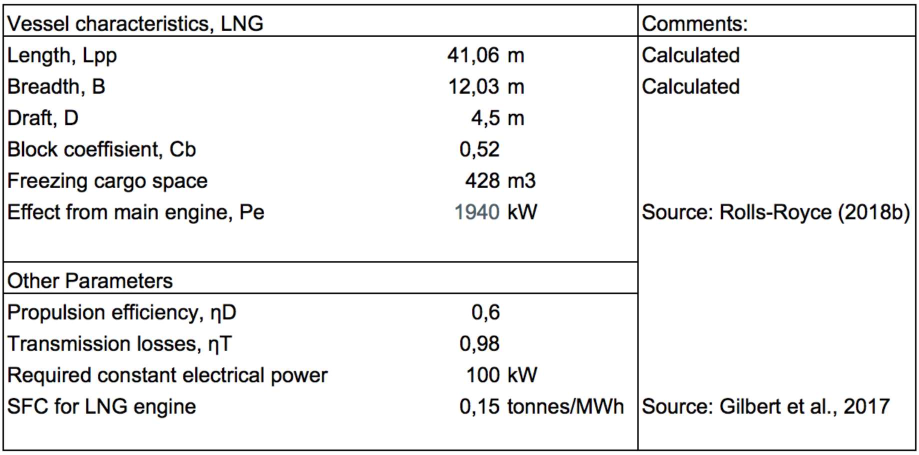
Appendix



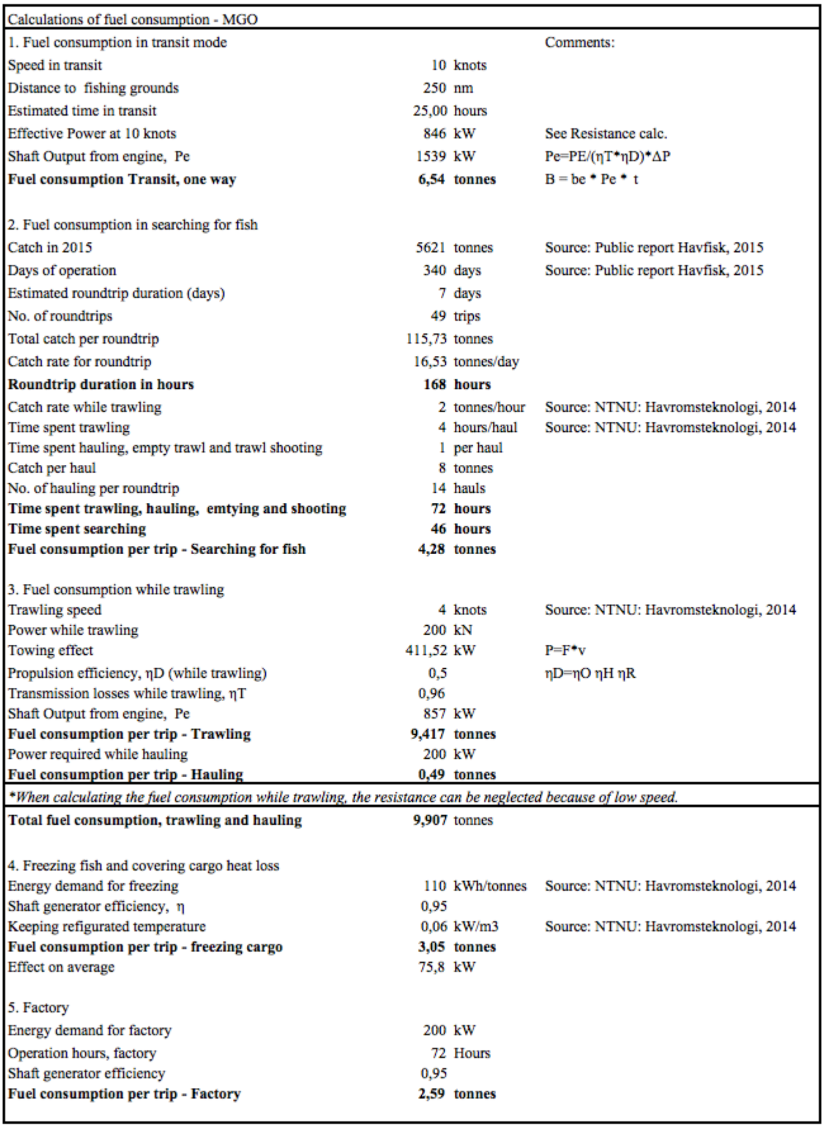
Vessel Characterstics		Comments:
Length, Lpp	35,83 m	Source: Skipslistene, ship-info.com, 2017
Breadth, B	10,5 m	Source: Skipslistene, ship-info.com, 2017
Design Draft, D	4,5 m	Source: Skipslistene, ship-info.com, 2017
Block coeffisient, Cb	0,52	
Freezing cargo space	428 m3	Source: Skipslistene, ship-info.com, 2017
Effect from main engine, Pe	1840 kW	Source: Skipslistene, ship-info.com, 2017
Homeport	Hammerfest	
Other Parameters		
Propulsion efficiency, ηD	0,6	Source: NTNU: Havromsteknologi, 2014
Transmission losses, ηT	0,98	Source: NTNU: Havromsteknologi, 2014
Required constant electrical power	100 kW	Source: NTNU: Havromsteknologi, 2014
SFC for MGO engine	0,17 tonnes/MWh	Source: Gilbert et al., 2018
Net calorific value, MGO	42,8 MJ/kg	Source: Gilbert et al., 2018

Figure A1: Vessel characteristics for MGO-fuelled vessel.



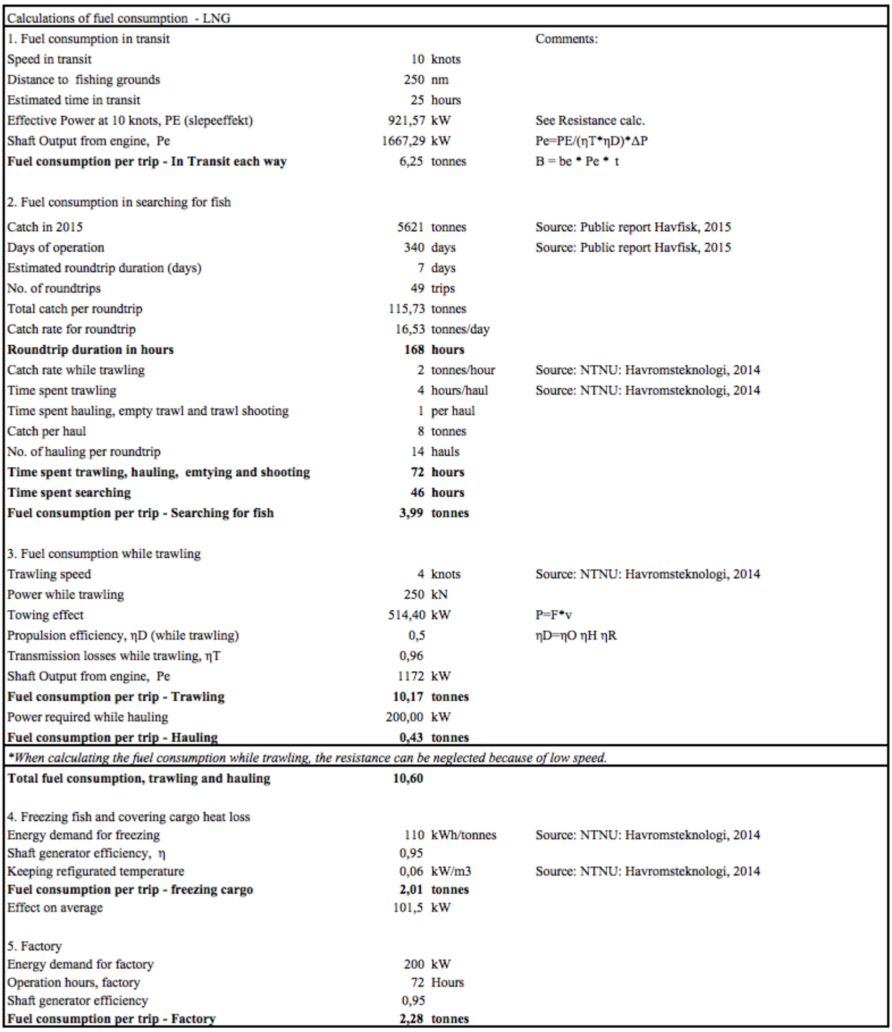
Vessel characteristics, LNG		Comments:
Length, Lpp	41,06 m	Calculated
Breadth, B	12,03 m	Calculated
Draft, D	4,5 m	
Block coeffisient, Cb	0,52	
Freezing cargo space	428 m3	
Effect from main engine, Pe	1940 kW	Source: Rolls-Royce (2018b)
Other Parameters		
Propulsion efficiency, ηD	0,6	
Transmission losses, ηT	0,98	
Required constant electrical power	100 kW	
SFC for LNG engine	0,15 tonnes/MWh	Source: Gilbert et al., 2017

Figure A2: Vessel characteristics for the LNG-fuelled vessel.



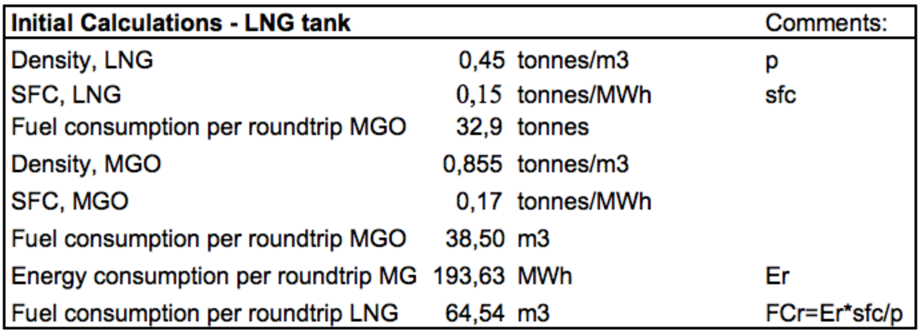
Calculations of fuel consumption - MGO			
1. Fuel consumption in transit mode			Comments:
Speed in transit	10	knots	
Distance to fishing grounds	250	nm	
Estimated time in transit	25,00	hours	
Effective Power at 10 knots	846	kW	See Resistance calc.
Shaft Output from engine, Pe	1539	kW	Pe=PE/(ηT*ηD)*ΔP
Fuel consumption Transit, one way	**6,54**	**tonnes**	B = be * Pe * t
2. Fuel consumption in searching for fish			
Catch in 2015	5621	tonnes	Source: Public report Havfisk, 2015
Days of operation	340	days	Source: Public report Havfisk, 2015
Estimated roundtrip duration (days)	7	days	
No. of roundtrips	49	trips	
Total catch per roundtrip	115,73	tonnes	
Catch rate for roundtrip	16,53	tonnes/day	
Roundtrip duration in hours	**168**	**hours**	
Catch rate while trawling	2	tonnes/hour	Source: NTNU: Havromsteknologi, 2014
Time spent trawling	4	hours/haul	Source: NTNU: Havromsteknologi, 2014
Time spent hauling, empty trawl and trawl shooting	1	per haul	
Catch per haul	8	tonnes	
No. of hauling per roundtrip	14	hauls	
Time spent trawling, hauling, emtying and shooting	**72**	**hours**	
Time spent searching	**46**	**hours**	
Fuel consumption per trip - Searching for fish	**4,28**	**tonnes**	
3. Fuel consumption while trawling			
Trawling speed	4	knots	Source: NTNU: Havromsteknologi, 2014
Power while trawling	200	kN	
Towing effect	411,52	kW	P=F*v
Propulsion efficiency, ηD (while trawling)	0,5		ηD=ηO ηH ηR
Transmission losses while trawling, ηT	0,96		
Shaft Output from engine, Pe	857	kW	
Fuel consumption per trip - Trawling	**9,417**	**tonnes**	
Power required while hauling	200	kW	
Fuel consumption per trip - Hauling	**0,49**	**tonnes**	
**When calculating the fuel consumption while trawling, the resistance can be neglected because of low speed.*			
Total fuel consumption, trawling and hauling	**9,907**	tonnes	
4. Freezing fish and covering cargo heat loss			
Energy demand for freezing	110	kWh/tonnes	Source: NTNU: Havromsteknologi, 2014
Shaft generator efficiency, η	0,95		
Keeping refigurated temperature	0,06	kW/m3	Source: NTNU: Havromsteknologi, 2014
Fuel consumption per trip - freezing cargo	**3,05**	**tonnes**	
Effect on average	75,8	kW	
5. Factory			
Energy demand for factory	200	kW	
Operation hours, factory	72	Hours	
Shaft generator efficiency	0,95		
Fuel consumption per trip - Factory	**2,59**	**tonnes**	

Figure A3: Calculations of fuel consumption for the MGO-fuelled vessel.



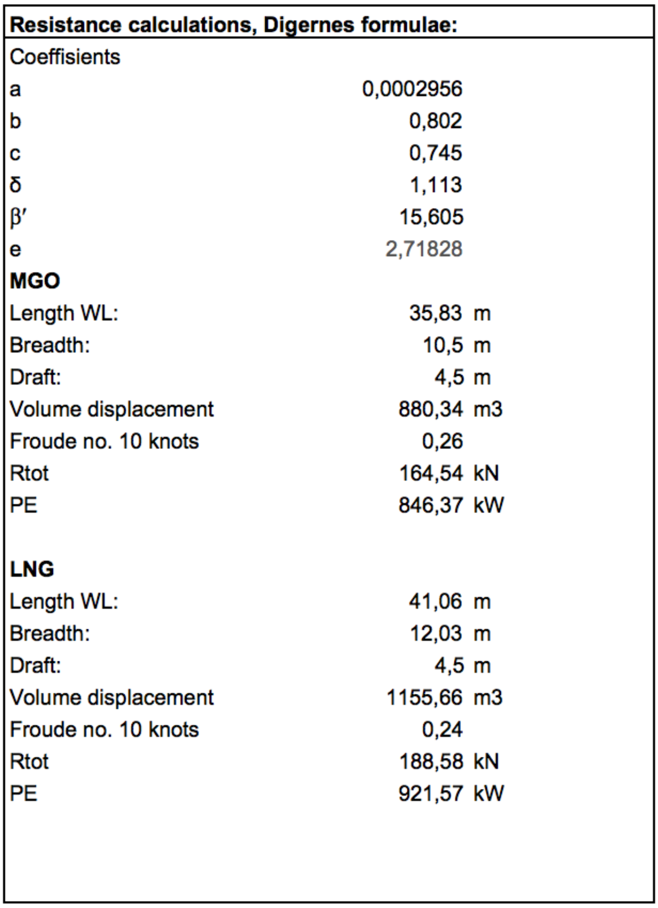
Calculations of fuel consumption - LNG			
1. Fuel consumption in transit			Comments:
Speed in transit	10	knots	
Distance to fishing grounds	250	nm	
Estimated time in transit	25	hours	
Effective Power at 10 knots, PE (slepeeffekt)	921,57	kW	See Resistance calc.
Shaft Output from engine, Pe	1667,29	kW	Pe=PE/(ηT*ηD)*ΔP
Fuel consumption per trip - In Transit each way	6,25	tonnes	B = be * Pe * t
2. Fuel consumption in searching for fish			
Catch in 2015	5621	tonnes	Source: Public report Havfisk, 2015
Days of operation	340	days	Source: Public report Havfisk, 2015
Estimated roundtrip duration (days)	7	days	
No. of roundtrips	49	trips	
Total catch per roundtrip	115,73	tonnes	
Catch rate for roundtrip	16,53	tonnes/day	
Roundtrip duration in hours	**168**	**hours**	
Catch rate while trawling	2	tonnes/hour	Source: NTNU: Havromsteknologi, 2014
Time spent trawling	4	hours/haul	Source: NTNU: Havromsteknologi, 2014
Time spent hauling, empty trawl and trawl shooting	1	per haul	
Catch per haul	8	tonnes	
No. of hauling per roundtrip	14	hauls	
Time spent trawling, hauling, emtying and shooting	**72**	**hours**	
Time spent searching	**46**	**hours**	
Fuel consumption per trip - Searching for fish	**3,99**	**tonnes**	
3. Fuel consumption while trawling			
Trawling speed	4	knots	Source: NTNU: Havromsteknologi, 2014
Power while trawling	250	kN	
Towing effect	514,40	kW	P=F*v
Propulsion efficiency, ηD (while trawling)	0,5		ηD=ηO ηH ηR
Transmission losses while trawling, ηT	0,96		
Shaft Output from engine, Pe	1172	kW	
Fuel consumption per trip - Trawling	**10,17**	**tonnes**	
Power required while hauling	200,00	kW	
Fuel consumption per trip - Hauling	**0,43**	**tonnes**	
**When calculating the fuel consumption while trawling, the resistance can be neglected because of low speed.*			
Total fuel consumption, trawling and hauling	**10,60**		
4. Freezing fish and covering cargo heat loss			
Energy demand for freezing	110	kWh/tonnes	Source: NTNU: Havromsteknologi, 2014
Shaft generator efficiency, η	0,95		
Keeping refigurated temperature	0,06	kW/m3	Source: NTNU: Havromsteknologi, 2014
Fuel consumption per trip - freezing cargo	**2,01**	**tonnes**	
Effect on average	101,5	kW	
5. Factory			
Energy demand for factory	200	kW	
Operation hours, factory	72	Hours	
Shaft generator efficiency	0,95		
Fuel consumption per trip - Factory	**2,28**	**tonnes**	

Figure A4: Calculations of fuel consumption for the LNG-fuelled vessel.



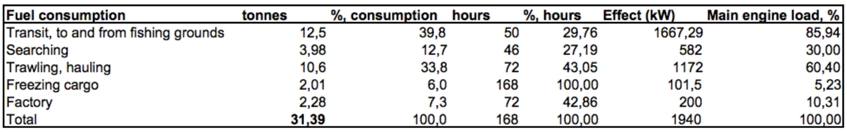
Initial Calculations - LNG tank			Comments:
Density, LNG	0,45	tonnes/m3	p
SFC, LNG	0,15	tonnes/MWh	sfc
Fuel consumption per roundtrip MGO	32,9	tonnes	
Density, MGO	0,855	tonnes/m3	
SFC, MGO	0,17	tonnes/MWh	
Fuel consumption per roundtrip MGO	38,50	m3	
Energy consumption per roundtrip MG	193,63	MWh	Er
Fuel consumption per roundtrip LNG	64,54	m3	FCr=Er*sfc/p

Figure A5: Initial calculations of volume for LNG storage tank.



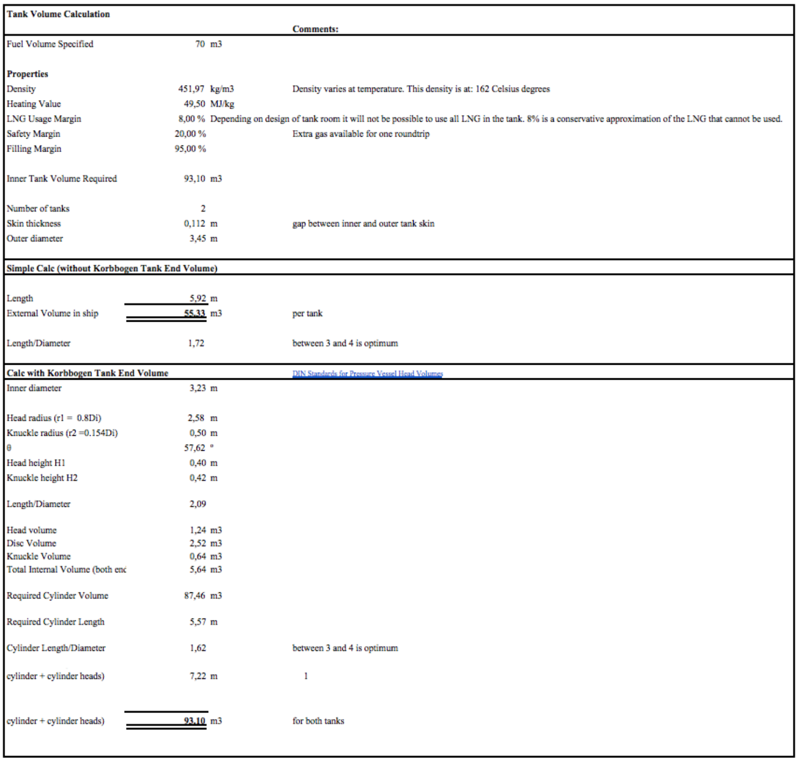
Resistance calculations, Digernes formulae:		
Coeffisients		
a	0,0002956	
b	0,802	
c	0,745	
δ	1,113	
β′	15,605	
e	2,71828	
MGO		
Length WL:	35,83	m
Breadth:	10,5	m
Draft:	4,5	m
Volume displacement	880,34	m3
Froude no. 10 knots	0,26	
Rtot	164,54	kN
PE	846,37	kW
LNG		
Length WL:	41,06	m
Breadth:	12,03	m
Draft:	4,5	m
Volume displacement	1155,66	m3
Froude no. 10 knots	0,24	
Rtot	188,58	kN
PE	921,57	kW

Figure A6: Resistance calculations using the Digernes formula.



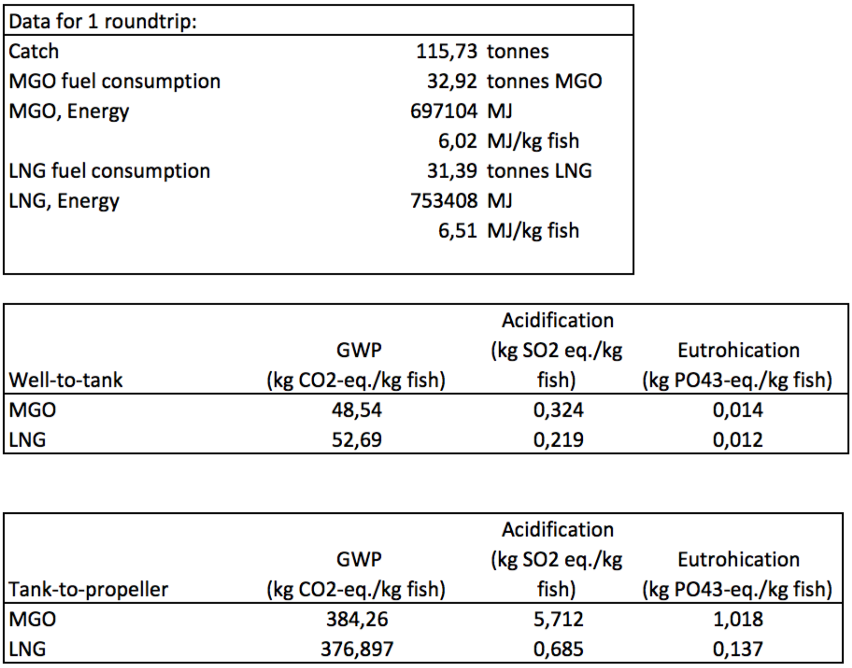
Fuel consumption	tonnes	%, consumption	hours	%, hours	Effect (kW)	Main engine load, %
Transit, to and from fishing grounds	12,5	39,8	50	29,76	1667,29	85,94
Searching	3,98	12,7	46	27,19	582	30,00
Trawling, hauling	10,6	33,8	72	43,05	1172	60,40
Freezing cargo	2,01	6,0	168	100,00	101,5	5,23
Factory	2,28	7,3	72	42,86	200	10,31
Total	**31,39**	100,0	168	100,00	1940	100,00

Figure A7: Total fuel consumption of LNG-fuelled vessel.



Tank Volume Calculation			
			Comments:
Fuel Volume Specified	70	m3	
Properties			
Density	451,97	kg/m3	Density varies at temperature. This density is at: 162 Celsius degrees
Heating Value	49,50	MJ/kg	
LNG Usage Margin	8,00 %		Depending on design of tank room it will not be possible to use all LNG in the tank. 8% is a conservative approximation of the LNG that cannot be used.
Safety Margin	20,00 %		Extra gas available for one roundtrip
Filling Margin	95,00 %		
Inner Tank Volume Required	93,10	m3	
Number of tanks	2		
Skin thickness	0,112	m	gap between inner and outer tank skin
Outer diameter	3,45	m	
Simple Calc (without Korbbogen Tank End Volume)			
Length	5,92	m	
External Volume in ship	55,33	m3	per tank
Length/Diameter	1,72		between 3 and 4 is optimum
Calc with Korbbogen Tank End Volume			DIN Standards for Pressure Vessel Head Volumes
Inner diameter	3,23	m	
Head radius (r1 = 0.8Di)	2,58	m	
Knuckle radius (r2 =0.154Di)	0,50	m	
θ	57,62	°	
Head height H1	0,40	m	
Knuckle height H2	0,42	m	
Length/Diameter	2,09		
Head volume	1,24	m3	
Disc Volume	2,52	m3	
Knuckle Volume	0,64	m3	
Total Internal Volume (both enc	5,64	m3	
Required Cylinder Volume	87,46	m3	
Required Cylinder Length	5,57	m	
Cylinder Length/Diameter	1,62		between 3 and 4 is optimum
cylinder + cylinder heads)	7,22	m	1
cylinder + cylinder heads)	93,10	m3	for both tanks

Figure A8: Calculation of LNG storage tank volume.



Data for 1 roundtrip:		
Catch	115,73	tonnes
MGO fuel consumption	32,92	tonnes MGO
MGO, Energy	697104	MJ
	6,02	MJ/kg fish
LNG fuel consumption	31,39	tonnes LNG
LNG, Energy	753408	MJ
	6,51	MJ/kg fish

Well-to-tank	GWP (kg CO2-eq./kg fish)	Acidification (kg SO2 eq./kg fish)	Eutrohication (kg PO43-eq./kg fish)
MGO	48,54	0,324	0,014
LNG	52,69	0,219	0,012

Tank-to-propeller	GWP (kg CO2-eq./kg fish)	Acidification (kg SO2 eq./kg fish)	Eutrohication (kg PO43-eq./kg fish)
MGO	384,26	5,712	1,018
LNG	376,897	0,685	0,137

Figure A9: Data for LCA of the fuel alternatives.

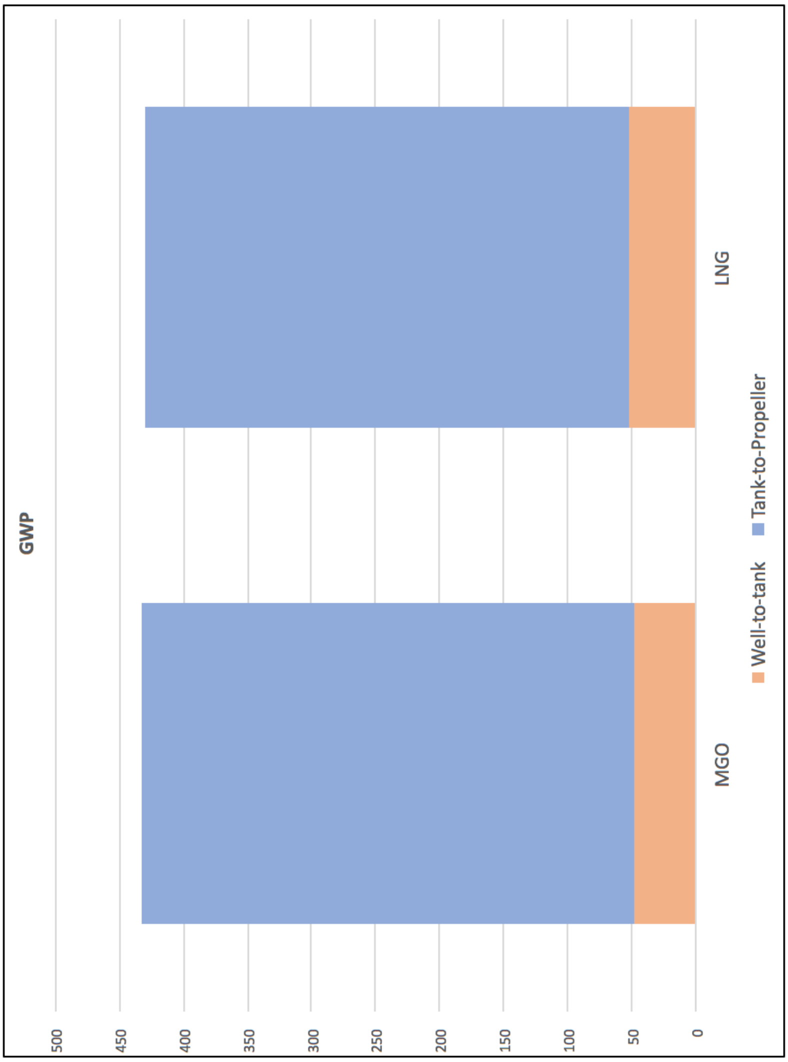


Figure A10: Life cycle global warming potential of the investigated fuels.

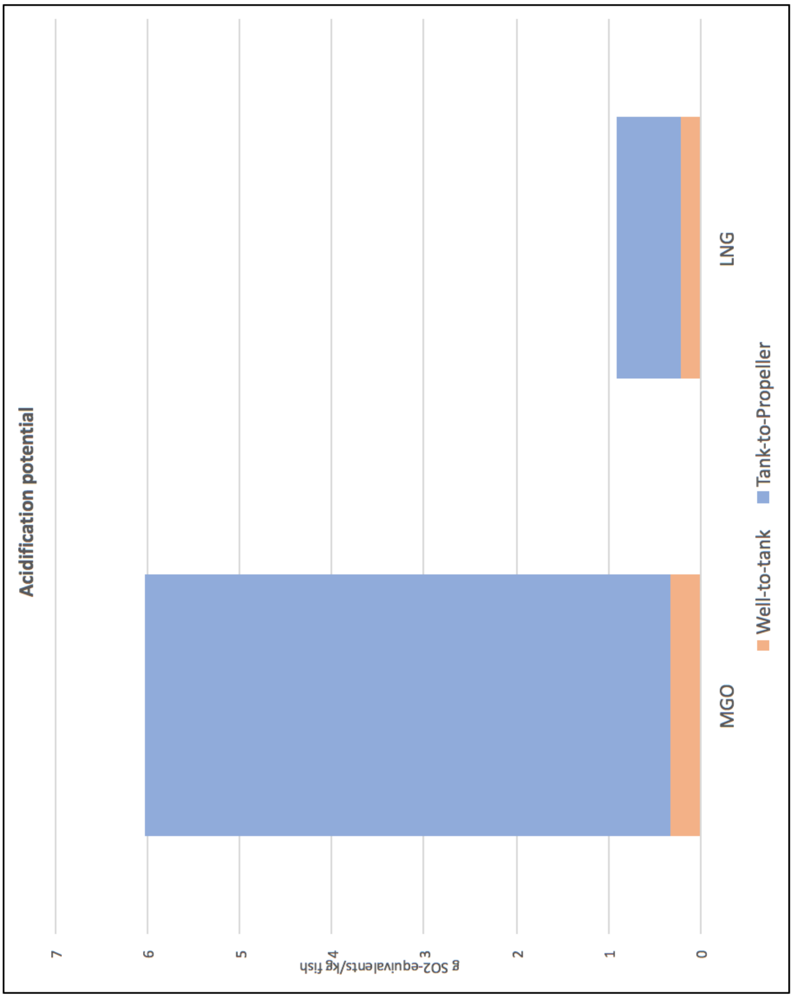


Figure A11: Life cycle acidification potentials of the investigated fuels.

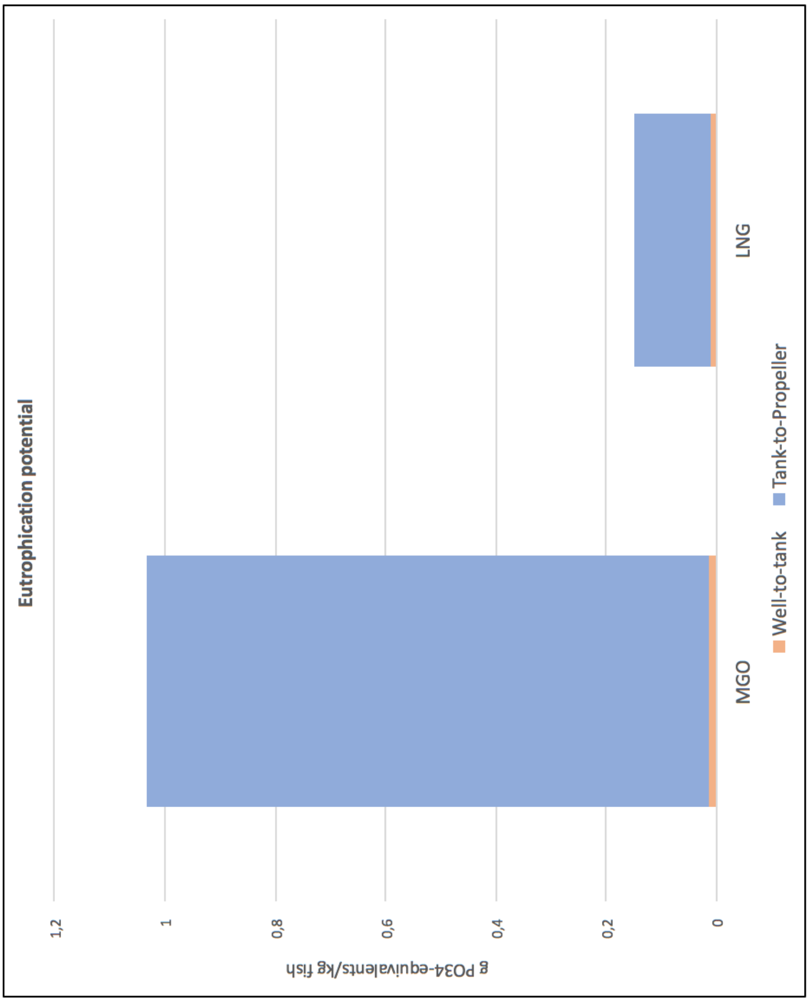


Figure A12: Life cycle eutrophication potential of the investigated fuels.

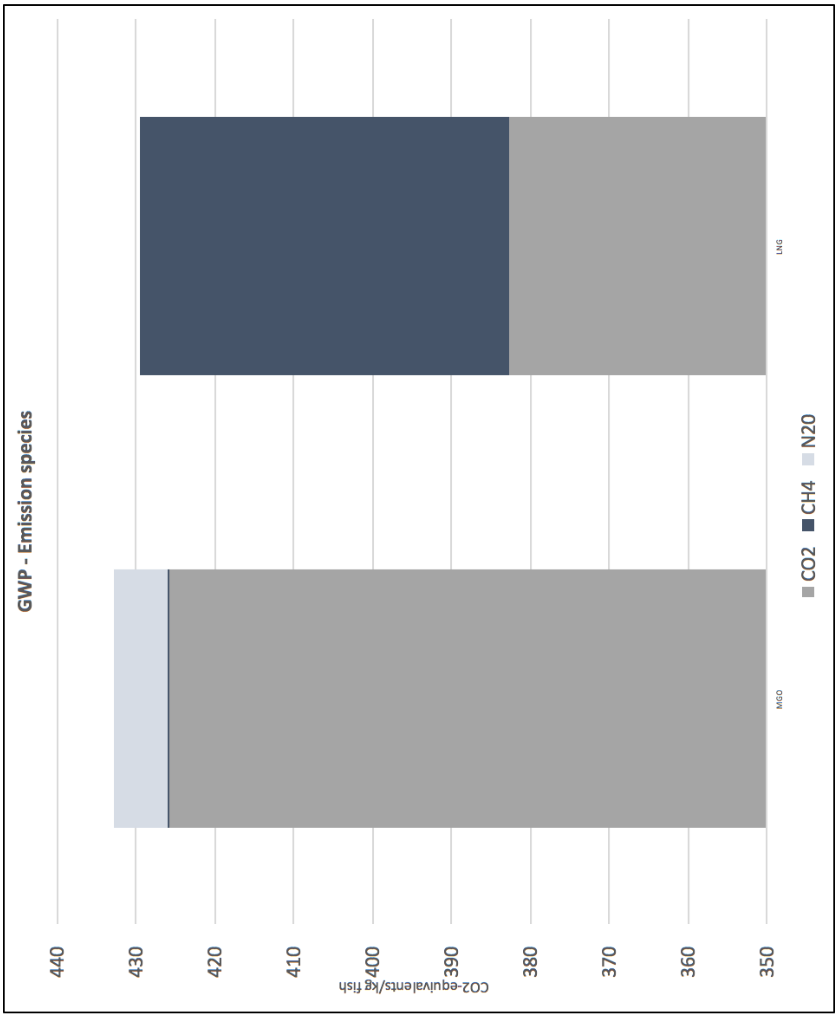
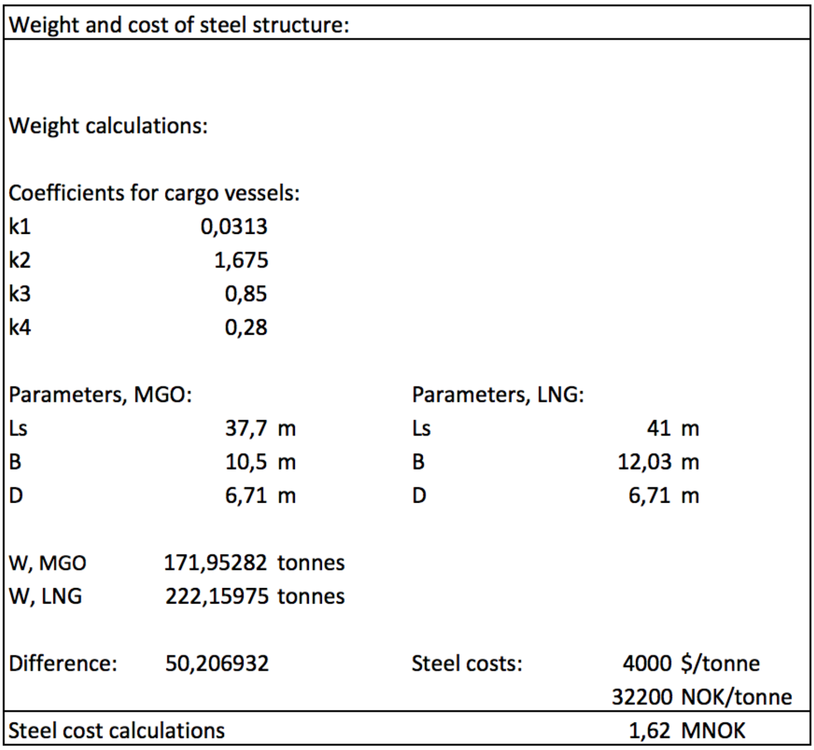


Figure A13: Life cycle global warming potential of the investigated fuels, contribution from different substances.



Weight and cost of steel structure:					
Weight calculations:					
Coefficients for cargo vessels:					
k1	0,0313				
k2	1,675				
k3	0,85				
k4	0,28				
Parameters, MGO:			Parameters, LNG:		
Ls	37,7	m	Ls	41	m
B	10,5	m	B	12,03	m
D	6,71	m	D	6,71	m
W, MGO	171,95282	tonnes			
W, LNG	222,15975	tonnes			
Difference:	50,206932		Steel costs:	4000	$/tonne
				32200	NOK/tonne
Steel cost calculations				1,62	MNOK

Figure A14: Additional cost and steel weight calculations.

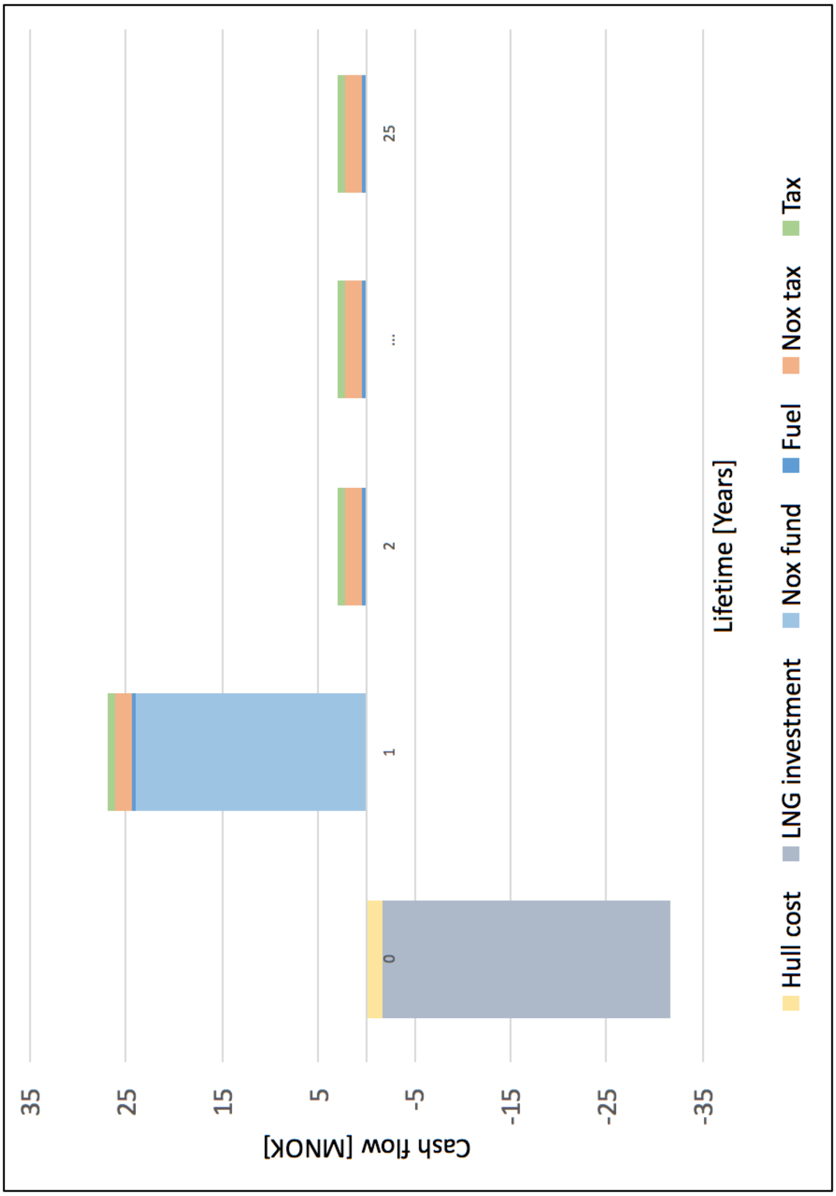


Figure A15: Cash flow for the LNG investment compared to MGO baseline during the predicted lifetime of the vessel.

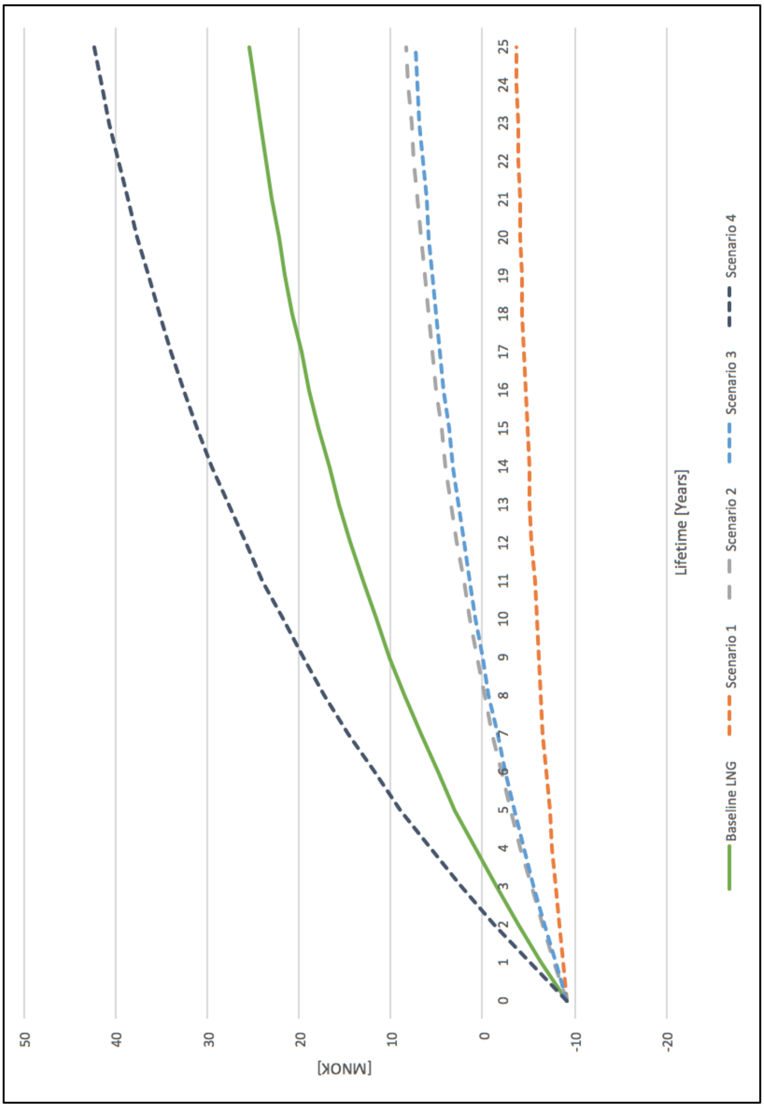


Figure A16: Result of scenario analysis.

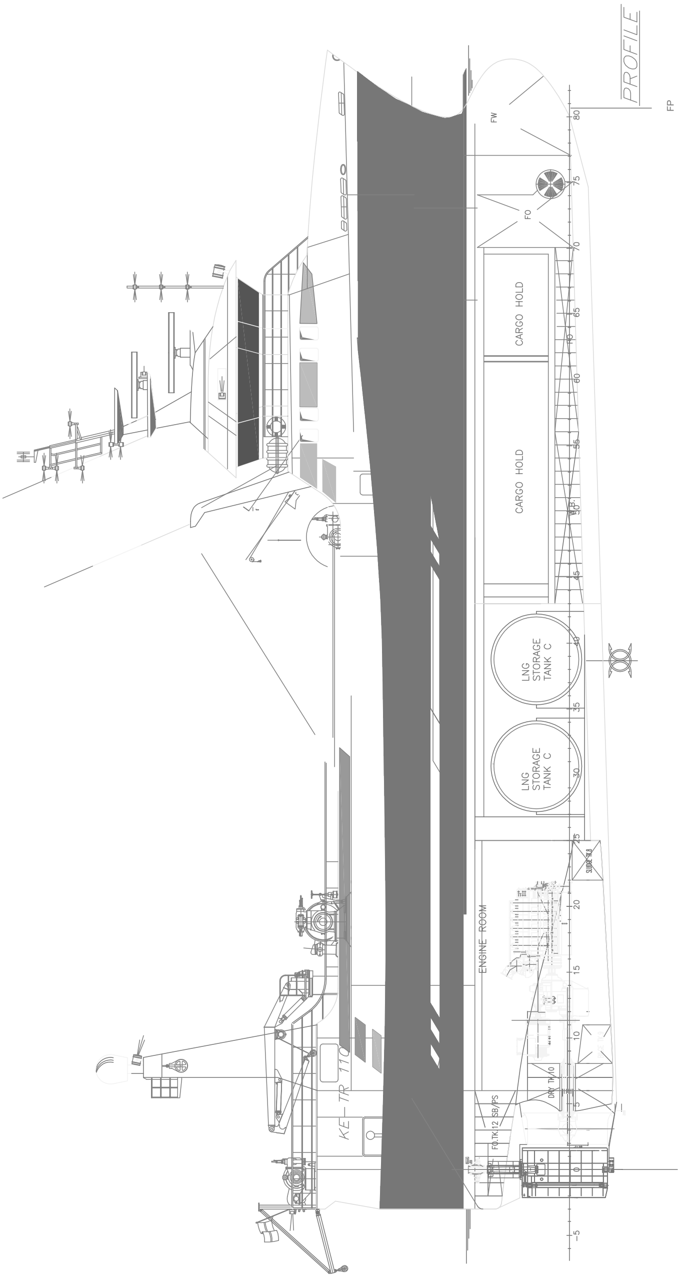


Figure A17: General arrangement of LNG-fuelled vessel, Profile.

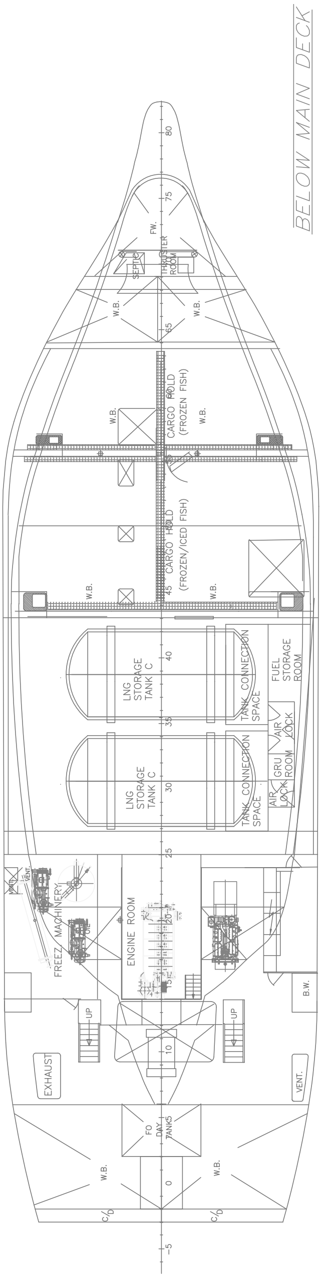


Figure A18: General arrangement of LNG-fuelled vessel, Below main deck.