LNG-fueled vessels in the Norwegian short-sea market

– a cost-effective response to environmental regulation

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Preface

This thesis is submitted in candidacy for the Master of Science in Economics and Business Administration at the Norwegian School of Economics and Business Administration (NHH) in Bergen, Norway.

During our years of studying at NHH, we learned how economics is about managing resources to meet individual needs and aspirations as well as achieving other social goals. Balancing economic and environmental goals seem to be an increasing challenge to society. Since we have a genuine interest in the shipping sector, we thought it would be interesting to write a thesis in which we could study more detailed how shipping can contribute to environmental sustainability, simultaneously as being cost-effective.

We would like to thank our supervisor Gunnar Eskeland for his helpful advice and his accessibility throughout the work on this thesis. We would also like to thank all the people within the Norwegian maritime cluster who have shared valuable information.

Bergen, 18. Juni 2010

Meike Baumgart Jon Halvard Bolstad Olsen

Executive summary

The objective of this thesis is to assess the environmental and economic advantages of using LNG as fuel for ships.

Air emissions from ships are an increasing environmental concern. Since the shipping sector can expect to face more stringent environmental regulations in the future, LNG's potential as a response to these regulations is analyzed. This study offers an overview of present environmental regulations as well as a description of the properties of LNG.

The aim of the final analysis is to identify the cost position of LNG-fueled vessels within different sectors of the Norwegian short-sea shipping market. Net present value (NPV) analysis sets the technical framework for the economic evaluation.

The analysis comes to the conclusion that using LNG as fuel for ships offers the potential for significant environmental improvement, regarding both air quality and climate protection, in all sectors subject to the analysis. Economically, LNG as fuel can compete with conventional marine fuel (MGO), at oil prices around approximately 60 $/bbl.

Hence, the results of this study indicate that from both an environmental- and economic perspective the investment in LNG powered ships is strongly recommendable. The study also presents some potential barriers with regards to commercial viability and technological feasibility that need to be overcome before LNG becomes fully competitive with other fuels.

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1. Introduction

1.1. Background

Emissions from shipping consist of various gases and particles that influence atmospheric concentrations of greenhouse gases and aerosols. These emissions are a significant contributor to greenhouse gas (GHG) emissions from the transport sector. 2,7 % of the global emissions of CO_2 in 2007 was emitted by international shipping (M. IMO 2009) and nearly 70% of these emissions occurred within 400 km of coastlines (V. e. Eyring 2009), causing air quality problems in regions with heavy traffic. Hence, ship emissions have an impact on the global climate, and the shipping sector can be expected to be subject to increasingly stringent emission standards.

At the same time, short-sea shipping is considered to be a sustainable mode of transport which contributes to energy efficiency, safety and a more environmentally-friendly transport chain. Compared to other modes of transportation, shipping contributes the least emissions per ton-km and is promoted by many regulatory regimes as a climate friendly way of transportation (European Parliament 2008).

There are several paths to climate friendly shipping. Especially options with non-conventional fuels, i.e. 2nd generation bio-fuels, hydrogen and nuclear are believed to be viable, but are not expected to be commercially available on a larger scale until after 2030 (S. Alvik 2009). An alternative to non-conventionals is a less carbon- intensive fuel like natural gas. Natural gas under pressure, compressed natural gas (CNG), or cooled down natural gas, liquefied natural gas (LNG), might be some of the most promising. In this thesis, aspects of LNG as a fuel for ships will be assessed in light of its environmental qualities, economic and technological feasibility, as well as commercial viability of the fuel.

1.2. Purpose

The purpose of this thesis is to examine the environmental and economic advantages of using LNG as fuel for ships. Particular attention is given to scenarios of escalating bunkers fuel prices. Furthermore, the trade-off between higher investment costs related to LNG engine technology on the one hand, and fuel cost savings on the other hand is analyzed.

1.3. Methodology

Historical data on oil prices and bunkers fuel prices are examined in this study. Data on oil prices and bunkers prices are received from Wilhelmsen Premier Marine Fuels. LNG figures are retrieved from Datastream[1] in combination with information from Marintek.

On the basis of historical pricing, conclusions about possible future bunkers prices at different oil price scenarios are drawn by using linear regression. The theoretical framework of the analysis is based on NPV analysis, considering the cost effectiveness of LNG-fueled vessels compared to ships utilizing conventional fuel. The analysis considers in particular economic consequences related to environmental tax exposure.

The primary information used in this study is obtained through a number of interviews. The purpose with the qualitative interviews was not to collect representative data, but to obtain first-hand descriptions, nuances and different opinions on the research topic. The interview objects have been corporate representatives in relevant positions in the following companies: GasNor, SeaCargo, RollsRoyce, Fjord1, DNV, the Norwegian Maritime Directorate, Wärtsila, Arctic, BarentsGass, Bergen Bunkers AS, Falkeid Shipping AS, Statoil Norge AS, Nordic LNG, Lyse, Marintek, Shell and LMG Marine.

The written background information basically accounts for research literature within the field of petroleum economics, environmental economics and political regulation relevant to the research topic.

1.4. Scope and limitations of analysis

This analysis relies on the technological status of gas engines today, even though technological advances can be expected in the future.

Due to cost structures and physical capacity on board ships, an important restriction in this analysis will be the focus on short-sea shipping. Even though LNG-fueled vessels can be expected to enter the deep-sea shipping market in the future, the present infrastructure allows LNG as fuel to be most convenient as for ships travelling short distances, capable of frequent refueling. The main focus lies on the Norwegian market due to the more stringent environmental policies in the country.

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[1] Datastream is a collection of a variety of data, statistics and indices. Datastream is available in the library at NHH.

Available data on the market price development of LNG is rather limited, restricting the reliability of the analysis.

1.5. Outline

This thesis is divided into three parts. Part 1 describes the relevant background and includes fundamentals of natural gas and LNG, as well as an overview of regulation regarding air emissions from ships and LNG engine technology. Segments analyzed in this thesis are also introduced briefly. Part 2 presents the technical framework and assumptions underlying the thesis. In part 3 the results are presented and analyzed. Final conclusions are presented and discussed in this part as well.

PART I

Background

This part will present background information relevant to the analysis of LNG-fueled vessels in the Norwegian short-sea market.

It starts with asking the question if LNG can be the solution to environmental challenges in shipping. There seems to be general consensus in society that global climate change is one of the most challenging problems facing the world at large. However, innovative solutions contributing to mitigation of climate change do not only need to be technological feasible, but also commercially- and economic viable to be successfully adopted.
After touching upon this question, fundamentals of natural gas and LNG will be presented. Part 1 continues with presenting the main sources of emissions to air caused by shipping and emission regulation in Norway concerning maritime activities. Further, the present state of LNG engine technology will be described as well as the segments subject to the analysis.

2. LNG: the key to environmental challenges in shipping?

2.1. Environmental superiority

As the global community is responding to the environmental challenges of the future it is important to notice LNG’s role as a cleaner fuel with regards to GHG reduction. LNG has lower emissions than many alternative fuels and offers major environmental benefits at local, regional and global levels.

Several studies have shown the impacts of emissions of exhaust gases and particles from ships on atmosphere and climate. The list of exhaust emissions from shipping is long, but CO_2, NO_x, SO_x, and particulates can be identified as the four most relevant substances.

Unlike other conventional fossil fuels, LNG has a higher hydrogen-to-carbon-ratio and therefore emits less carbon dioxide per unit energy produced. This is one reason why LNG propulsion contributes significantly less to climate gas emissions.

Second, SO_x emissions, which are related to the sulfur content of the fuel, are an important substance for emitting aerosols. If the sulfur content of the fuel is lowered, emissions are reduced. The sulfur content of LNG is near zero; therefore LNG as a fuel contributes virtually to no emissions of air contaminants.

Third, NO_x emissions that contribute to ground-level ozone from burning LNG are negligible. LNG has lower nitrogen content than oil, causing combustion of LNG instead of conventional marine fuels to reduce emissions.

An additional benefit of LNG is the non-existent release of particulates into the environment.

Hence, this environmental superiority of using LNG for propulsion on ships will not only contribute to climate change mitigation, but also to improved air quality especially in regions with heavy ship traffic.

Figure 1 illustrates the expected emission reductions from the four most relevant substances, when switching from regular engines with conventional fossil fuels to LNG-powered engines.

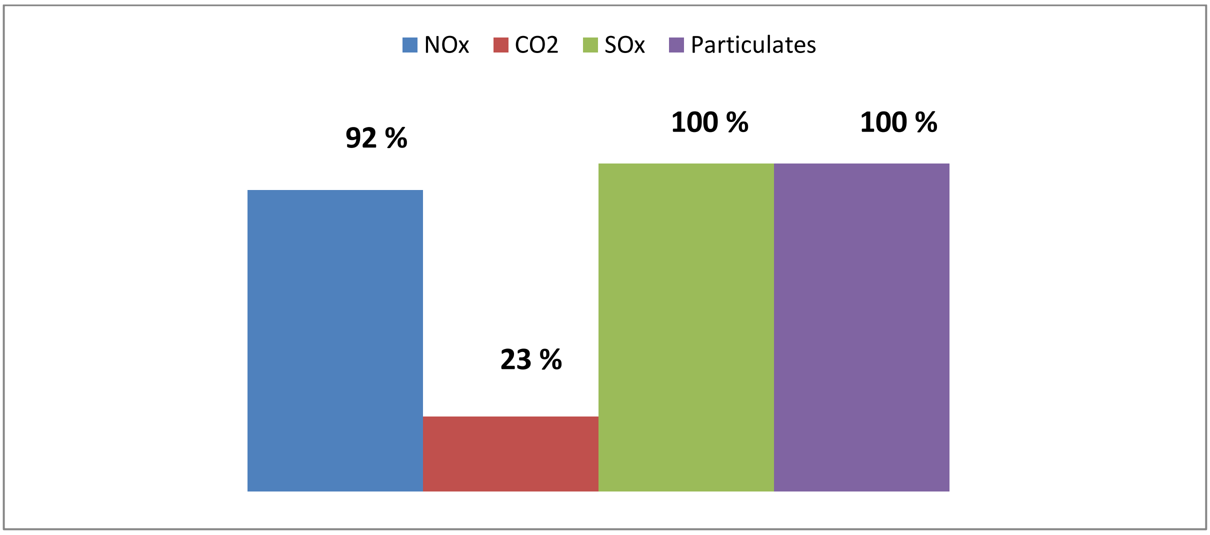

Figure 1: Emission reduction of medium ships with gas engine (Nogva 2008)

2.2. Feasibility of LNG as a transport fuel

Liquefied natural gas (LNG) has recently been introduced as a marine fuel for coastal vessels in the short sea shipping market in Norway and can be expected to be a valuable choice of fuel in the future considering the environment.

In addition to environmental regulations driving this technology, aspects of LNG as a transport fuel in the maritime sector can be split into three:

1. Technological feasibility
2. Commercial viability
3. Economic feasibility

An assessment of LNG as a cost-effective and environmentally friendly shipping fuel for the Norwegian short-sea shipping sector will be presented. In the following section LNG-fueled ships will be reviewed as a solution to future challenges in shipping. LNG will be examined as a fuel for ship propulsion due to its technological- and economic feasibility as well as its commercial viability.

2.2.1. Technological feasibility

LNG has been used for power generation in the industry for many decades, but is relatively new as a transport fuel.

In the maritime industry, LNG is currently used in two ways. First, LNG is used as "boil-off" fuel on LNG carriers and has been used this way for several years. Second, LNG-fueled ships have been introduced in the recent past. These vessels have gas engines that utilize LNG as a dual fuel engine or as a lean-burn gas engine. It will be returned to the more technical details of LNG engines in chapter 6.

LNG has successfully been demonstrated as an alternative energy source for several types of ships. The best examples of LNG as a fuel for vessels can be found in Norway which has been *"the forerunner for LNG-fuelled ships"* (Hannula, Levander og Sipila 2005). Norway's LNG-powered fleet consists today of several ferries, platform supply vessels, coast guard vessels and even LNG carriers. This has been made possible by manufacturers of engines who offer different solutions to how shipping companies can utilize LNG as a fuel.

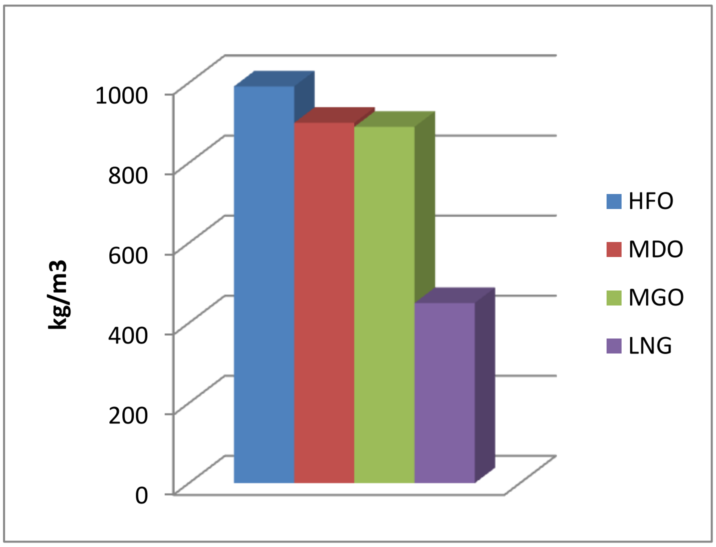

Figure 2: Density of fuels (DNV 2010)

Nevertheless there are several technical challenges related to the usage of LNG as a fuel for ships. A shortcoming of LNG as a fuel is the lower energy density compared to conventional fuel oil. Figure 2 compares energy density of fuels normalized to HFO and shows that LNG has only about half the energy density of heavy fuel oil (HFO). The practical implication is that LNG demands more volume, hence larger tanks and tank rooms relative to HFO, marine diesel oil (MDO) and marine gas oil (MGO). Also, LNG requires cryogenic storage which requires special installations to avoid the liquid from boiling-off. As cargo capacity is reduced due to larger bunker space, LNG is a more suited fuel alternative for vessels that can re-fuel frequently.

A crucial importance is that in order to use gas as a fuel for propulsion on ships, safety has to be a main priority. Comprehensive risk analyses have been conducted for the use of LNG as a fuel for ships and the authorities have been setting safety requirements. Studies from the Norwegian gas ferries show that LNG is an at least as safe fuel as diesel propulsion (Maritimt Magasin 2006). This is not surprising, as the LNG industry has been operating to the highest standards of safety for several decades.

2.2.2. Commercial viability

Currently LNG as a transport fuel faces commercial issues with regards to infrastructure and supply. This means gas availability in regions far away from LNG production facilities and sufficient bunkering possibilities in ports can be a challenge, but that there are feasible solutions to these issues. A developed LNG infrastructure and supply network is emerging, resulting in increased LNG availability and reduced costs (P. M. Einang 2009). Currently, LNG is not available in all ports in Norway, but enough LNG is being produced to supply large parts of the Norwegian short-sea shipping sector. Supply of LNG will be elaborated on in chapter 7.

2.2.3. Economic feasibility

With a rising oil price, increased fuel costs will cause ship-owners a financial burden. As LNG is less related to the oil price than other conventional maritime fuels, LNG could have a significant price margin to conventional shipping fuel. This can be explained from the cost-structure of a shipping company. The total costs for running ships can be divided into operating costs (fixed costs), voyage costs (variable costs) and capital costs (Stopford 2009).

A shipping cash flow model is illustrated in figure 3, showing revenue and operating- and capital costs from Stopford’s Maritime Economics (Stopford 2009). On the left side of this model, the ship revenue is represented. From this revenue, both annual cost of operating the fleet (top), and annual costs of maintaining and financing the fleet (bottom) must be deducted. After this, some ship-owners might be subject to tax, and finally the residual will be paid out in dividends or retained within the business.

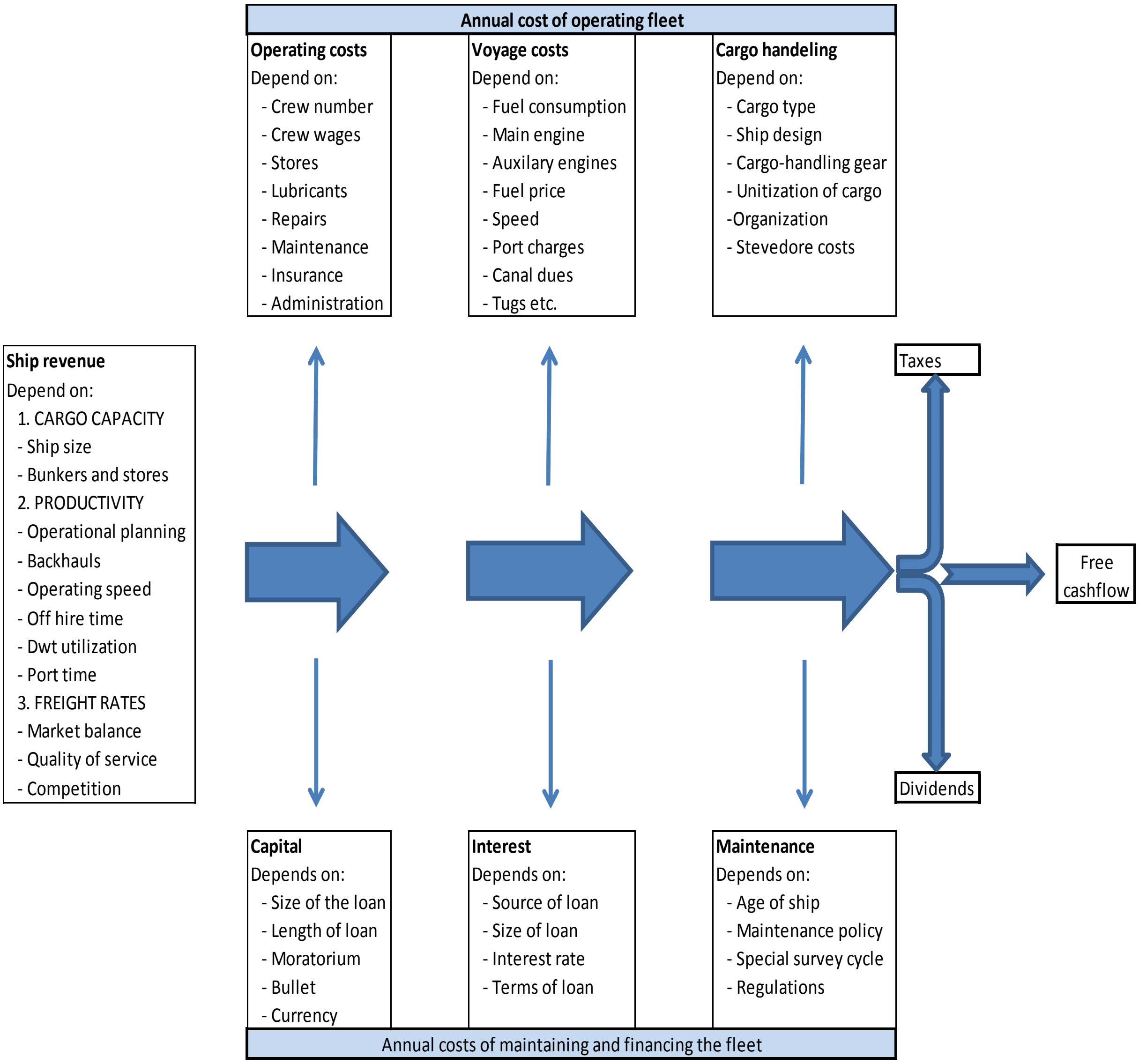

Figure 3: Shipping cashflow (Stopford 2009)

While figure 3 above represents the financial performance, it is also essential to look more specifically at the cost structure. A cost analysis of the major costs of running a bulk carrier is presented below. Even though the cost structure differs between ship types, this is still somewhat representative for other ship types.

General Cost Classification		Cost Items	
Operating costs	14 %	Manning costs	42 %
		Store & lubricants	14 %
		Repair & maintenance	16 %
		Insurance	12 %
		General costs	16 %
Periodic maintenance	4 %		n.a.
Voyage costs	40 %	Fuel oil	66 %
		Diesel oil	10 %
		Port costs	24 %
		Canal dues	n.a.
		Emission costs	?
Cargo-handeling costs	n.a.		
Capital costs	42 %	Interest/dividend	?
		Debt repayment	?
SUM	100 %		
Note: This analysis is for a 10-year-old Capesize bulk carrier under the Liberian flag at 2005 prices. Relative costs depend on many factors that change over time, so this is just a rough guide.			

Table 1: Cost structure for bulk carrier (Stopford 2009)

Table 1 illustrates that capital costs related to the purchase of a vessel are the largest cost component. LNG-fueled ships have per today a higher initial capital cost than equivalent vessels without LNG-propulsion. The difference in capital expenditure will vary between different vessel types and may also be expected to change over time due to technological progress and market acceptance of LNG-fueled ships.

Furthermore, it is important to notice that disregarding capital cost, bunkers cost (diesel oil and fuel oil) in total consists of more than 50 % of all costs, as illustrated in figure 4. This explains why small changes in bunkers price will have a large impact on the profitability of a vessel. Fuel costs are the most important element in voyage costs (Stopford 2009) and will vary depending on hull condition, operating speed and, of course, design of the main engine.

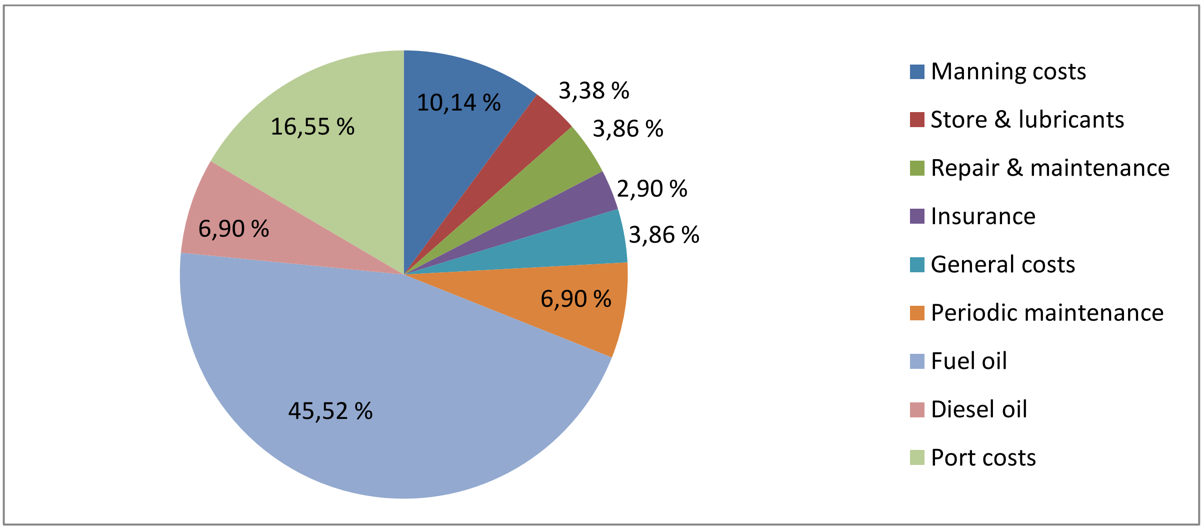

Figure 4: Operating costs (Stopford 2009)

Being one of the main cost drivers, development of bunkers prices will be a key focus later in this study when economic profitability is analyzed. The competitive position of LNG will crucially depend on the development of the price of oil and the price-relationship between the different types of marine fuels. The final analysis will examine more carefully the oil price scenarios under which LNG is cost-competitive. During times with high oil prices, the maritime sector has been pushing more fuel-efficient ship designs. Assuming that high oil prices persist or rise in the future, fuel-efficient ship designs and ships running on alternative fuels have a cost-advantage.

Regarding emission costs, charges related to ship emissions have not been a prominent account for many shipping companies until now. It can nevertheless be expected that this picture will change, especially with regards to environmental taxation as the authorities, customers and public demand increased environmental regulation. National and international legislators have already been making efforts to tax environmental performance of ships, such as in Norway, where e.g. a charge on NO_x emissions was introduced in 2007, giving an economic advantage to less emitting ships. Port-charges can be expected in the future for emitters as well.

LNG propulsion for ships has the prospects of avoiding some of the cost burdens stricter regulations of air emissions from ships may impose on ship operators. Nevertheless, these savings do not come for free, since capital costs related to building LNG engines are higher in comparison to conventional engines. This thesis will explore in more detail whether, and to what extent, the benefits of reduced environmental taxation and reduced fuel costs may outweigh the higher investment costs related to less emitting ship engines.

3. Fundamentals of Natural Gas

Natural gas is the fastest growing energy source in the world as well as the most flexible of all fossil fuels (Chandra 2006). It can be burned directly for power generation or it can be converted and chemically altered to produce a variety of products, such as fertilizers, chemicals and of course transportation fuels.

In order to be able to analyze the market for LNG, an understanding of the basics of natural gas is a must. In the following a brief overview of the characteristics of natural gas, production, reserves and consumption is given. Modes of transportation for natural gas, and price determination will also be described.

3.1 Definition and chemical composition

Natural gas is a fossil fuel, usually found beneath the earth's surface in reservoirs that trap the gas in porous rock pockets, occluded by solid rocks. Many gas discoveries are made in marine environments, but gas can also be found onshore. Furthermore, gas can coexist with crude oil in the same reservoir. It is common to differ between *conventional* and *unconventional gas resources*. Conventional gas resources are gas molecules that occur with or without oil, while unconventional gas resources occur with coal, ice crystals, sandstone or in other difficult geologic environments.

Natural gas is colorless, shapeless and odorless (Chandra 2006) in its pure form. It consists of a flammable mixture of different hydrocarbon gases, where methane (CH_4) is the primary component. The composition of natural gas can vary widely between different gas sources, but table 2 below illustrates a typical composition of natural gas, where ethane, propane, and butane are the most common components aside from methane.

NATURAL GAS COMPOSITION (Mole Percent)		
Major hydrocarbon components:		
Methane	C_1	65% - < 95%
Ethane	C_2	2% - 15%
Propane	C_3	0,25% – 5%
Butane	C_4	0% - 5%
Non-hydrocarbon components:		
Carbon Dioxide	CO_2	0% - < 20%
Nitrogen	N_2	0% - < 20%
Hydrogen sulfide	H_2S	0% - < 15%
Rare gases	e.g. A, He, Ne	trace

Table 2: Typical Composition of Natural Gas (Chandra 2006)

3.1.2. Units of Natural Gas

Generally gas is sold by energy content and not per unit of volume. The heat energy combusting gas generates is related to the proportion of “lighter” methane relative to the “heavier” compounds as ethane, propane and butane. The heat energy, which is released when a unit volume of gas is burned, is measured in units of calorific value as the common *British thermal units (Btu).* It is fairly universal to state the costs of gas to the customers in dollars (or local currency) per Btu.

For estimation of reserves or production volumes, gas volumes are usually measured by multiples of cubic feet (ft^3) or cubic meters (m^3) and converted into *barrel of oil equivalent (boe).* A table of conversion units can be found in the appendix, as it has been necessary in the analysis to convert gas units to metric tons (MT) or energy content (kWh)

3.2. Reserves and Production

3.2.1. Reserves

Natural gas is known as a non-renewable resource and is therefore scarce. It is important for this study to have some idea of how much natural gas is available, as this sets the time frame for possible production and consumption. It is unfortunately impossible to know exactly how much natural gas reserves are left in the ground and one can only rely on estimations. Even though proved reserves make up a small proportion of total gas resources, table 3 provides an indication of the amount of natural gas left in different regions of the world. Total proved natural gas reserves in 2008 were around 185 thousand cubic meters (Tcm).

	At end 1988	**At end 1998**	**At end 2008**		
Region	**Tcm**	**Tcm**	**Tcm**	**Share of total**	**R/P (yrs)**
USA	4,76	4,65	6,73	3,6%	11,6
Total N. America	**9,51**	**7,24**	**8,87**	**4,8%**	**10,9**
Total S. & Cent. America	**4,79**	**6,35**	**7,31**	**4,0%**	**46,0**
Norway	2,30	3,79	2,91	1,6%	29,3
Russian Federation	n/a	43,51	43,30	23,4%	72,0
Total Europe & Eurasia	**44,53**	**59,09**	**62,89**	**34,0%**	**57,8**
Iran	14,20	24,10	29,61	16,0%	*
Qatar	4,62	10,90	25,46	13,8%	*
Saudi Arabia	5,02	6,07	7,57	4,1%	96,9
United Arab Emirates	5,66	6,00	6,43	3,5%	*
Total Middle East	**34,34**	**53,17**	**75,91**	**41,0%**	*****
Algeria	3,23	4,08	4,50	2,4%	52,1
Nigeria	2,48	3,51	5,22	2,8%	*
Total Africa	7,68	10,77	14,65	7,9%	68,2
Total Asia Pacific	**8,86**	**11,39**	**15,39**	**8,3%**	**37,4**
Total World	**109,72**	**148,01**	**185,02**	**100,0%**	**60,4**

* More than 100 years

Table 3: Reserves and R/P-ratio (BP 2009)

As seen from table 3 above, natural gas reserves are geographically unevenly spread, with Russia and the Middle East holding the greatest known reserves. Furthermore, the countries in the Middle East have a reserves/production ratio (R/P) exceeding more than hundred years, along with Algeria and Nigeria. Hence, there are large reserves of gas resources in some parts of the world. In Western Europe, Norway holds the largest reserves lasting for about three more decades at a steady production rate.

It has to be noted here that the R/P-ratio is quite controversial and serves as a theoretical illustration only.

3.2.2. Production

The amount of natural gas extracted has been rising over time. Extraction development is mainly dependent on the capital invested in seismic-related activities and geological knowledge (Afgan, Pilavachi and Carvalho 2007). Price expectations and the need for meeting the world's growing energy demand has resulted in new capital investments which have triggered the discovery of new natural gas fields.

With steady research and development in the petroleum sector, revolutionary and unpredictable progress can be made at any time, e.g. the development of unconventional natural gas resources in the USA. The USA has been a large consumer of natural gas, while having traditionally a rather gas-deficient energy market (see R/P ratio in table 3). However, this picture has been changed recently, as new drilling technology has released a flood of shale-gas supply to the U.S. market. Exactly how these discoveries will affect the global energy market remains uncertain.

Figure 5 below shows the development of natural gas production in different regions of the world. Europe & Eurasia and North America have been the largest producers of natural gas. Especially North America stands out as a large producer, even though the region does not hold comparably large reserves. Hence, there exist discrepancies between the countries with large production and countries with large reserves of natural gas.

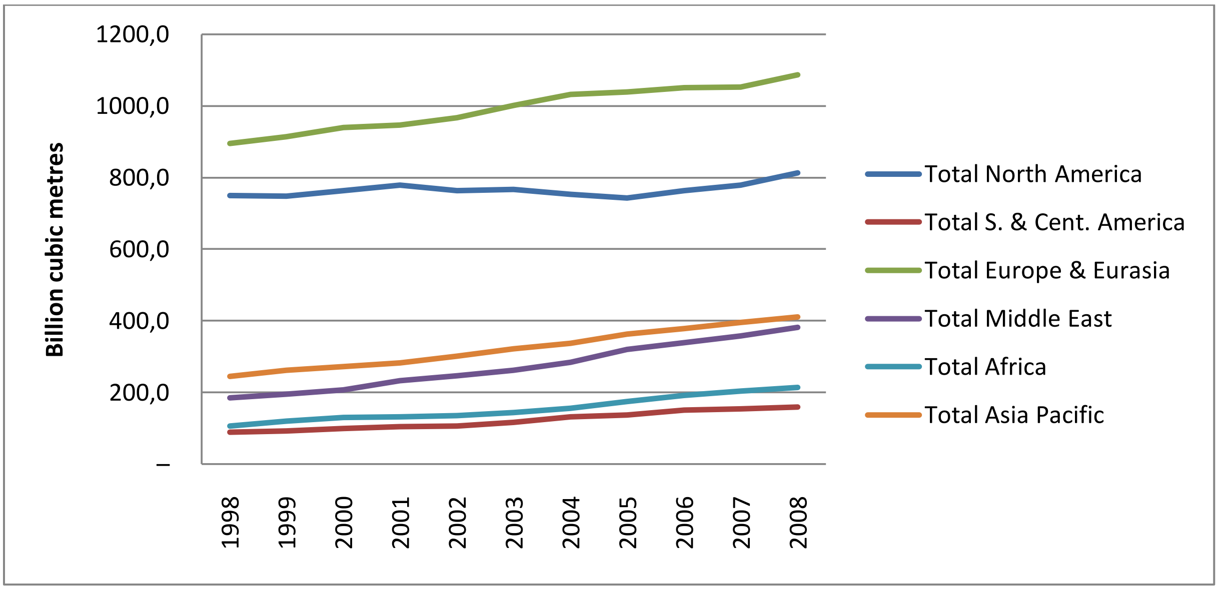

Figure 5: Natural gas production by region (BP 2009)

3.3 Consumption

Natural gas has a variety of usages and new improved distribution channels are making more consumers demand this fossil fuel. Natural gas is the second most important energy source after oil. According to BP (BP 2009), natural gas accounted for 24% of world energy consumption in 2008.

Consumption of natural gas has been constantly increasing over time, as illustrated by figure 6. Europe & Eurasia and North America are not only the largest producers, but also the largest consumers of natural gas. Demand from the developing economies in Asia has been growing rapidly. Japan is together with North America and Europe the largest consumers of natural gas. Their large consumption may eventually make these countries increasingly dependent on international gas trade with countries holding larger reserves.

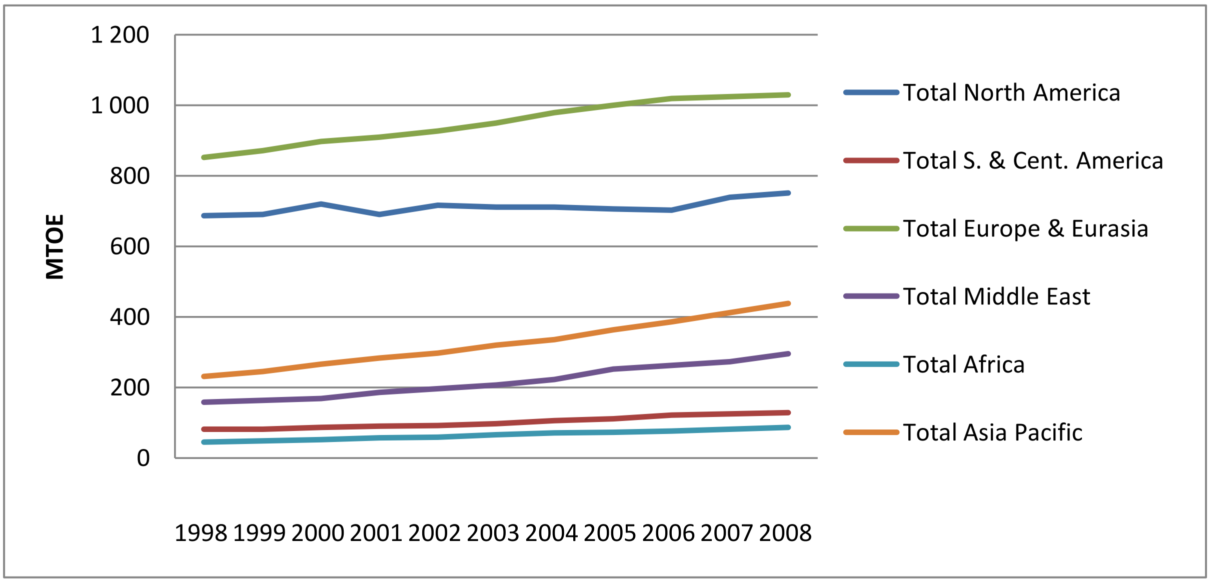

Figure 6: Consumption of natural gas by region (BP 2009)

Demand for natural gas can basically be divided into demand from 5 different sectors (Natural Gas Supply Association 2004):

- Residential demand
- Commercial demand
- Industrial demand
- Electric generation demand
- and newest: Transport sector demand

The usage of natural gas in the residential sector has become quite popular, as natural gas is well suited for heating, cooking and cooling in households. Moreover, natural gas has proven to be a relatively cheap fuel for electricity generation compared to many other fossil alternatives, such as coal. Reduced tolerance for nuclear energy production, more stringent emission standards coupled with high costs for renewable energy have also influenced the increase in demand for natural gas (Chandra 2006).

3.4. Modes of transportation

As described earlier, natural gas is found mostly in offshore reservoirs, far away from its market and has to be transported to where the demand is. Because of its physical nature, gas is a rather difficult commodity to transport, needing compression and possibly also low temperatures to enlarge its bulk density.

Natural gas has a lower energy-to-volume ration than crude oil (Hannesson 1998). As a consequence, natural gas requires more space per unit of energy than oil. Storage difficulty related to the bulkiness of natural gas is the main reason for gas usually being transported to its destination as soon as possible.

The current major methods of transporting natural gas from oil and gas fields to markets is mainly via pipelines or in liquefied form by ships, even though there exist other modes of transportation.

Figure 7 illustrates the natural gas chain from production to delivery to the end-user.

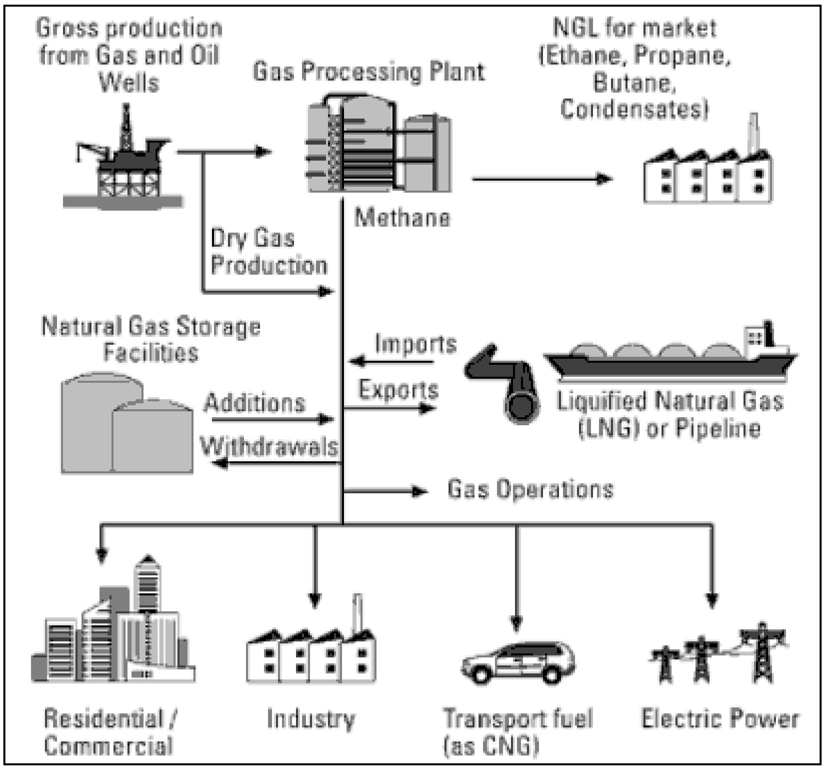

Figure 7: Illustration of the natural gas chain (Chandra 2006)

There are high capital costs related to transportation of natural gas with transport via pipelines. Gas transmission pipelines are the major cost component of transportation as a result of two special features of the industrial structure. First, gas producers tend to be unwilling to engage in development of new fields unless there exists a certain contractual security with regard to long-term purchase. Second, transporting gas by pipeline is a typical case of natural monopoly (Hannesson 1998).

Figure 8 shows the major trade movements of natural gas by pipeline transport and by so-called LNG carriers in 2008. It appears from the illustration that LNG carriers become the convenient method for long distances, as the costs of transporting LNG outperforms pipeline transport after a certain distance. This is due to the spread of fixed costs of liquefaction and regasification of LNG over larger distances (Hannesson 1998). The figure does not include recent changes in trading due to the new exploration technology for unconventional resources, but gives a fairly good illustration of the major trade movements by pipeline and LNG shipping.

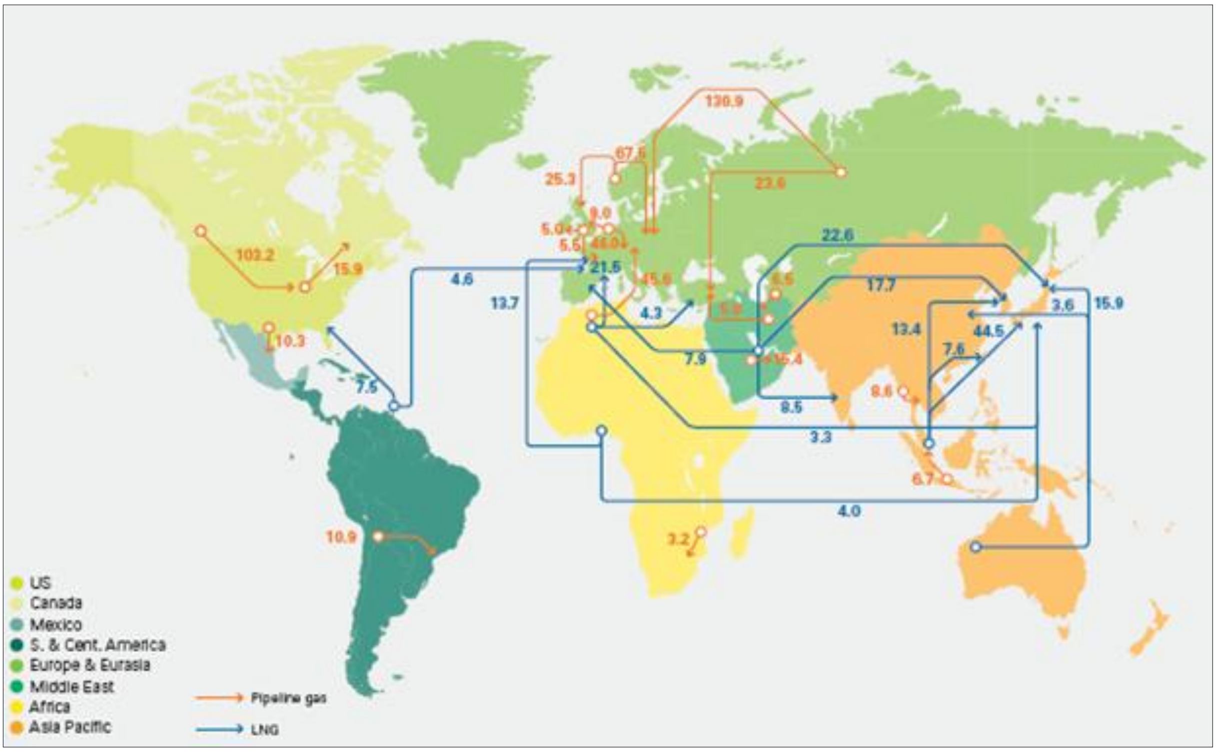

Figure 8: Worldwide natural gas trade in bcm (BP 2009)

An important aspect to consider regarding transportation of natural gas is not only the costs of transport, but also risks related to possible terrorist activity, political changes and trade restrictions related to the different modes of transport.

3.4.1. Pipelines

Pipelines are a convenient way of transporting large amounts of gas over large distances, but inflexible in the sense that one pipeline only has one destination, and the gas cannot be led directly to where demand is highest. This is especially the case for economies located far from pipeline networks, as the Asian countries shown in figure 8. Furthermore, there are large investment costs, technical difficulties and also political issues related to the construction of pipelines. The largest component in pipeline transportation costs is directly related to the construction of gas transmission pipelines, determined by pipe diameter, distance and topography.

3.4.2. LNG-carriers

Regarding the second major option of transportation, liquefying natural gas (LNG) for transport implies cooling the gas and stowing it in storage tanks and transported in special refrigerated ships, LNG-carriers, to the market. Figure 8 illustrates that this transport method is commonly used for long-distance trade. Transport via LNG-carriers gives among other flexibility of supply and avoids difficulties related to crossing borders as in the case with constructing pipelines. As with pipelines, there are also large investment costs related to this mode of transport, since liquefaction and regasification of natural gas require special facilities and arrangements.

Chapter 4 deals more thoroughly with the concept of LNG and its value chain.

3.5. Market mechanisms

The world market for natural gas has traditionally been fragmented in different regional markets, mainly due to lack of pipeline infrastructure and little availability of LNG transport capacity which have lead to price differences between countries (L'Hégaret 2004). Financial risks related to gas imports used to be absorbed by regional monopolies of transmission and/or distribution companies (L'Hégaret 2004), while industry and households had to pay for this security of supply through relatively high prices.

As a liberalization wave over the past years has been sweeping away many of the monopolistic features of the industry, governments have been introducing so-called “gas-to-gas competition”, based on third-party access with the desire to lower prices and improve service quality and innovation.

Regional Markets

There are today three distinct regional gas markets: the Asian market, the European market, and the North American market. Each market is characterized by specific supply costs and conditions, gas demand patterns and structures of competition (L'Hégaret 2004).

Both the regional and inter-regional natural gas markets are expected to become more integrated in the future. The main forces for this development are lower costs in the LNG value chain, accelerating spot trade and increased demand in key markets for natural gas (Aune, Rosendahl and Sagen 2010). A study conducted by Asche, Osmundsen and Tveterås (Asche, Osmundsen and Tveterås 2000) finds proof of price convergence between natural gas prices in the inter-regional European markets, while Neumann (Neumann 2008) identifies LNG trading as the key driver for the observed integration between the three regional markets.

3.5.1. Pricing

Natural gas prices can be measured at different stages of the supply chain. Prices differ also among the different end-user groups, i.e. residential, commercial, industrial consumers or electric utilities, receiving natural gas through pipeline transport or LNG shipments.

Traditionally, natural gas contracts are long-term contracts between integrated natural gas companies and users, specifying fixed prices. Fixed prices reduce supply- and price risk, but give little flexibility (UNCTAD 2003). Unfortunately, it is generally not possible to get access to these long term contract prices as gas sales contracts are not public.

As implementation of government reforms to increase efficiency in supply, spot markets emerge. The advantage of spot markets is greater flexibility to balance supply and demand under changing market conditions, in addition to increased transparency. Further, market participants can combine long and short-term contracts in their portfolios. However, long-term contracting is still the dominant form for international gas trade.

Usually, spot markets emerge where buyers and sellers concentrate; e.g. close to large consuming regions or major terminals of gas producing countries near major pipeline interconnections. Main references for spot prices in Europe are the Heren Index (British National Balancing Point, NBP) or the Zeebruge Hub (Belgium) (UNCTAD u.d.)), while in the U.S. it is the Henry-Hub (NYMEX).[2]

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[2] cif = cost + insurance + freight (average freight prices)

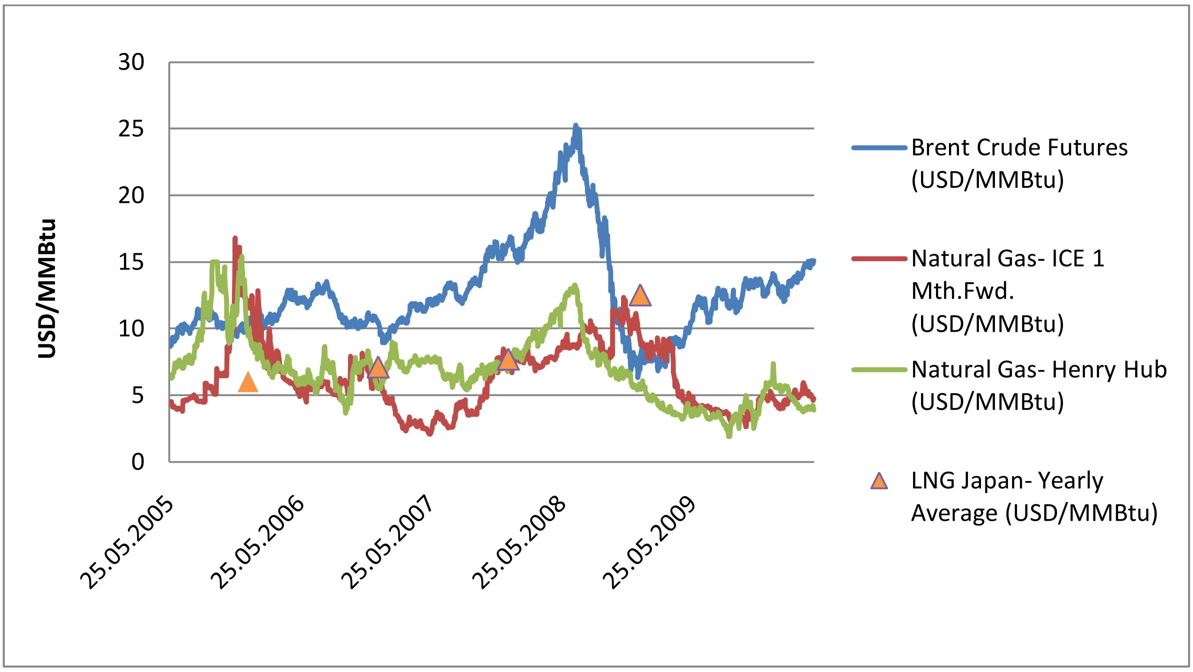

Figure 9: Natural Gas and Crude Oil Price Development (Source: Datastream, BP 2009, Wilhelmsen Premier Marine Fuels)

Figure 9 illustrates the development of average natural gas prices over the past along with the development of crude oil prices. The graphs show spot prices from the day-ahead-market from NBP and from the Henry Hub pricing point for natural gas future contracts. The average annual import price for LNG into Japan is also plotted. The interlinking of natural gas prices is quite evident, even though there is some variation between the regions.

Furthermore, the historically tight linkage between natural gas and crude oil prices can be seen from figure 9. Gas prices have historically been lower than crude oil prices but have been following the development of the crude oil price. However, there has been increasing divergence in the later years. Over the past year, correlation of oil and natural gas prices has been rather negative. The true economic potential of LNG as a fuel for ships lies in the divergence of natural gas and crude oil prices in advantage for natural gas. The future development of the oil-gas ratio is not predictable, but is the crucial part of LNG’s success as a marine transport fuel as will be seen later in this study. It is, on the other hand, a fact that both these resources are scarce, but since natural gas has larger reserves than oil, it could be expected that the current divergence will increase in the future.

4. Fundamentals of Liquefied Natural Gas (LNG)

In this chapter, fundamentals of LNG will be presented. LNG has become an exciting aspect of the international natural gas landscape, as will be seen below. Following, technical specifications of LNG will be presented, as well as the value chain, market mechanisms, cost structure and environmental properties of LNG as a ship's fuel.

4.1. Technical specifications and concept

Liquefied natural gas (LNG) is natural gas that has been converted to liquid form by cooling the gas to more than minus 161,5°C at atmospheric pressure (Chandra 2006). It is then 1/600th of its original volume (Chandra 2006) making efficient transport and storage possible. LNG is clear, odorless, non-explosive and non-flammable (Energy Information Administration n.d.). One ton of LNG contains the energy equivalent of 1.380 m^3 of natural gas (Chandra 2006).

The process of natural gas liquefaction has been known since the 19th century, and the first commercial liquefaction facility was already built in the United States in 1941. There exists different processes for liquefaction today, but all involve the removal of impurities, such as water and carbon dioxide prior to cooling. As a result, the main containment of LNG is methane (CH_4).

Even though LNG has a good safety record today, the industry is not without safety incidents and there exist some potential hazards with LNG related to its cryogenic nature, dispersion- and flammability characteristics. As a liquid, LNG will freeze any material it comes in contact with. While when LNG is warmed, e.g. during regasification, it becomes flammable when in contact with an ignition source (Foss 2003). Due to this, LNG faces potential threats with regards to terrorism to LNG carriers and land-based facilities.

4.2. LNG value chain

During the past decade, the LNG industry has developed from an "infant" towards a "mature" industry (Rüster and Neumann 2006). Major investments in infrastructure, in addition to technological improvements related to the different steps in the value chain have together been the drivers of this development.

The LNG value chain is part of the natural gas chain, as illustrated in figure 7 (chapter 3), and consists of several different operations which depend on each other. The value chain can be broken down into five major steps (Foss 2003). In the first step, natural gas is extracted and delivered to a processing facility. Next, the liquefaction process takes place, transforming natural gas into LNG. Transportation mainly takes place by shipment in special purpose build vessels, so-called LNG carriers. The next step is regasification at the receiving location, where LNG is converted back to is gaseous state. Finally, natural gas is delivered and distributed to end users.

If LNG is used as a fuel, the value chain is cut off at an earlier stage. In this case, LNG is directly delivered from the liquefaction facility to the end-user and no regasification takes place.

4.2.1. Liquefaction and Regasification

As already noted, liquefaction is the process of refrigerating natural gas to cryogenic temperatures, where gas becomes liquid.

Worldwide, there were 20 LNG liquefaction (export) terminals in 2008 and 63 regasification (import) terminals (GIIGNL 2009). The geographical distribution of large-scale facilities in the European area is illustrated in figure 10.

Currently, several facilities are being built or extended, which gives expectations of increased export- and import capacity of LNG in the next few years to come (IEA 2009).

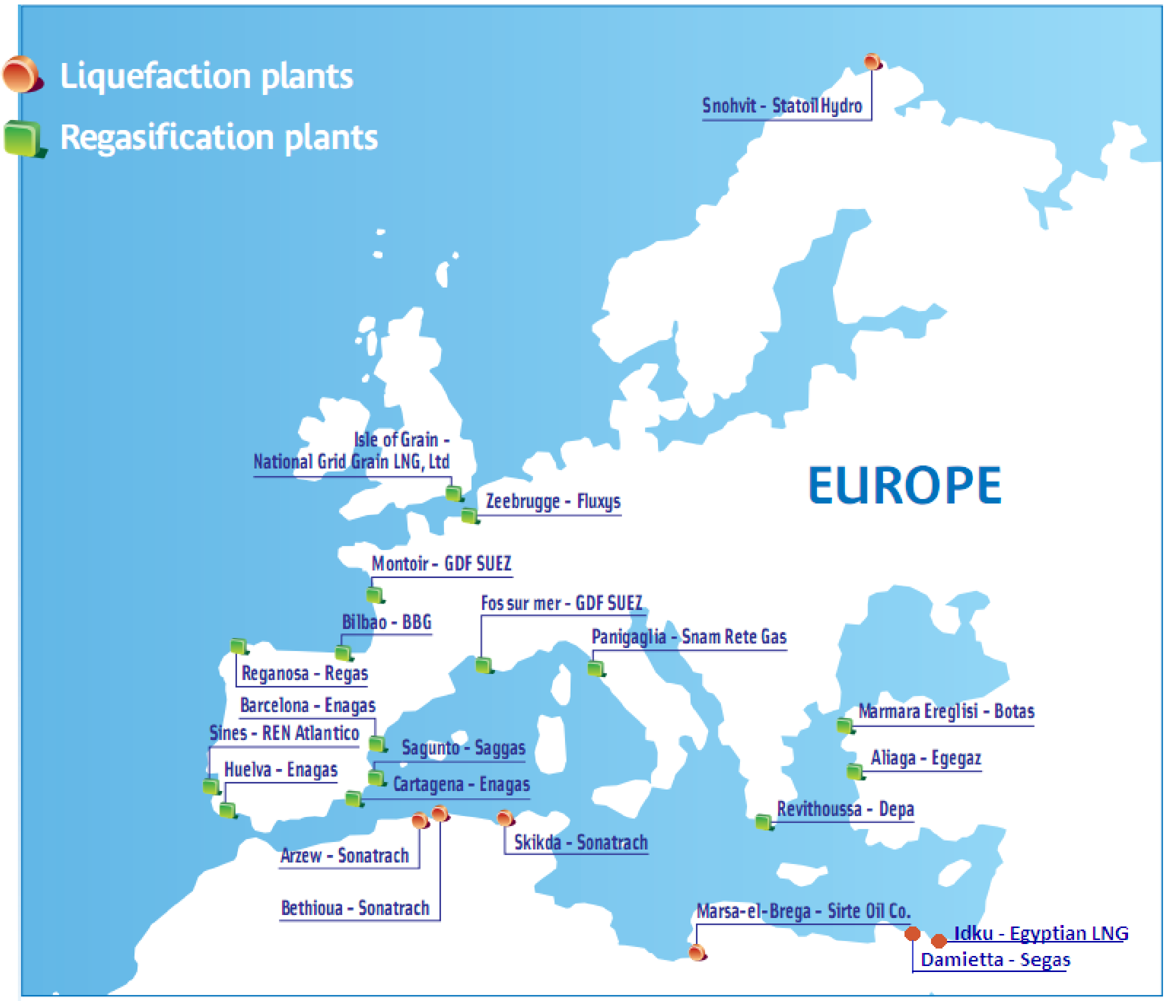

Figure 10: Large scale liquefaction and regasification Plants (GIIGNL 2009)

4.2.2. Large scale and small scale LNG

The LNG value chain can be based on a large scale or a small scale concept. Large scale LNG is commonly understood as (intercontinental) transport of large volumes of LNG, from high-capacity production facilities to import terminals which are part of a pipeline network (I.M. Skaugen SE 2009). Small scale LNG on the other hand has a more regional focus, and implies transportation of smaller volumes of LNG directly to end-users via ships and trucks (I.M. Skaugen SE 2009). This way, LNG can be made available on markets with a lower demand, where development of a pipeline grid system is not feasible. Due to its natural gas resources, topography and sparse population, Norway is especially suited for development of small scale LNG.

Even though small scale facilities cannot make use of economies of scale, as the case with large scale facilities, they have some cost advantages. Small scale facilities have a shorter construction period and hence lower construction costs. Furthermore, the independency from pipeline grids make small scale infrastructure flexible and adjustable in respect to demand fluctuations (I.M. Skaugen SE 2009).

4.3. Market mechanisms

As far as it is possible to talk about a global LNG market, the marketplace has been historically divided into two distinct markets: the Atlantic market and the Pacific market. The Pacific market, covering buyers in the Asia Pacific and North America (West Coast), is supplied by liquefaction projects in Indonesia, Malaysia, Australia, Brunei, Alaska and the Middle East. The Atlantic market covers European and North American buyers, supplied by ventures from Africa, the Caribbean, the Barents Sea and the Middle East (American Gas Foundation 2008). The growth in LNG trade has been impressive over the past decade; Cedigaz (Cedigaz 2009) estimated annual growth in LNG trade to be on average 7,8% between 1982 and 2007.

Contracts and Pricing

Traditionally, LNG markets have been associated with long-term take-or-pay contracts between suppliers and buyers enabling the sharing of large up-front investment risks that characterize LNG projects (Jensen, James T. 2004). This business model has been changing: short-term contracting has been growing rapidly over the last decade, creating more flexibility and transparency in the market. One reason for this development is the increasing import of LNG into deregulated gas markets, i.e. the UK- and the US-market, where buyers are demanding more flexibility and transparency (Chandra 2006). Further, the reduction of long-term contract periods, as well as the willingness of companies to have parts in projects not covered by fixed long-term contracts, is also increasing the share of flexible volumes (Jensen, James T. 2004)

Regarding pricing of LNG, different pricing systems exist in the different regional markets. While prices in the Asia Pacific are indexed to crude oil prices, gas pricing in the USA is driven by supply and demand and further set by gas-to-gas competition (L'Hégaret 2004). In Europe, LNG is priced relatively to pipeline gas, typically following the lead of competing fuels as crude oil or other oil products, even though its indexing may also include elements of coal, electricity or inflation indexation (L'Hégaret 2004). LNG-delivery prices are typically based on Henry Hub natural gas prices (NYMEX) and adjusted for local differences between the LNG delivery point and the Henry Hub gas price. Figure 9 (chapter 3) illustrates the close relationship between LNG import prices in Japan, European import prices of pipeline gas and prices from Henry Hub.

4.4. Cost structure

The LNG industry is past its pioneering stage and has developed into a more mature industry with a supporting infrastructure. The result of this is access to larger volumes of LNG and a result of bulky investments in LNG specific infrastructure.

LNG has developed from being an expensive and rather regional traded fuel to a globally traded commodity with a falling cost-structure (Rüster and Neumann 2006). Still, value chain costs are inherently high, even though advances in technology and design have lead to major cost savings and efficiency improvements over time. Table 4 offers an indication of costs related to each segment in the LNG chain as introduced above. The largest cost components can be associated with LNG processing; liquefaction, storage and regasification. However, it has to be noted that these costs are mainly an indication, for large scale LNG. Moreover, cost estimates of LNG projects can vary significantly, depending on differences such as location, availability of supporting facilities, distance to market and governmental regulations and subsidies.

LNG chain, indicative costs	
Process	**Cost range (NOK/MWh)**
Gas production (upstream)	10,92 – 16,38
Gas processing and liquefaction	28,40 – 39,32
Shipping (1000-8000 km)	8,74 – 21,84
Delivered LNG cost	**48,05 – 77,54**
LNG storage and regasification	21,84 – 32,76
Total LNG cost	**69,90 – 110,31**

Table 4: LNG chain costs (Chandra 2006)

Figure 11 illustrates cost reductions taken place in the LNG value chain during the last two decades. The efficiency achievements related to cost reductions have contributed significantly to making LNG a cost-competitive fuel (Chandra 2006).

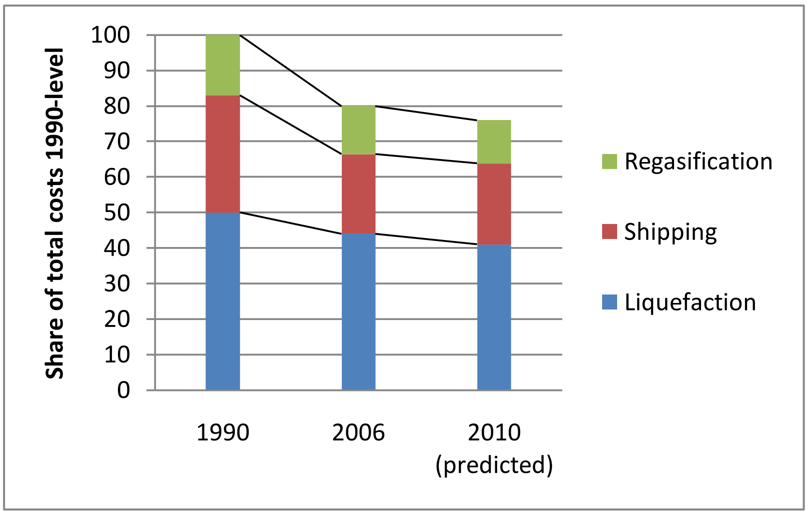

Figure 11: Cost Decrease in the LNG Value Chain (Lange 2006)

Even though Lange (Lange 2006) noted a cost decrease in the LNG value chain, a study carried out by Poten & Partners (Poten & Partners 2008) claims that the construction costs for new import terminals in Europe have risen sharply over the past few years, undermining efforts to attract LNG supply (Poten & Partners 2008). According to the study, costs have risen on average by 12% per annum for both new- and expansion projects. This is due to the shortage of qualified labor and sufficient engineering- and construction resources, as well as increasing material costs (Chandra 2006). But even though market players have to cope with escalating costs in the short term, expanding terminal capacity will have the advantage of reducing dependency on pipeline gas or other energy resources in the longer term.

Cost structure for small scale delivery of LNG

According to the MAGALOG Project[3] (MAGALOG Project 2008) the costs of supplying LNG can be split into two main components:

Cost of small scale LNG = Market based gas price + Cost of supply logistics

The MAGALOG project made an effort to outline the costs related to the small scale LNG supply structure (MAGALOG Project 2008). The costs of the main components are:

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[3] The Maritime Gas Fuel Logistics Project (MAGALOG) was a study carried out in 2007-2008 under The Intelligent Energy Executive Agency addressing LNG as an alternative fuel to reduce emissions from shipping in coastal- and port areas, especially in the region of the Baltic Sea and the North Sea. The study, based to a large extend on Norwegian experience and expertise, reviews the conditions necessary for making LNG as a ship's fuel available. The study concludes that LNG-fueled ships have a large potential in contributing to reduced air pollution in Baltic Sea and the North Sea.

- production cost
- freight & terminal cost
- bunkering

Production costs include elements such as construction costs for the LNG plant, energy costs and utilization. Freight and terminal costs depend mainly on distance and volume supplied. An important cost-driver is the size of the tank storage capacity at the terminal. Bunkering costs are related to the way the ship tanks are supplied with fuel from the terminal. Bunkering can be done by truck, barge or fixed line delivery (Jarlsby, Stenersen og Svendgård 2008).

Costs related to the LNG value chain in general have been falling over the past years, as illustrated in figure 11. Infrastructure costs for small scale logistics can also be expected to decrease in the future. As more facilities are built, cost elements such as freight- and transport costs will most likely decrease.

For the composition of a representative price of LNG in the Norwegian market, the natural gas price (Henry Hub) serves as a basis with an added average mark-up for supply logistics obtained from the MAGALOG Project in this analysis. This mark-up is constituted as the average of the following indicative costs:

Small scale LNG chain, indicative costs	
Process	**Cost range (NOK/MWh)**
Production costs	64 – 112
Freight and terminal costs	40 – 96
Costs of bunkering	8
Sum	**112 – 216**

Table 5: The table illustrates indicative costs related to the small scale LNG chain in Norway (MAGALOG Project 2008)

4.5. Environmental properties of LNG as ship's fuel

The environmental superiority of natural gas in comparison to conventional marine fuels has contributed to a rising demand for LNG fueled ships. The environmentally superiority of LNG has already been touched upon earlier. Emissions of CO_2, NO_x, particulates and SO_x are lower compared to burning heavy fuel oil, diesel fuel or gasoline in marine transportation, as illustrated in figure 12 below.

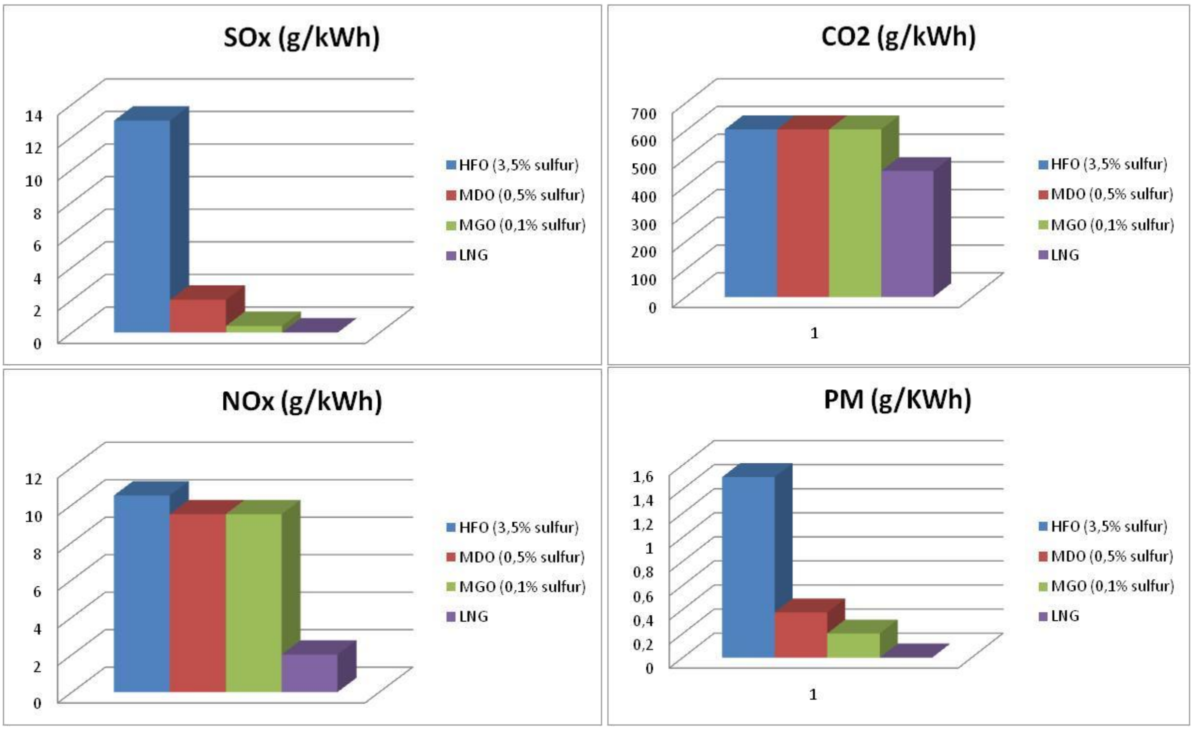

Figure 12: Emissions of LNG and conventional liquid fuels (Nogva, Børge (Rolls-Royce) 2009)

According to engine manufacturer Roll-Royce, gas engines for medium ships are expected to reduce emissions by the according values by going from HFO to LNG:

- SO_x = 100 %
- PM = 100%
- NO_x = 92 %
- CO_2 = 23 %

One problem related to the environmental properties of LNG is that methane is the major component of natural gas and a significant GHG. The consequence of this is that any methane slip, i.e. incomplete combustion of methane, has a negative effect on reduction of GHG emissions. Methane which is 20 times more powerful than CO_2 can spoil the potential gain with just small volumes of methane spills. Due to this, manufacturers are aware of the challenge and prospects for improvement seem very good. The effect of potential methane slips causes the net greenhouse gas reduction effect of LNG as ship's fuel to be about 15 % (DNV n.d.)

Further, it is important to consider the total value chain of LNG to assess fully its environmental properties. These include all emission related to extraction, processing, transport and final combustion to produce energy. As mentioned, it is important to look at the total value chain of LNG, but with regards to the scope of this analysis it is reasonable to assume equal energy consumption and emissions in fuel production of conventional bunkers fuel and LNG. More specific, this means that the environmental properties of the total value chain of LNG are disregarded since the focus in this analysis lies on LNG as an economically and environmentally reasonable fuel for enterprises within the shipping industry.

5. Emissions to air from ships

A significant fraction of anthropogenic emissions of air pollutants are caused by maritime activities. According to “The International Maritime Organization’s (IMO) second GHG study 2009” international shipping is estimated to have emitted 870 million tons of CO_2, equivalent to 2,7 % of the global emissions of CO_2 in 2007 (M. IMO 2009). The emissions from the maritime sector affect the chemical composition of the atmosphere, the climate and regional air quality and health. According to the Norwegian Maritime Directorate, DNV and V. Eyring et al. (V. Eyring 2009), there are especially six main sources of emission to air.

5.1. Sources of emission to air

The six main sources of emission to air are:

1. CO_2 – Carbon Dioxide
2. NO_x – Nitrogenious Oxides
3. SO_x – Sulfur Oxides
4. VOC – Volatile Organic Compounds
5. Particulates
6. Ozone depleting substances

Carbon Dioxide

CO_2 is a colorless and odorless gas produced when carbon is burned in an excess of oxygen. CO_2 is naturally released into the atmosphere, e.g. through breathing, forest fires, decay of dead plants and animals and volcanic eruptions. It is also removed from the atmosphere naturally, i.e. through photosynthesis, absorption by seawater or ocean-dwelling plankton. The unnatural release of CO_2 happens when fossil fuels are combusted in engines.

Nitrogenious Oxides

Nitrogenious Oxides include all types of oxides of nitrogen, e.g. NO and NO_2. Nitrogen dioxide (NO_2) is the most common and has a reddish brown color and is a highly reactive gas created in the ambient air through the oxidation of nitric oxides (NOs). In addition to reacting with VOCs to form ground level ozone, it also contributes to the formation of acid rain and explosive algae growth which again leads to depletion of oxygen in water that increases levels of toxins harmful to the ecosystem.

Sulfur Oxides

Sulfur Oxides include all types of oxides of sulfur, e.g. SO and SO_2. Same as with nitrogenious oxides, sulfur dioxides (SO_2) are the main oxides. The gas is a colorless, non-flammable gas with a penetrating odor which irritates mucous membranes. Emission of sulfur oxides from ships occur when fuel containing sulfur is combusted. Currently shipping contribute to 20 % of all sulfur emissions in Europe and it expected to be the single most important source of SO_x emissions in 2020 (N. M. DNV 2006).

Volatile Organic Compounds (VOCs)

Volatile Organic Compounds are organic chemicals that easily vaporize in room temperatures. The reason they are called organic is due to the carbon their molecular structures consist of. VOCs have no color, smell or taste. VOCs are generally released when liquid cargo enters a storage tank, during transportation of the liquid and some limited emissions during unloading. This type of emission is mainly restricted to tankers.

Particulates

Release of particulates in shipping is related to fuel combustion. Particulate matter can be divided into primary and secondary particulates according to their origins. Primary particulates are particulates emitted directly into the atmosphere, while secondary particulates form reactions with other pollutants. Emissions from particulates are mostly a local emission problem and can be a threat to human health and the environment. In shipping this means emissions mainly in ports, straits and other places where ships travel close to land.

Ozone depleting substances

Ozone depleting substances are chlorofluorocarbons (CFCs – a.k.a. Freon), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs) and halons. As the name of the substances implies, these are ozone depleting, meaning they have the potential to destroy stratospheric ozone.

CFCs are non-toxic, non-flammable and non-carcinogenic. CFCs have historically mainly been used for refrigeration and air-conditioners, fire-extinguishers and solvents in cleaners. As a consequence of the Montreal Protocol they have been phased out and it is anticipated that emissions of these substances have been greatly reduced the last 10 years.

HCFCs are accepted as a temporary alternative to CFCs, while HFCs are accepted as a long-term alternative to CFCs. Both have shorter atmospheric lifetimes and deliver less reactive chlorine to the stratosphere. HCFCs are currently regulated by a mandated production cap.

Halons are primarily used in fire extinguishers and have been phased out in developed countries since 1996 (N. M. DNV 2006). Production and consumption of new halons has stopped after the Montreal Protocol, but systems that use these halons currently recycle them or use material from redundant installations. As with CFCs the emission of these substances has been greatly reduced the last 10 years.

5.2. Regulations

Table 6 offers an overview over sources of emission to air and regulation in Norway.

Sources	**Regulations**	**Environmental impact**	**Reduction methods**
Carbon Dioxide	Kyoto Protocol	Global warming	Technical and operational means
			Alternative fuels
			Alternative propulsion systems
Nitrogenious Oxides	MARPOL 73/78, Annex VI, Regulation 13	Acid rain	Selective catalytic reduction + Engine tuning and injection retard
	Gothenburg Protocol	Ground level ozone	**Alternative fuels**
		Local air pollution	Water injection
Sulfur Oxides	MARPOL 73/78, Annex VI, Regulation 14	Acid rain	Reduce sulfur content in current fuel
	Gothenburg Protocol	Local air pollution	**Alternative fuels**
	Council Directive 1999/32/EC		Sea water scrubbing
Volatile Organic Compounds	MARPOL 73/78, Annex VI, Regulation 15, VOC	Global warming	Tanker VOC recovery
	Gothenburg Protocol	Ground level ozone	VOC generation minimization
Particulates	Partly covered by regulation of sulfur oxides	Local air pollution	Selective catalytic reduction
			Reduce sulfur level in current fuel
			Filters and Cyclones
Ozone depleting substances	MARPOL 73/78, Annex VI, Regulation 13	Ozone layer depletion	Media replacement
	Montreal Protocol	Global warming	

Table 6: Emission sources and regulation in Norway

Altogether four regulations exist to regulate emissions to air in Norway:

1) Kyoto Protocol
2) MARPOL 73/78 Annex VI
3) Gothenburg Protocol
4) Montreal Protocol

Some guidance through these regulations will be given now, along with a description of how these regulations implicate to shipping in Norway.

5.2.1. The Kyoto Protocol

The Kyoto Protocol is a protocol under the United Nations Framework Convention on Climate Change (UNFCCC), which is an international treaty. The protocol is aimed at fighting global warming, or dangerous anthropogenic interference with the climate system, and was initially adopted in Kyoto, Japan, on 11 December 1997. It entered into force on 15 February 2005 and as of today 191 countries ((UNFCCC) 2010) have signed and ratified the protocol.

Under the protocol, Annex I[4] countries commit themselves to reduction of four greenhouse gases (GHG); CO_2, Methane, NO_x and sulfur, in addition to the two gases; hydrofluorocarbons and perfluorocarbons. Even though Annex I countries collectively have agreed to reduce GHG by 5,2 % from 1990 levels, international shipping is not included. Shipping contributes to 2,7 % of all anthropogenic CO_2 emissions ((IMO) 2009) and due to this, strong forces such as the EU and possibly the US will try to regulate emissions from shipping through either taxes or emission trading systems.

Since this thesis mainly considers short-sea shipping within Norwegian ports (domestic shipping), goals set by the Norwegian Government to reduce CO_2 emissions have a consequence for shipping. In 1991 Norway introduced taxes on bunkers and mineral oils. The taxes are listed in Toll Customs' list of Excise duties (Toll Customs 2010), along with the NO_x tax which will be described further in this chapter.

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[4] There are 40 Annex I countries and the European Union is also a member. These countries are classified as industrialized countries and countries in transition.

Today (2010) there are three taxes related to marine fuels; CO_2-tax, a base-tax and a sulfur tax.

CO_2 tax on bunkers amounts to NOK 0,58 per liter of bunkers (Statoil Norge AS 2010) and NOK 1,80 per liter of mineral oil. All of these taxes are included in the price when either bunkers or mineral oil is purchased. Important to mention is that the Norwegian Government agreed upon putting a CO_2 tax on natural gas as of 1 July 2010, but given acceptance from the European Economic Community, all domestic sea transport will be exempted from this rule.

In addition to the CO_2 tax, Norway introduced a base tax on gasoil and diesel oil in 2000. As of 1 January 2010 the base tax equals NOK 0,886 per liter (Toll Customs 2010). If oil used for the purpose of international shipping, domestic transport of either people or merchandise, supply shipping or fishing exception from this tax is given.

The last tax related to maritime fuels is the sulfur tax. All fuels containing more than 0,05 % sulfur are assigned a tax of NOK 0,075 for each 0,25 percentage of sulfur per liter. This means that fuels with a 0,05% sulfur content (500 ppm) are exempted from the sulfur tax, while fuels with a 0,1% sulfur content (1000 ppm) are charged with NOK 0,075 per liter.

5.2.2. MARPOL 73/78 Annex VI

The six previously mentioned sources of emissions to air have an impact on atmospheric composition, human health and climate. Due to especially acid rains impact on regional areas and oil spills regulations with regards to shipping and the environment, regulations in the maritime sector started to develop in 1970 (IMO 2010). Today, MARPOL 73/78 Annex VI (Prevention of air pollution from ships) put limits on NO_x and SO_x emissions from ship exhaust and prohibits deliberate emission of ozone depleting substances. MARPOL 73/78 is today the most influential regulation on international shipping.

Historical development of MARPOL 73/78

In 1973 a comprehensive instrument regarding prevention of environmental damage from ships called "The Convention for the Prevention of Pollution from Ships" was signed during a diplomatic conference. The Convention was in short called MARPOL 73. Five years later the Protocol of 1978 rectified MARPOL 73's shortcomings and the Convention was from there on known as MARPOL 73/78. The agreement from the convention has today six annex', where Annex VI is the most important with regards to emissions to air.

Annex	Regulation	Came into force	
I	Prevention of pollution by oil	2 October 1982	Compulsory
II	Control of pollution by noxious liquid substances in bulk	6 April 1987	Compulsory
III	Prevention of pollution by harmful substances carried by sea in packaged form	1 July 1992	Optional
IV	Prevention of pollution by sewage from ships	27 September 2003	Optional
V	Prevention of pollution by garbage from ships	31 December 1988	Optional
VI	Prevention of air pollution from ships	19 May 2005 (amended 27 September 1997)	Optional

Table 7:Overview of Marpol Annexes

Annex VI came into force on 19 May 2005, but was amended by the MARPOL Convention on 27 September 1997 by the "1997 Protocol". It is regulation related to Annex VI which has the largest impact on the usage of LNG as a fuel. The IMO emission standards which are contained in MARPOL 73/78 are known as Tier I, II and III. Tier I was introduced after the "1997 Protocol" and became effective on 18 May 2004 (one year before it came into force) when 15 states with not less than 50% of the world merchant shipping tonnage accepted the protocol .

In 2005, one year after MARPOL Annex VI came into force, all ships with a weight of 400 gt (gross ton) or more sailing international voyages were required to bunker with a fuel oil which has a maximum sulfur content of 4,5 % m/m (mass to mass percent) and complied with the requirement of Regulation 14 (Sulfur Oxides) and 18 (Fuel Oil Quality). After Annex VI was added, steps were taken to strengthen the emission limits and a number of other identified matters. This work caused the adoption of a revised Annex VI in 2008 by the means of resolution MEPC 176(58) and would be enforced from 1 July 2010. The revised Annex VI introduced;

1) New fuel quality requirements (from July 2010)
2) Tier II/III NO_x emission standards for new engines
3) Tier I NO_x requirement for existing pre-2000 engines. Tier II is a global standard from 2011, while tier III will come into force in 2016 in NO_x Emission Control Areas. These control areas are similar to the already existing Sulphur Emission Control Areas that will be explained in further detail.

The amendments in 2008 gave the following NO_x emissions limits for engines depending on the engine maximum operating speed (n, rpm).

Tier	Date	Nox Limit, g/kWh		
		$n < 130$	$130 \le n < n^{-0,2}$	$n \ge 2000$
Tier I	2000	17	$45 \cdot n^{-0,2}$	9,8
Tier II	2011	14,4	$44 \cdot n^{-0,23}$	7,7
Tier III	2016ᵻ	3,4	$9 \cdot n^{-0,2}$	1,96

ᵻ In NO_x Emission Control Areas (Tier II standards apply outside ECAs).

Note: n is an engine specific parameter

Table 8: MARPOL Annex VI NO_x Emission Limits (Pedersen 2008)

An intuitive description of the table above is given figure 13 below.

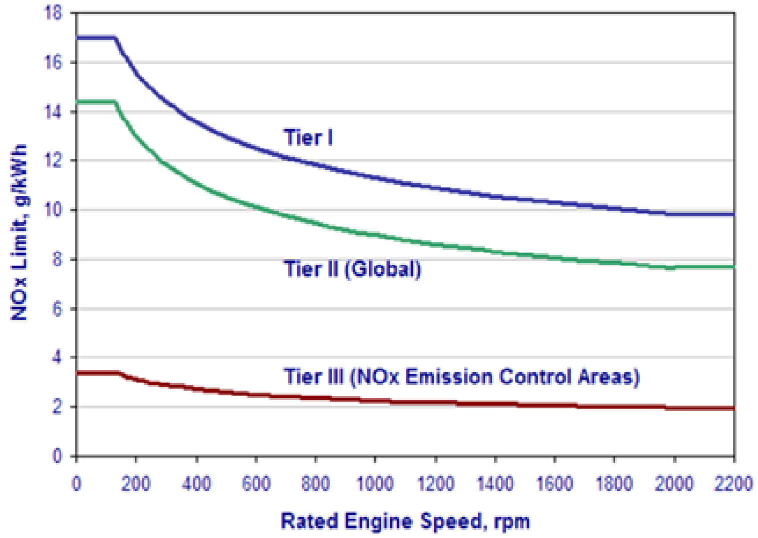


Figure 13: MARPOL Annex VI NO_x Emission Limits

The revised version of Annex VI contains 18 regulations which cover most sources to air pollution (except CO_2 and particulate matter). Altogether 53 countries have rectified MARPOL 73/78 Annex VI, covering 81,88% of tonnage (MAN 2008).

Emission Control Area (ECA)

Annex VI defines two sets of emission and fuel quality requirements, 1) global requirements, and 2) Emission Control Areas (ECA). ECAs can be designed for NO_x, SO_x and particulate matter, or all three types. Currently there are two SO_x Emission Control Areas (SECA), one in the Baltic Sea (adopted 1997, entered into force 2005) and one in the North Sea (entered into force 2005/2006).

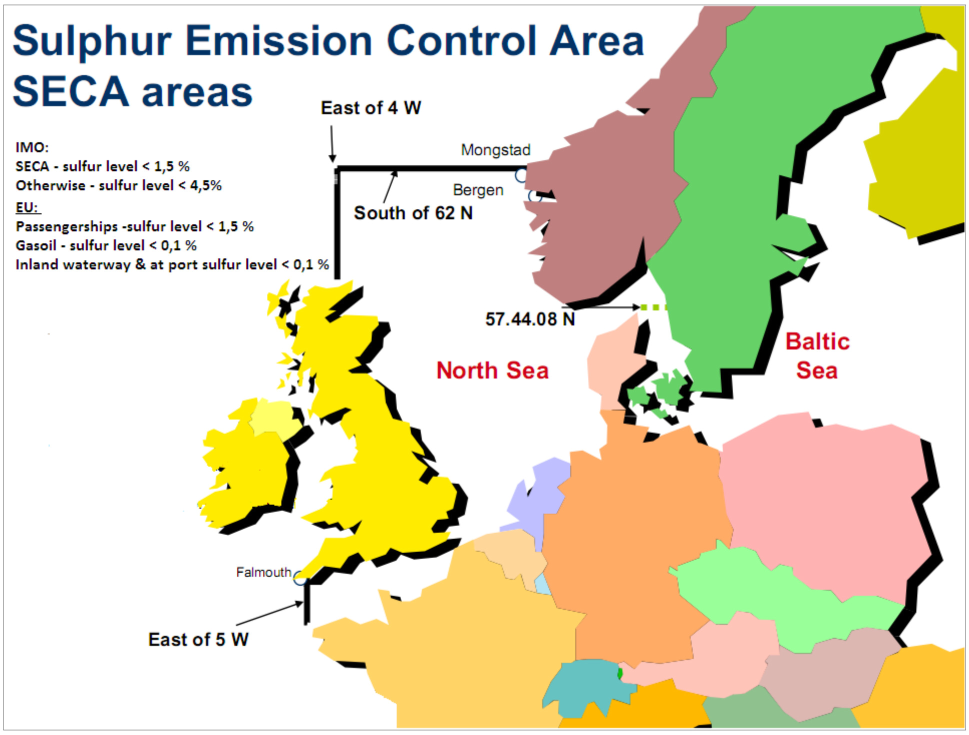


Figure 14: Map over Sulphur Emission Control Area (SECA)

As seen in figure 14 above, Annex VI puts a cap on sulfur content in fuel with intent to limit SO_x emissions. Ships trading within Sulphur ECAs (SECA) have to adapt even stricter rules than the global maritime sector, currently restricting them to use fuel oil with a maximum sulfur content of 1,5 % m/m (mass to mass percent). This forces ships running in this area to either purchase the more costly fuel gas with a low sulfur level, or fit in an approved gas cleaning system or other technological systems which reduced the sulfur emissions (i.e. use of scrubbers). If approved cleaning systems are utilized, then ships have to comply with regulations stating that emissions of sulfur oxides must not exceed 6.0 g SO_x/kWh.

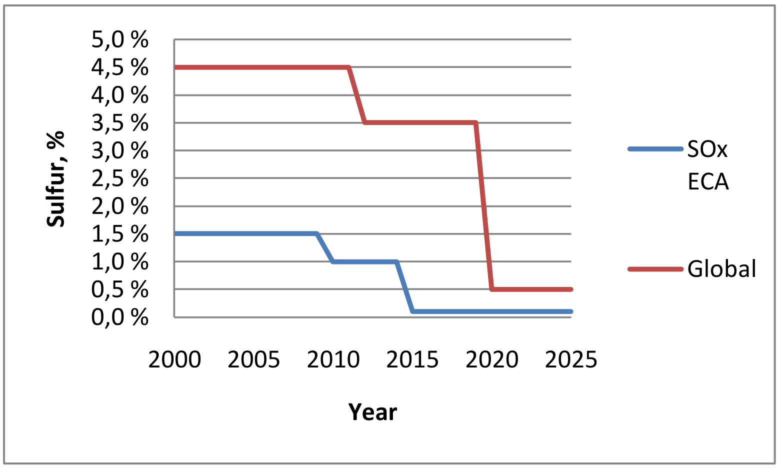


Figure 15: MARPOL Annex VI Fuel Sulfur Limits

The sulfur limits and date of implementation in SECAs is listed in detail in table 9 beneath.

Date	Sulfur Limit in Fuel (% m/m)	
	SO_x ECA	Global
2000	1,5 %	4,5 %
07/2010	1,0 %	
2012		3,5 %
2015	0,1 %	
2020[a]		0,5 %
a - alternative date is 2025, to be decided by a review in 2018		

Table 9: MARPOL Annex VI Sulfur Limits

Ozone Depleting Substances

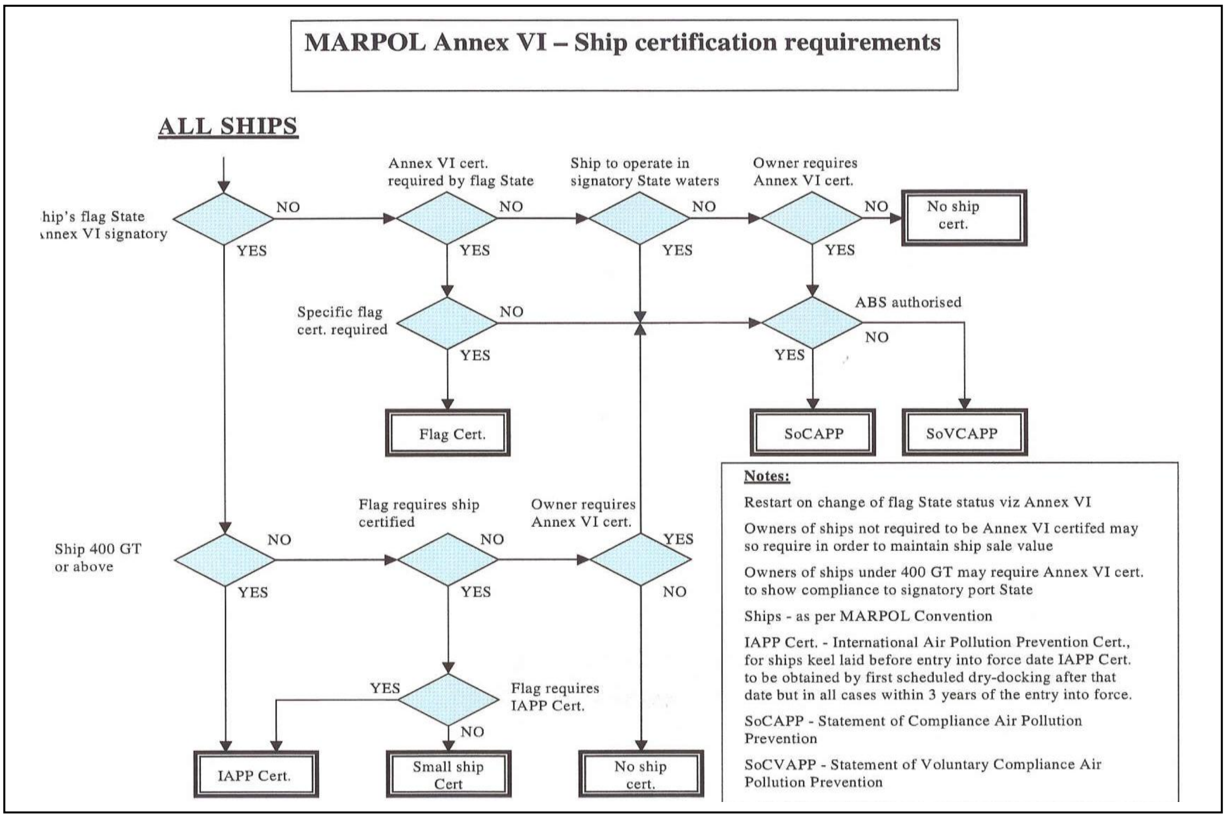
According to Annex VI, deliberate emissions of ozone depleting substances, which include halons and chlorofluorocarbons (CFCs), are prohibited. Any new installation containing ozone-depleting substances are allowed on any ship, while new installations containing hydro-chlorofluorocarbons (HCFCs) are allowed until 1 January 2020.

In addition, Annex VI also forbids incineration of certain products, e.g. contaminated packaging and polychlorinated biphenyls (PCBs), on board ships of certain products.

Compliance

Periodic inspections and surveys determine the compliance with Annex VI. If the survey is passed, the ship is issued an “International Air Pollution Prevention Certificate” (IAPP), which is valid for up to 5 years. According to the “NOx Technical Code” the ship operator is responsible for in-use compliance (not the engine manufacturer).

Figure 16 describes ship certification requirements according to MARPOL Annex VI:



Notes:

Restart on change of flag State status viz Annex VI

Owners of ships not required to be Annex VI certifed may so require in order to maintain ship sale value

Owners of ships under 400 GT may require Annex VI cert. to show compliance to signatory port State

Ships - as per MARPOL Convention

IAPP Cert. - International Air Pollution Prevention Cert., for ships keel laid before entry into force date IAPP Cert. to be obtained by first scheduled dry-docking after that date but in all cases within 3 years of the entry into force.

SoCAPP - Statement of Compliance Air Pollution Prevention

SoCVAPP - Statement of Voluntary Compliance Air Pollution Prevention

Figure 16: MARPOL Annex VI Ship certification requirements (Rauta 2005)

5.2.3. The Gothenburg Protocol

The Gothenburg Protocol is by some said to be the most advanced international environment agreement. Most countries in Europe are signatories of this protocol which is the latest adopted protocol under "The Convention on Long-range Transboundary Air Pollution" from 1979. The Gothenburg Protocol entered into force in 2005 and sets limits for emission of nitrogen (NO_x), sulfur (SO_2), ammonia (NH_3) and volatile organic compounds (NMVOC). The current status of the emission reductions are the following:

Component	Emissions 1990	Emissions 2009	Emission ceiling 2010	Necessary reduction 2009-2010
Nitrogen oxides (NO_x)	204	167	156	11500 tons (7 per cent)
Sulfur dioxide (SO_2)	52	16	22	Emission ceiling appr. Reached at the moment
NMVOC	300	161	195	Emission ceiling appr. reached at the moment
Ammonia (NH_3)	20	23	23	Emission ceiling appr. reached at the moment
CO	868	365	-	No quantified emission ceiling

Table 10: Emission ceiling 2010 according to the Gothenburg Protocol and status 1990 and 2009 (numbers in 1000 tons) (Statistics Norway 2010)

NO_x – tax

The NO_x-tax was adopted 28 November 2006 by the Norwegian Parliament (Stortinget) and introduced 1 January 2007. The tax on NO_x -emissions came as an effect of the Gothenburg Protocol and affects all ships with an installed power of more than 750 kW (approx. 1000 horsepower).

Even though the tax applies to all vessels in Norway, there are many vessels that are exempted from the NO_x tax:

- vessels in direct traffic between Norwegian and foreign ports
- vessels engaged in fishing and hunting in remote waters (more than 250 nautical miles ashore)
- vessels with an environmental agreement with The Ministry of the Environment concerning NO_x reducing measures
- vessels which are considered worthy of preservation (according to specific regulations)
- vessels in innocent passage in Norwegian territorial water and vessels which sail between ports around Svalbard (Norwegian Maritime Directorate 2010)

The emissions of NO_x will be directly measured on the ship or through a NO_x-factor. The NO_x tax equals NOK 16,14 pr kg emission (Toll Customs Norway 2010) from 1 January 2010.

An example of an environmental agreement with the Ministry of the Environment, subject to exemption of the NO_x tax, is enterprises who have signed an agreement with “The Business Sector’s NO_x Fund”. This agreement, also known as the Environmental Agreement, gives all enterprises obliged to pay the NO_x tax an opportunity to sign the Environmental Agreement. According to the agreement, enterprises who have signed the agreement must report their NO_x emissions to the Business Sector’s NO_x Fund, implement NO_x reducing measures and pay the Business Sector’s NO_x Fund per kg of NO_x emission. If the Environmental Agreement is signed, then the company is obliged to pay NOK 4 per kg NO_x. Undertakings of the Environmental Agreement may also apply for support for measures to reduce NO_x emissions. Measures applied for in 2010 may be given up to 75% support of investment costs, as well as operational costs, with an upper limit of up to NOK 100 per kg NO_x reduced (NHO 2010).

Originally this Environmental Agreement is planned to exist until 2010, with 2011 as the last year of implementation of NO_x-reducing measures. However, the Norwegian Government has on the other hand expressed that they would like to continue with this agreement, and representatives of the NO_x-fund have expressed that they expect the fund to exist until 2016.

5.2.4. Montreal Protocol

The Montreal Protocol (MP) was agreed upon 16 September 1987 and is today ratified by all countries in the world. According to the MP, countries that have ratified the agreement are obliged to limit and, after a period of time, stop usage of ozone depleting substances mentioned in 5.1..

The protocol has been strengthened four times since it was agreed upon. Today developed countries have been granted a deferment of the strict emission limits.

6. LNG engine technology

6.1. Current propulsion technology

Most ships today utilize a diesel-mechanical concept where combustion engines provide propulsion power to propellers via reduction gears and shaft lines. With such a concept, engine speed (rpm) has to be adjusted to reach the target speed. Vessels also have auxiliary engines which generate electric power for other needs than propulsion power.

The concept adopted for natural gas powered vessel until 2008 has been a gas-electric propulsion system. This is similar to the diesel-electric concept, where combustion engines provide propulsion power via generators and electrical motors. In such a system, combustion engines have to operate on a fixed engine speed (rpm) generating electric power at 50 to 60 Hz (MAGALOG Project 2008). Since the combustion engine has to generate electric power on a relatively constant level, regulation of the combustion engine becomes simpler. With such concepts, auxiliary engines are not needed.

Today a gas-mechanical concept is under development and will be available from Rolls-Royce Marine and Wärtsilä from 2010/2011. Such concepts will be similar to the diesel-mechanical concept, only utilizing LNG instead of diesel or other fuels.

Today combustion engine concepts that utilize LNG as a transport fuel to provide propulsion power can be divided into two categories (DNV 2009):

a.) Dual fuel engines (e.g. Wärtsila, Man)
b.) Lean-burn gas engines – spark ignited engines (e.g. Rolls-Royce, Mitsubishi)

In addition to these options, gas-diesel engines exist, but these can only utilize natural gas and not LNG.

6.1.1. Dual fuel engines (DF)

Both diesel and LNG can be burned to create propulsion power with a dual fuel diesel electric engine (DFDE). In general DFDE engines run either on gas with 1% diesel (when in gas mode) or on diesel (when in diesel mode). The DF engines offer a switch from one fuel to the other without interruption in power generation. In this type of engine, gas and air mixture is combusted in an Otto cycle by pilot diesel ignition (micro pilot diesel flame) or alternatively, diesel and air mixture is combusted when in diesel mode.

Wärtsilä dual-fuel engines

Wärtsilä is seen as the market leader in production of DF engines. The company offers two types of dual-fuel engines, either dual-fuel electric (DF-E) engines or dual-fuel mechanic (DF-M) engines. Both engines have complete fuel flexibility (LNG, IFO 380 cst. and MDO/MGO), but there are some differences between the two.

The DF-E engine converts the energy from the engine in generators which again use electrical engines to rotate the shaft. According to Wärtsilä, the DF-E engine has a propulsion power efficiency of 43,4 %. The DF-M engine on the other hand, uses only a reduction gear to rotate the shaft directly. It has a propulsion power efficiency of 46,1 %, but needs auxiliary engines in addition to the main engines. All together the DF-E system needs more space due to the electrical drives, in addition to having a higher operational and capital cost compared to the DF-M. It must be noted that a dual-fuel concept demands separate fuel tanks for LNG and conventional fuels which increases space demand. As conventional fuels are only expected to be utilized as ignition source or reserve capacity, only small tanks for conventional fuels are needed.

Wärtsilä currently offers the following engines utilizing LNG as fuel:

Engine	In-line (cylinders)	Output (power)	Power range
Wärtsilä 20DF	6, 8, 9	146/176 kW per cyl.	841-1584 kW
Wärtsilä 34DF	6, 12, 16, 18, 20	450 kW per cyl.	2610-8700 kW
Wärtsilä 50DF	6, 8, 9, 12, 16, 18	950/975 per cyl.	5700-17550 kW

Table 11: Overview of LNG engines by manufacturer Wärtsilä

Wärtsilä has a lean-burn gas engine, 34SG, but it is not yet available for maritime usage.

6.1.2. Lean-burn gas engines

Lean-burn gas engines operate with a mix of gas and air in an Otto cycle by the help of spark plug ignition. Rolls-Royce Marine is the leading producer of such engines with LNG as a fuel.

Rolls-Royce Marine (RRM) Bergen gas engines

Rolls-Royce Marine engines all have a lean-burn concept applied to its three types of marine engines; K-type engines, B-series and C-series. The K-type engine was the first type of engine RRM built on a vessel with LNG as a fuel. As a gas-electric system, the engine managed to provide 44% propulsion power efficiency according to Marintek (Einang, Per Magne 2003).

Currently RRM offers the B- and C-series. The two series are adopted for LNG as a fuel, and named Bergen C25:33 Gas Engine and Bergen B35:40 Gas Engine. The engines have a shaft efficiency of 48% according to RRM, and are available for both gas-electrical and gas-mechanical applications. The gas-electrical engine demands additional space and costs with regards to the electrical system needed. In comparison, the gas-mechanical engine inflicts additional costs and space requirements with regards to the need for auxiliary engines. All over, the gas-mechanical system demands less space and investment costs, and also has the benefit of being more efficient combined with lower operational costs. The two gas engines are expected to meet with MARPOL Annex VI NO_x Tier III emission regulations.

Rolls-Royce Marine currently offers the following engines with LNG as a fuel:

Engine	In-line (cylinders)	Output (power)	Power range
RRM Bergen B35:40 Gas	12, 16, 20	420/440 kW per cyl.	2320-8500 kWmech
RRM Bergen C25:33 Gas	6, 8, 9	270 kW per cyl.	1460-2430 kWmech

Table 12: Overview of LNG engines by manufacturer Rolls-Royce

Sea-Cargo's new multipurpose RoRo vessel will be the first vessel with a gas-mechanical concept with Rolls-Royce's newest propulsion technology. The main engine will be the Bergen B35:40V12PG and the vessel is expected to be delivered in 2010/2011.

6.1.3. Cost related to engines

Building costs are higher for LNG-fueled vessels due to implications related to the gas engine. Even though one might expect costs of building LNG-fueled vessels to decrease in the future, due to diffusion and knowledge accumulation of the technology, the exact reduction in costs is impossible to predict. All in all, the economic feasibility of LNG driven vessels will depend on the ship-owners view if higher building costs can be justified by (possibly) lower operating and voyage costs.

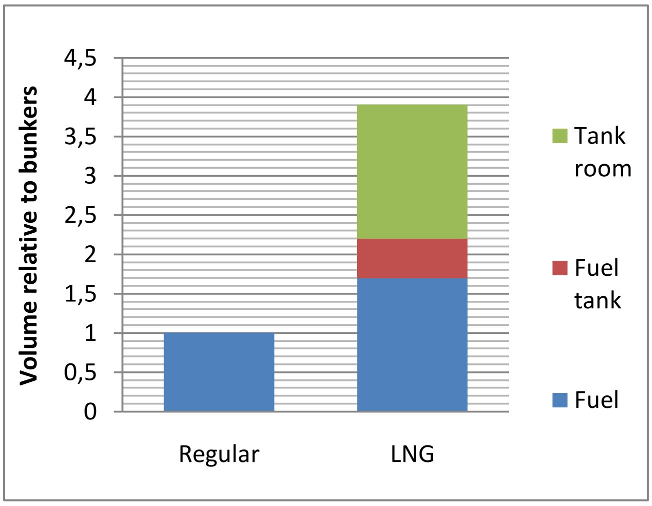


Figure 17: LNG storage volume (Levander 2007)

Figure 17 illustrates how LNG storage demands more space. The LNG tanks themselves have until today only been developed to be cylinder formed, meaning they demand a larger tank room compared to regular fuel tanks. In addition to this, LNG must be kept at a cool temperature demanding a thermos-like tank which also demands more space than regular fuel tanks. Considering the fact that LNG demands more space due to its lower density compared to regular fuels, LNG-fueled vessels could experience a reducted loading capacity.

6.2. Segments suited for LNG propulsion

In principle any ship is suited to use LNG for propulsion, even though some segments are more suited than others due to bunkering possibilities and the capability of installing a LNG fuel system onboard.

Segments especially suited for using LNG propulsion share the following characteristics:

a.) A regular sailing pattern
b.) Operation in environmental sensitive areas (highly regulated areas)
c.) LNG fuel system is suited in relation to storage of gas and other onboard processes

A regular sailing pattern will have the benefit of the ship calling at bunkering locations frequently, which reduces the need for large LNG tanks on board. The ferry and the cruise ship segment are therefore especially suited for LNG propulsion. In addition, these vessels often operate in environmentally sensitive areas close to the coast. These sensitive areas with heavy traffic benefit especially from the reduction of pollution to water and harmful exhaust emissions. In Norway vessels demonstrating the suitability for LNG propulsion, aside from ferries, are coast guard vessels, LNG carriers, and offshore supply vessels.

6.3. Cases

In the following, the three shipping segments subject to the analysis will be presented. A variety of segments is suited for LNG propulsion systems, but the scope of this analysis allows only a few of them to be addressed. The market segments analyzed in this study are:

- The platform supply segment
- The ferry segment
- The bulk carrier segment

The PSV segment

Platform supply vessels (PSV) are service vessels used in the offshore oil and gas industry. These vessels operate under harsh weather conditions in the North Sea and require both large cargo capacity and engine power. Norway has a large PSV-fleet due to the country’s large offshore industry. Offshore vessels are also a large component of the Norwegian shipbuilding industry. If potential cost-flows support the investment in LNG-fueled PSVs in the analysis, LNG has a prospective future in the PSV segment.

The ferry segment

Ferries are vessels using Ro-Ro (roll-on-roll-off) technology to transport cars and accommodate passengers on a regular sailing line (E-Dea 2008). Moreover, most ferries operate in environmental sensitive areas near the coast. The predictability of bunkering needs through the regular liner-service and environmental considerations make ferries especially suited for LNG propulsion. The ferry segment is also the “oldest” LNG-segment in Norway. Furthermore, ferries are an important part of the transport network in Norway. It is part of the Norwegian transport policy to subsidize ferry operators to offer sufficient transport, also in regions with low traffic volumes (Samferdselsdepartementet 1999-2000). The analysis does not take these subsidies into account. However it is important to notice the effects of cost-reductions for private operators, as well as for public budgets. Hence, the potential market for LNG-fueled ferries is expected to be rather large if the analysis reveals LNG-fueled ferries to be profitable under the considered conditions.

The bulk carrier segment

Bulk carriers transport bulk cargo, such as grain, iron ore, coal or liquids. Since the focus in the bulk cargo market is generally on low-cost transport (Stopford 2009), the financial consequences of shifting to LNG-propulsion are especially interesting to this segment.

7. Commercial aspects of LNG as transport fuel

The application of natural gas as a transport fuel has been successfully implemented in several vehicle types in many countries. The major benefits are the independency of conventional petroleum fuels and the potential of reducing harmful exhaust emissions. In road-transport compressed natural gas (CNG) is the most common application of natural gas. However, CNG has a lower energy density and requires a larger storage volume compared to LNG, which makes LNG the superior, yet the more cost-intensive, solution for marine-transport.

Previous chapters have shown that LNG as a fuel is more environmentally friendly and especially compatible with regards to environmental regulations. The technical feasibility of LNG as a fuel has also been pointed out. The intention of this chapter is to provide a more detailed description of LNG as a commercial marine fuel, especially in Norwegian seawater. The benefits of using LNG for engine propulsion are influenced by factors as supply access and sector demand. These commercial issues will be covered in this chapter; however the scope of this paper is limiting the discussion to Norwegian short-sea shipping.

7.1. Supply and demand of LNG in Norway

7.1.1. Supply

LNG's availability depends crucially on the accessibility of natural gas. As mentioned in chapter 3, Norway holds the largest reserves in Western Europe. Reserves, as measured today, offer almost 30 year long lasting reserves if production continues at the same rate (table 3). These prospects offer consumers of LNG a good security of supply and can be seen as a competitive advantage for LNG. Reports have also indicated that reserves are expected to increase as new areas in the North Sea and Barents Sea will be opened for exploration.

In Norway, foremost small scale LNG has been developed. As previously noted, small scale LNG offers an opportunity to distribute natural gas under geographical conditions that make pipeline transport difficult. Norway has today five LNG production plants, supplied with natural gas from offshore production facilities in the North Sea. LNG is then distributed locally via LNG tankers or by truck. Some of these production plants offer ships fuelling of LNG, while others are planning on offering this service in the future. Table 13 below lists the current LNG production facilities in Norway.

LNG Production Plants				
Melkøya	Operated by Statoil	Only large scale LNG production facility in Europe	4.300.000 tons/year	Truck loading only
Tjeldbergodden	Operated by Statoil	Small scale facility	12.000 tons/year	Truck loading only
Kollsnes	Operated by Gasnor	Small scale facility	143.000 tons/year	Ship + truck loading
Snurrevarden (Karmøy)	Operated by Gasnor	Small scale facility	20.000 tons/year	Truck loading only
Risavika	Operated by Lyse / Skangass	Small scale facility (under construction)	300.000 tons/year	Ship + truck loading

Table 13: LNG production plants in Norway

Availability of LNG depends on access to LNG infrastructure and facilities, as production and re-gasification facilities or bunkering stations. Over the past decades, natural gas demand has been rising steadily reflecting the word's rising energy demand. Only in the later years, deregulation of gas markets and environmental concern has contributed to the rapid increase in gas demand. This increase in gas demand has lead to a growth in the LNG industry as well, with a growing number of producers, buyers and terminals contributing to an improved infrastructure.

In addition to production plants there have been established regional and local depots for LNG around in Norway. There are today more than 26 truck terminals and 8 ship terminals which receive/deliver LNG (Einang, Per Magne 2008). The sizes of these terminals vary between 30 m^3 and 3500 m^3. At these terminals, LNG is stored in cylindrical pressurized tanks with a multi-layer-vacuum-insulation with a highly effective power-vacuum which ensures long-time storage with limited vaporization (Stenersen, Svendgård and Jarlsby 2008). The terminals capable of supplying vessels with LNG, generally have a capacity between 500 and 700 m^3.

In addition to being supplied from terminals, ships can also be provided with LNG directly from trucks or LNG vessels. Currently rail transportation has been discussed, but has not been undertaken in Northern Europe.

7.1.2. Demand

Demand for LNG in Norway has been steadily growing over the past years as indicated by figure 18 below. Reasons for this development might be a growing energy demand combined with the expansion of LNG supply infrastructure. The growth in LNG demand in the shipping sector has been remarkable and is directly related to the market penetration of LNG as a ship's fuel (figure 18). Total LNG consumption has flattened out recently; which might indicate current market saturation. Reasons might be Norway's low population density, topographical conditions or domestically large coverage of hydro energy as alternative energy source.

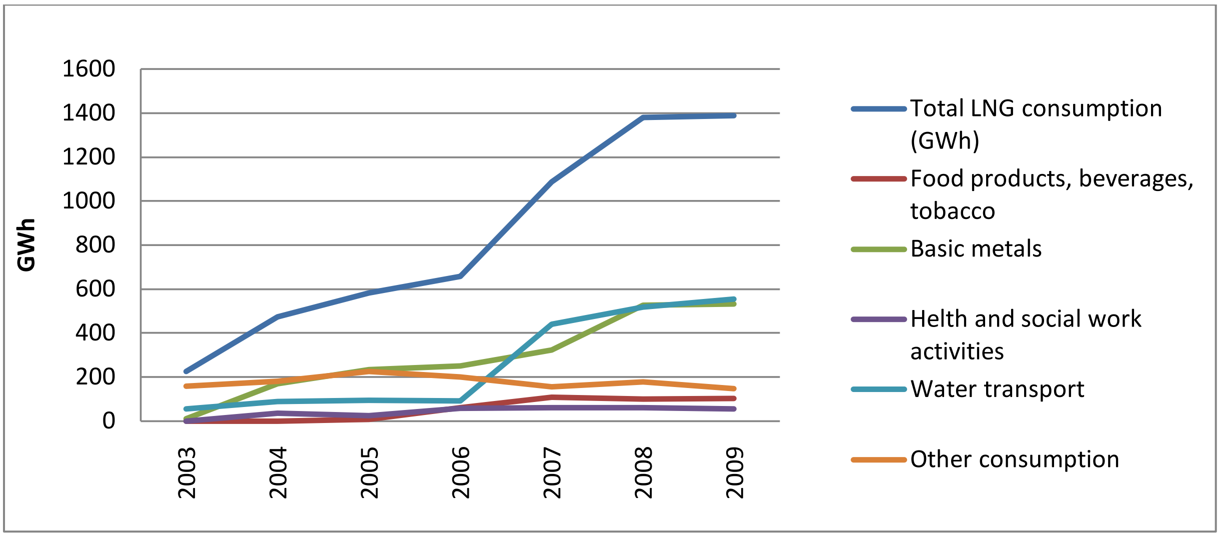


Figure 18: Net domestic consumption of LNG (GWh) in Norway, by group of purchasers, time and contents (Statistics Norway 2010)

Demand for LNG as ships fuel

Several LNG-fueled vessels are operating around the world, with Norway being at the forefront of introducing LNG fueled systems in coastal vessels. Hence, Norway dominates the LNG-fueled fleet and has a growing demand for LNG as a fuel in water transport.

Figure 19 below presents the Norwegian LNG fueled ship inventory. The first vessel, the car-ferry Glutra, was introduced in Norway already a decade ago. Several car-ferries have followed since, making the RoPax segment the largest one for LNG propulsion. In 2009, a total of 15 LNG-driven vessels were consuming 553 GWh (Statistics Norway 2010) of LNG-about 36 426.26 metric tons (MT)[5]- making the marine transport sector the largest single consumer of LNG in Norway.

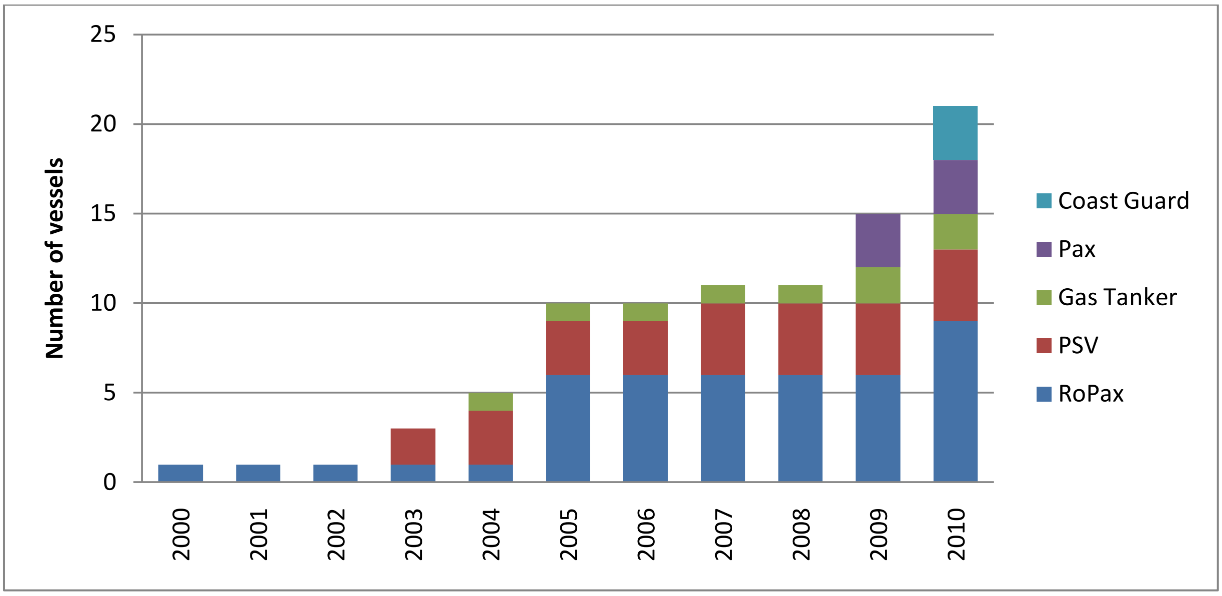


Figure 19: Number of LNG driven vessels in Norway (cumulative)

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[5] 553 GWh = 553 000 MWh = 1 227 372,01 m^3 = 36 426,26 MT

PART II

Technical Framework

In this part, the technical framework for comparing cost flows for the three typical case ships is presented. The objective is to assess whether LNG-fueled vessels are cost-competitive to those utilizing conventional fuels.

On the basis of historical pricing, the relationship between bunkers prices and oil prices is assessed in this chapter. Since the cost of bunkers is the main component in voyage costs, it can be expected that vessels utilizing lower-priced fuels could have a cost-advantage. The technical framework presents the methodology and data needed to study the relationship between bunkers prices at different oil price scenarios.

8. Technical framework for analysis

The modeling approach used in this analysis is based on Tronstad and Endresen (Tronstad 2006) and Longva et al. (Longva 2008). The following approach is applied to the analysis:

a) Exogenous parameters (those that are not changed in the model) for operational profile and ship characteristics for three case ships are drawn **(Equations 1 – 6).**

b) Endogenous (those changed in the model) values are assumed for future fuel prices, operational costs and emission taxes and/or other emission reducing initiatives **(Future scenarios).**

c) Economic results are compiled for each year (*n*) of operation and used to assess the competitiveness of LNG relative to the incumbent technology **(Equation 7).**

The modeling approach is presented in detail in the following.

8.1. Calculating costs

Establishing the environmental tax exposure, capital investment and operational running cost make an economic evaluation of LNG-fueled vessels possible. The aim of the analysis is to identify the cost position of LNG-fueled vessels within different sectors and at different oil price scenarios. Net present value (NPV) analysis is a suitable method when providing a comparison of the different cost-flows.

The different propulsion systems (IFO 380 cst., MGO, LNG) are analyzed and hereafter denoted as *a*.

8.1.1. Calculating economic performance

The economic performance can be calculated by summing cost for the different segments subject to the analysis.

Equation 1 gives a total cost function and includes Eq. 2, 3, 4, 5 and 6.

$$\mathbf{C^{a}_{Total}} = \mathbf{C^{a}_{CapEx}} + \sum_{\mathbf{i=0}}^{\mathbf{n}} \mathbf{C^{a,i}_{Annual}} \tag{1}$$

with

$$\mathbf{C^{a,i}_{Annual}} = \mathbf{C^{i}_{OpEx}} + \mathbf{C^{a,i}_{Fuel}} + \mathbf{T^{a,i}_{Em}}\ , \tag{2}$$

where

$C^{a}_{Total} = Total\ cost\ (NOK),$

$C^{a}_{CapEx} = Capital\ expenditure\ (NOK),$

$C^{a,i}_{OpEx} = Operational\ cost\ (NOK),$

$C^{a,i}_{Fuel} = Fuel\ cost\ (NOK),$

$T^{a,i}_{Em} = Environmental\ tax\ exposure\ (NOK).$

Capital expenditure

The first variable in Eq. 1 is C_{CapEx} which is the purchase cost and investment sum (total investment cost). It is assumed that the total investment cost is a present value and does not need to be discounted in a net present value analysis. This means the vessel is purchased and paid for in year 0, while how the vessel is financed is not assessed. All additional costs of investing in LNG-fueled vessels are included in C_{CapEx} (e.g. fitting of LNG tank). Eq. 3 describes how the power installed affects the investment cost.

$$\mathbf{C^{a}_{CapEx}} = \mathbf{P_C} * \mathbf{p} * \mathbf{M} + \mathbf{Extra\ costs} \tag{3}$$

where

P_C = *Investment cost (NOK/kW),*

p = *Installed power (kW),*

M = *technology mark-up for LNG engine (% of normal 4-stroke IFO 308 cst.).*

Operational costs

Operational costs include costs related to spare parts and maintenance costs (Eq. 4). These costs are dependent on how the engine is operating. Costs related to operational costs can be split into two. One part covers how the engine is operating; a function of running hours per year (h), installed power (p) and engine load (l). Part two of the function covers operational unit costs and can be defined as operational costs per kWh.

$$\mathbf{C_{OpEx}^{a,i} = p * h * l * P_{Op.cost}^{i}} \tag{4}$$

where

h = *Running hours per year,*

l = *Engine load (%),*

$P_{Op.cost}^{i}$ = *Operational unit cost (NOK/kWh).*

Fuel costs

Fuel cost, C_{Fuel}, describes the price of fuel multiplied by fuel consumption per output.

$$\mathbf{C_{Fuel}^{a,i} = p * h * l * F^{a} * P_{Fuel}^{a,i}} \tag{5}$$

where

F^a = *Fuel consumption per output (kg/kWh),*

$P_{Fuel}^{a,i}$ = *Fuel price (NOK/kg).*

Environmental tax exposure

The last factor from Eq. 2 is cost related to environmental tax exposure, (T_{Em}) which is based on a tax per ton emissions emitted.

$$\mathbf{T_{Em}^{a,i} = p * h * l * P_{Emissions}^{i} * E^{a}} \tag{6}$$

where

$P_{Emissions}^{i}$ = *Tax per ton emitted (NOK/kg),*

E^{a} = *Emissions per kWh (kg/kWh).*

Net present value

The net present value discounts future costs so that present value of the cost flow can be represented:

$$\mathbf{NPV^a = C_{Capex} + \sum_{i=0}^{n} \frac{C_{Annual}}{(1+r)^i}} \tag{7}$$

where

n = Expected lifetime (years),

r = Discount rate.

In this thesis, final results are presented as cost (NOK) per MWh, to reflect the exact costs related to different engines and fuels, independent of engine size. Therefore, NPV is divided by MWh:

$$\mathbf{C_{pe}^{a} = \frac{NPV}{p * h * n}} \tag{8}$$

C_{pe} = Cost per energy unit of output (NOK/MWh)

8.2. General assumptions

Discount rate (r)

The opportunity cost of invested capital is commonly referred to as the discount rate. In many investment projects it is common to use a riskless discount rate, for example with reference to government bonds, and augment the rate by a risk premium to reflect less predictability in the returns of a project. In Norway bond yield has been around 4% during the past year (DnB NOR 2009). Ship owners will require a higher rate of return and in addition a risk premium should be applied to cover the uncertainties related to the investment. This analysis uses a discount rate of r = 8% to reflect a higher risk in the investment capital. In other words it can be said that the discount rate reflects a company's risk profile and scenario for economic development.

Lifetime (n)

Costs are calculated annually during the expected lifetime of the vessels and discounted to the NPV. An expected operational lifetime (*n*) of 25 years is assumed for all vessels.

Engine load (l)

Engine load in this analysis reflects demand placed on engine in percentage. Engine load will differ between segments depending on trade routes and demand in each sector. For simplicity an engine load (l) to be equal to 1 (100%) in all case scenarios is assumed.

Currency

All costs are denominated in Norwegian Kroner (current prices) and inflation or currency movements are not taken into consideration. For simplicity, the following exchange rate has been used for all calculations in the analysis:

1 EUR = 1,25 USD = 8 NOK (1 USD = 6,4 NOK)

9. Fuel Costs

This chapter describes the fuel costs, also known as “bunker costs”, relevant to the profitability-analysis. As mentioned in the introduction, fuel costs are the largest cost components in voyage costs. The economic potential of using LNG as a fuel for ships lies to a major extent in the price difference between LNG- and conventional fuel prices.

9.1. Conventional marine fuels

Conventional marine fuels used by commercially operating ships are commonly divided into two categories, residual fuel oil and distillates. Residual fuel oil, often referred to as heavy fuel oil (HFO), is the heaviest marine fuel in respect to viscosity and sulfur content. Distillate fuels can be divided further into two categories, marine gas oil (MGO) and marine diesel oil (MDO). When residual fuel oil is blended with distillates, the blend is called intermediate fuel oil (IFO).

The most common blends are IFO 180 cst. and IFO 380 cst.. These are the heaviest marine fuels used in this analysis and have historically been the cheapest sources of marine fuel. Due to its heavy sulfur content, IFO 380 cst. is only used as a reference value to illustrate the price of marine fuels without any concern for the environment.

Low sulfur heavy fuel oil (LSHFO) has lower sulfur content than IFO 380 cst. and can be made by blending HFO with low sulfur products as diesel oil. As described in chapter 5, maximum permissible sulfur content within a SECA is currently 1,5% m/m and will be 1,0% m/m from 07/2010. From 2015 it will be 0,1% m/m. As a result of this regulation, mostly LSHFO on account for IFO 380 cst. is sold in Norway.

In Norway, only MGO with a sulfur content of either 0,1 % m/m or 0,05% m/m is sold due to environmental regulation. In this analysis only “MDO Rotterdam Platts Mean”[6] prices are used as historical data. This type of MDO contains 0,2% m/m, so to make it comply with regulations in Norway a cost of reducing the sulfur level is added, as well as an additional cost of delivery in Bergen.

Table 15 below illustrates the characteristics of the different fuel types used in the analysis.

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[6] Platts is an information service providing daily assessments of market prices for a large variety of products.

Fuel Type	Description	Energy MJ/kg	Sulfur content
IFO 380 cst.[7]	Residual fuel containing distillate fuels	40,6	3,5 %
LSHFO 380 cst.[8]	Residual fuel with low sulfur content	40,6	1 % or 1,5%
MDO	Heavier distillate containing some residual components	42,7	0,2 %
MGO	Destillate only	42,7	0,1 % -0,05 %
LNG	Liquefied natural gas	49,2 -49,5	0 %

Table 14: Overview of conventional marine fuels (DNV 2010) (Wärtsilä 2006)

International historical price development

As the case with most petroleum products, different bunkers are bought and sold in their respective regionally-based markets which are commonly interlinked with the development in the crude oil market. A careful assessment of the development of bunker fuel sales and prices is rather challenging because prices vary a lot.

The crude oil price used in the analysis is Brent blend, i.e. crude oil from the North Sea, obtained from the international petroleum exchange in London and based on future contracts.

Figure 20: Interdependence of different bunker fuels and crude oil (Source: Platts and Wilhelmsen Premier Marine Fuels)

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[7] The same energy content is assumed for IFO380 cst. as for HFO.
[8] The same energy content is assumed for IFO380 cst. and LSHFO 380 cst.

Prices are given in USD, the common currency for petroleum products. Brent crude oil is normally given as a price per barrel, but is in this case converted into metric tons with a conversion factor of 7,5 barrels per MT (international standard). All data are gathered from Platts with Rotterdam figures.

Figure 20 above illustrates how marine fuel prices are strongly correlated with Brent Crude Future prices. LSHFO price data only runs from the beginning of 2009 and it can be seen how similar prices for LSHFO and IFO 380 cst. are. On average, LSHFO has a premium of approximately 20 USD/MT.

Since this study presents the results of the final analysis in NOK per MWh, the cost of a MWh of the different fuel types is illustrated in figure 21 below.

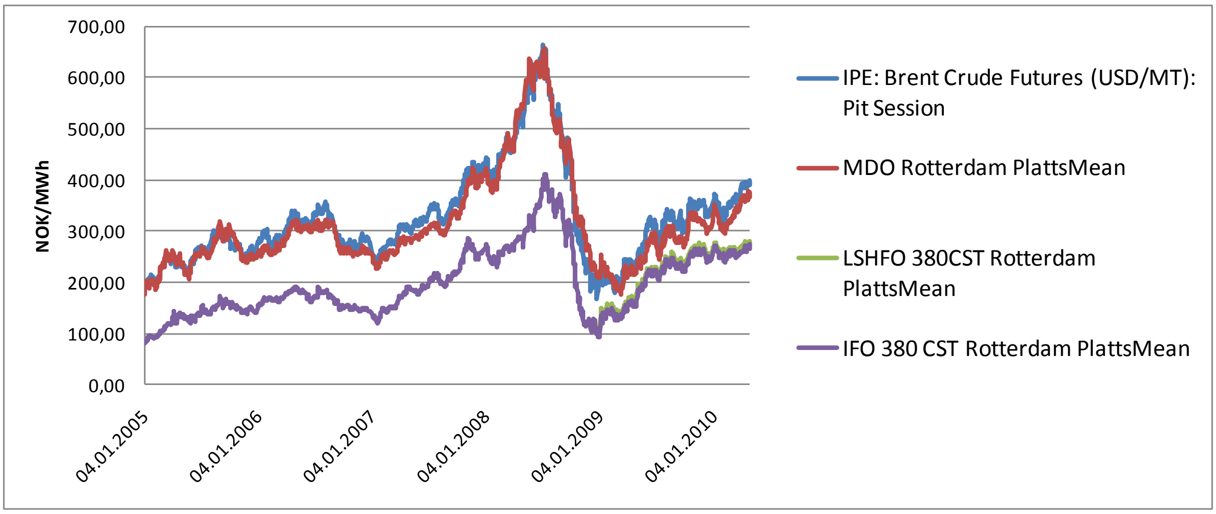

Figure 21: Historical development of fuel prices in NOK per MWh (Source: Platts and Wilhelmsen Premier Marine Fuels)

The historical development of fuel prices in NOK per MWh shows a much smaller difference between e.g. IFO 380 cst. and MDO prices given in USD per MT. This is due to MDO’s higher energy content.

9.2. Fuel costs pricing for Norwegian market

So far, international prices have been presented. These prices reflect the trends and volatility of fuel prices, but do not exactly represent prices on the Norwegian market. For delivery in Norway additional cost due to taxes and delivery must be added.

9.2.1. Conventional marine fuel pricing

As mentioned earlier IFO 380 cst. is only used as a reference price to see what costs would be if there would be no environmental regulation. Due to this fact no additional costs are added to IFO 380 cst. prices.

LSHFO is currently a legal fuel within SECA's, also after 1. July 2010 if the has sulfur content lower than 1% m/m. This is not the case after 2014. After this date LSHFO need scrubbers and CSR's to clean the fuel. Since this thesis disregards these options as a response to environmental regulation, only MGO is a feasible solution to future regulations.

Internationally MDO is the normal low sulfur alternative to IFO 380 cst. and LSHFO. In Norway this is not the case since much of the Norwegian coast lies within a SECA. MGO is a cleaner alternative than MDO and the fuel used in this analysis. Due to difficulties retrieving price data from Norwegian suppliers, MDO price data (MDO Rotterdam Platts Mean) with price premium for additional cleaning and delivery in Bergen is used.

MGO costs	
Costs of cleaning:	307,20 NOK/MT
Delivery and storage costs:	153,60 NOK/MT
Sum	**460,80 NOK/MT**

Table 15: Costs related to supply of MGO in Norway (Fevang 2010)

In addition to this, premium taxes must be added. Relevant taxes in Norway are the CO_2-, base- and sulfur-tax.

The correlation between marine fuel prices and oil prices have been shown previously. This means high oil prices will lead to a rise in marine fuel prices and therefore influence voyage costs. Expectations of different oil price scenarios can show associated bunkers prices.

Based on this, a regression of IFO 380 cst. and MGO is conducted on Brent Crude Oil prices to predict future marine fuel costs.

The basic price relationship can be represented as follows:

$$\boldsymbol{P_{Fuel}^{a.i} = \alpha + \beta * (oil\,price),} \qquad (9)$$

where α is the intercept and β is the coefficient for the oil price. The different fuel prices are represented by a.

9.2.2. LNG pricing

While the prices for present conventional bunkers fuels are quite observable in the market place, the fuel price for LNG is not publically observable. Finding a price of LNG for the purpose of this study is rather challenging. The price of LNG for bunkering at a certain terminal is likely to be strongly related to regional natural gas prices with a difference for LNG fuel logistics.

As mentioned in chapter 3, the MAGALOG Project (MAGALOG Project 2008) expresses that the costs of supplying LNG can be split into two main components:

Cost of small scale LNG = Market based gas price + Cost of supply logistics

Hence, the relationship between crude oil prices and the price for LNG can be represented as follows:

$$\boldsymbol{P_{Fuel}^{a,i}(LNG) = [\alpha + \beta * (oil\,price)] + \gamma,} \tag{10}$$

where α is the intercept and β the coefficient for the oil price in the linear regression of the natural gas price (Henry Hub NYMEX) on the crude oil price. γ represents the constant mark-up for LNG supply logistics.

Chapter 4 offers a general indication of the supply costs for small scale LNG (table 5). As noted, these costs vary dependent on different factors as location and infrastructure. Based on the MAGALOG Project, the average indicative mark-up cost for small scale supply of LNG is expected to be, as presented in equation 10:

$$\boldsymbol{\gamma = 164\ \mathrm{NOK/MWh}} \tag{11}$$

Historical price development in Norway

The following graph (figure 22) is obtained by taking historical international prices and adding the mark-up and taxes for supply in Norway, both for LNG and MGO.

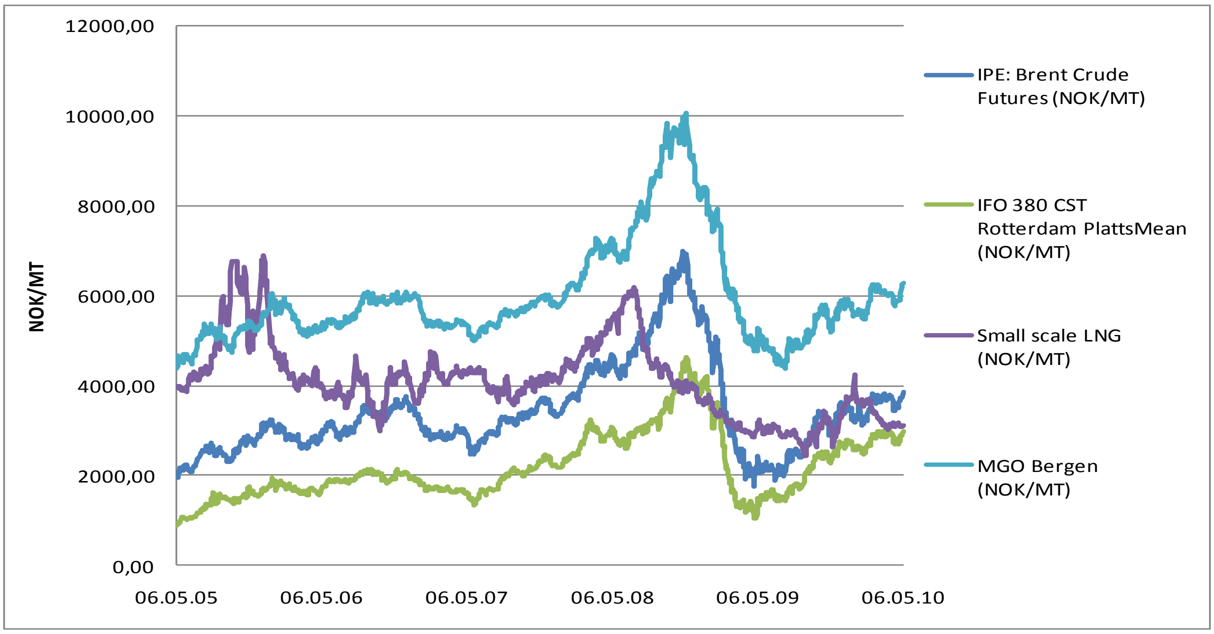

Figure 22: Historical oil and local fuel prices (NOK/MT) (Source: Datastream, Platts and Wilhelmsen Premier Marine Fuels)

Figure 22 depicts the price difference between MGO, other fuels and the oil price over the past five years. It is worth noticing that there is less correlation between the price of Brent crude oil and LNG than with the other fuels. The prices of MGO and IFO 380 cst. change approximately in line with the oil price, while LNG does not follow the same linear pattern and is more “resistant” towards changes in the oil price. Here all prices are given in NOK per MT.

9.3. Computing fuel prices

The results of the regression analysis conducted show that all values are significantly different from 0, but there are differences in how much of the variation in fuel prices can be explained by the oil price. The linear regressions of figure 23 are computed by using equation 9 and 10. The coefficients and variables of the linear functions are presented in table 16.

Fuel Type	Intercept	Variable
IFO 380 cst.	-34,4884	5,301266
MGO	66,51039	8,247666
LNG	183,8149	2,431379

Table 16: Regression coefficients and variables

As conventional fuels and LNG traditionally have been used for different purposes, and based on the fact that oil and gas have different production costs and reserves, regressing gas on crude oil shows that less of the variation in gas prices can be explained by crude oil prices compared to conventional fuel prices.

Figure 23 illustrates the linear relationship between Brent Crude Oil and different fuels:

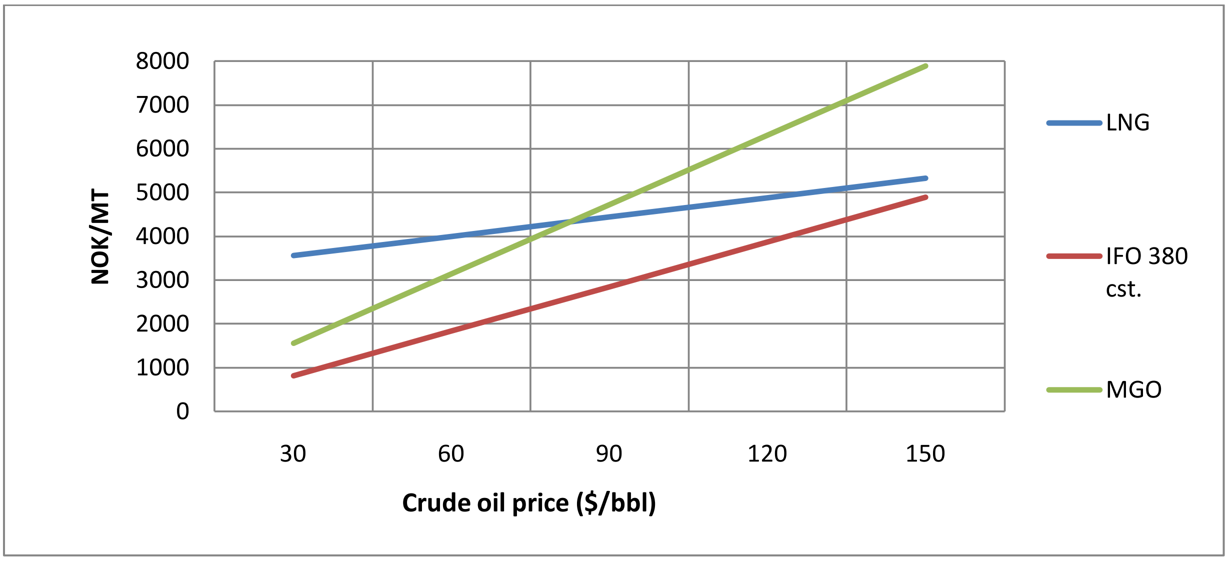

Figure 23: Fuel prices compared to crude oil prices with delivery in Norway

There are quite different linear function describing the relationship between the crude oil price and the different bunkers fuel prices illustrated in figure 23. For the linear relationship between crude oil prices and bunkers fuel prices obtained in this analysis, IFO 380 cst. is the cheapest fuel (NOK/MT) for the considered price range. However, IFO 380 cst. is not allowed in Norwegian seawater, as Norwegian regulation prohibits fuels with sulfur contents like the one of IFO 380 cst. This proves that regulation has a direct impact on costs for shipping companies.

9.4. Calculating fuel consumption

Fuel consumption of a vessel depends on several factors. The design of the main engine has the largest influence on fuel consumption. Engine operating speed, fuel consumption and fuel efficiency are important factors influenced by the main engine (Stopford, 2009). Further, operating conditions, such as weather, hull condition tonnage loaded and engine load influence fuel consumption.

Variance between these factors for each individual vessel makes it difficult to compare fuel consumption of even very similar vessels. This is why this analysis assumes equalitity of operating conditions influencing fuel consumption between vessels employed by normal 4-stroke engines and vessels with gasengines. Fuel consumption is calculated as energy consumed per annum, derived from the multiplication of installed engine power[9] and yearly operating hours, stated in MWh/yr. Hence, fuel consumption can be represented as:

$$\boldsymbol{F^{a,i} = MWh/yr} \tag{12}$$

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[9] Derived from energy input (MJ) needed to obtain a certain engine output (MW).

10. Taxes due to air emissions

In Norway, cost implications from environmental regulations can be divided into two. One implication is rules of compliance, while the other is regulations which have a direct impact on operational costs.

MARPOL 73/78 Annex VI and the Montreal Protocol are regulations with regards to compliance. These regulations put ship-owners under strict regulation which incur large indirect costs. This thesis disregards other options to reducing emissions than converting to LNG as a fuel.

The NO_x tax and indirectly the Kyoto Protocol and Gothenburg Protocol, have an impact on operational costs.

The NO_x tax implies either a cost of NOK 4,00 per kg NO_x emitted if an enterprise has signed the Environmental Agreement or a cost of NOK 16,14 per kg NO_x emitted if the agreement is not signed. In this analysis, all enterprises are expected to have signed the Environmental Agreement.

The Kyoto Protocol and Gothenburg Protocol have only an indirect impact on cost, as the Norwegian Government has decided to tax marine fuels as a result of these environmental agreements. The taxes mentioned below are added directly to the bunkers price, but refunded if the company purchasing the fuel is exempted from the tax. All of the three segments used in this analysis are exempted from the base tax.

Tax	Price	Unit
CO_2 tax	0,58	NOK/liter
Base tax	0,886	NOK/liter
Sulfur tax	0,075	NOK/0,25 % of sulfur in each liter

Table 17: Taxes related to fuels in Norway

To achieve correct price data, CO_2-, base- and sulfur tax are all included in the fuel price analysis and not included as tax due to emissions. Only the cost of the NO_x tax must be added to a ship's costs according to its NO_x emissions. As the fund is expected to only continue for five more years, only NO_x tax for the next five years will be added.

11. Capital expenditure

Chapter 2 has shown that capital cost related to the purchase of a vessel is the largest cost component of the shipping cost structure. An understanding of LNG engine technology was established in chapter 6, presenting the additional costs related to the LNG propulsion system.

This study regards engine costs to be the primary factor influencing capital expenditure. This is why all other factors having impact on capital values besides engine costs are considered similar between the different propulsion systems.

$C_{CapEx,}$ capital expenditure, is computed by taking a representative engine cost for each vessel with incumbent technology and multiply these costs with a factor representing a cost premium for LNG engine technology. Engine costs are dependent on installed engine power, as well as engine system, e.g. there is a difference in costs between gas-mechanical and gas-electric systems.

The investment costs related to conventional vessels are based on quite reliable and representative market information from shipping companies, while the premium is based on information from engine suppliers and experience from existing LNG-vessels. Since this analysis is also considering a segment (bulk carrier) that has not seen LNG-propulsion in practice yet, it is only possible to rely on feasible cost estimates.

12. Operational expenditure

Operating costs are costs related to cost items such as manning, maintenance or insurance as shown in chapter 2. Manning costs are the largest cost component of operating costs. This analysis is based on operation in the Norwegian short-sea market and therefore it can be assumed that manning costs are fairly similar between different shipping companies. Since it is further assumed that LNG-propulsion requires no special knowledge or training of the crew, manning costs are set equal in the analysis and do not influence cost difference between different propulsion systems of the vessels.

Regarding repairs and periodic maintenance, it seems that lifetime of LNG-engines is longer than the one of conventional engines (P. M. Einang, The Norwegian LNG Ferry 2000). A reason for this might be that LNG does not contain any sulfur, avoiding the corrosive effect of this substance on the machinery. Nevertheless, there is limited experience with LNG-engines in different segments and this analysis does not consider or quantify cost differences regarding repair and maintenance related to LNG engines.

Since manning and maintenance are the major specific cost items of operational costs, the analysis assumes further equality between all other factors influencing operational expenditure.

PART III

Results

This part will present the results of the economic evaluation for the segments analyzed. The results are resolved to obtain a better understanding of the practical implications related to LNG as a fuel for ships. First, costs will be presented in units per energy equivalent to illustrate the distribution of costs according to engine size. Second, the results will be set into a more practical context by comparing costs in compliance with distance in nautical miles driven.

The results are discussed in light of changing environmental regulation and development of LNG prices before an overall conclusion of the thesis is drawn in the end.

13. Analysis of profitability

As specified in chapter 6, this thesis looks at the economic effect of transferring from conventional fuel (MGO) to LNG as a fuel for vessels in three different segments;

1. Supply shipping
2. Ferries
3. Bulk carrier shipping

In this analysis, the fuel IFO 380 cst. is used only as a reference price to show the effect of regulations, meaning the transfer to other type of fuels than the original IFO 380 cst.. IFO 380 cst. does in no cases, in this analysis, include any environmental taxes. LNG's main competitor is MGO which has a low sulfur level and is compatible with MARPOL Annex VI NO_x Tier III emission regulations. In the different examples the average costs of three different engines with LNG are compared to a 4-stroke engine running on IFO 380 cst. and MGO. Engine size (kW) will impact both fuel consumption and emissions.

13.1. Supply shipping

The following example is illustrative for an average supply ship running 6800[10] hours a year with different engine types and sizes. For the vessel assumed in this analysis, capital expenditure for a LNG-fueled platform supply vessel (PSV) is assumed to be 20%[11] above capital expenditure of a conventional-fueled vessel. Annual operational expenditure is assumed to amount to NOK 24.000.000[12]. Fuel costs are calculated as presented in equation 5, considering installed engine power of 7500 kW for conventional engines and approximately 8200 kW for gas engines. With this engine power, conventional- and LNG-vessels are assumed to have a service speed of 14 and 16 knots respectively.

Figure 24 illustrates expected costs (NOK/MWh) related to supply shipping at different oil price scenarios.

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[10] 6800 hours equals a vessel running 24 hours a day 283 days a year. However, 6800 hr/yr is a theoretical number and each ship operator has to adjust operational hours to match the demand for the services of his fleet.

[11] 12% of additional costs are due to LNG propulsion and 8% are due to larger engine size.

[12] Operational expenditure is based on figures from representative companies in the three segments.

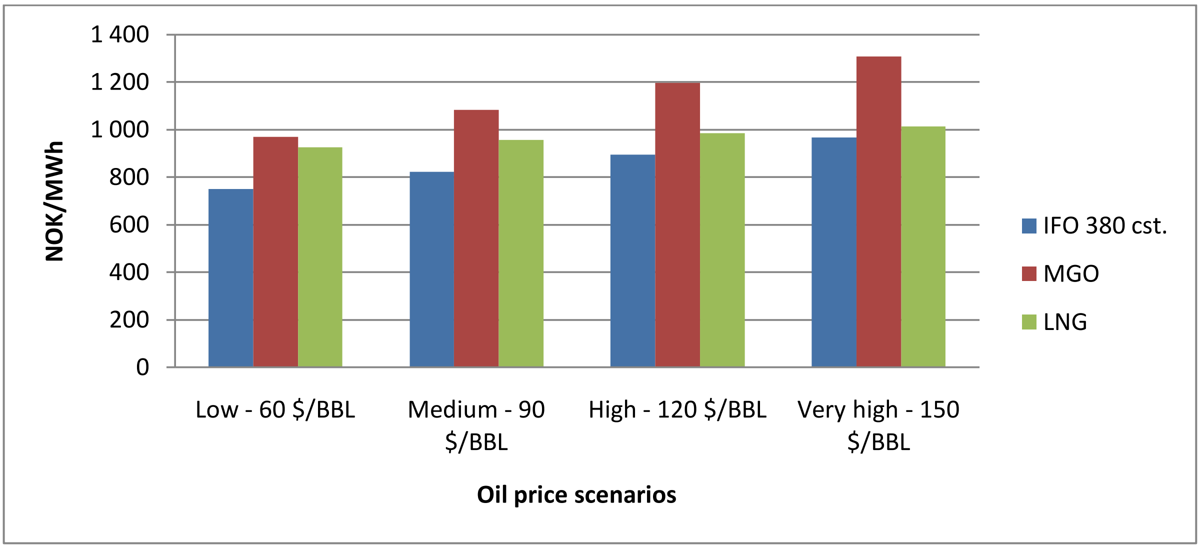

Figure 24: Costs (NOK/MWh) for a PSV

As can be seen, LNG as a fuel compared to MGO is the more cost-effective alternative under all oil price scenarios. The costs of MGO and LNG are fairly similar when the oil price is at 60 USD/bbl, but as the oil price increases, costs related to MGO grow more relative to LNG. This means that a rising oil price will give LNG engines a cost advantage compared to an engine running on MGO under the assumptions taken in this analysis.

In the cases assumed, LNG vessels operate at higher service speed and have the potential to cover more distance during their lifetime. Therefore, it is not only interesting but also practical applicable to look into the differences between LNG and MGO engines for distance (NM) driven.

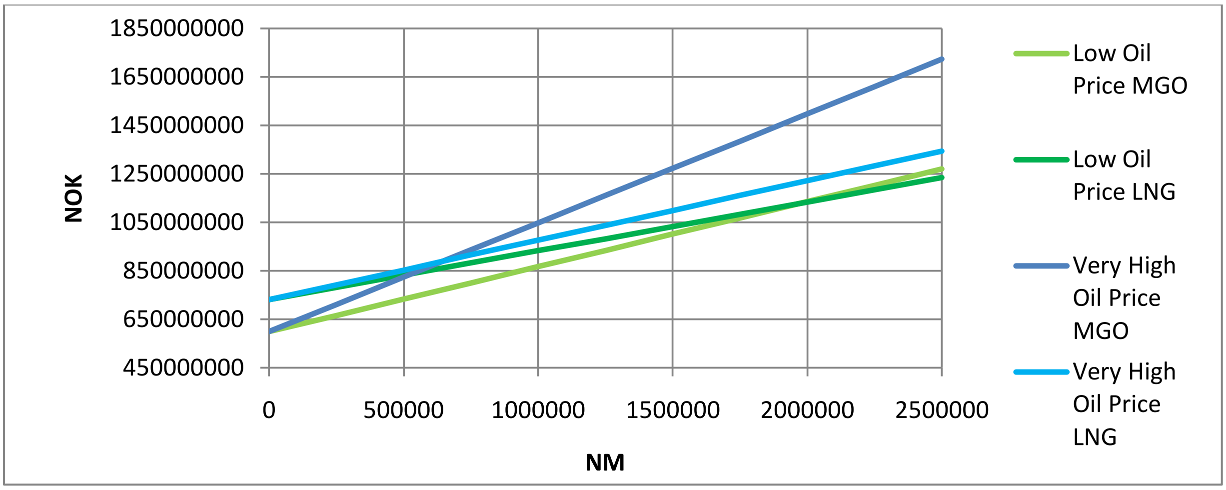

Figure 25: Intersection of costs (NOK) per nautical mile (NM) driven for a PSV

Figure 25 illustrates that under a low oil price scenario a distance of about 2.000.000 nautical miles (NM) has to be covered for higher capital costs related to LNG to be leveled out by lower fuel prices. For very high oil prices this distance changes to about 750.000 NM.

As many offshore supply vessels operate on a twenty-four hours a day basis, with certain endurance, high distances per year are travelled. If one assumes a PSV to be travelling about 100.000 NM per year, LNG propulsion would become cost-competitive to MGO only towards the end of its assumed lifetime, after 20 years of service, if low oil prices prevail. However, under a very high oil price scenario LNG-fueled PSVs would already become cost-competitive after approximately seven years of operation.

Long-lasting business relations are often a focus for many PSV operators and many PSVs are under long-term charter contracts with offshore oil and gas companies. Therefore, investment in LNG propulsion can be seen as a rewarding strategic move if high oil prices can be expected. Moreover, LNG-fueled vessels can contribute to GHG-reduction across the value chain of petroleum companies, which is preferable for the petroleum companies who charter these vessels.

Environmental regulation

An interesting case is the effect of regulations in Norway on the cost-effectiveness of LNG-fueled vessels. Table 19 depicts the cost-effectiveness (NOK/MWh) of LNG in absence of environmental regulation, i.e. taxes on CO_2, NO_x and sulfur, versus present environmental regulation. With no environmental regulation, LNG is not cost-competitive with MGO under low oil prices. Therefore, it can be concluded that environmental regulation is needed to make investment in LNG-fueled PSVs feasible at low oil prices. However, for oil prices above 90 $/bbl, LNG propulsion is a profitable investment in the absence of environmental regulation. Hence, as the oil price increases LNG propulsion becomes increasingly more self-standing.

	No environmental regulation				Environmental regulation			
Oil price	**Low 60 $/bbl**	**Medium 90 $/bbl**	**High 120 $/bbl**	**Very high 150 $/bbl**	**Low 60 $/bbl**	**Medium 90 $/bbl**	**High 120 $/bbl**	**Very high 150 $/bbl**
Fuel Type:								
IFO 380 cst. (NOK/MWh)	750,94	823,38	895,81	968,25	750,94	823,38	895,81	968,25
MGO (NOK/MWh)	911,17	1023,86	1136,55	1249,25	970,71	1083,41	1196,10	1308,79
LNG (NOK/MWh)	926,20	954,76	983,32	1011,88	926,95	955,51	984,07	1012,63

Table 18: Economic impact of environmental regulations for a PSV

Change in the price of LNG

The technology behind LNG fuel solutions is currently at an early stage and further technological developments are expected to make the technology more cost-efficient and environmentally friendly. Currently, the fuel has comparative advantages with regards to its environmental properties, but combustion of LNG does unfortunately release unwanted CO_2 emissions. As the technology matures it could be expected that also LNG would have to comply with a CO_2 tax. If LNG would be inflicted with the same CO_2 tax as MGO, this would still not be enough to make MGO less costly than LNG at a medium oil price (90 $/bbl).

As any increase in environmental taxes would affect MGO in the same way (or more) than LNG, the profitability of LNG is quite “stable” against changes in environmental regulation. Previous comparison between MGO and LNG under different oil price scenarios has shown that LNG has a significant cost-margin to MGO in terms of energy units (MWh). At medium oil prices (90 $/bbl), a 30 %[13] increase in LNG prices is needed to make LNG and MGO equally costly. This gives LNG quiet a huge buffer for how much LNG prices can rise before LNG propulsion becomes unprofitable compared to MGO. Other reasons why the price of LNG could rise are demand- and supply shocks due to shortage of supply or increase in demand beyond the capacities of small scale production plants.

However, the cost-margin to MGO makes LNG prices generally cost-competitive against MGO even if one takes expectations of rising LNG prices and increased environmental taxes into account.

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[13] At an oil price of 90 $/bbl, the cost of LNG amounts to 4,7 NOK/kg. The price for LNG has to rise to 6,8 NOK/kg for the LNG investment to be unprofitable.

13.2. Ferries

For the analysis of the ferry segment, a technology premium of 12% for LNG propulsion is added to investment costs of conventional-fueled vessels. Annual operational expenditure is assumed to amount to NOK 15.000.000. Fuel costs are calculated as presented in equation 5, considering installed engine power of 7500 kW for conventional engines and ca. 12000 kW for gas engines. With this engine power conventional- and LNG vessels are assumed to have a service speed of 14 and 21 knots respectively. Yearly operating hours are set to 6800.

Results are shown in figure 26, summarizing performance of the case ferry in the four oil price scenarios. The results are presented as costs (NOK) per MWh, meaning costs will be distributed according to engine size.

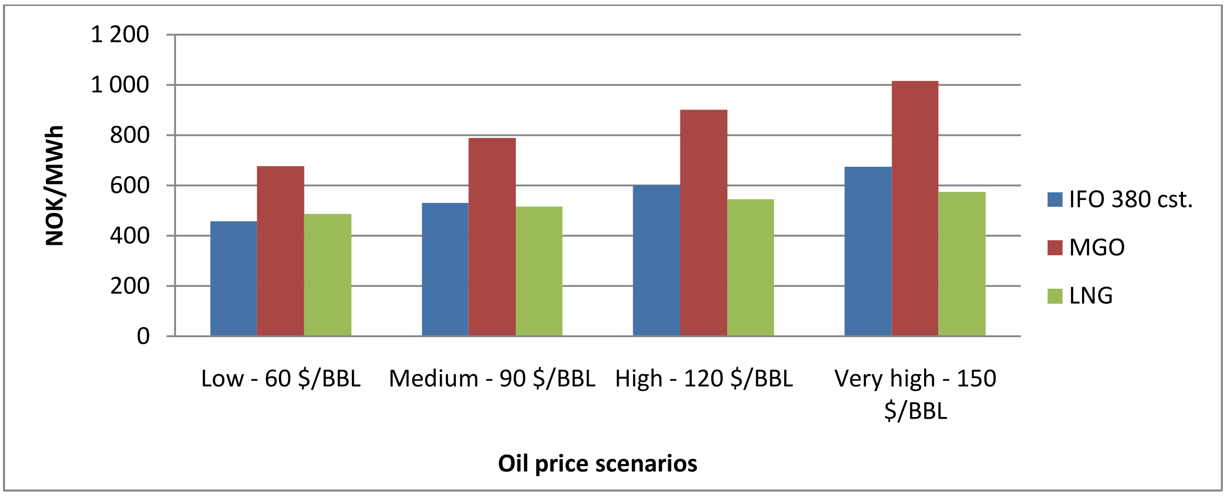

Figure 26: Costs (NOK/MWh) for a ferry

Per MWh, LNG propulsion is the more cost-effective alternative under all oil price scenarios. LNG-fueled vessels are even profitable for oil prices of 60 $/bbl.

As in the case with the supply segment, this analysis also looks at the distance a LNG-fueled vessel has to travel to be cost competitive with MGO. The results are presented in figure 27.

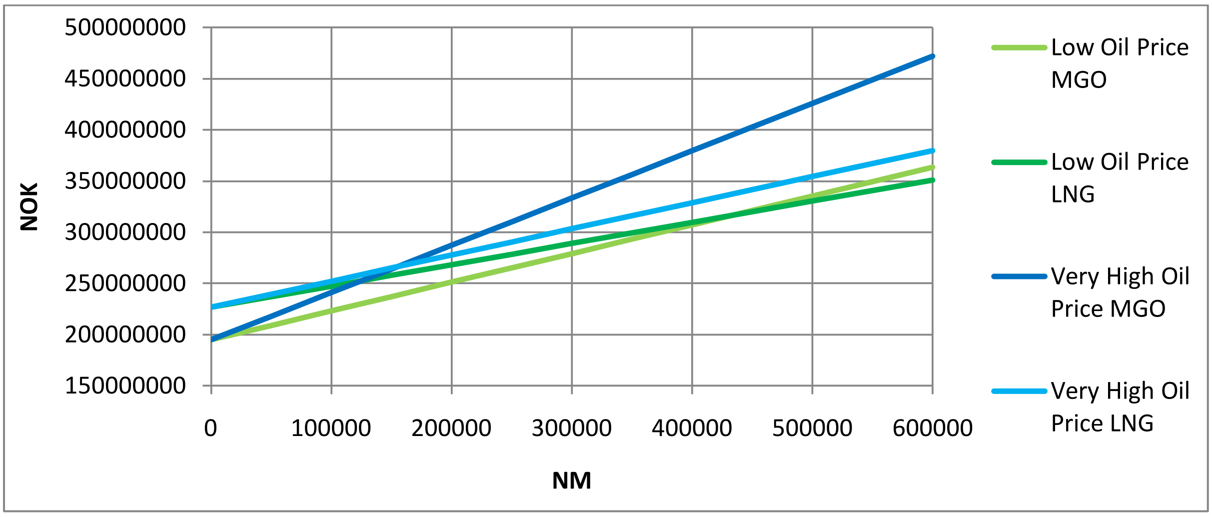

Figure 27: Intersection of costs (NOK) per nautical mile (NM) driven for a PSV

MGO- and LNG-fueled vessels will be equally expensive after approximately 450.000 traveled NM at a low oil price (60 $/bbl) and after ca. 150.000 traveled NM at a very high oil price (150 $/bbl), as illustrated in figure 29. After this, LNG-fueled vessels will be more cost-effective for each NM travelled. In praxis this could mean that a ferry operating a distance of 250 NM, 283 days a year would be profitable after approximately 6 years of operation under the low oil price scenario. LNG propulsion would turn out to be profitable for such a ferry operation after even fewer years in service under a higher oil price scenario. The same is the case for a ferry travelling more NM per day, either through a larger distance between two harbors or through more frequent departures. Hence, it can be concluded that LNG ferries can generally be expected to be a financially rewarding investment.

Nevertheless, LNG propulsion might turn out to be not feasible for ferries operating only short distances and infrequently i.e. travelling a distance less than 150.000 NM during their lifetime in case of the very high oil price scenario.

In Norway it is common for the Ministry of Transport and Communications to put operation licenses on certain ferry route out to tender. The contract period varies, but is usually between 8-15 years. Ferry operators might be influenced by this time horizon when making investment decisions with respect to pay-back periods. In other words, from a risk-strategic point of view the length of the licenses might give ferry operators the needed operational security to invest in a LNG-fueled vessel.

The overall conclusion for the ferry sector is that decision makers have multiple factors to consider when assessing the relative costs of running a LNG ferry. Of particular importance is the distance travelled over the lifetime of the ferry. Under the given assumptions, LNG propulsion has a significant cost margin to MGO propulsion. However, it is not to be expected that LNG ferries will be present at all ferry quays in the near future in Norway. The reason for this is that in especially sparsely populated areas, sailing distance cannot weigh up for the high investment costs related to LNG engines and infrastructure needed. On the other hand it can be expected that LNG ferries will replace older ferries at the most busy and longest routes, contributing to fuel cost-savings and emission reductions.

Environmental regulation

Table 19 illustrates the cost-competitiveness of LNG-fueled ferries in absence of environmental regulation. LNG is cost-competitive even at low oil prices (60 $/bbl) in the case of no environmental regulation. Therefore, environmental regulation is not an as important decision criterion in making investment in LNG-fueled ferries feasible at low oil prices as in the case of the supply segment.

No environmental regulation					**Environmental regulation**			
Oil price	**Low 60 $/bbl**	**Medium 90 $/bbl**	**High 120 $/bbl**	**Very high 150 $/bbl**	**Low 60 $/bbl**	**Medium 90 $/bbl**	**High 120 $/bbl**	**Very high 150 $/bbl**
Fuel Type:								
IFO 380 cst. (NOK/MWh)	456,83	529,26	601,70	674,13	456,83	529,26	601,70	674,13
MGO (NOK/MWh)	617,05	729,74	842,44	955,13	676,60	789,29	901,98	1014,68
LNG (NOK/MWh)	482,97	511,53	540,09	568,65	483,72	512,28	540,84	569,40

Table 19: Economic impact of environmental regulations for a ferry

Change in the price of LNG

The price of LNG might change due to LNG becoming subject to stricter environmental regulation. However, at low oil prices (60 $/bbl), a price increase of more than 40% is needed to make LNG and MGO equally costly. A significant rise in the price of LNG is therefore needed to make LNG unprofitable compared to MGO. Compared to the supply segment, the profitability of LNG-fueled ferries is even more robust against changes in environmental tax exposure.

13.3. Bulk carrier shipping

For the analysis of the bulk segment, an additional ship investment cost of 12% of conventional-fueled vessels for LNG propulsion is assumed (Stenersen, et al. 2010). Annual operational expenditure is assumed to amount to NOK 15.000.000. Fuel costs are calculated as presented in equation 5, considering installed engine power of 1800 kW for conventional engines and 2400 kW for gas engines. With this engine power conventional- and LNG-fueled vessels are assumed to have a service speed of 10 and 14 knots respectively. Yearly operating hours are set to 6800.

Results are shown in figure 28, summarizing performance in Norwegian kroner (NOK) per Megawatt-hour (MWh) of the bulk vessel in the four oil price scenarios. LNG-fueled bulk carriers appear to be cost-competitive to the ones utilizing MGO already for low oil prices of 60 $/bbl.

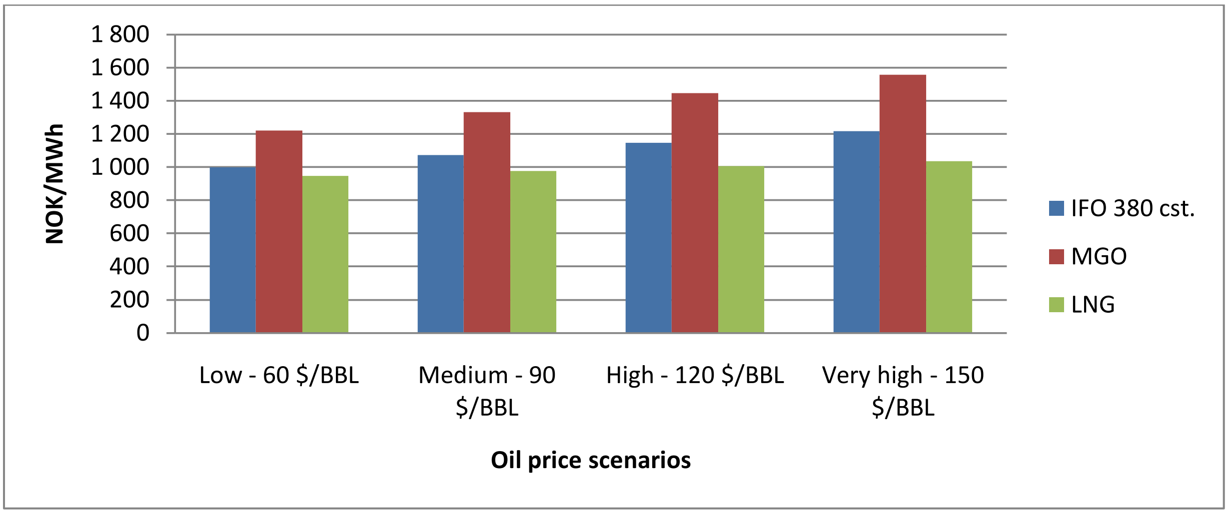

Figure 28: Costs (NOK/MWh) for a bulk carrier

The distance a LNG-fueled bulk carrier has to travel to become cost-equivalent with MGO-fueled bulk carriers is illustrated in figure 29.

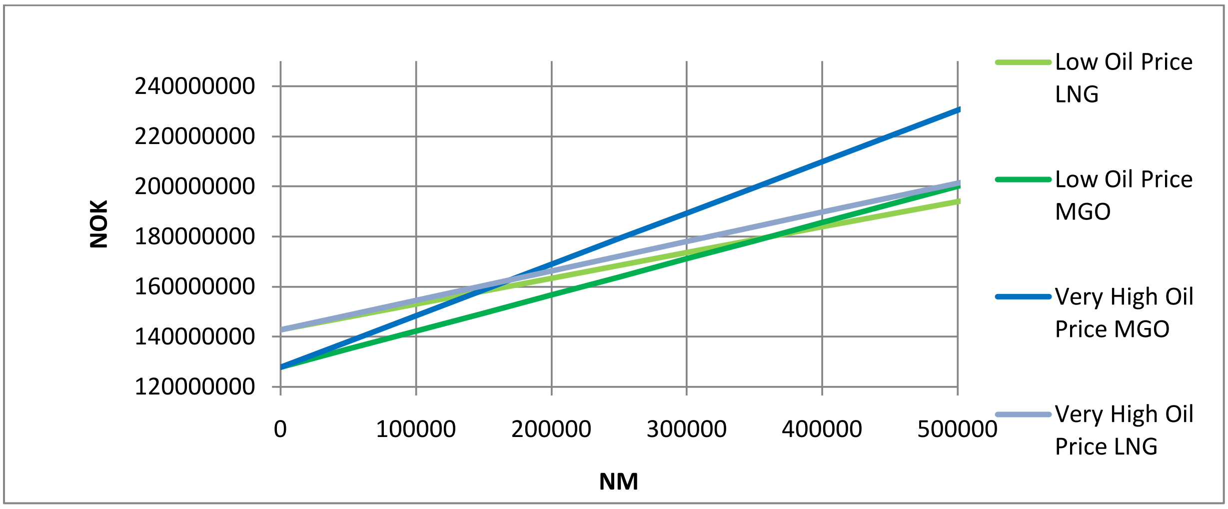

Figure 29: Intersection of costs (NOK) per nautical mile (NM) driven for a bulk carrier

About 400.000 NMs have to be travelled for LNG to be more cost-effective than MGO in terms of distance travelled under the low oil price scenario. Hence, a LNG-fueled bulk carrier travelling 6800 hr/yr at 14 knots would have to be in service for about 4 years to reach cost-equivalence with conventional MGO-fueled vessels.

Environmental regulation

As in with previous segments, the table 20 depicts the cost-effectiveness of LNG in absence of environmental regulation, i.e. taxes on CO_2, NO_x and sulfur, versus present environmental regulation. As LNG is cost-competitive even at low oil prices for the bulk segment, removing environmental costs does not affect LNG's position as the more profitable fuel. The environmental costs for the bulk segment amounts to approximately 60 NOK/MWh and confirms LNG's strong position. Therefore it can be concluded that environmental regulation is not needed to make investment in LNG-fueled bulk carriers less costly than a conventionally-fueled carriers at low oil prices.

	No environmental regulation				Environmental regulation			
Oil price	**Low** **60 $/bbl**	**Medium** **90 $/bbl**	**High** **120 $/bbl**	**Very high** **150 $/bbl**	**Low** **60 $/bbl**	**Medium** **90 $/bbl**	**High** **120 $/bbl**	**Very high** **150 $/bbl**
Fuel Type:								
IFO 380 cst. (NOK/MWh)	994,94	1067,37	1139,81	1212,24	994,94	1067,37	1139,81	1212,24
MGO (NOK/MWh)	1155,16	1267,85	1380,55	1493,24	1214,71	1327,40	1440,09	1552,79
LNG (NOK/MWh)	943,57	972,13	1000,69	1029,25	944,32	972,88	1001,44	1030,00

Table 20: Economic impact of environmental regulations for a bulk carrier

Change in the price of LNG

Any change in LNG prices, either from environmental taxes or increases in LNG costs, would have to be very large to defend building a conventionally-fueled bulk carrier under the assumptions taken. An increase in the price of LNG of more than 50% is needed to make LNG and MGO equally costly under a low oil price scenario.

14. Conclusion

LNG as a fuel for ships in the Norwegian short-sea market has proven to be an environmentally friendly and cost-competitive alternative to MGO for all segments analyzed.

The results of this analysis have shown that under current environmental regulation and under the assumptions taken, LNG becomes evidently the more cost efficient alternative for PSVs when oil prices move to around 90 USD/bbl in the long run. For the ferry segment, LNG is cost efficient at an oil price of 60 USD/bbl, as well as in the case for bulk carriers.

How the different sectors will adapt to LNG propulsion technology is difficult to predict. Under the prospects of raising oil prices it can be expected that more LNG-fueled PSVs will be built in the future. The offshore oil and gas industry has traditionally been embracing technology advancements and the possibility to reduce emissions in the oil- and gas value chain contributes further to making LNG-fueled PSVs a feasible investment.

It can also be expected that the LNG-fueled ferry fleet will continue to grow in the future, especially for vessels serving frequent and long sailing distances. The analysis has shown that LNG propulsion for ferries is generally a very cost-competitive alternative since higher investment costs related to MGO can be justified by lower voyage costs already after few years of operation. In addition, ferries have the most regular sailing pattern of all segments analyzed, allowing regular bunkering.

Even though LNG-fueled bulk carriers have shown to be a cost-efficient alternative, the adaptation of LNG technology in this segment is presently weaker than in the other ones. The reason for this is bulk carriers having usually a more irregular sailing pattern, making frequent bunkering more challenging under the present distribution infrastructure. However, with expectations of a growing LNG infrastructure, also LNG-fueled bulk carriers might become prominent.

As this study sets annual operational hours equal for all vessels, operational implications of high-powered higher-speed LNG ships are disregarded. It is beyond the scope of this study to discuss the corporate and socio-economic consequences of operating at higher speeds through LNG propulsion.

Regarding the opening question if LNG is the key to environmental challenges in shipping, this thesis has shown that LNG as a ship’s fuel has superior environmental properties compared to conventional fuels. Although this study concludes that LNG is foremost not dependent on environmental taxation to be cost-competitive with its alternatives, environmental advantages of LNG as an alternative fuel can still be seen as a fundamental driver. Environmental awareness and emission control regulation systems have triggered innovations making shipping more environmental friendly. Today there exist a variety of ship designs demonstrating more environmental sustainable shipping, and it seems that ship operators in general are positive towards greening of the industry. However, the Norwegian short-sea shipping sector is generally characterized by many small actors not necessarily having the financial capacity of making large investments in a renewed and environmentally-sound fleet. This might be a reason for LNG-fueled vessel not being more widespread in light of both environmental properties and cost-efficiency recognized in this thesis.

Other main factors regarding the viability and feasibility of LNG as a ship’s fuel is the importance of supply and distribution, as well as the development of the price of LNG. Security of supply and sufficient bunkering possibilities will therefore have a large impact on the investment decision regarding the purchase of a LNG-fueled vessel. Furthermore, with only few and small distributers of LNG in Norway at the moment, prices for LNG have shown to be neither transparent nor can these be assumed to be based on perfect competition. The price of LNG could therefore currently be higher than computed in the analysis. However, as the market for small scale LNG matures, more suppliers are expected to enter the market and a market with decreasing prices might come forward.

As a final word it may be concluded from this thesis that value aside economic profitability can be assigned to LNG as a ship’s fuel. LNG-fueled ships can contribute to mitigating climate change and help meeting national and international emission targets. The Norwegian Government has a relatively high interest in being at the forefront in making efforts to reduce GHG-emissions. Therefore, LNG-fueled vessels are a key in successful management towards more sustainable means of Norwegian short-sea shipping.

Proposal of further studies of this topic

LNG ships for the Norwegian short sea shipping market have shown to be a cost-effective investment under present regulation for medium high oil prices of about 90 $/bbl. A suggested further study of this topic is therefore to analyze deep-sea shipping. Deep-sea shipping will on the one hand have the possibility to bunker LNG at major terminals near large consuming regions and the price for LNG might therefore be less as assumed in this study. On the other hand, deep-sea shipping might rely on larger fuel tanks and DF-engines to be able to travel with long endurance without being dependent on frequent refueling. It would be interesting to see if possibly larger investment costs related to deep-sea LNG technology could justify lower fuel costs.

Regarding environmental regulation, this analysis focuses mainly on the comparison between MGO and LNG, as cheaper IFO 380 may not be feasible in the Baltic/North Sea after 2016. If IFO 380 cst. became feasible, then the competitiveness of IFO 380 cst. with a low sulfur content would depend on the development and price of scrubbers and SCR's. The development and the effect of these cleaning systems will have an impact on the shipping sector, opening up for new possibilities within the maritime cluster.

Low sulfur IFO or other non-conventional fuels (e.g. renewable energy sources) could be competitors to LNG, but currently MGO is the closest. Figures in this thesis suggest that LNG is a preferable step to take, with regards to the environment and economy, before shipping moves on to even cleaner fuels, such as bio-fuels. The total effect and potential of non-conventionals within shipping could also be subject to further analysis.

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Appendices

Abbreviations

A - Argon

ASE - Average specific emissions

bbl - barrel

Btu - British thermal unit

bcm - Billion cubic metres

CFC - Chlorofluorocarbons

CNG - Compressed Natural Gas

CO_1 - Methane

CO_2 - Carbon Dioxide

CO_3 - Propane

cst - Centistokes (viscosity)

DF - Dual Fuel

EU - European Union

gt - gross ton

H_1S - Hydrogen sulfide

He - Helium

HCF - Hydrochlorofluorocarbons

HFC - Hydrofluorocarbon

HFO - Heavy Fuel Oil

IMO - International Maritime Organization

ISO - International Organization for Standardization

J - Joules

kWh - Kilowatt hour

LNG - Liquefied Natural Gas

MDO - Marine Diesel Oil

MGO - Marine Gas Oil

MM Btu - 1 million Btu

MT - Metric ton

MWh - Megawatt hour

Ne - Nitrogen

NG - Natural Gas

NM - Nautical Mile

NOx - Nitrogen Oxides

NPV - Net Present Value

o.e. - Oil Equivalents

PM - Particulate Matter

PSV - Platform Supply Vessel

RPM - Revolutions Per Minute

SECA - Sulfur Emission Control Area

SFC - Specific Fuel Consumption

SO_2 - Sulfur Dioxide

SO_x - Sulfur Oxides

Tcm - Trillion cubic metres

USA - United States of America

VOCs - Volatile Organic Compounds

Conversion factors

Table of conversions
1 MT LNG is equal to:
49500 kJ
51,8135 MMBtu
2,17 m^3 LNG
1 m^3 LNG is equal to:
0,46 MT LNG
23,9 MMBtu LNG
1 m^3 natural gas is equal to:
35540 kJ
0,770 kg LNG
1 MT Brent crude oil is equal to:
7,5 bbl
1192,4 liter
Other energy equivalents:
1 MMBtu = 293 kWh
1 kWh = 3600 kJ = 3412 Btu

Table 21: Table of conversions