Liquefied Natural Gas

An Alternative Fuel for Volvo Penta?

Master's thesis in Product Development

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Gothenburg, Sweden 2014

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Cover: The Volvo Penta Logotype

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Preface

This master thesis was performed at the department of Product Management, Marine Commercial at Volvo Penta in Gothenburg, Sweden during the autumn semester of 2014. The thesis was made in collaboration with the Product and Production Development department at Chalmers University of Technology in Gothenburg, Sweden.

The thesis gives a brief overview of Liquefied Natural Gas and how it can be used as a fuel by Volvo Penta. The report is divided into a theoretical part and a results part which later is discussed to finally end up in some conclusions.

I would like to thank my supervisor Hans Johannesson at Chalmers Uni. for his guidance and help regarding structure and approach. I would also like to express my gratitude to my supervisor Björn Säljö at Volvo Penta, for all his guidance regarding limitations and procedure. Furthermore I would also like to thank everyone that spent time and helped me.

Fredrik Danielsson
Gothenburg, Sweden, December 2014

List of Abbreviations

LNG – Liquefied Natural Gas

CNG – Compressed Natural Gas

MDO – Marine Diesel Oil

MGO – Marine Gas Oil

HFO – Heavy Fuel Oil

IMO – International Maritime Organization

EPA – Environmental Protection Agency (US)

USCG – United States Coast Guard

ECA – Emission Controlled Area

SECA – Sulfur Emission Controlled Area

NECA – NO_x Emission Controlled Area

SCR – Selective Catalytic Reduction

EGR – Exhaust Gas Recirculation

DPF – Diesel Particulate Filter

NRMM – Non-Road Mobile Machinery

IWV – Inland Waterway Vessel

SI – Spark-Ignited

HPDI – High Pressure Direct Injection

DF – Dual Fuel

GHG – Green House Gases

TTS – Truck to Ship (Bunkering procedure)

PTS – Shore/Pipeline to Ship (Bunkering procedure)

STS – Ship to Ship (Bunkering procedure)

TCO – Total Cost of Ownership

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Abstract

Liquefied Natural Gas (LNG) has been used as a marine fuel on LNG cargo ships for a long while. But the usage area is growing, and it is at the date of this report approximately 100 vessels (excluding LNG cargo ships) worldwide that either are planned or already operates on LNG. Volvo Penta is a marine engine manufacturer and is interested in how this will impact their business. The aim of this thesis is therefore to investigate the possibilities and challenges for Volvo Penta to enter this market. This is mainly done by trying to find the driving factors for LNG, as well as map the competition.

The investigation is based on several literature studies and interviews with people from both inside and outside Volvo Penta. The theory chapter is presenting basic information about LNG, regulations, and today's market and technology. This is later summed up in the result chapter, and further discussed in the discussion chapter.

The major conclusion that came out of this study is that current and future LNG vessels are bigger and outside of Volvo Penta's propulsion range. But, it consequently means that Volvo Penta can find a possible market opening in terms of developing a LNG engine suited for auxiliary and genset usage on those vessels. It is also of interest to further investigate the possibilities of developing a propulsion LNG engine for inland waterways. The optimal solution seems to be one LNG engine for both purposes, and perhaps even in collaboration with Volvo Group.

Keywords: Liquefied Natural Gas, LNG

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Introduction

This thesis is aimed to be a study of Volvo Penta's possibilities to enter the Liquefied Natural Gas (LNG) market for marine commercial used engines. The LNG industry has been growing rapidly for the past 20 years (Baily & Lidgate, 2014), and are projected to continually grow with 10% per year in the upcoming 10 years (Kumar, o.a., 2011). LNG on marine applications is not excluded. Det Norske Veritas (DNV GL (b), 2014) expects LNG to grow as a fuel on "relatively small ships" in the upcoming 5-10 years, where LNG is available for bunkering. LNG will then replace HFO on larger ships, when the availability of LNG as a bunker fuel is increased.

Volvo Penta, as a marine engine manufacturer is interested in how this will impact their businesses.

Company background

Volvo Penta is a global company with a presence in more than 130 countries. The company develops, manufactures and markets complete power systems for marine and industrial applications. Volvo Penta is a part of Volvo Group and accounts for approximately 3% (in 2013) of Volvo Group's total net sales (273 billion SEK (Volvo Group, 2014)). Volvo Penta's sales are shared approximately 50-50 between industrial and marine.

Volvo Penta has a firm presence in the marine leisure segment but is a rather small actor in the marine commercial segment. This is mostly due to historical reasons, since the company has always been focusing on a greater presence in the marine leisure segment. Volvo Penta used to have two product management departments, one dedicated to marine products, and one committed to industry products. They have since 2012 separated the product management marine department into two segments though, one is product management marine leisure, and the other is product management marine commercial. That latter is where at this thesis is written. This separation was made to enable a better focus on marine commercial products, since the belief is that Volvo Penta can gain a better market share within marine commercial applications.

Volvo Penta's marine commercial applications, i.e. auxiliary engines (aux), marine diesel generators (genset) and propulsion power systems are ranging from 77–588 kW, with engine sizes between 2.4 and 16.1 liters.

The company has approximately 1400 employees, and their head quarter is located in Gothenburg, Sweden. Gothenburg is also the place where all the development work for the diesel engines is located. All Volvo Penta plants are listed below.

- Gothenburg, Sweden. Volvo Penta head-quarter. Development and manufacturing marine diesel engines.
- Vara, Sweden. Manufacturing marine diesel engines.
- Skövde, Sweden. Manufacturing industrial and marine diesel engines.
- Köping, Sweden. Manufacturing IPS-units.
- Chesapeake, VA, USA. Developing marine gasoline engines.
- Lexington, TN, USA. Manufacturing marine gasoline engines.
- Lingang, China. Manufacturing industrial and marine diesel engines.
- Lyon, France. Manufacturing industrial and marine diesel engines.

This section is based on internal documents from Volvo Penta.

Purpose

The purpose of this thesis will be to investigate if LNG can be used as an appropriate alternative fuel to more conventional fuels, like diesel and gasoline for Volvo Penta's marine commercial applications. The study is done at the department of product management, marine commercial. The head of the department, Björn Säljö, who also has supervised this thesis wants this study to be done to find out if Volvo Penta should or should not consider LNG for marine propulsion motors, marine auxiliary motors or for both kinds of applications. The aim is to find the driving factors that make a marine commercial customer to choose LNG as a marine fuel, and to put this in relation to the usage of conventional marine fuel. It should also be investigated how LNG engines best can be introduced to the market, e.g. if it is only suited for new-built vessels or if it is appropriate for retrofit as well.

The study should be done by investigating the questions above with a time perspective of 5-10 years in mind.

Question

How should Volvo Penta approach the LNG-market within the marine commercial segment?

Limitations

Limitations are crucial in this kind of investigations; the scope can otherwise be too wide and complex. It is therefore decided to stay within certain limits. The thesis is made as a market analysis and will focus on finding the potential driving factors for LNG as a marine fuel, from a customer perspective.

The technology for the LNG combustion process already exists, and it is assumed to be possible to implement it in Volvo Penta's products even if it requires some development work before it can be used. What needs to be considered at this point though is what kind of combustion process that suits best, e.g. a 100% gas or a dual fuel engine, lean or stoichiometric combustion etc. It is also of interest to investigate if this should be done at Volvo Penta, or if a third part company can be of use. It is also not known how the LNG-tanks together with piping systems will fit on a vessel powered by Volvo Penta. This is because the size of the LNG-tanks requires a bigger space than the conventional diesel tanks, if the same amount of energy should be maintained. This can be a factor that affects the customer's decision, whether to go with LNG or not, and will therefore be included in the thesis.

The thesis will not further investigate the processes of extraction of LNG, but will just present a brief background about natural gas and where it can be found. This should be compared with the conventional fuels, to let the reader obtain a good overview about natural gas. The bunkering process will as well as the extraction process be omitted.

An important aspect to be aware of if a LNG-engine is introduced, is how Volvo Penta should approach the aftermarket questions, e.g. service intervals, product life length and dealer network. This is a major question, but will not be reflected upon in this thesis, because of the time limit. But it is also because this is more naturally suited as a proceeding stage.

The aim of the thesis is, as written above, to find the driving factors that make a customer to invest in a LNG-engine rather than a conventional diesel engine. The thesis will consequently dig deeper into areas that can be perceived as driving factors. One of them is the infrastructure of LNG-bunkering stations, which needs to be mapped.

Volvo Penta is obviously competing with other marine engine companies and it is therefore of importance to monitor their strategic moves and understand how they are approaching the markets of alternative fuels. This kind of competitor analysis should be included in this thesis as well.

The thesis will also explore what kind of emission and safety regulations that needs to be considered today, as well as in the future. This could also be a major driving factor for using LNG, as an alternative to diesel.

It is also of interest to investigate the current and future volume of LNG powered ships and vessels. Even if many boats are outside of Volvo Penta's propulsion range, it can still be of interest for the auxiliary engines. It is therefore important to make a careful market analysis.

What the thesis should consider:

- Infrastructure of LNG-terminals
- Competitors
- Emission regulation
- Safety regulations
- Efficiency
- Dual fuel
- Some technical aspects (background info)
- Market analysis of volume

Hypotheses

Volvo Penta's current idea about how LNG can be used for their marine engines is only based on an internal feeling. Volvo Penta feels that the size of their engines is too small and that LNG is better suited for bigger ships and vessels. One reason for this is because the LNG-tanks require more room than the conventional fuel tanks. This argument applies only for propulsion engines, and not for auxiliary used engines, since those can be used in bigger vessels where more space is available.

Method

This thesis started out with several literature studies to obtain a solid perception about what LNG as a marine fuel really means. Most of the used literatures were articles found at the Chalmers library *summon* database as well as on Google's *scholar* service. Books and previous student theses at Chalmers library were also of use to gain knowledge about LNG. These studies required attention since it is important to screen all the available information and find the most usable parts of it. The screening was even more important when the information derived from companies within the fuel business since it tends to be written from a biased point of view. This part has been a major share of the thesis.

The next step in the knowledge gathering stage was to find out information about the current and future regulations of emissions and safety, which plays a major role when deciding if LNG could be of interest for Volvo Penta or not. Most of this information is available online at the respective agencies, but this information needs to be interpreted in a correct manner to make any sense. Volvo Penta's department of laws and regulation was therefore a good source to help out with this. Hence, the meetings with them were very useful for this kind of knowledge.

Meetings with various people from Volvo Group have overall been a good source of information. Both for information about technical knowledge but also regarding how Volvo Penta, and Volvo Group plan to approach the alternative fuel market. Some of this information should be kept in-house at Volvo and are therefore not presented in the published version of this thesis. Some sources are presented as "(internal)", which obviously means that the information derives from in-house. Selected numbers are changed to arbitrary numbers in the published report, which is due to the same reason above.

A LCA-analysis for marine fuels has been used as a base. This has been used to enable a comparison of the total impact on the environment measured in greenhouse gases (GHG).

A total cost of ownership (TCO) analyze has been conducted, to make an economical comparison between LNG and distillate fuel (marine diesel oil (MDO) / marine gas oil (MGO)). The TCO is based on numbers in the *frame of reference* chapter. The analysis is coarse, and should not be interpreted as anything else than just an indication. This is due to several reasons, e.g. that it is difficult to predict a price of, at the moment, a non-existing LNG engine, but also because the analysis spans over several thousands of running hours (4000 and 16000 respectively).

The result is also containing several alternatives of combustion methods, which is analyzed and presented in advantages and disadvantages. Appropriate methods are connected with suitable types of vessels.

Frame of Reference

This chapter is aimed to be a base of knowledge. The information in this chapter is later used to establish a result. Some very basic knowledge is assumed to be generally recognized by the reader of this report.

Marine Fuels

Liquefied Natural Gas (LNG) is an alternative fuel to diesel and gasoline. LNG can also be described as liquefied methane, since LNG consists of 85-99% methane (Energigas Sverige, 2014). LNG is made of natural gas which is cooled down to approximately minus 162 °C and stored in cryogenic tanks. Minus 162 °C is right below the boiling temperature of natural gas. It requires about 10-20% of the natural gas's initial energy content to cool it down. This percentage depends on the gas's original quality and the liquefaction plant's size and process, (ACSF, 2012). The liquefied gas is reduced in volume by an approximate ratio of 618 (Drewry Maritime Reasearch, 2012). This could be compared with Compressed Natural Gas (CNG) which is reduced by a ratio of 200-250 (AFDC, 2013). Hence, LNG requires about 40% of the space needed for CNG at 250 bars, and is accordingly a more appropriate solution where space is limited. A disadvantage is that LNG storage system usually is more expensive than a CNG storage system (ACSF, 2012).

TABLE 1. THE NUMBERS ARE CONVERTED TO METRIC UNITS AND DERIVES FROM AMERICAN CLEAN SKIES FOUNDATION (ACSF, 2012).

Fuel	Lower Heating Value	Higher Heating Value
CNG	47.143 MJ/kg	52.225 MJ/kg
LNG	20.847 MJ/liter	23.665 MJ/lit
Gasoline	32.389 MJ/liter	34.691 MJ/lit
Marine distillate fuel	35.838 MJ/liter	38.329 MJ/lit

Table 1 shows the heating values for four different fuels. The values for CNG need to be translated to kJ/volume to enable an easier comparison to the other fuels. The density of CNG is 0.21 kg/liter at 250 bars (Unitrove, 2014), which gives 0.21*47143≈9900 kJ/liter. This is one reason why LNG is more attractive than CNG when storage space is limited. The numbers above are very dependent on the gas's composition and temperature and should consequently be observed carefully. One can easily point out though, that the marine distillate fuel (also known as marine diesel oil (MDO) or marine gas oil (MGO) depending on e.g. sulfur content) contains more energy per volume unit than both LNG and CNG.

According to (ACSF, 2012), "One million Btu (British thermal unit) is equivalent to approximately 7.3 gallons of marine distillate fuel" and "one million Btu is equivalent to approximately 13 gallons of LNG". This gives a comparable value, Diesel Gallon Equivalent (DGE) at $\frac{13}{7.3} \approx 1.78$, which means that it requires 1.78 volume units of LNG to correspond to 1 volume unit of diesel. If the thermal insulation for the LNG tanks is added, Herdzik (2012) says that the required LNG tanks size ought to be 2-3 times bigger than MDO/MGO tanks if the same energy content should be maintained. This is, according to (Sweco, 2009) not enough. This source claims that the required size is about 3-4 times bigger than conventional oil. This can however be seen as a major drawback with LNG. This is also confirmed in IMOs study about GHG, "However, the bulky pressure storage tank requires a large space, and the actual volume requirement is in the range of three times that of diesel oil." (International Maritime Organization, 2009)

Natural gas consists primarily of methane, about 90% (in Sweden), where the rest 10% manly consists of other hydrocarbons (biogas.se, 2011). The percentages can vary in different regions, with a methane ratio between 87-97% (UnionGas, 2014). The methane percentage impacts the quality of the gas, which in turn impacts the combustion process.

A disadvantage with LNG is that it cannot practically be stored on vessels for a long time, since it needs to be kept at a very low temperature. What happens with the liquefied gas after a while is that the gas starts to evaporate, which consequently means that the gas needs to be released to the air by some kind of venting system to maintain the pressure and temperature inside the tank (ACSF, 2012). The common term for the released gas is "boil-off gas" (Drewry Maritime Reasearch, 2012). The boil-off gas is often used as fuel on LNG-carries, which obviously is better than just releasing it to the atmosphere, since 1 kg of methane gas, is equivalent to 21 kg of CO_2 gas (Naturvårdsverket, 2010).

Natural gas has a density of about 0.7-0.8 kg/m^3 (Drewry Maritime Reasearch, 2012). The density of air at atmospheric pressure and 20˚C is 1.205 kg/m^3 (The Engineering Toolbox, 2014). This obviously shows that natural gas is lighter than air, which consequently means that in case of a leakage in the LNG system, the natural gas will just rise into the atmosphere and not stay at the boats deck. This is different compared to e.g. propane, which has a density of 1.882 kg/m^3 (The Engineering Toolbox, 2014) and are therefore heavier than air.

It is possible to convert from diesel propulsion to LNG propulsion, but it is not as relevant as new-buildings both because of the engine conversion itself, but also because of the allocation of the bigger fuel tanks that are required for LNG (International Maritime Organization, 2009).

Classification societies

A classification society is an organization that is developing standards for ship and vessel construction. The organizations are non-governmental. There exist several classification societies all over the world. Some of the biggest and most recognized are presented below.

- DNV GL – Det Norske Veritas & Germanisher Lloyd. The two organizations merged into DNV GL in 2013.
- Lloyd's Register
- American Bureau of Shipping (ABS)
- Bureau Veritas

Most of the LNG vessels today have been classified by DNV GL (Svensen T. E., 2010).

Emissions

A major benefit with LNG is its low emissions. The small amount of sulfur that exists in natural gas is removed during the liquefaction which accordingly means that no SO_2 emissions are released when LNG is burned (Brett, 2008). The nitrogen oxides (NO_x) emissions are reduced by 85- 90% (this is dependent on the combustion method) compared to the more conventional marine fuels, this is because of lower peak temperatures in the combustion process (International Maritime Organization, 2009). CO_2 is reduced by 20-25% and PM is also reduced to almost zero emissions (Svensen T. E., 2010). A drawback with LNG is unburned methane (CH_4) which is just released in the exhaust gas. This phenomenon is called methane slip. Methane emissions make the net global warming to sum up to approximately 15%, instead of 25% (International Maritime Organization, 2009).

LNG will be a beneficial fuel to use in future IMO Tier III areas (IMO Tier III will apply in 2016) since some LNG-engines (depending on combustion method) will not need any after treatment of the exhaust gas to pass the legislation. (International Maritime Organization, 2009)

(Svensen T. E., 2010) is also presenting a comparison case where a 547 TEU container vessel (5000 GT) with a propulsion power of 3960 kW is powered by LNG and low-sulfur HFO (LS380 with 1% sulfur) respectively. The emissions are presented in a table, which also is shown below in

Table 2.

TABLE 2 YEARLY EMISSIONS, TONS/YEAR. THE NUMBERS APPLIES TO A 547 TEU CONTAINER VESSEL (5000 GT), 3960 KW. (SVENSEN T. E., 2010)

	SO_x	NO_x	CO_2	Particle emissions
LNG	0	31	5500	0
Low-sulfur	50	180	7250	4

Other ways to reach the Tier III limits for NO_x-levels is to use a selective catalytic reduction (SCR), which is a treatment of the exhaust gas. It is also possible to adjust the inlet air, by using (either cooled or non-cooled) Exhaust Gas Recirculation (EGR), which sends back parts of the exhaust air to the charge air. This is made to reduce the oxygen level and hence the combustion temperature. (International Maritime Organization, 2009).

The SO_x emissions (predominantly SO_2) depend on the sulfur content in the used fuel. To use a fuel with lower sulfur content is therefore a way to reduce the SO_x emissions. It can also be combined with an exhaust gas scrubber system, which aims to clean the exhaust gas from SO_x. A drawback with this kind of system is that it requires energy, approximately 1-2% of the engines maximum continuous power (International Maritime Organization, 2009). Scrubbers are only used in bigger 2-stroke engines where HFO is used. This is not interesting for Volvo Penta, since the company is only producing 4-stroke engines.

The methane slip phenomenon is practically reduced to zero in modern 2-stroke engines, but is still a concern in 4-stroke engines. Further improvements, i.e. less methane slip are although expected even in 4-stroke engines (DNV GL (b), 2014).

Regulations

Emission regulations could as mentioned be a driving factor for using cleaner fuel like LNG instead of conventional diesel fuel. There are various kinds of regulations, made by different organizations, and it is therefore important to understand which regulations that concern the products of Volvo Penta.

International Maritime Organization (IMO)

International Maritime Organization (IMO) is as the name hints about an international organization that deals with maritime questions. IMO is an organization under United Nations (UN). The organization has developed certain regulations about emissions at sea. The regulations that are of interest for Volvo Penta are written in the *International Convention for the Prevention of Pollution from Ships* (MARPOL). The legislation consists of six different annexes, where "Annex VI Prevention of Air Pollution from Ships" is the one that concerns Volvo Penta the most. This document is in turn divided into different regulations, where Regulation 13 controls NO_x emissions and Regulation 14 controls SO_x emissions as well as particulate matter (PM) (DNV, 2009).

Emission control areas (ECA)

The Baltic Sea has since May 19th 2006 been a so called Emission Control Area (ECA). This means that stricter emission regulations are applied to this certain area. More areas has since 2006 been classified as ECAs. The ECAs entail a stricter regulation regarding SO_x or NO_x emissions, or both. The current ECAs and their effective days can be seen in table 3 and figure 1.

TABLE 3 EMISSION CONTROL AREAS (ECA)

Emission Control Areas	
Area and regulated emissions	In Effect From
Baltic Sea (SO_x)	19 May 2006
North Sea (SO_x)	22 Nov 2007
North America (SO_x, NO_x and PM)	1 Aug 2012
United States Caribbean Sea (SO_x, NO_x and PM)	1 Jan 2014

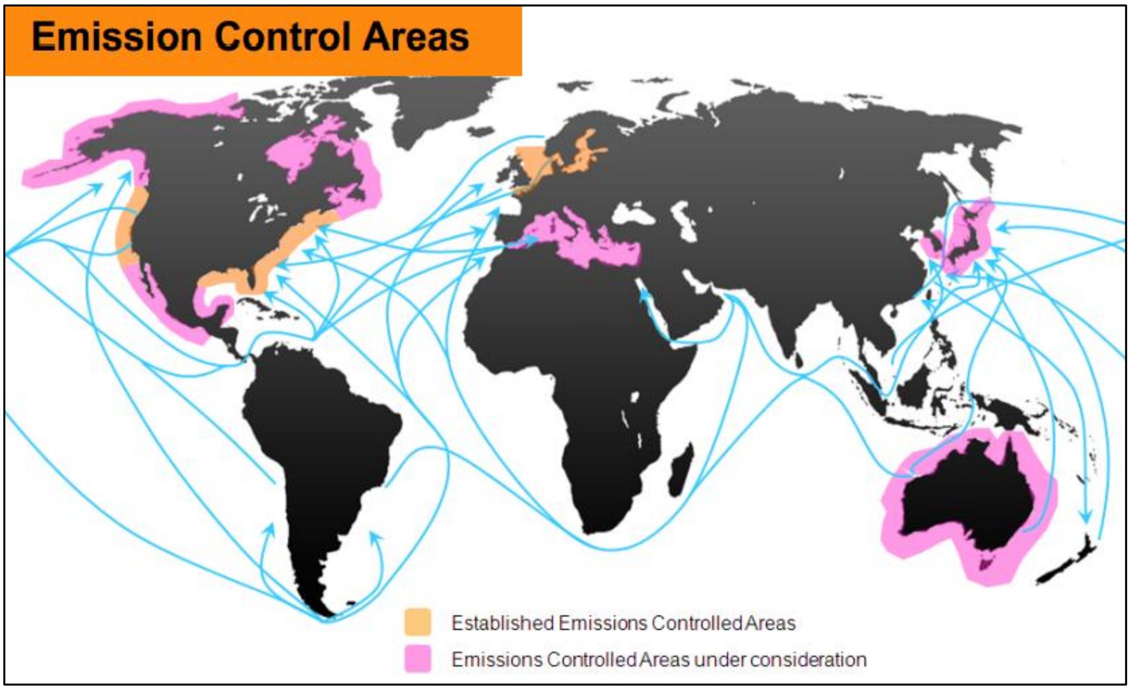


FIGURE 1 EMISSION CONTROL AREAS (ECAS), CURRENT AND AREAS UNDER CONSIDERATION. FIGURE FROM (WÄRTSILÄ, FERRY BUSINESS CASE FOR LNG, 2014).

MARPOL Annex VI – Regulation 13

The first step of NO_x control was introduced by IMO at January 1st 2000. That step is called *Tier I* and applies for diesel engines installed on vessels from the date above.

TABLE 4 IMO TIER I, NO_x EMISSIONS. (N=RPM)

Tier I	
RPM	Allowable NO_x emissions
n < 130	17.0 g/kWh
130 ≤ n < 2000	$45.0 * n^{(-0.2)}$ g/kWh
2000 ≤ n	9.8 g/kWh

The next (and current) step, *Tier II,* was introduced at January 1st 2011.

TABLE 5 TIER II NO_x LEVELS. (N=RPM)

Tier II	
RPM	Allowable NO_x emissions
n < 130	14.4 g/kWh
130 ≤ n < 2000	$44.0 * n^{(-0.23)}$ g/kWh
2000 ≤ n	7.7 g/kWh

The upcoming step of NO_x emission is *Tier III*, which will apply on vessels built after January 1st 2016 and only to vessels operating in North American NO_x Emission Control Areas (NECA). Tier II is applicable outside those areas. Tier III will be applied for other ECAs as well, but the application date is to be decided. It will probably be between 2018 and 2021, according to internal sources. Tier III will be valid for both international and domestic operating vessels, except from in North America, where Tier III only will be valid for international shipping (Laws and regulations (Volvo Penta), 2014), (DNV, 2009).

Table 6 Tier III. (n=rpm)

Tier III	
RPM	Allowable NO_x emissions
n < 130	3.4 g/kWh
130 ≤ n < 2000	$9*n^{(-0.2)}$ g/kWh
2000 ≤ n	2.0 g/kWh

MARPOL Annex VI – Regulation 14

The purpose with this regulation is to control the SO_x and particulate matter (PM) emissions. This will be done by regulating the sulfur content in marine fuel oils. To put this in a relation, see table 7, where some of the most common and most interesting fuels for this study are presented in, together with their respective sulfur content.

Table 7 Data derived from (Verbeek, o.a., 2013) and (LR & UCL, 2014)

Fuel		**Sulfur Content**
MDO	Marine Distillate Oil	< 0.5%
MGO	Marine Gas Oil	0.1%
HFO	Heavy Fuel Oil	< 3.5%
LSHFO	Low Sulfur HFO	< 1.5%
LNG	Liquefied Natural Gas	≈ 0%

The global limits can be seen in table 8 and the limits within the Sulfur Emission Controlled Areas (SECAs) can be seen in table 9 (DNV, 2009). The global limit of 0.5% sulfur in 2020 will be reviewed in 2018. The review will consider low sulfur fuel availability. This regulation could therefore be postponed to 2025. EU has decided to adapt the regulation in 2020 though, independently of IMOs decision (Würsig, 2014).

Table 8 Global SO_x limits (m/m = mass percentage)

Global sulfur limits	
m/m	Date
4.5%	Prior to January 1st 2012
3.5%	On and after January 1st 2012
0.5%	On and after January 1st 2020

Table 9 ECA SO_x limits

ECA sulfur limits	
m/m	Date
1.5%	Prior to July 1st 2010
1.0%	On and after July 1st 2010
0.1%	On and after January 1st 2015

The SO_x limits will apply on all vessels operating in the SECAs, i.e. not only vessels built after a certain date (Laws and regulations (Volvo Penta), 2014).

Environmental Protection Agency (EPA)

EPA is an agency in the United States with a mission to protect humans and their health as well as protecting the environment. EPA is conducting exhaust emission regulations for the United States, and Volvo Penta is affected by those. The EPA regulations concerns CO-, PM- and NO_x+HC -emissions and are presented as figures below.

§1042.101 Exhaust emission standards for Category 1 engines and Category 2 engines.

(a) *Duty-cycle standards.* Exhaust emissions from your engines may not exceed emission standards, as follows:

(1) Measure emissions using the test procedures described in subpart F of this part.

(2) The following CO emission standards in this paragraph (a)(2) apply starting with the applicable model year identified in §1042.1:

(i) 8.0 g/kW-hr for engines below 8 kW.

(ii) 6.6 g/kW-hr for engines at or above 8 kW and below 19 kW.

(iii) 5.5 g/kW-hr for engines at or above 19 kW and below 37 kW.

(iv) 5.0 g/kW-hr for engines at or above 37 kW.

(3) Except as described in paragraphs (a)(4) and (5) of this section, the Tier 3 standards for PM and NO_X+HC emissions are described in the following tables:

Figure 2 EPAs CO regulations.

Table 1 to §1042.101— Tier 3 Standards for Category 1 Engines Below 3700 kW[a]					
Power Density and Application	Displacement (L/cyl)	Maximum Engine Power	Model Year	PM (g/kW-hr)	NOx+HC (g/kW-hr)[b]
All	disp.< 0.9	kW <19	2009+	0.40	7.5
		$19 \le kW < 75$	2009-2013	0.30	7.5
			2014+	0.30	4.7
Commercial engines with $kW/L \le 35$[b]	disp.< 0.9	$kW \ge 75$	2012+	0.14	5.4
	$0.9 \le disp. < 1.2$	all	2013+	0.12	5.4
	$1.2 \le disp. < 2.5$	kW < 600	2014-2017	0.11	5.6
			2018+	0.10	5.6
		$kW \ge 600$	2014+	0.11	5.6
	$2.5 \le disp. < 3.5$	kW < 600	2013-2017	0.11	5.6
			2018+	0.10	5.6
		$kW \ge 600$	2013+	0.11	5.6
	$3.5 \le disp. < 7.0$	kW < 600	2012-2017	0.11	5.8
			2018+	0.10	5.8
		$kW \ge 600$	2012+	0.11	5.8
Commercial engines with kW/L > 35 and all recreational engines[b]	disp. < 0.9	$kW \ge 75$	2012+	0.15	5.8
	$0.9 \le disp. < 1.2$	all	2013+	0.14	5.8
	$1.2 \le disp. < 2.5$		2014+	0.12	5.8
	$2.5 \le disp. < 3.5$		2013+	0.12	5.8
	$3.5 \le disp. < 7.0$		2012+	0.11	5.8

[a] No Tier 3 standards apply for commercial Category 1 engines at or above 3700 kW. See §1042.1(c) and paragraph (a)(7) of this section for the standards that apply for these engines.
[b] The applicable NOx+HC standards specified for Tier 2 engines in Appendix I of this part continue to apply instead of the values noted in the table for commercial engines at or above 2000 kW. FELs for these engines may not be higher than the Tier 1 NOx standard specified in Appendix I of this part.

FIGURE 3 EPAS TIER 3 PM AND NO_X+HC REGULATIONS. VOLVO PENTA HAS ENGINES IN BOTH COMMERCIAL SEGMENTS OF THIS TABLE, I.E. KW/L ≤ 35 AND KW/L > 35.

TABLE 3 TO §1042.101—TIER 4 STANDARDS FOR CATEGORY 2 AND COMMERCIAL CATEGORY 1 ENGINES ABOVE 600 KW

Maximum engine power	Displacement (L/cyl)	Model year	PM (g/kW-hr)	NO_X (g/kW-hr)	HC (g/kW-hr)
600 ≤kW <1400	all	2017+	0.04	1.8	0.19
1400 ≤kW <2000	all	2016+	0.04	1.8	0.19
2000 ≤kW <3700[a]	all	2014+	0.04	1.8	0.19
kW ≥3700	disp. <15.0	2014-2015	0.12	1.8	0.19
	15.0 ≤disp.<30.0	2014-2015	0.25	1.8	0.19
	all	2016+	0.06	1.8	0.19

FIGURE 4 TIER 4 STANDARDS ARE ONLY APPLICABLE FOR ENGINES ≥600 KW.

Figure 2, 3 and 4 derives from the U.S. Government (2014).

EU: Non Road Mobile Machinery (NRMM) (Inland waterways)

The European Commission has established a *proposal* for a regulation of emissions at the EU inland waterways. This is still just a proposal, which means that the emission levels can be changed. The regulations' introduction dates are dependent of the engine type and sizes as follows:

- Auxiliary engine, 56-130 kW: January 1st 2020
- Auxiliary engine, 130-560 kW: January 1st 2019
- Auxiliary engine, 560-1000 kW: January 1st 2020
- Propulsion engine <300 kW: January 1st 2019
- Propulsion engine 300-1000 kW: January 1st 2020

The dates are representing engines released after those dates.

The NRMM regulation is very demanding, since it will both regulate particulate number (PN) and methane emissions (A). Those two parameters are not regulated by IMO or EPA. Three of the categories in the regulation will concern Volvo Penta, and those are *NRE engines (article 4.1), IWP engines (article 4.5),* and *IWA engines (article 4.6).*

The emission levels for Volvo Penta's auxiliary engine range can be seen below in table 10.

TABLE 10 NRMM EMISSION LEVELS FOR GENSET AND AUXILIARY ENGINES

Genset/Aux	**Limits [g/kWh]**					
Engine size	CO	NOx	HC	PM (mass)	PN [#/kWh]	A
56-130 kW	5,0	0,4	0,19	0,015	$1*10^{12}$	1,1
130-560 kW	3,5	0,4	0,19	0,015	$1*10^{12}$	1,1

The emission levels for Volvo Penta's propulsion engine range can be seen below in table 11.

TABLE 11 NRMM EMISSION LEVELS FOR INLAND WATERWAY VESSELS (IWV) (PROPULSION).

Propulsion	**Limits [g/kWh]**					
Engine size	CO	NOx	HC	PM (mass)	PN [#/kWh]	A
37-75 kW	5,0	Σ : 4,70		0,30	-	6,0
75-130 kW	5,0	Σ : 5,40		0,14	-	
130-300 kW	3,5	2,10	1,00	0,11	-	
300-1000 kW	3,5	1,2	0,19	0,02	$1*10^{12}$	

All of the information above (in this chapter) derives from the European Commission (2014) with annexes.

The HC and methane emissions combined are often mentioned as THC (Total HC, (HC+A)). This is only a concern for engines powered by a gaseous fuel, since the methane slip phenomena is unique for gas fueled engines. The reason to regulate exhaust gas containing methane is to compensate for the total GHG emissions.

PN emissions exist on both diesel and gas fueled (Dual Fuel) engines though. This regulation can therefore be interpreted as beneficial for a 100% LNG engine, since the LNG combustion process emits almost zero particles. Today’s diesel engines would need to use a diesel particulate filter (DPF) to meet the upcoming emission levels.

Technology of Today

This chapter is supposed to work as an overview of what kind of technology that exists today, regarding combustion, after treatment etc.

Volvo Penta does already have an engine suited for natural gas. This engine (TWG1663GE) is not for marine purposes but only for industrial applications. The engine is basically a conversion from a D16 diesel genset, which now also can be operated on natural gas. The diesel-natural gas ratio is up to 30-70 under normal loads. The amount of diesel is increased under higher loads though. This engine is utilizing the principle described under "alternative 5" in the *results* section.

Prevent SO_x emissions

The SO_x emissions are, as written under *emissions,* related to the sulfur content in the fuel. This is, hence, not a big concern, since Volvo Penta's engines are made for MDO (sometimes referred to as DMB) or MGO (DMA) which has relatively low sulfur content. Volvo Penta does not have any particular after treatment technology to reduce the sulfur level further. It is just dependent on what kind of fuel that is being used.

Prevent NO_x emissions

The NO_x emissions are a bigger concern for Volvo Penta, particularly when (if) the NRMM regulation comes into force. The company is solving this by using after treatment solutions like selective catalyst reduction (SCR) and also exhausts gas recirculation (EGR) on some industry engines. The NO_x particles could also be reduced by using LNG as fuel, but not always to the demanding levels. This is also dependent on which combustion process that is used.

Combustion

Today's Volvo Penta engines are running on either diesel, where the combustion is ignited by compression, or on gasoline, where the ignition is made by electrical spark plugs. Those are the two ways to ignite a combustion engine, regardless if the fuel is gasoline, natural gas or diesel. The alternatives in the case with a LNG-engine are either a spark ignited (SI) (100% LNG) or a compression ignited, which needs a small amount of diesel (called a pilot diesel) to ignite. The latter one is often referred to as dual-fuel. The amount of diesel depends on how the fuels are injected, which will be described below.

There is two common ways to inject the fuel to the combustion chamber. This is done either by port injection or by direct injection. High pressure is a requirement for using direct injection. It is much easier to achieve a high pressure direct injection (HPDI) with a fluid than with a gas. LNG is therefore better than CNG in this aspect. By using HDPI, 95% of the diesel (by energy) can be replaced with LNG (Westport (a), 2014). HPDI technology can result in efficiency at about 44% (under highway operation). This can be compared with efficiency at 37% in an SI-engine. The lower efficiency is due to the risk of engine knocking in a SI-engine (Westport (b), 2013)

There is also two common ways to combust fuel. One way is a stoichiometric combustion ($\lambda=1$), whilst the other way is a lean combustion ($\lambda>1$). Stoichiometric combustion means what the name says; the air-fuel ratio is stoichiometric. A three-way catalyst (TWC) can be used when the process for combustion is stoichiometric. This is an effective and relatively cheap way to reduce HC, CO and NO_x. A drawback is that the process is more sensitive against knock (compared to a lean combustion) and that the combustion causes a higher temperature and lower compression ratio (Willner, 2013). The efficiency is lower than when the combustion is operated under lean conditions (Advanced engineering (Volvo Penta), 2014).

Lean burn means that the air-fuel ratio is increased, i.e. less fuel per the same amount of air. This kind of combustions comes along with some benefits. It requires less fuel, and emits less unburned GHG-gases at the same time as it maintains its power. This is due to a higher pressure and heat during the combustion, which also leads to a drawback (Gable & Gable, 2014). A lean burn engine is producing more NO_x emissions (compared to $\lambda=1$ with TWC), and a SCR after treatment is therefore needed. A lean burn engine will be more costly than a stoichiometric burn engine, since the SCR is more complex and expensive compared to a TWC (Willner, 2013).

Gas quality

There are several parameters that define the quality of LNG. The properties that usually are mentioned are methane number, heating value, wobbe index and sensitivity to weathering. Wobbe index is defined as $\frac{heating\ value}{\sqrt{\rho}}$. Sensitivity to weathering is related to the amount of higher hydrocarbons within LNG. Higher hydrocarbons lead to a lower methane number (Verbeek, o.a., 2013).

The methane number indicates the gas's resistance against self-ignition, similar to a conventional fuel's research octane number (RON). A methane number of 100 correspond to 120-140 RON. A higher methane number indicates a higher resistance against knock (Stålhammar, Erlandsson, Willner, & Johannesson, 2011). A benefit with an assured relative high methane number is that the engine can be designed for a higher efficiency (Verbeek, o.a., 2013).

There is two different ways to measure quality in gas, those are either prescriptive or performance based. The prescriptive method is based on the content of the gas, i.e. the share of methane, ethane etc. Performance based quality is instead stating methane number, wobbe index and energy content. This latter is the way to indicate quality for a LNG piston engine. (Buhaug, 2011)

An engine gas standard is under development, but is not available yet (Alternative fuels (Volvo), 2014).

Safety

The safety records for LNG vessels are almost clean. I.e. "no reported major incidents e.g. fire, explosion, grounding" and no significant LNG release during a bunkering process. This statement is valid for all 38 DNV classed LNG vessels at the time of the presentation (Shinta, 2013).

IMO are developing a "Code of Safety for Ships using Gases or other Low flashpoint Fuels" which will be identified as "IGF Code". The following text is copied from IMOs website:

> "The basic philosophy of the IGF Code is to provide mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low flashpoint fuels, such as liquefied natural gas (LNG), to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved.
>
> The Code addresses all areas that need special consideration for the usage of low flashpoint fuels, based on a goal-based approach, with goals and functional requirements

specified for each section forming the basis for the design, construction and operation of ships using this type of fuel." (Internation Maritime Organization, 2014)

Both DNV GL and US Coast Guard are referring to the IGF Code when they are talking about installation of LNG on a vessel. The IGF Code will come in force earliest 2017 (USCG, 2014).

Fuel consumption

This subchapter contains approximations of fuel consumption for various kinds of vessels. It is very difficult to establish a reliable prediction, but that is less important in this case, since the numbers will just work as references in case of a conversion to LNG. The assumptions are based on internal sources, to make as much sense as possible.

An inland waterway vessel consumes about 1.3 liter of diesel per 100 ton and kilometer (Konings, Priemus, & Nijkamp, 2005) and (PoH, 2012).

Assume 120 liters/h at 23 knots for a 16 meter long pilot boat. That is equal to 120 liter diesel per 23 nautical miles (nm). Also assume a 2200 liter tank (which gives about 420 nm).

A ferry of about 25 meters and 12 knots consumes approximately 100-200 liter diesel per hour depending on its operating profile.

The fuel consumption for a tug boat is difficult to assume and predict since it is depending on its operating profile. It has been omitted on purpose, both because of this reason, but also since it will not affect the result for this case.

Methanol/Di-Methyl Ether (DME)

Methanol and di-methyl ether is two other alternative fuels that need to be briefly mentioned in this thesis. Neither methanol nor DME need cryogenic tanks which means cheaper and easier storage compared to LNG. A drawback with both those fuels is the limited infrastructure. The emissions are reduced and are anticipated to comply with IMOs ECA regulations (Chryssakis, 2014). The same source is also stating that a conversion to methanol is less complicated and less expensive than a conversion to LNG.

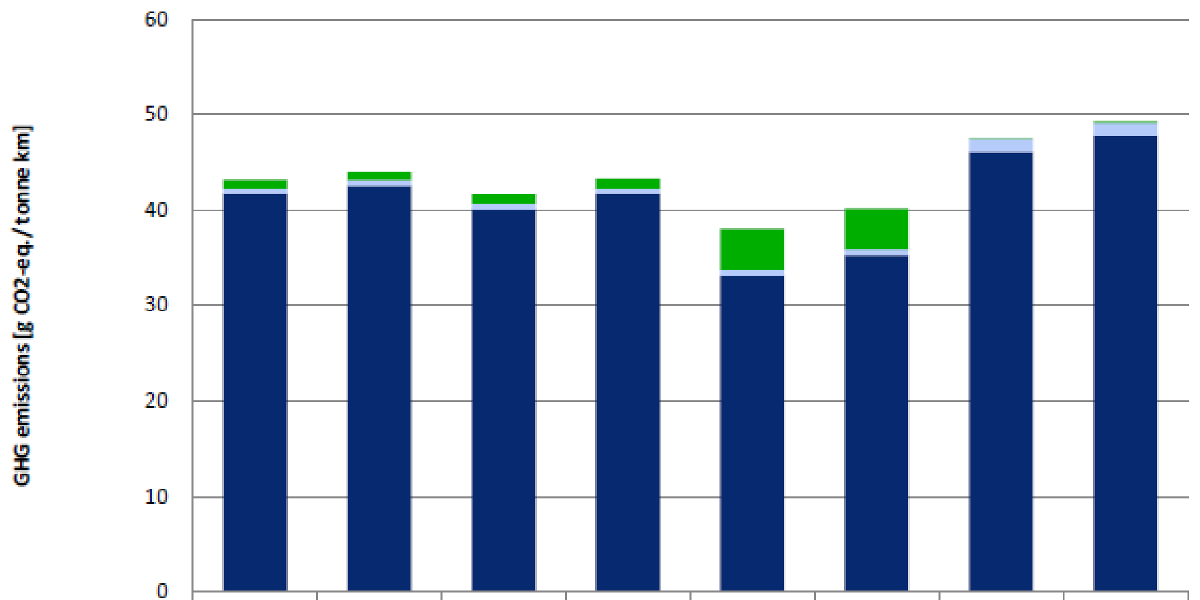
Methanol as a marine fuel implies the same reductions of emissions as LNG, but without methane slip. It is definitely cheaper and less complex to convert a vessel to methanol combustion compared to a conversion to LNG. Stena Line believes in methanol rather than LNG as an alternative marine fuel. IMOs IGF code are covering methanol as well as LNG (Westling, 2013).

Methanol is expected to be comparable in price with LNG at least until 2030 (LR & UCL, 2014).

Life Cycle Assessment (LCA) analysis

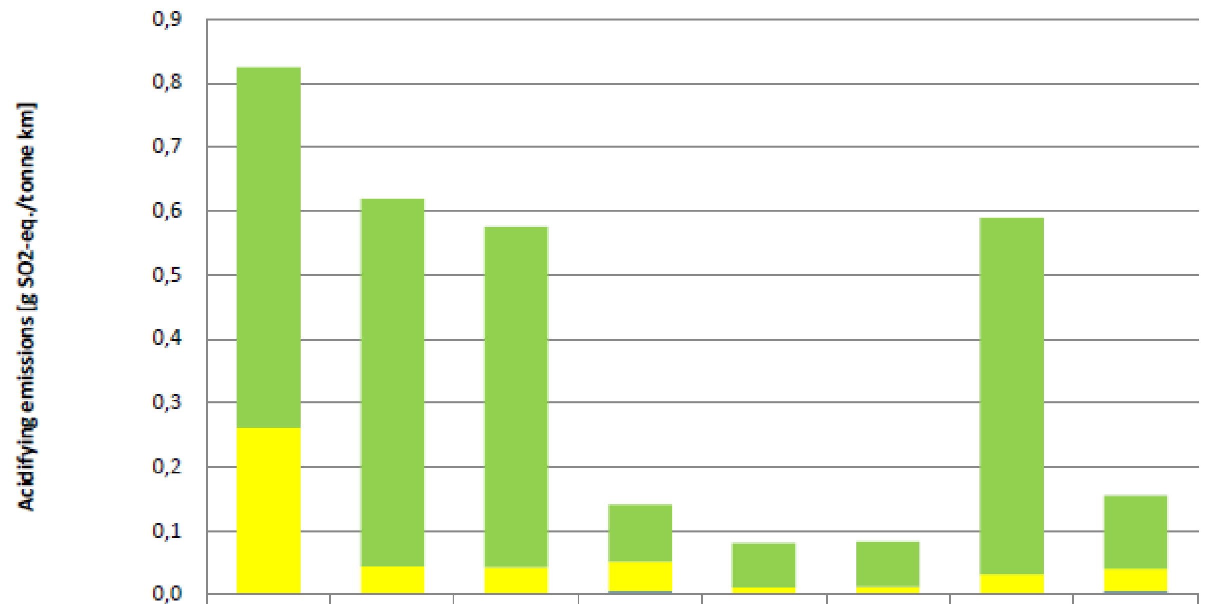
A good way to compare the environmental effect of different products is by conducting a life cycle assessment (LCA) analysis. Such an analysis has already been made at Chalmers University, where four marine fuels were compared and analyzed. This LCA-analysis " (Bengtsson, Andersson, & Fridell, 2011)" has been used as source for this chapter.

The results are presented in diagrams were different marine fuels and their respective GHG; acidifying and eutrophication emissions are compared. Those diagrams are attached (with permission) below. The results are presented in a functional unit, which is one ton cargo transported one km with a Ro-Ro vessel. Transportation of cargo, urea ("fuel" for SCR) and fuel production, fuel distribution and raw material extraction is considered in all diagrams. A lean burn 100% gas engine represents the LNG vessel, which is supposed to operate in Gothenburg, Sweden.



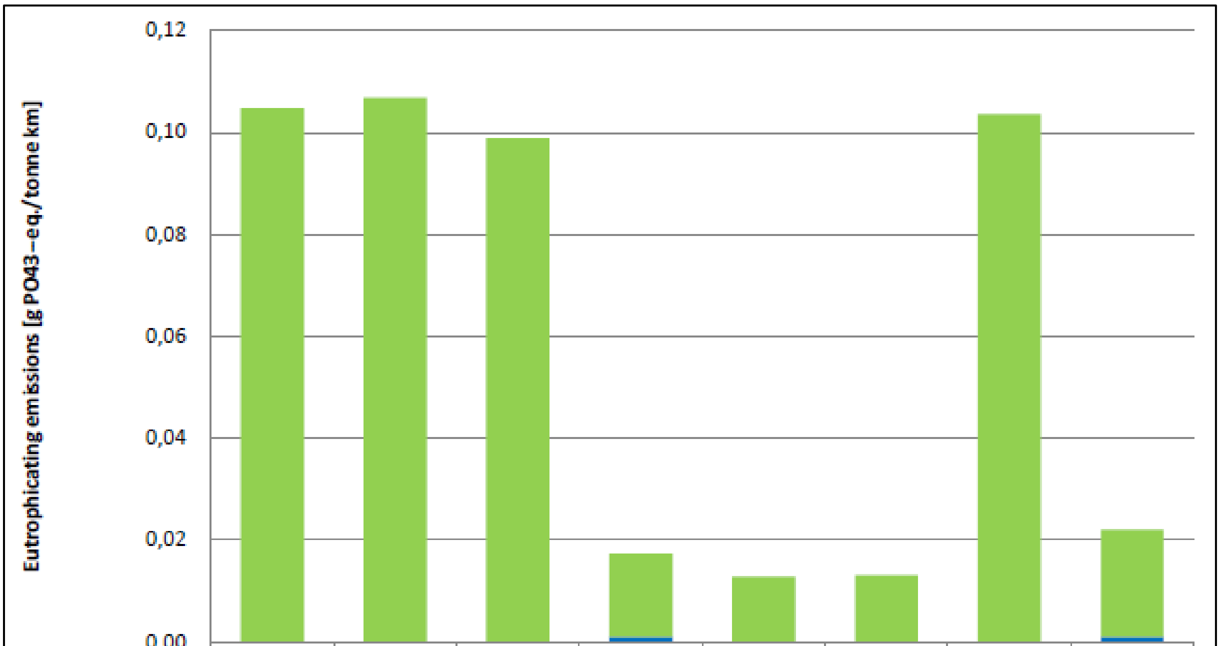
	HFO	HFO with scrubber	MGO	MGO with SCR	LNG from North Sea	LNG from Qatar	GTL	GTL with SCR
methane	9,0E-01	9,1E-01	9,7E-01	1,0E+00	4,3E+00	4,3E+00	9,3E-02	1,4E-01
nitrous oxide	5,5E-01	5,6E-01	5,5E-01	5,5E-01	5,5E-01	6,0E-01	1,4E+00	1,4E+00
carbon dioxide	4,2E+01	4,3E+01	4,0E+01	4,2E+01	3,3E+01	3,5E+01	4,6E+01	4,8E+01

FIGURE 5 GHG EMISSIONS IN CO_2 EQUIVALENTS AND WHERE IT DERIVES FROM (BENGTSSON, ANDERSSON, & FRIDELL, 2011).



	HFO	HFO with scrubber	MGO	MGO with SCR	LNG from North Sea	LNG from Qatar	GTL	GTL with SCR
Nitrogen oxides	5,6E-01	5,7E-01	5,3E-01	8,8E-02	6,9E-02	7,0E-02	5,6E-01	1,1E-01
Sulphur oxides	2,6E-01	4,4E-02	4,3E-02	4,7E-02	1,2E-02	1,2E-02	3,2E-02	3,6E-02
Ammonia	3,9E-04	4,0E-04	3,9E-04	5,3E-03	0,0E+00	0,0E+00	3,3E-04	5,2E-03

FIGURE 6 ACIDIFYING EMISSIONS AND WHERE IT DERIVES FROM (BENGTSSON, ANDERSSON, & FRIDELL, 2011).



	HFO	HFO with scrubber	MGO	MGO with SCR	LNG from North Sea	LNG from Qatar	GTL	GTL with SCR
Nitrogen oxides	1,0E-01	1,1E-01	9,9E-02	1,6E-02	1,3E-02	1,3E-02	1,0E-01	2,1E-02
Ammonia	7,2E-05	7,4E-05	7,3E-05	9,9E-04	0,0E+00	0,0E+00	6,2E-05	9,8E-04

FIGURE 7 EUTROPHICATING EMISSIONS AND WHERE IT DERIVES FROM (BENGTSSON, ANDERSSON, & FRIDELL, 2011).

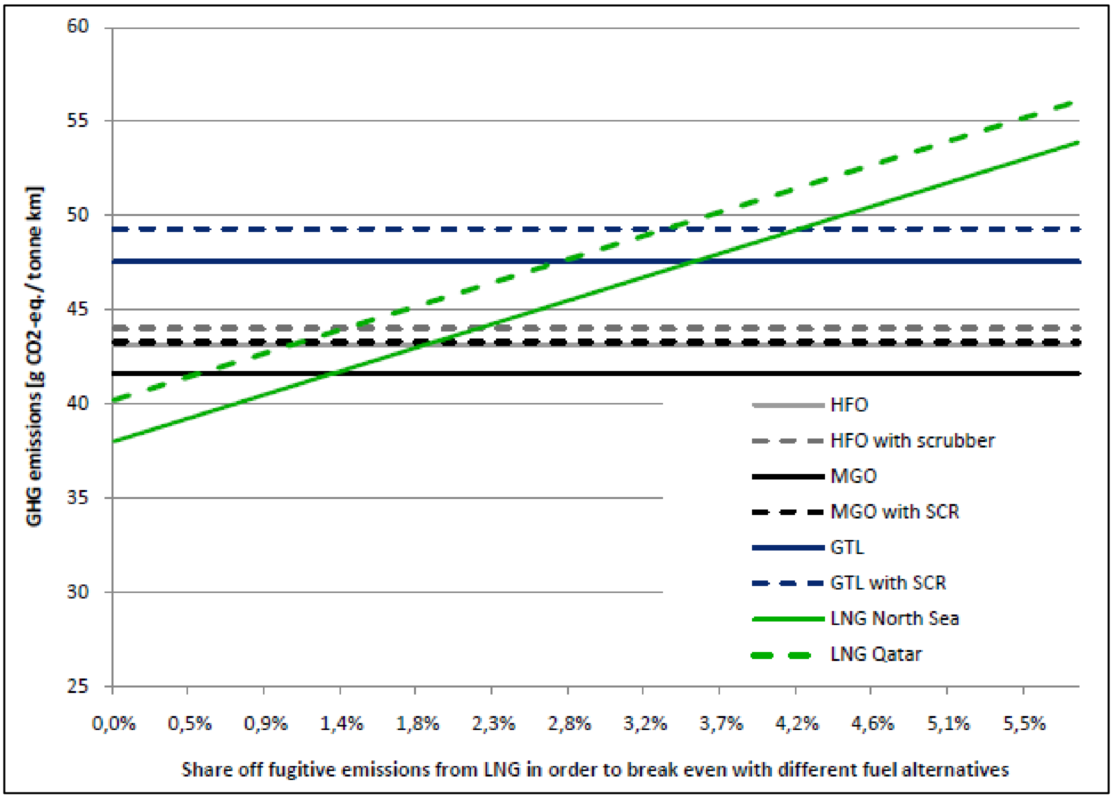


FIGURE 8 METHANE SLIP "ALLOWANCE" (BENGTSSON, ANDERSSON, & FRIDELL, 2011).

Figure 8 shows how big amount of fugitive emissions (methane slip) that is allowed to break even with the conventional fuels. Hence, a total life cycle leakage of 1.4% of the LNG from the North Sea has equal global warming emissions as MGO.

Market of Today

The proved global natural gas reserves were about 194 trillion cubic meters in 2013. This can be compared to the global reserves of crude oil, which were about 196 trillion liters the same year (U.S. EIA, 2014).

Forecast

The study of “Global marine fuel trends 2030” (LR & UCL, 2014) is divided into three different scenarios of the future. Those are called “Status Quo”, “Global Commons” and “Competing Nations”. The scenarios are described in figure 9.

GMT 2030 Scenario	Description
Status quo	Business as usual, economic growth at the current rate, short term solutions, rapid regulatory change. In this scenario, shipping will develop but in a controlled rate
Global commons	More economic growth, more international cooperation, regulation harmonisation, international trade agreements, emphasis on environmental protection and climate change, expansion of globalisation. Shipping will be favoured in this scenario.
Competing nations	Dogmatic approaches and regulatory fragmentation, protectionism, local production and consumption, trade blocks, brake in globalisation. Shipping will be negatively impacted in this scenario.

FIGURE 9 THREE DIFFERENT SCENARIOS OF THE FUTURE. AS PRESENTED IN "GLOBAL MARINE FUEL TRENDS 2030" BY (LR & UCL, 2014).

The findings of this study are later presented in different outcomes. An interesting outcome for this study is the global marine fuel demand, which gives a hint about where the future is heading. The reader has to analyze which scenario that is most likely to occur on her own, though. The marine fuel demand prediction is presented in figure 10.

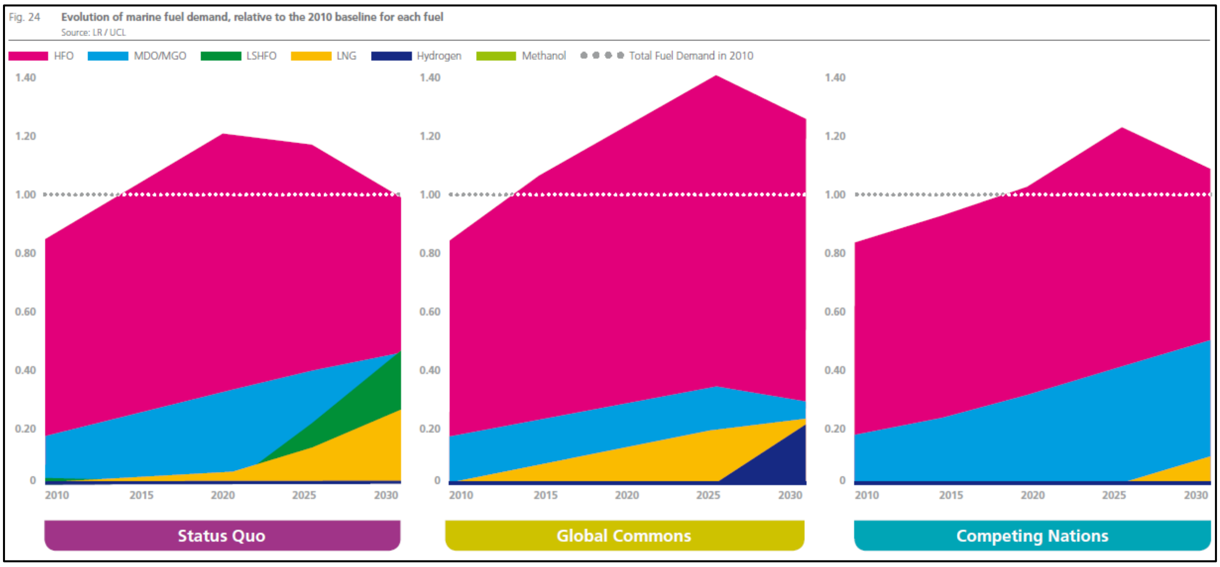


Figure 10 Marine fuel demand (2010-2030) prediction (LR & UCL, 2014).

It is obvious that LNG will play a bigger role in the future, something that also is confirmed by DNV in a presentation called "LNG as fuel – recent development" (DNV GL (c), 2013). The same source have published a map of "Global LNG bunker demand by 2020", which can be seen in figure 11.

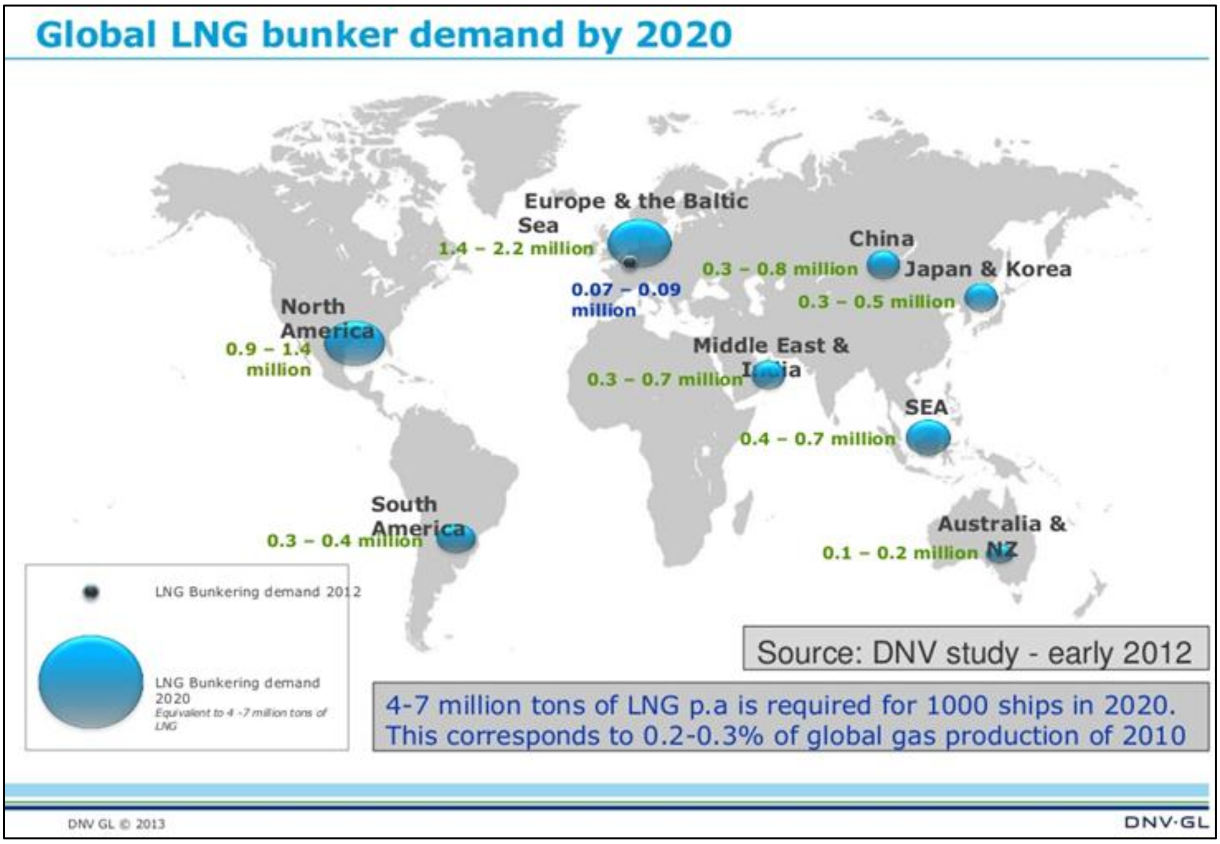


Figure 11 Global LNG bunker demand by 2020 (DNV GL (c), 2013).

Current fleet & order book

The current fleet of LNG vessels is growing but it is still small. There are only 48 LNG fueled vessels, excluding LNG carriers all over the globe (DNV GL (d), 2014). But 53 new LNG vessels are confirmed at the same time. The same source is stating that the LNG market is expected to grow considerably in the upcoming 5-10 years. This statement is enhanced by the fact that the LNG carrier fleet was consisting of 359 vessels, together with another 86 vessels in the order book (≈24% increase), in July 2012 (Drewry Maritime Reasearch, 2012).

The current order book for LNG vessels consists of different kinds of vessels; see figure 12 (it is excluding both LNG carriers and IWV). Hence, the order book for IWV needs to be mapped to make the list complete for this thesis. Reuters (2012) published a press release about the *ECO_2 Inland Vessel project,* a project that basically is helping the inland waterways shipping industry to be more aware of the environment. The project aims to encourage the design and testing of three natural gas vessels to enable a possibility to measure the most efficient and economical systems for inland shipping. Two Wärtsilä 6L20DF engines will power the first one of those three vessels, and is, according to the press release, the first "medium speed, dual-fuel, mechanically driven" LNG-IWV (95-99% LNG) ever.

It is currently forecasted that the LNG fleet will consist of vessels with fixed routes until at least 2020. The reason for this is the insufficient possibilities of bunkering LNG (Sweco, 2009).The same source has also conducted a list of possible vessels types that can be seen as pioneers within this market. The same list is presented (and translated) below:

1. Passenger ferries with a few amount of destinations (including archipelago ferries etc.)
2. Ferries for vehicles and passengers (i.e. Ro-Pax)
3. Ships with rolling cargo (i.e. Ro-Ro)
4. Tanker ships (e.g. for LNG or petroleum)
5. Road ferries
6. Coast guard or other governmental vessels

This list can be extended with Inland Waterway Vessels (IWV), particularly IWV that is intended to operate along the same route for a long. This statement refers to internal sources at Volvo Penta.

53 confirmed LNG fuelled newbuilds

Confirmed orderbook

Year	Type of vessel	Owner	Class	Year	Type of vessel	Owner	Class
2014	Ro-Ro	Norlines	DNV	2015	LEG carrier	Evergas	BV
2014	Ro-Ro	Norlines	DNV	2015	LEG carrier	Evergas	BV
2014	Patrol vessel	Finish Border Guard	GL	2015	LEG carrier	Evergas	BV
2014	Car/passenger ferry	Society of Quebec	LR	2015	Bulk ship	Erik Thun	LR
2014	Car/passenger ferry	Society of Quebec	LR	2015	Container Ship	Brodosplit	DNV GL
2014	Car/passenger ferry	Society of Quebec	LR	2015	Container Ship	Brodosplit	DNV GL
2014	Tug	Buksér & Berging	DNV	2015	PSV	Siem Offshore	
2014	PSV	Harvey Gulf Int.	ABS	2015	PSV	Siem Offshore	
2014	PSV	Harvey Gulf Int.	ABS	2015	Container Ship	TOTE Shipholdings	ABS
2014	PSV	Harvey Gulf Int.	ABS	2016	Container Ship	TOTE Shipholdings	ABS
2014	PSV	Harvey Gulf Int.	ABS	2016	Icebreaker	Finnish Transport A.	LR
2014	Gas carrier	SABIC	BV	2016	PSV	Siem Offshore	
2014	Gas carrier	SABIC	BV	2016	PSV	Siem Offshore	
2014*	Product tanker	Bergen Tankers	LR	2016	Chemical tanker	Terntank	
2014	General Cargo	Egil Ulvan Rederi	DNV	2016	Chemical tanker	Terntank	
2014	General Cargo	Egil Ulvan Rederi	DNV	2016*	Ro-Ro	TOTE Shipholdings	ABS
2014	PSV	Remøy Shipping	DNV	2016*	Ro-Ro	TOTE Shipholdings	ABS
2014	Car/passenger ferry	AG Ems	GL	2016	Car carrier	UECC	LR
2014*	Car/passenger ferry	AG Ems	GL	2016	Car carrier	UECC	LR
2014	Car/passenger ferry	Samsoe Municipality	DNV	2016	Car/passenger ferry	Boreal Transport	
2014	Ro-Ro	Sea-Cargo	DNV	2016	Car/passenger ferry	Boreal Transport	
2014	Ro-Ro	Sea-Cargo	DNV	2017	RoPax	Brittany Ferries	BV
2015	PSV	Siem Offshore	DNV	2017	Container Ship	Crowley Maritime	DNV GL
2015	PSV	Siem Offshore	DNV	2017	Container Ship	Crowley Maritime	DNV GL
2015	PSV	Simon Møkster	DNV	2018	Container Ship	Matson Navigation	DNV GL
2015	PSV	Harvey Gulf Int.	ABS	2018	Container Ship	Matson Navigation	DNV GL
2015	PSV	Harvey Gulf Int.	ABS				

Updated 07.03.2014

***Conversion project**

Excluding LNG carriers and inland waterway vessels

3 DNV GL © 2013 DNV·GL

Figure 12 Confirmed order book (excluding LNG carriers and IWV) (DNV GL (a), 2013).

The LNG fleet is expected to be even bigger in the future. Svensen T. (2012) (president DNV Maritime and Oil and Gas) predicts that 1000 ships, or about 10-15% of the new built ships (tankers, bulk carriers, containerships, offshore supply vessels) will be powered by LNG in 2020. This ratio will be about 30% in 2018-2020, according to the same study. He also states that larger ships (powered by HFO) will benefit more than smaller ships of LNG. But on the other hand, he also states that small tankers and general cargo carriers which spend all their time in ECAs will be affected the most.

Competition

The existing LNG engines for ships and vessels today are mainly outside Volvo Penta's power range. MAN, Wärtsilä and Caterpillar are offering LNG engines in the range >5000kW. But there also exists some smaller options as well. E.g. Mitsubishi GS12R-PTK (675 kW), which is installed in "Glutra", the first LNG powered vessel in the world. Glutra is powered by four ultra-lean burn Mitsubishi GS12R-PTK natural gas engines. The displacement of 49 liters per engine is out of Volvo Penta's range, but it is still comparable considering the power output.

The next smallest gas engine on the marine market is Wärtsilä's 6L20DF which is rated at 1110 kW. The 6L20DF can run on either HFO/MDO or natural gas. It also has the ability to switch between those fuels under operation. The engine operates on the principle of lean burn combustion (Wärtsilä, Wärtsilä 20DF, 2014)

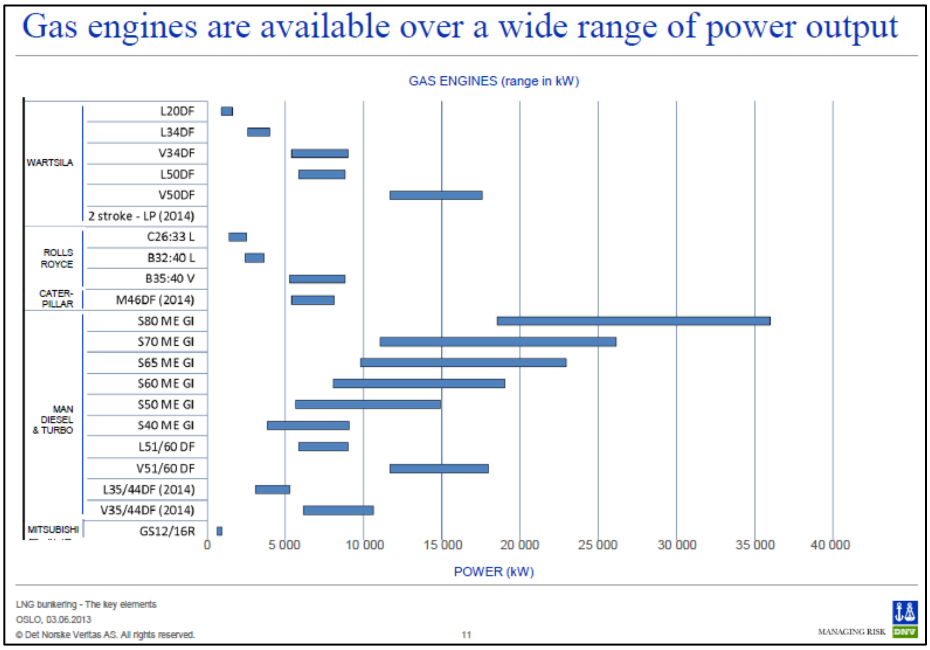


FIGURE 13 CURRENT MARINE GAS ENGINES ON THE MARKET (SHINTA, 2013)

Scania, another Swedish engine manufacturer is offering a 100% LNG (or rather 100% natural gas) engine in cooperation with Sandfirden, a company based in the Netherlands. The engine is based on a 16 liters V8 engine and has an effect of 285 kWe, and 60 Hz (Sandfirden, 2012).

Price LNG versus distillate fuel

It is difficult to predict prices of LNG for the future. The forecast in this chapter should therefore not be trusted completely.

LNG as fuel is cheaper than MDO, MGO and HFO. A LNG vessel itself is about 10-15 % more expensive than a conventional vessel though (CNSS, 2014). Internal sources show that just a LNG engine in Volvo Penta's range is approximately 100% more expensive in purchase than a conventional diesel engine at the same power output.

American Clean Skies Foundation (ACSF, 2012) states that the cost of a LNG system will be cheaper to install on a new built vessel compared to retrofit an existing vessel with such a system.

The currently low cost together with the cost predictions of using LNG instead of MDO is one of the biggest driving factors for LNG, as mentioned before. DNV (Blikom, 2013) has made a cost estimation of LNG, MDO and HFO until 2035, which can be seen in figure 14. Blikom emphasizes that this is only an estimate, and it is based on the International Energy Agency's *new policies scenario* in their document called *World Energy Outlook 2012.*

LNG, delivered for marine use is in the USA expected to be at least 57% cheaper than distillate fuel (per energy unit) in the upcoming ten years (ACSF, 2012).

Cotty Fay (Chief Naval Architect) at WSDOT Ferries Division states a delivered LNG price at $0.75 per gallon, while the diesel fuel is around $3.34 per gallon (Fay, 2013). The LNG price is therefore 60% cheaper per energy unit than diesel in this study. This vessel is intended to operate in Washington State in USA, and the prices are therefore valid for that area.

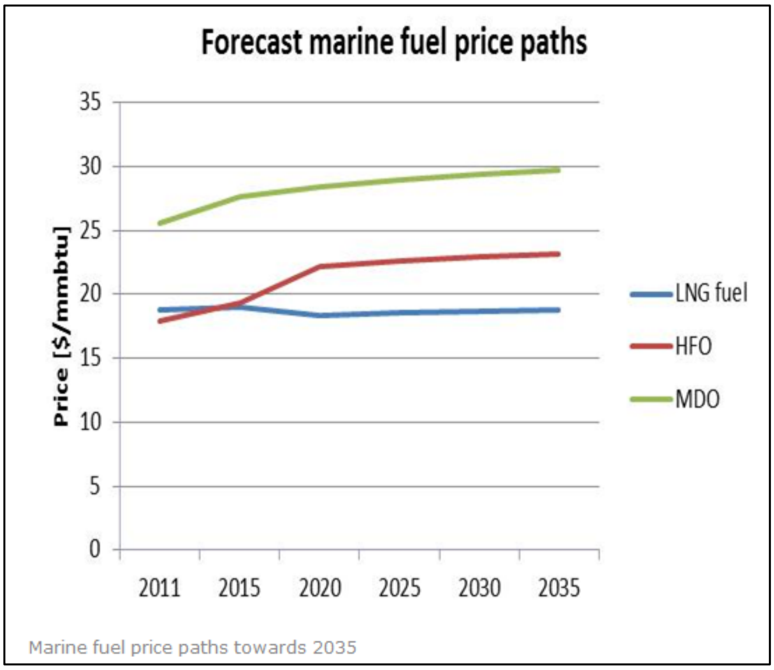


FIGURE 14 FORECAST, MARINE FUEL PRICES (BLIKOM, 2013). LNG IS APPROXIMATE 36% LESS EXPENSIVE THAN MDO (CALCULATED ON A LNG MEAN PRICE OF $18/MMBTU AND A MDO MEAN PRICE OF $28/MMBTU). NOTE THAT THIS IS CALCULATED PER ENERGY UNIT (MMBTU).

The price of LNG is about 60% more expensive in Europe, compare to in the USA (Wärtsilä, Ferry Business Case for LNG, 2014). This relation is assumed to be kept during the upcoming years, and will therefore be used as a baseline in the *results* chapter. This assumption is based on the cost prediction until 2020 in table 12.

The tank and its belonging systems is expensive for LNG. Internal sources shows a total initial cost of about 800 000 – 1100 000 EUR for a 70 m^3 tank system. It is difficult to estimate a price for smaller tanks (since it is not commonly used) but another internal source states that a 30 m^3 tank system costs no less than 750 000 EUR. It is difficult to estimate a cost for a diesel tank though, since such a tank often is custom made and integrated in the hull. A *very* coarse estimation for a 15-20 m^3 tank with belonging systems is 10 000 EUR.

The International Energy Agency (IEA) has made a price estimate for crude oil and natural gas. This estimation just gives an indication of MDO and LNG prices, since both fuels require "treatment" before they can be used. The reader should also be aware of that this is only a prediction which consequently does not mean that this is going to coincide with the reality.

TABLE 12 PRICE ESTIMATIONS FOR CRUDE OIL AND NATURAL GAS (DOLLARS PER UNIT) (IEA, 2012). MBTU (MILLIONS BTU, IT IS IN SOME LITERATURE ALSO WRITTEN AS MMBTU).

Current Policies Scenario		**Year**					
Fuel type	Unit	2011	2015	2020	2025	2030	2035
Crude oil imports	barrel	107.6	118.4	128.3	135.7	141.1	145.0
Natural gas (USA)	MBtu	4.1	4.6	5.5	6.4	7.2	8.0
Natural gas (Europe imports)	MBtu	9.6	11.2	12.1	12.9	13.4	13.7
Natural gas (Japan imports)	MBtu	14.8	15.3	14.7	15.2	15.6	16.0

TABLE 13 CONVERTED NUMBERS OF TABLE 12 INTO DOLLARS PER GJ. GJ IS NOT COMMONLY USED, BUT CAN GIVE A BETTER PERSPECTIVE FOR A READER USED TO SI-UNITS.

Current Policies Scenario		**Year**					
Fuel type	Unit	2011	2015	2020	2025	2030	2035
Crude oil imports	GJ	16.14	17.83	19.52	20.48	21.45	21.93
Natural gas (USA)	GJ	3.89	4.36	5.22	6.07	6.83	7.59
Natural gas (Europe imports)	GJ	9.11	10.62	11.48	12.24	12.71	12.99
Natural gas (Japan imports)	GJ	14.04	14.51	13.94	14.42	14.80	15.18

Some internal sources says that the repair and maintenance costs on a LNG engine will be lower than on a distillate fuel engine, since LNG is a cleaner fuel and will therefore have an extended time between services. Carlier (2012) states the opposite though, he claims that the maintenance costs, according to "some studies" will be about 20% higher for a LNG engine. This will be considered in the *results* chapter.

Natural gas production

Natural gas is produced all over the globe. The biggest production is located in Europe & Eurasia, which were producing $933*10^6$ tons of oil equivalents in 2011 (31.6% of the world's total production). The next biggest production is in North America, which in 2011 produced $784*10^6$ tons of oil equivalents (26.5%) (Drewry Maritime Reasearch, 2012). The production of natural gas is rapidly increasing in the USA because of all newfound shale gas reserves that are extracted with fracking.

Today's infrastructure

There are several ways to bunker LNG to a ship or vessel. The four most common ways to bunker are:

- Truck to ship (TTS)
- Shore/Pipeline to ship (PTS)
- Ship to ship (STS)
- Portable tanks

The possibilities for a ship to bunker LNG from a facility (PTS) are still limited. At this point, it is only possible to bunker LNG at some places in Europe, as well as in Incheon, South Korea and Buenos Aires, Argentina (DNV GL (b), 2014). LNG terminals for the shipping industry exist in several European countries. A benefit with this way of bunkering is that big amounts of LNG can be transferred.

The most common way of bunkering is TTS, which benefits from the fact that the bunkering can be done on various places, wherever the vessel are. This is even the case with STS, which also can be performed at open sea (DNV GL (e), 2014). It takes about 2 hours to bunker 47 m^3 LNG with this approach (Sweco, 2009).

Portable tanks can be transferred to a ship or vessel and basically be used as portable fuel. A 40-foot tank (a typical LNG truck tank) can hold about 49000 liter of LNG (DNV GL (e), 2014).

It is difficult to map the real LNG infrastructure, since the most common way of bunkering is a portable method. The trucks basically come to where the vessels are located. But one should be aware of the current development of bunkering terminals, and also that some terminals already exists. The global LNG bunkering infrastructure in January 2014 can be seen in figure 15.

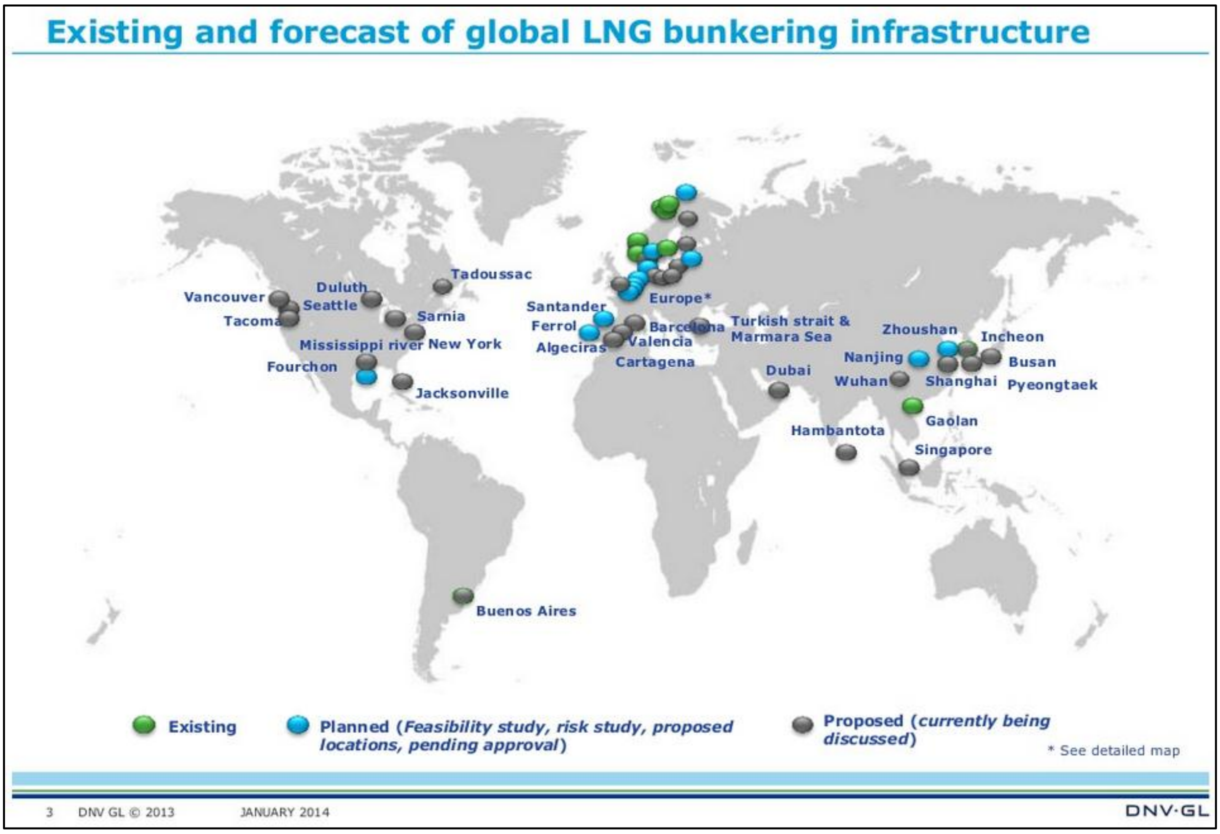


FIGURE 15 GLOBAL LNG BUNKERING INFRASTRUCTURE (DNV GL (F), 2014).

LNG storage

The LNG is, as mentioned above, cooled down to minus 162 °C. The LNG is stored in tanks, which positioning is regulated by different classification organizations. American Bureau of Shipping (ABS) are presenting design requirements that is based on IMOs "Resolution MSC.285(86) Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships" (apopted 1st of June, 2009) and IMOs "International Code of Safety for Gas-Fuelled Ships (IGF Code)" (which still is under development). Those two regulations are a base for how a LNG-fueled vessel should be designed. Both regulations are covering a lot of information, which are critical to understand before developing a vessel with LNG (or CNG) as fuel. They are containing too much information to fit in this report, and it is therefore recommended to read them separately. The entire interim regulation can be found in *ABS Guide for Propulsion and Auxiliary Systems for Gas Fueled Ships, page 7.* One can basically state that a LNG tank can be stored on open deck as well as in an enclosed space (enclosed space entails more restrictions) (ABS, 2011). US Coast Guard have published a policy letter (CG-521, "Equivalency determination – Design criteria for natural gas fuel systems"), which is based on IMOs MSC.285(86) Interim Guidelines, but is also containing some small additions. The IGF Code will be applied to various vessel alternatives under *results*.

LNG can be stored in three different kinds of tanks. The tanks should be independent of the vessels hull, which is not ultimate for the strength of the hull. The tank alternatives are known as type A, B and C. Tank type A and B are not pressurized, while type C is identified as "cryogenic pressure vessels" (Thomas & Patel, 2013), (Shinta, 2013).

A drawback with storage of LNG is the inevitable phenomena of boil-off. The LNG is cooled down and stored in cryogenic tanks, and could not be stored longer than 5 days before it starts to boil off (Alternative fuels (Volvo), 2014). A Type C tank can hold LNG for up to 30 days under right conditions, without venting but with increased pressure (DNV GL (e), 2014). This is of course a benefit with Type C tanks. A drawback with the type C tanks though, or rather a benefit with so called Type A tanks since they are not pressurized, is that they can be designed to follow the hull and will therefore require a smaller space (Sweco, 2009).

MS GMBH (2014) claims that a LNG tank equivalent to a 40 feet container (external size: 77 m^3, internal size 33.4 m^3 at 82% filling rate) can keep LNG for up to 80 days. Note that this requires a very thick layer of insulation. This tank is classified as a type C tank according to the IGC Code.

According to Chalmers, Maritime Operations (2014), it is almost necessary to operate a LNG vessel 24 hours a day, to avoid boil-off.

Short sum-up

The so far presented information will be used as a base when determining the results. The right headings will be referred, if numbers or other specific information is being used. The approach is tried to be as clear as possible, since this is a rather comprehensive study which contains a lot of information.

One can basically say that the result is mainly focusing on price, storage, accessibility and environment. Those factors are used to compare LNG with distillate fuel.

Results

This chapter will sum up all gained knowledge and apply the theory to Volvo Penta's situation. It is aimed to end up in a recommendation for Volvo Penta, i.e. how the company should approach the growing LNG market.

If one is observing the emission regulation accurately, it becomes obvious that the NRMM (EU commission) levels are the most stringent. Those levels are very stringent but will not work as design requirements because of three reasons. First since the inland waterway market is not big enough. The second reason is that this regulation is still just a proposal, and could possibly be changed to harmonize better with the industry. The third reason is that this regulation is too stringent, and it would require too much after treatment and development work to harmonize with the low levels of emissions. The regulation does not make any real sense if it is compared to the previous, as well as the concurrent regulations (IMO and EPA).

LNG is, according to the findings in the theory part, a cleaner fuel than MDO and MGO. But the interesting thing for Volvo Penta is how this impacts the customer and his or her decision. This chapter aims to investigate how different customers most likely will act in those questions, depending on cost, availability and reliability.

Total Cost of Ownership (TCO) analysis

One of the main drive factors for LNG is its low price. This chapter is aimed to show potential savings if a LNG engine is chosen instead of a conventional engine.

Two coarse total costs of ownership (TCO) analyses have been conducted to enable an economic comparison between MDO and LNG (both in USA and Europe). The first analysis is based on two (twin installation) Volvo Penta D13-800 MC (Rating 4)[1] with an assumed time between overhaul of 4000 hours. The second analysis is established with two Volvo Penta D13-400 (Rating 1) as base for the calculations. The D13-400 has an assumed time between overhaul of 16000 hours. Both of the analyses are based on LNG tanks with a capacity of 30m^3, which is appropriate for a rather big inland waterway vessel.

Analyze 1. An assumed average power output of 500 kW (per engine) in 4000 hours has been used as base for this calculation (see red ring in figure 16).

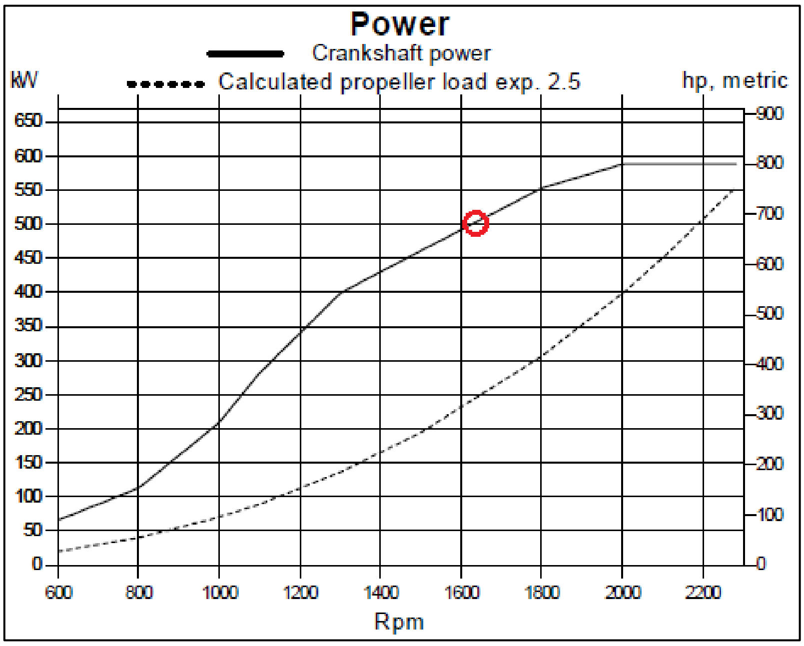


FIGURE 16 VOLVO PENTA D13-800 MC. KW IS PLOTTED AGAINST RPM (VOLVO PENTA, 2014).

This is also giving the torque force by the equation below: (where P = [kW], M= [Nm] and ω = [rpm])

[1] Rating: Volvo Penta's allowed power output. The following text is copied from Volvo Penta's website:

RATING 1 (Heavy Duty Commercial) For commercial vessels with displacement hulls in heavy operation. Load and speed could be constant, and full power can be used without interruption.	**RATING 2** (Medium Duty Commercial) For commercial vessels with semiplaning or displacement hulls in cyclical operation. Full power could be utilized max 4 h per 12 h operation period. Between full load operation periods, engine speed should be reduced at least 10% from the obtained full load engine speed.
RATING 3 (Light Duty Commercial) (Light Duty Commercial) For commercial vessels or craft with high demands on speed and acceleration, planning or semi-planning hulls in cyclical operation. Full power could be utilized maximum 2 h per 12 h operation period. Between full load periods, engine speed should be reduced at least 10 % from the obtained full load engine speed.	**RATING 4** (Special Light Duty Commercial) For light planning craft in commercial operation. Recommended speed at cruising = 25 knots. Full power could be utilized max 1h per 12 operation period. Between full load operation periods, engine speed should be reduced at least 10 % from the obtained full load engine speed.
*** RATING 5** This power is intended for pleasure craft applications, and can be used for high speed planning crafts in commercial applications with special limited warranty, see warranty and service book.	**PRIME POWER** For Gensets and Auxiliary engines with constant speed ratings. For continuous service – over loadable by 10% for one hour within an operating period of 12 hours.

(Volvo Penta (b), 2006)

$$P = \frac{M * \omega * 2\pi}{60 * 1000} \rightarrow M = \frac{P * 60 * 1000}{\omega * 2\pi} \rightarrow M = \frac{500 * 60 * 1000}{1650 * 2\pi} \approx 2894\ Nm$$

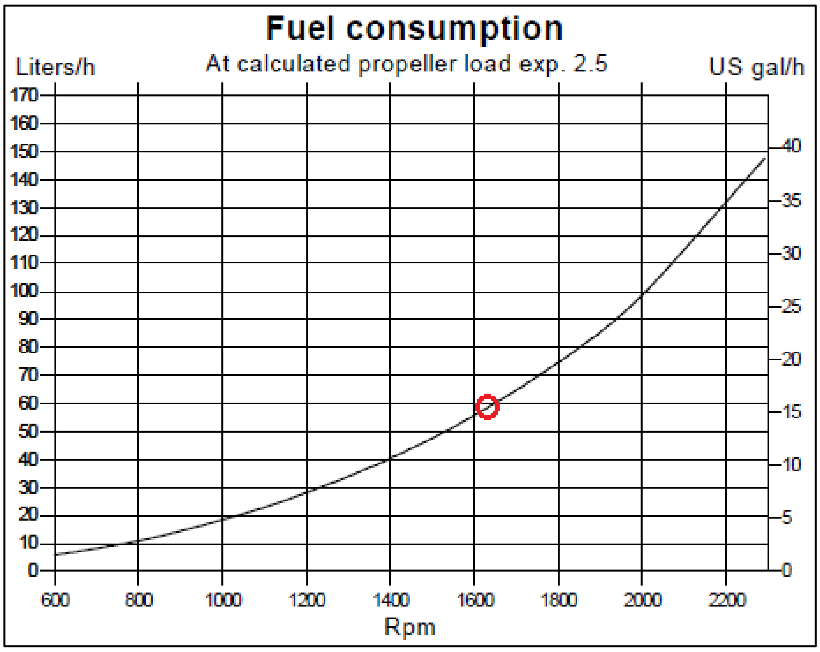


FIGURE 17 FUEL CONSUMPTION FOR VOLVO PENTA D13-800 MC. LITERS/H PLOTTED AGAINST RPM (VOLVO PENTA, 2014).

The power output of 500 kW is obtained at approximately 1650 rpm, which consequently gives a fuel consumption of 58 liters of diesel per hour. This is equal to a lower heating value of 2079 MJ per hour, which accordingly is equal to approximately 100 liters of LNG per hour. (The calculation is based on numbers from the *market of today* chapter). (Note that the price of LNG is said to be 57% cheaper (in USA) and 36% cheaper (in Europe) than diesel per *energy* unit.)

If 4000 hours is assumed as a life length, it gives a total fuel consumption of 232 m^3 diesel, or 400 m^3 LNG. Those numbers are multiplied with two (twin installation) and inserted in

Table 14 for a total comparison. The tank system costs are taken from the *Price LNG versus distillate fuel* chapter. Note that only one tank system is needed even for a twin installation.

The repair and maintenance (R&M) cost (including labor cost of €87.43/h) is assumed to be an average between the two findings, and is therefore set to 110% of the current costs. It could also be such as those costs are higher in the beginning years but gets lower with time. The assumption of 110% is appropriate in this scenario as well. This assumption could be applied with high certainty on the purchase cost as well, i.e. it will probably be relatively cheaper with time, since the technology is still not fully developed. The origin cost for R&M is deriving from a Volvo Penta internal tool, which is based on engine setup, operating profile and total time of operation.

TABLE 14 TOTAL COST OF OWNERSHIP, A COMPARISON BETWEEN MDO AND LNG OVER 4000 HOURS. PRICES ARE IN THOUSANDS € AND THE MDO PRICE IS ASSUMED TO BE 1.00 €/LITER (THIS IS JUST A REFERENCE NUMBER). THE LNG PRICE FOR THE USA market is based on (ACSF, 2012), which states that LNG will always be at least 57% cheaper than distillate fuel. The European price of LNG is assumed to be 60% more expensive than in the USA.

Costs [€]	Distillate fuel (MDO)		LNG	
	USA	**Europe**	**USA**	**Europe**
Fuel cost (today's prices)	464	464	199.4	319.0
Purchase	200	200	400	400
R&M	23.6	23.6	26	26
Tank system	10	10	750	750
TCO:	697.6	697.6	1375.4	1495.0

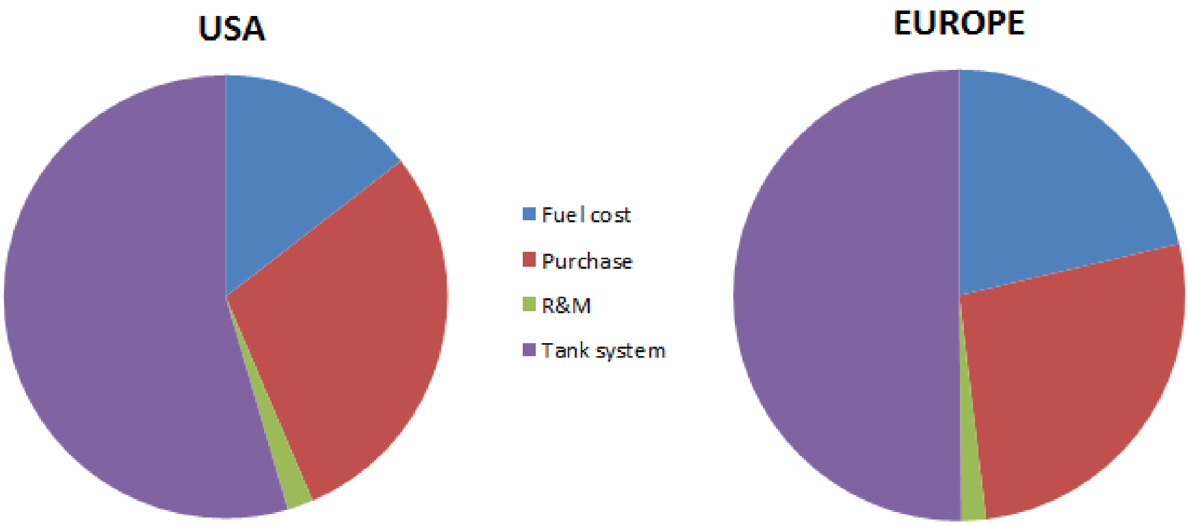


Figure 18 Cost distribution for the LNG option in analyze 1

Analyze 2. The second analyze has been made with an assumed power output of 298 kW (400 hp), (per engine) i.e. maximum power output. The reason for this setup is because it has to align with Volvo Penta's rating profile. 298 kW can be obtained at 1600 rpm, which results in approximately 52 liter diesel per hour (see figure 19).

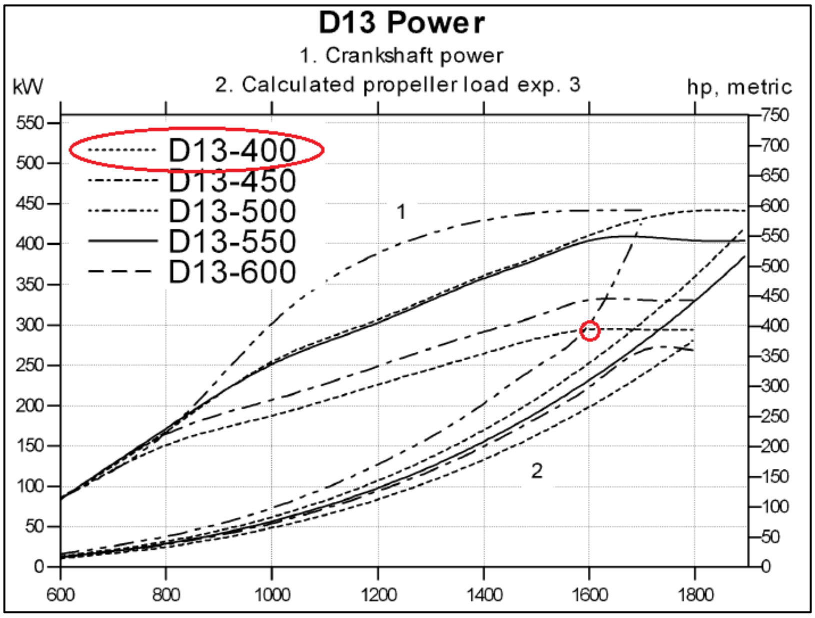


FIGURE 19 VOLVO PENTA D13-400, KW AGAINST RPM (VOLVO PENTA, 2014).

The same equations as in analyze 1 can be applied to obtain the torque force in this analyze as well:

$$P = \frac{M * \omega * 2\pi}{60 * 1000} \rightarrow M = \frac{300 * 60 * 1000}{1600 * 2\pi} \rightarrow M \approx 1790\ Nm$$

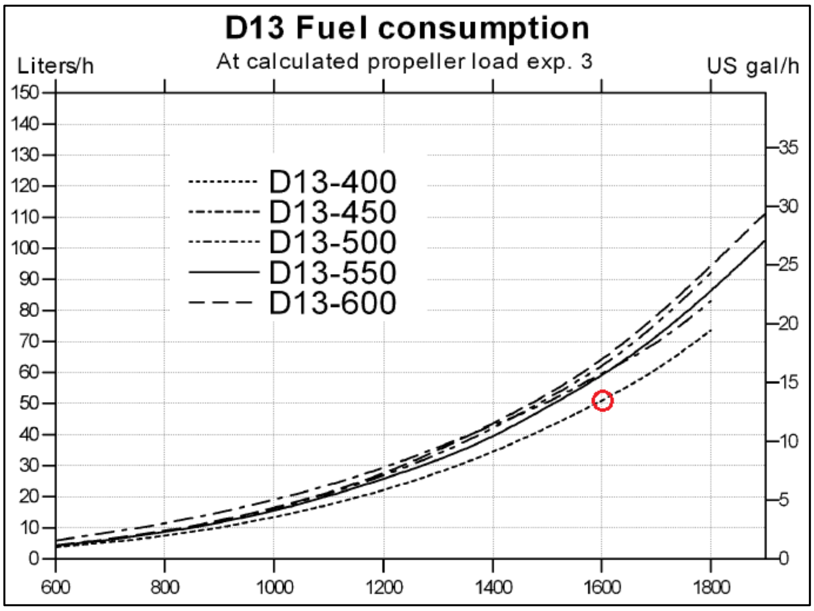


FIGURE 20 VOLVO PENTA D13-400 FUEL CONSUMPTION (VOLVO PENTA, 2014).

This is equal to 1864 MJ which is about 89 liter LNG. The analyze is based on a 16000 hour interval, which gives a total fuel consumption of 832 m^3 diesel, or 1424 m^3 LNG. Those numbers are multiplied with two (twin installation) and summed up in table 15.

TABLE 15 TOTAL COST OF OWNERSHIP, A COMPARISON BETWEEN MDO AND LNG OVER 16000 HOURS. PRICES ARE IN THOUSANDS € AND THE MDO PRICE IS ASSUMED TO BE 1.00 €/LITER. THE LNG PRICE IS BASED ON (AMERICAN CLEAN SKIES FOUNDATION, 2012), WHICH STATES THAT LNG WILL ALWAYS BE 57% CHEAPER THAN DISTILLATE FUEL IN USA. THE EUROPEAN PRICE OF LNG IS ASSUMED TO BE 60% MORE EXPENSIVE THAN IN THE USA.

Costs [€]	Distillate fuel (MDO)		LNG	
	USA	Europe	USA	Europe
Fuel cost (today's prices)	1664	1664	715.6	1145
Purchase	200	200	400	400
R&M	98.8	98.8	108.6	108.6
Tank system	10	10	750	750
TCO:	1972.8	1972.8	1974.2	2403.6

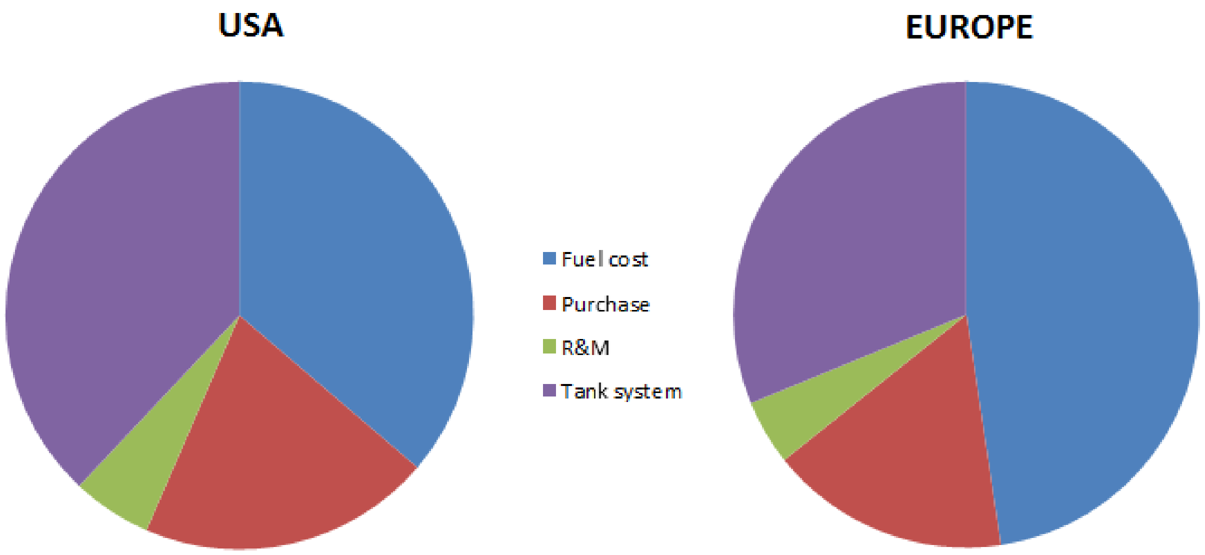


FIGURE 21 COST DISTRIBUTION FOR THE LNG OPTION IN ANALYZE 2

LNG is a cheaper alternative than distillate fuel, if multiple engines are used under a very long time frame. One should be aware of that those TCO analyzes has been done by comparing 100% MDO with 100% LNG, which not necessary has to harmonize with the reality, where e.g. 10 % MDO together with 90% LNG could be a case, which will impact the result by fuel cost but also by tank arrangement.

The reader should notice that the residual value of the two different engines is not included in this analyze. It has been excluded on purpose, since the residual value of a LNG engine is very uncertain at the moment. This kind of analyze is depending on many factors e.g. where the engine is located. It is with high certainty a factor that gives high deviations in residual and fuel prices, which needs to be analyzed closer.

This TCO analysis could of course also be applied to conversions of vessels as well, where estimated fuel savings is based on the remaining life length to obtain a net present value. The reason to why such an analysis is omitted is because it is difficult to estimate a conversion cost since it is completely dependent on the actual vessel.

Trade-off

The reader can understand that there is a certain amount of hours that is required for a LNG engine to be cheaper than a conventional engine. This number is completely dependent on the engine set-up, as well as the cost relations. Some calculations have been made to clarify this for both analyzes.

TABLE 16 CALCULATION NEEDED TO FIND A TRADE-OFF IN ANALYSIS 1. (X = HOURS).

	MDO/MGO	LNG	
	USA & Europe	USA	Europe
Fuel cost/h	$\frac{464000}{4000} = 116$	$\frac{199400}{4000} = 49.85$	$\frac{319000}{4000} = 79.75$
Initial cost	200 000	400 000	400 000
R&M	23 600	26 000	26 000
Tank system	10 000	750 000	750 000
Total cost/h	233600 + 116x	1176000 + 49.85x	1176000 + 79.75x

The trade-off is now found by setting the equations of total cost equal. Hence,

$$For\ USA: 233600 + 116x = 1176000 + 49.85x \ \rightarrow 66.15x = 942400 \ \rightarrow x \approx 14246\ hours$$

$$For\ Europe: 233600 + 116x = 1176000 + 79.75x \ \rightarrow 36.25x = 942400 \ \rightarrow x \approx 25997\ hours$$

TABLE 17 CALCULATION NEEDED TO FIND A TRADE-OFF IN ANALYSIS 2. (X = HOURS).

	MDO/MGO	LNG	
	USA & Europe	USA	Europe
Fuel cost/h	$\frac{1664000}{16000} = 104$	$\frac{715600}{16000} = 44.725$	$\frac{1145000}{16000} = 71.563$
Initial cost	200 000	400 000	400 000
R&M	98800	108600	108600
Tank system	10 000	750 000	750 000
Total cost/h	308800 + 104x	1258600 + 44.725x	1258600 + 71.563x

The same procedure as above gives trade-offs at:

$$For\ USA:\ 308800 + 104x = 1258600 + 44.725x \ \rightarrow 59.275x = 949800 \rightarrow x \approx 16024\ hours$$

$$For\ Europe:\ 308800 + 104x = 1258600 + 71.563x \ \rightarrow 32.437x = 949800 \rightarrow x \approx 29281\ hours$$

Combustion processes

Both LNG and diesel can be used in different kind of combustion processes. The different processes have both advantages and disadvantages, and it is therefore interesting to investigate and connect the processes with various engine applications. 5 different LNG combustion processes together with respective advantages and disadvantages are described below. One should notice that this is just theory and the reality could somewhat deviate from what is written. It is also difficult to predict exactly how the different alternative will comply with the different regulations. The NRMM regulation is not finalized yet, which makes the prediction even more difficult.

Alternative 1

<u>Spark-ignited, lean burn (λ>1.5), with SCR</u>

This alternative can also be operated without a SCR, and still comply with IMO Tier III. I.e. it will comply with IMO III without any after treatment at all, which obviously is a huge benefit. It could also probably work with a very small diesel pilot instead of spark plugs. λ is almost equal to 2. It operates with an Otto cycle.

Advantages: This setup does not need a DPF, and it will comply with NRMM (if a SCR is used), EPA and IMO regulations. The EPA and IMO regulations can be fulfilled even without a SCR. The efficiency is very good at optimal rpm's.

Disadvantages: It runs on 100% gas, and will evidently not be able to run on diesel only, which can be seen as a drawback. It will also emit high parts of methane.

Alternative 2

<u>Spark-ignited, stoichiometric burn (λ=1), with cooled EGR and TWC</u>

This alternative will have a lower efficiency than alternative 1, since lean burn is a more efficient way of combustion. This alternative without EGR would have remarkably lower efficiency and a λ=1 engine would therefore require EGR. This would increase the cost and complexity, since Volvo Penta does not produce any marine EGR-engines today. A TWC is not seen as a drawback due to its relatively easy design. It operates with an Otto cycle. The possibilities of cooling the EGR are good, since raw water is available on marine applications.

Advantages: It will comply with NRMM, EPA and IMO regulations, and will be almost as good as alternative 1 considering efficiency.

Disadvantages: It runs on 100% gas, and will not be able to run on diesel. It also has a less efficiency compared to alternative 1. It will need EGR.

Alternative 3

<u>Dual Fuel, lean burn (λ>1) , with SCR and DPF</u>

There is a high probability that a diesel oxidation catalyst (DOC) is needed if this setup is used. A DOC is used to oxidize CO and HC. The SCR could probably be omitted but still comply with IMO Tier III. It operates with a mixed Otto and diesel cycle.

Advantages: It will be able to run on both gas and diesel and it will comply with IMO and EPA.

Disadvantages: It is not known if it will comply with the NRMM regulation. It will also emit high parts of methane. It will require two fuel tanks.

Alternative 4

<u>High Pressure Direct Injection (HPDI), lean burn (λ>1)</u>

This alternative will not comply with the NRMM (genset/aux) proposal without a SCR. It will possibly meet the requirements of the NRMM proposal for propulsion. It is perceived as a good alternative. Volvo Trucks are developing a HPDI alternative for their D13. Volvo Penta can probably adapt this engine for use in marine environments. A HPDI engine is mainly a LNG engine, but with a pilot injection of diesel (about 5%) to be able to ignite the fuel by combustion. This alternative is operating according to a diesel cycle.

Advantages: It keeps the diesel performance which consequently means that it also has a good efficiency.

Disadvantages: The technique for this does exist, but does not work as intended. A HPDI engine will not run on diesel only. It will require two fuel tanks.

Alternative 5

<u>Easy conversion of standard diesel engine (about 50-50 LNG-diesel) (a simple dual fuel)</u>

It is possible to just convert an existing Volvo Penta diesel engine to run partly on LNG. It comes with some advantages and disadvantages as well.

Advantages: Relatively easy and cheap to convert (compare to develop a SI or HPDI-engine). It will be able to let the engine operate on about 50-70% LNG (to make it able to cut some fuel costs). This alternative also has a good efficiency, particularly on constant rpm's. It could therefore be used as gas-electric.

Disadvantages: Will need the same after treatment as diesel to meet the requirements of the regulations. It will require two fuel tanks.

Sum-up of the alternatives

The obvious question at this point is then; which method, if any, will suit Volvo Penta's applications best? The answer to this question is not as obvious, since it depends on many variables, e.g. the type of the vessel, operating profile, operating area etc. Target specifications from different customers would therefore be the best input at this moment. But the knowledge to make such a specification today is not sufficient. One can formulate it such as this thesis is aimed to find out how those specifications will most possibly look like in the future.

The regulations by IMO and EPA needs to be met, while the NRMM proposal are not set yet, and could therefore not be set as design requirements. The inland waterway sales is not either a very big market for Volvo Penta, at least not big enough to function as overall requirements, but also because of the proposal's very stringent levels.

LCA

The LCA analysis speaks for itself; it is shown that LNG is the cleanest fuel among the alternatives when measuring GHG-gases. But that does not necessary mean that LNG is the best alternative, since it is the regulations that decides if a fuel is useable or not. That is not presented in the LCA analysis, but will be reviewed below.

One should also be aware of that the LCA is done for a 100% LNG lean burn engine. The emissions can change depending of what combustion method that is used. But it is fair to say that the emission levels are similar, since the combustion method is just a part of the entire life cycle.

Applications

A LNG tank can only keep the fluid for a maximum of 30 days (if a type C-tank is used). This reduces the usage to fewer applications. It is e.g. not suitable to use LNG as fuel in an emergency engine (which often is installed close to the chimney on ships), since this always is supposed to be on standby and could therefore not rely on a LNG-tank.

LNG is an alternative for vessels with a defined operating schedule, since it requires some planning of when and how often it is desired to bunker to avoid boil-off.

The optimal vessel to operate on LNG would be a vessel that goes on a specific route, every day, all year around. Then, the boil-off phenomena would not be an issue. The access to LNG would also be easier to handle if the vessel goes back and forth to the same harbor (where LNG is available). This optimal case is perfectly suited for the first alternative of combustion processes. It would just need one type of fuel tank, *if* the auxiliary engines operate on LNG as well.

Auxiliary and genset engines can be found in all bigger vessels. According to the *competition* chapter, most LNG engines today are out of Volvo Penta's range and are installed in bigger vessels. Auxiliary engines in bigger vessels are therefore considered an interesting market, since it will probably be easier to use just one kind of fuel on a vessel. Mail conversations with boat builders are also pointing on this.

The reason to why LNG is more common on bigger vessels is probably because a conversion from HFO to LNG comes with more benefits than a conversion from MDO/MGO to LNG. A major benefit that only comes along when going from HFO to LNG is the reduction of sulfur. The IMO regulation of a maximum sulfur content of 0.1% (in the ECAs) will come in force January 1st 2015, and that could only be met with HFO if it is combined with an expensive and complex scrubber system. This limit is almost automatically met with an engine suited for distillate fuel (Volvo Penta engine), since the content of sulfur in MGO is ≤0.1%.

It is not perfectly suitable to power a small vessel with high demands on speed and range with LNG. This is because of the increased weight from the bigger tanks, and a slightly decreased power output (based on 100% LNG with spark ignition). But on the other hand, it should not be considered as impossible. The importance of emission levels and fuel costs should also be considered.

Design

Various types of vessels and their respective possibilities of being powered by LNG are presented below. This will also be further discussed under *discussion.*

Inland Waterway Vessel

Assume that an IWV (dry bulk) should operate in Germany from the Dortmund-Ems Canal to the Elbe River (north of Magdeburg). This is a distance of approximately 321 km. The IWV's Dead weight tonnage (DWT) is 3000, which accordingly means that $(1{,}3\ (100\ ton\ per\ liter\ and\ km) * 30 * 321\ (km) =)$ 12519 liters of diesel is needed for a one-way route. A 28000 liter (28 m^3) tank is assumed to be used for this kind of route (to reach back and forth). This implies that a LNG tank, which contains the same amount of energy, would need to be about 70 m^3 in outer dimensions (approximately 2.5 times bigger), according to the *marine fuels* chapter. Consequently, the bulk storage has roughly to be decreased with 42 m^3. Everything therefore comes down to an optimization problem that is impossible to answer, without more information about the cargo and time schedule.

A possible tank solution would be to use *Marine Service GMBH's* fuel tanks of 33.4 m^3 each. Two of those containers would need the space equivalent to two 40 feet containers $(2 * 77 =)$ 154 m^3. The company is also claiming that the tanks can keep LNG for up to 80 days because of the thick insulation. The amount of possible storage days can therefore be seen both as an advantage, but also as a disadvantage.

To get any sense out of this, an existing case has been used as reference; the 110 meter long Greenstream vessel (see figure 22), powered by 4 100% LNG lean burn, spark-ignited (i.e. alternative 1 in this thesis) Scania-Sandfirden engines on 285 kW each (note: this is just below the 300 kW level for the NRMM proposal, which means a NO_x emission regulation of 2.1 g/kWh instead of 1.2 g/kWh). The vessel has a cargo capacity of 3124 m^3 (Ship Technology, 2014). If this vessel would operate on diesel, the selected route would cost about $12519 * 2 * 1\ EUR/l =$ 25038 EUR, while the same route on LNG will cost approximately $25038 * 0.43 * 1.6 =$ 17226 EUR. (This is excluding the cost of repair and maintenance). One can therefore save $25038 - 17226 =$ 7812 EUR, but the cargo capacity will be reduced by 42 m^3 (1.3%). This assumes that there is possible to find a storage area for the bigger LNG tanks. That is a rather safe assumption, since it has been proven to be feasible in the Greenstream case where the tanks have been placed on the aft deck.

FIGURE 22 GREENSTREAM WITH SCANIA-SANDFIRDEN SI 100% LEAN BURN LNG ENGINES AT 285 KW EACH (SHIP TECHNOLOGY, 2014).

It obviously seems that this is an easy choice; LNG is both cleaner and cheaper (as long as the reduced cargo capacity is not worth more than 7812 EUR). But one has to remind that this is close to an optimal vessel to power with LNG, both in terms of operating route and global location (European inland waterways).

Pilot boat

Damen Stan Pilot 1505 (see figure 23) is chosen as a pilot boat reference for usage of LNG. The vessel is 15.40 meters long and is powered with 1050 kW. The fuel capacity is 2.6 m^3 and is located according to figure 24. This is not an allowed location of LNG ("unless the arrangement is accepted by the Commandant (CG-521)") according to US Coast Guard's Policy letter CG-521 (chapter 2.3) which is treating LNG as a marine fuel. The reason to this is that "natural gas fuel storage tanks must not be located below accommodation spaces, service spaces, or control stations".

The required size of LNG is $(2.6 * 2.5 =)$ 6.5 m^3, if the current range should be kept.

FIGURE 23 DAMEN STAN PILOT 1505 (DAMEN (A), 2011).

The required tank volume could probably be reduced in many cases, where lesser fuel is sufficient. It could also be combined with Volvo Penta IPS (a forward facing propeller pod), which is reducing fuel consumption with 30%. Hence, a LNG fuel tank of $(6.5 * 0.7 =)$ 4.55 m^3 is needed to maintain the same distance range.

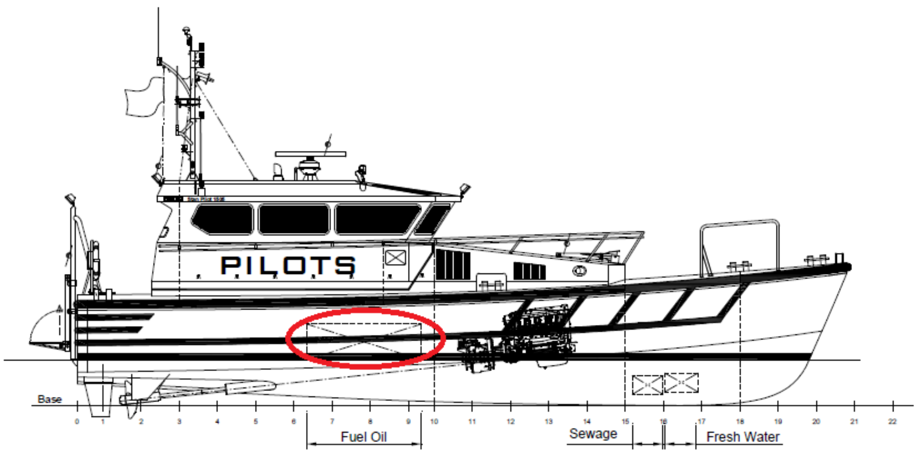


FIGURE 24 PILOT WITH HIGHLIGHTED FUEL TANK POSITIONS (DAMEN (A), 2011).

Tug boat

A Damen tug boat of 16.76 meters has been evaluated for LNG use. The tug boat is only used as a reference for size and consumption, not for conversion of the actual vessel. The vessel is powered with 894 kW and has a fuel capacity of 14.2 m^3, which location can be seen in figure 26. This is not an allowed position for storage of LNG (according to the IGF Code, chapter 5.3.4.1, which says):

> "The fuel tanks shall be located at a minimum distance of B/5 or 11.5 m, whichever is less, measured inboard from the ship side at right angles to the centreline at the level of the summer load line draught;
> where:
> B is the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught). Refer to SOLAS regulation II-1/2.8."

Hence, a new location has to be found for the $(14.2 * 2.5 =)$ 35.5 m^3 LNG tanks.

FIGURE 25 DAMEN STAN TUG 1606 (DAMEN (B), 2011).

This vessel could as well as the pilot boat, be equipped with Volvo Penta IPS. The IPS is reducing the fuel consumption by 30%, and the tank size could therefore be decreased to $(35.5 * 0.7 =)$ 24.85 m^3, which still is a challenge of space though. Particularly if on-board working area is prioritized, which often is the case on tug boats.

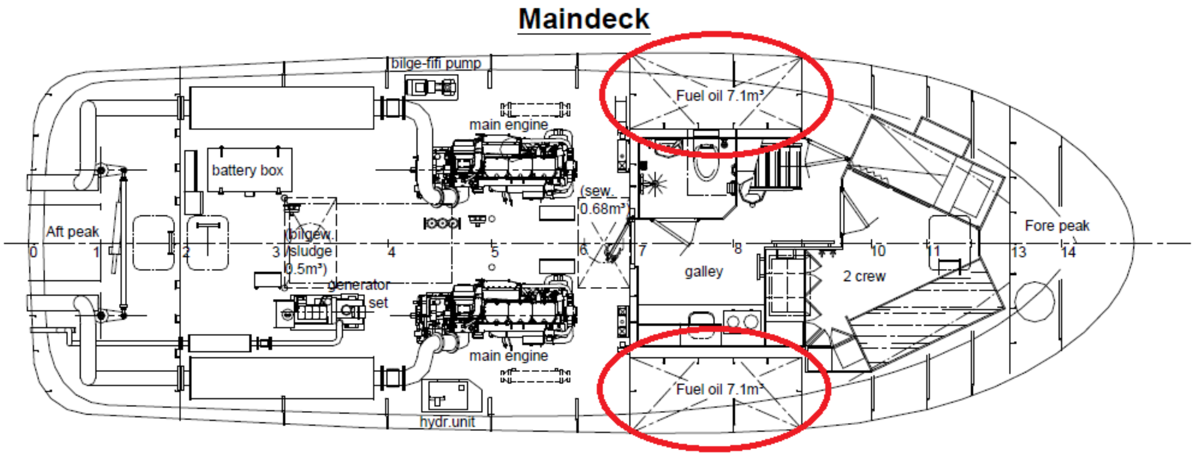


FIGURE 26 DAMEN TUG BOAT WITH HIGHLIGHTED FUEL TANK POSITIONS (DAMEN (B), 2011).

Bigger ships

LNG is at this moment most common as a marine propulsion fuel in bigger vessels. But as mentioned before, bigger ships still need auxiliary power, and that is where Volvo Penta can provide power. Mail conversations with people from the business are pointing on the benefits with having just one fuel on a vessel. Another benefit with providing LNG engines to bigger ships is that Volvo Penta does not have to be concerned about the tank allocation and the related pipe systems if a vessel already is certified for LNG. This is probably a potential and growing market for Volvo Penta, since most of the vessels in the current "LNG vessels order book" are out of Volvo Penta's range in regards to propulsion power.

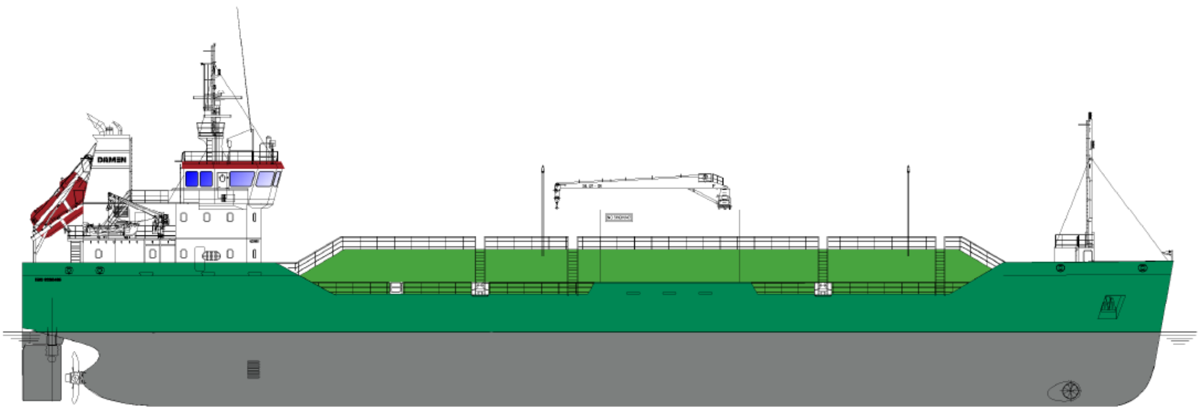


FIGURE 27 DAMEN LIQUEFIED GAS CARRIER 3500 (DAMEN (C), 2011).

An example of a ship that could be powered with LNG auxiliary engines is *Damen Liquefied Gas Carrier 3500* (LOA: 89.28 m) (see figure 27). This ship is powered by MAN 6L35/44DF, which is a big dual fuel engine. The vessel also accommodates one shaft generator (435 kVA) and two diesel generator sets (280 kVA). Those could possibly be substituted with LNG gensets. But since the main engine is running on both diesel and LNG, it is still necessary to carry diesel tanks onboard. Hence, the only benefits with LNG gensets would be a lower cost (but maybe just a small fraction overall) and cleaner exhaust gases. It exist more incentives to run the auxiliary engines on LNG if the main engines are suited for LNG only (like Greenstream, the IWV example), which also seems to be more common.

Ferries

Älvsnabben is a public transportation ferry route in the town of Gothenburg. The route is operated by about 7 ferries, which all are about the same size. *Älvsnabben 3* has been chosen as reference vessel.

Älvsnabben 3 (see figure 28) has a LOA of 27.24 m and a displacement (with load) of 117 tons. The fuel capacity is 7100 liters, which today is containing of MK1 diesel (Swedish Miljöklass 1 diesel, maximum 10 mg sulfur per kg fuel). It is power by two Volvo Penta TAMD 122 with a total power of 559 kW. The ferries are operating all year round and daily from approximately 5.30 – 00.30. The cruising speed is 11.5 knots.

FIGURE 28 ÄLVSNABBEN 3 (S&H, 2014).

The *Älvsnabben* ferries have different life length, and no more ferries are scheduled at the moment (except from two ferries that already has been ordered). The two ordered ferries are prepared for diesel-electric propulsion. An engine conversion, from diesel to natural gas could still be relevant in the future; it mainly depends on decisions from Gothenburg city. Combustion method 5 seems to be the easiest and cheapest solution for this kind of vessel. That is also confirmed by *Styrsöbolaget*, who owns and maintains the ferries. A conversion would probably not happen without any leverage from Gothenburg City, since most of the engines in the *Älvsnabben* vessels are already replaced with new diesel engines.

A benefit with these kinds of vessels is that it operates along the same short route (2-3 nautical miles), back and forth every day. It means that it is always able to bunker natural gas at the same spot, and it is never far away. With that said, one can assume that a tolerance against a smaller range is acceptable, if the natural gas gives lower fuel consumption together with lower emissions.

The current vessels have an upper deck, which today is used for passengers. It could instead be a possible area for storage of LNG or CNG tanks. If so, stability would most likely be an issue. It therefore seems like new buildings are most interesting. The information in this sub chapter derives from (Styrsöbolaget, 2014).

Summarize of various vessels

The IWV together with auxiliary engines for bigger ships seems to be the most appropriate type of vessels to power with LNG. But one still has to keep in mind that the IWV example in this thesis is an optimal case. The case with auxiliary engines operating on LNG will be most beneficial if the main propulsion is running on LNG only. DF main propulsion vessels could also have use of LNG auxiliary engines as well, especially if it uses the auxiliary engines when it is standing still in ports inside an ECA.

Ferries could also be an alternative for natural gas, especially new ferries where the tank arrangement can be optimized before it is built. This is particularly due to stability and space reasons.

Customer's decision

The customer's decision whether to invest in a new vessel powered with either conventional fuel or LNG is obviously based upon several aspects. LNG would be a very interesting option if a low TCO is the primary incentive. But it still has to harmonize with the other factors, like infrastructure, operating profile, available space and location. This study is therefore showing that LNG for engines in Volvo Penta's power range has a rather small business segment, as it is today. This is mainly due to available space and various operating profiles.

Auxiliary engines and IWV is found to be the most possible markets for Volvo Penta to market LNG engines. But other vessels, mostly depending on its operating profile could also be adequate for LNG. This is therefore a very individual question, but one can generally state that a vessel with an even and predictable operating profile could be appropriate to run on LNG. This is because of the inevitable boil-off, which obviously is supposed to be kept to a minimum or preferably zero. The reason for this is because of both environmental and economic aspects. A regulation regarding releasing methane by venting (boil-off) is non-existing today, but could also be a major factor in the future, if such a regulation will be introduced.

Other factors that could be of importance are the infrastructure and time spent in NECAs. The infrastructure is not only dependent on the outspread of LNG terminals, since most of the bunkering is performed by truck to ship and is therefore rather flexible. But the LNG needs to be supplied to the trucks from somewhere, which is limiting the areas of where a LNG vessel could operate.

Most of Volvo Penta's engines are operating in the upcoming NECAs, which implies that the NO_x emissions will be forced to be kept under 2.0 g/kWh (if rpm>2000 or 2.03 if rpm=1700). This could be met by just using LNG, without any after treatment. This is a benefit compared to if distillate fuel is used, which will require a usage of after treatment.

Engine size

Volvo Penta has a span of engines from 77-588 kW, and 2.4-16.1 liters in displacement. The most potential cases for a LNG engine are shown to be for auxiliary use or IWV propulsion. It is therefore most possible that an eventual LNG engine would be as big as possible. Hence, Volvo Penta D13 and D16 are the most interesting options to convert to LNG. A gasoline engine can also be a case for conversion, particularly into a 100% SI-engine.

Discussion

The findings in this report derive as written above, from meetings with people from Volvo Penta, Volvo Group and also from people outside Volvo. A big share of the gained knowledge also derives from literature like publications, articles, books, websites etc. It is difficult to find a clear pattern, since the deviation of the material is widespread. Some sources are pointing in one direction, whilst other is pointing in the opposite direction. The content has therefore been carefully analyzed, to find the best solution for Volvo Penta's situation. One should be aware of this, and not blindly trust the result in this report, but rather treat it as guidance for how to approach this, for Volvo Penta, new market segment.

The results are showing that LNG could be interesting for Volvo Penta. It does not clarify very much regarding when and where this could be an opportunity for a new business though. This chapter is therefore aimed to clarify this.

The NRMM regulation is still under development, and the proposal can be changed. In fact, some sources are saying that an adjustment of the emission levels is likely to happen. Volvo Penta should therefore be careful and wait until this regulation is completed. This is because of the findings that say that the inland waterways most likely will be one of the biggest market opportunities for LNG propulsion. It could likely be such a scenario which means that new IWV will benefit from the new regulation, if they are operating on LNG instead of distillate fuel. This regulation is aimed to be done by 2016 which accordingly means that Volvo Penta should wait with a decision (whether to investigate and develop a LNG engine) at least until then.

The other potential market for LNG engines is auxiliary engines and marine gensets. This market is at the moment too small, and a LNG engine just for those purposes is not profitable. It could instead be wise to develop an engine that could be used for both this and the inland waterways, to keep the costs down. It is in other words a good idea to wait for the NRMM regulation even due to this reason.

The reasons to why LNG is growing rapidly as a marine fuel are both because of its lower price, but also because of lower emissions. This can be interpreted as an unavoidable alternative, but this thesis has been digging deeper and shows that the disadvantages with LNG are heavier than those two benefits in most cases. It is mainly because of the inevitable phenomenon of boil-off. This makes it difficult for vessels that do not operate all day, all year to utilize the benefits of LNG. Today's infrastructure is also making it difficult to bunker LNG, which obviously is a drawback, even if vessels in Volvo Penta's range can utilize TTS (Truck-to-ship) as bunker method. The TTS method makes it difficult to assess the infrastructure, since a truck is not stationary, but not totally flexible either. Most sources are claiming that LNG is (or at least will be) available, as long as a vessel is operating close to European harbors. I.e. the European infrastructure should not be considered as a major issue, but well a challenge. Another reason to why LNG is growing fast as a fuel for bigger ships is that the amount of fuel is very high. As the reader understands from the TCO- and the trade-off-calculations; the more fuel used, the easier it is to reach and pass the trade-off value (due to very high investment costs). This means that it seems difficult for Volvo Penta to provide engines that will give a high (or any) return on investment as of today, but it will probably be different if the investment costs are decreasing.

It could be an alternative for Volvo Penta's marine department to utilize the same engine that already is developed for industrial purpose. This engine could work as gas-electric, and therefore also be used as propulsion engine for e.g. IWV, like in the example with the IWV Greenstream. It can also be used as an auxiliary engine both for marine and industrial purposes. This is an easy solution for Volvo Penta, both in terms of money and time. Even if, according to internal sources, it needs to be further developed and optimized. Other benefits with this kind of solution are that it can be operated on any forms of natural gas, not just LNG. The customer can then decide on its own whether they think CNG or LNG is best suited. It is also, as mentioned, better from an economical point of view if Volvo Penta can use the same natural gas engine for their segments, industry and marine.

As written above, propulsion for IWV and auxiliary engines seems to be the best market for a LNG engine in Volvo Penta's range. One should notice that the current fleet and order book today is containing about 100 vessels though. It is still a very small market. Even if it is said to be rapidly increasing, the market is still in its first phase, and today's customers can be defined as pioneers. Some oral sources claims that the fact of a thin order book shows that customers are choosing other ways than LNG to meet the upcoming regulations. It is therefore not obvious if LNG really is a fuel of the closest future.

The reader should be aware of that the fuel cost savings presented in the TCO is valid only if LNG is easy accessible and if the cost relation between MDO and LNG is kept. That the cost relation is kept and that the infrastructure is developed is according to this thesis the most possible outcome.

It should also be mentioned that the very expensive LNG tank systems will probably decrease in cost with time, given that the current development continues. The performance (i.e. days before boil-off) of the tank systems will probably also increase together with the current development. Volvo Penta's situation would of course be impacted by this, and should therefore not just discard LNG because of the current situation. It is also possible that ports in Europe will offer a discount for vessels powered by LNG, which could be another incentive for vessels to operate on LNG instead of MDO/MGO.

The overall reliability of this thesis is difficult to assess, since it is mainly a forecast. But what needs to be mentioned is that numbers, such as fuel consumption, fuel prices, diesel fuel systems etc. is made on coarse assumptions. One should be aware of the fact that those are only estimated, although based on articles, books and interviews with high reliability.

The findings in this thesis are based on today's knowledge, and since this is a relatively new rapidly changing technology, it is not safe to say that the findings are valid for a longer time. This developing market need to be constantly monitored, particularly the order book and the regulations. Those are the factors that indicate how the development is proceeding. It could as mentioned be wise to just monitor the development in the closest future; any direct actions are not necessary. The major changes on the market (infrastructure and price development) are probably going to affect bigger vessels most.

This thesis has not provided much information about any other alternative fuels than natural gas (LNG and CNG), but knowledge about other alternatives has been gathered along the way. The most interesting fuel besides natural gas seems to be methanol/DME. Methanol and DME are two fuels that could be produced from natural gas (with some losses) and it is a fluid in normal temperatures. It contains roughly the same amount of energy per volume unit as LNG, but the tanks do not need to be insulated.

Conclusions

This thesis has led to numerous conclusions. The most obvious is that LNG as a marine fuel is increasing, but perhaps not as rapidly as some sources are stating. There is about 50 LNG powered vessels worldwide at the moment, and about 50 more in the order book. Almost all of those vessels are out of Volvo Penta's power range. Hence, it seems like marine engines less than 1000 kW will continue to be operated on distillate fuel. Although, this means that bigger vessels probably will need LNG auxiliary engines, which can be a market opening for Volvo Penta.

Another market could possibly be IWV, but it is not recommended to decide a go / no-go at this moment, since the regulation for NRMM is not finalized and will probably be changed from today's draft. The amount of engines in this market also seems to be restricted, which could imply a too small market, without any economic benefits. The TCO analysis shows that the trade-off, i.e. when LNG starts to payback the high investment costs is between 14000 and 30000 running hours, given the used parameters (D13, twin installation) (this trade-off will obviously be easier to achieve with a quad engine installation with high total fuel consumption). Those numbers, particularly the fuel system cost, are rather uncertain. The cost for LNG tanks will most probably be decreased with time and an increased production. But it is today rather safe to say that a development for LNG engines will not be economically positive for Volvo Penta. It is also safe to say that retro-fit solutions should be avoided, not because the engine conversion itself, but since the needed modification to an existing vessel is too comprehensive and expensive.

LNG seems at a first glance to be unavoidable as a marine fuel, but this thesis shows that there are many heavy disadvantages, that really matters in a smaller vessel. Those are primarily the required space for tanks and the boil-off phenomenon. NO_x emission is also a concern, mostly for lean burn engines. Spark-ignited and HPDI engines are not able to run on diesel only, which requires a 100% stable supply of LNG. Dual Fuel engines with a share of diesel (more than just a pilot) on the other hand, will require a DPF. Dual Fuel engines are the easiest and cheapest alternative if Volvo Penta will develop a gas engine, but it will require equal after treatment as a conventional MDO engine.

It would be wise to co-operate with either Volvo Trucks or with Volvo Penta's industrial segment if a LNG engine would be of interest in the future. By doing so, cost and knowledge can be better optimized. The market for the marine commercial segment seems at the moment to be too small to be able to stand alone. It is a good idea to focus an eventual conversion on a D13, if Volvo Trucks are succeeding with their HPDI (D13). This is also because D13 is an appropriate size for usage in marine applications, since the required power for IWV or auxiliary engines on bigger ships often are rather high. The D16 would therefore also be of interest to convert into a natural gas engine.

LNG price is dependent on market, which is unlike the oil market where the price is more or less equal before taxes. An investigation that shows prices on different market could be of use. This thesis is an overview. The price is predicted to be lower than MDO and HFO, but what if this prediction is false? This is something that the customer is scared of, and "if no other competitors are entering this market, then it is not so possible that I will do it either" is probably a common thought among customers today. It is probably (obviously) worth to lose what you can gain on switching to LNG. If customers fully believed in LNG, then the order book would have been filled up in 2013 already. But the customers are obviously trusting MDO/HFO with after treatment like SCR, EGR and scrubbers instead.

It is easy to be fooled by all advertisement and information about LNG. LNG as marine fuel is still in its concept/testing phase, particularly considering marine engines in Volvo Penta's size range. Scania-Sandfirden is the only engine manufacturer in this range, and it should be noticed that they have only provided two vessels with LNG engines at this moment. Volvo Penta does, according to the findings, not have to worry about being too late into this market.

A good scenario for Volvo Penta would be if a big customer (particularly an inland waterway customer) wants Volvo Penta to develop a LNG engine. They could in such a case obtain better ways of testing and optimizing an engine on natural gas. It is probably not profitable for Volvo Penta to start and develop a LNG engine without a certain customer, since the wishes and demands according to this study is very scattered depending on the type of application. It could therefore be more efficient to focus on an establishment with a customer that wants to cooperate with Volvo Penta, rather than trying to develop an engine on its own.

LNG seems to be an appropriate substitution for HFO, both because it is cheaper and reduces emissions. A main incentive for HFO vessels to convert to LNG is the reduced SO_x emissions, which is going to be very restricted from January 1st 2015 (when the IMO ECA regulation comes into force) and also in 2020 (when the IMO global regulation comes into force). This is an incentive that does not apply to a transition from MDO/MGO to LNG, since bunkering with MGO will fulfill the 0.1% sulfur level. LNG is therefore more interesting for a ship that has engines suited for HFO. The predicted cost reduction is therefore basically the only solid incentive for a vessel to convert from MDO/MGO to LNG. This implies that the main share of the LNG vessels in the order book (as well as already existing LNG vessels) are vessels that otherwise would have been powered by HFO. As the reader may understand, a ship that spends a major share of its operating time in ECAs will have a greater reason to operate on LNG instead of HFO. Volvo Penta's engines are mostly operating inside those areas, but without any impact of this regulation, since Volvo Penta's engines are suited for MDO/MGO (low sulfur fuel) anyway. It could be smart to just monitor LNG as a marine fuel and see how it affects the market of bigger ships, before Volvo Penta are acting. It is also recommended to keep the eyes open for discounts in ports for LNG powered vessels, since that seems to be rather likely to happen.

The TCO result shows that LNG is an economically profitable fuel given very high fuel consumption over very long time. This is the major incentive for LNG as a replacement for MDO/MGO in smaller engines. Since the fuel price for the future is rather uncertain and the fuel consumption relatively low, Volvo Penta would take a big risk by introducing a marine 100% LNG engine under the current circumstances.

It should be mentioned that methanol/DME should be monitored by Volvo Penta, since some sources are stating that this is a better option in some perspectives. E.g. since it is easier to handle (no cryogenic tanks) and that the risk of boil-off is non-existent. Volvo Penta should *not* ignore DME/methanol as marine fuel. The fuel is not a big success on bigger ships, which also could be a reason for the lack of information about methanol/DME. But it could very well be a useful fuel for smaller engines. It can be produced from methane, with some losses. Infrastructure is not developed at all, but it is a strong recommendation to monitor the development, even if this thesis has not been digging deep into this market.

The recently falling price of crude oil is making LNG less profitable. This probably has a big impact on customers, particularly customers who were considering LNG-MDO as 50-50 before even if the decrease happens to be just temporary.

If an alternative fuel engine is introduced by Volvo Penta, questions like the following will inevitably appear: How many engines need to be sold to pay back the development cost? What is the expected time frame for this value? What does Volvo Penta make in terms of money, per engine? What is the development cost? Etc. Those questions are difficult to answer at this stage.

Lastly, if Volvo Penta is deciding to develop a LNG engine, they have to consider the aftermarket questions as well. I.e. How are a customer supposed to take care of his/her engine? Where, how often, by whom? etc. There are also aftermarket questions that need to be considered regarding, e.g. service intervals, life length and dealer network.

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