

# CHALMERS



## A Feasibility Study on LPG as Marine Fuel

Master of Science Thesis in Nordic Master in Maritime Management

SVEINBJÖRN KJARTANSSON

Department of Shipping and Marine Technology  
CHALMERS UNIVERSITY OF TECHNOLOGY  
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Department of Shipping and Marine Technology  
CHALMERS UNIVERSITY OF TECHNOLOGY



**Abstract**

With the upcoming stricter emission rules fast approaching and the requirements for higher quality fuel, it is inevitable that there will be a change of fuel from HFO to cleaner options. These changes are driven by the knowledge of the health problems associated with emissions from ships in coastal areas. One viable option for meeting these demands for reduced emission is to utilize LPG as a marine fuel.

This thesis investigates the harmful chemicals that are present in the exhaust gases, followed by introduction of LPG. Transport options for LPG and existing motor technology is presented and the feasibility of LPG as a fuel option on the European / Swedish market is studied.

The conclusion from this study is that sufficient infrastructure for distribution of LPG is in place to serve potential marine market demand. Motor technology for using LPG as fuel has been developed for a wide range of power output. The economic incentive in the fuel price difference alone is likely to attract ship owners to invest in LPG fueled fleet.



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## Nomenclature.

MGO:	marine gas oil	PAHs:	polycyclic aromatic hydrocarbons
MFO:	marine fuel oil	EC:	European Commission
HFO:	heavy fuel oil	PSSAs:	particularly sensitive sea areas
LSHFO:	low sulphur heavy fuel oil	NMVOC:	non-methane volatile organic compound
MDO:	marine diesel oil	VOC:	volatile organic compound
FO:	fuel oil	HC:	hydrocarbon
DO:	diesel oil	RoRo:	Roll on/Roll off vessel
NG:	natural gas	Ro-Pax:	RoRo & Passenger vessel
LPG:	liquefied petroleum gas	ISO:	international organization for standardization
LNG:	liquefied natural gas	IGC:	international gas code
CNG:	compressed natural gas	IGF:	international gas fuel
GHG:	greenhouse gas	SIGGTO:	society of international gas tanker and terminal operators Ltd
CO <sub>2</sub> :	carbon dioxide	OCIMF:	oil companies international maritime forum
SO <sub>2</sub> :	sulphur dioxide	MSB:	land regulations from the Swedish civil contingencies agency
SO <sub>3</sub> :	sulphur trioxide	IMDG:	international maritime dangerous goods
SO <sub>4</sub> :	sulphate	ADR:	agreement on dangerous goods by road
H <sub>2</sub> SO <sub>4</sub> :	sulphuric acid	RID:	international transport of dangerous goods by rail
NO <sub>x</sub> :	nitrogen oxides	RTCs:	rail tank car
SO <sub>x</sub> :	sulphur oxides		
PM:	particulate matter		
LR:	Lloyd's Register		
DNV:	Det Norske Veritas		
ECA:	emission control area		
SECA:	sulphur emission control area		
IMO:	international maritime organization		
UN:	united nations		
EC:	elemental carbon		
BC:	black carbon		
Mj:	mega joule		

## **1 Introduction**

LPG has successfully been used as fuel in the car industry for many years. Given that the onshore industry has been cutting emission, ship emissions are becoming a proportionally more significant part of total emissions.

It is estimated that the ship emissions account for 2-4% of global CO<sub>2</sub> emissions, 10-20% of global NO<sub>x</sub> emissions and 4-8% of global SO<sub>2</sub> emissions (Einang 2007).

With the further development of stringent regulations regarding ship emissions there is an opportunity being created that encourages the exploration of developing a future market for Liquefied Petroleum Gas (LPG) as a marine fuel.

LPG emissions are significantly lower compared with conventional fuels like HFO and MDO. Consequently, there are very good environmental reasons for using LPG in coastal areas and on inland waterways.

Two sets of emission and fuel quality requirements are defined by MARPOL 73/78 Annex VI: global requirements, and more stringent requirements applicable to ships in Emission Control Areas (ECA). An Emission Control Area can be designated for SO<sub>2</sub> and PM, or NO<sub>x</sub>, or all three types of emissions from ships.

From 2010, Annex VI to MARPOL 73/78 limited the sulphur content of marine fuel oil to 1.0% per mass in designated SO<sub>x</sub> Sulphur Emission Control Areas (SECA) and 0.1% by 2015.

In addition, from 1 January 2010 the directive 2005/33/EC came into force, limiting all ships on European inland waterways and in ports to use fuel with a sulphur content of 0.1% of mass.

The IMO emission standards for NO<sub>x</sub> are commonly referred to as Tier I, II and III standards. On January 1, 2011 Tier II went into effect. From this date onward, marine diesel engines may emit no more than 7,7 to 14,4 g/Kwh of NO<sub>x</sub> depending on rating.

Tier III enters into effect on January 1, 2016 with NO<sub>x</sub> limit of 2,0 to 3,4 g/Kwh.

## **2 Goal and problem formulation**

The goal of this thesis is to explore the future potential of LPG as a sustainable marine fuel alternative in the context of the European and Swedish markets.

In the effort to explore potential problems within the formulation I have focused on two major questions.

- 1) What is the full potential of LPG as marine fuel in the European and Swedish markets?
- 2) What conditions will be required for the successful establishment of LPG as marine fuel in the European and Swedish market?

## **3 Method.**

In order to answer the goal of this study and qualitative method was used and a great care was taken to use only approved literature and reports from leading experts in relevant fields.

The information in this thesis has mainly been gathered by a literature study and interviews.

Academic books, previous research reports, articles and other relevant literature have been studied.

The purpose with the qualitative interviews was to obtain first-hand descriptions and different opinions on the LPG market.

Information about the Swedish gas market and distribution was gathered by interviews with representatives in relevant positions in the following companies: Svenskt Gastekniskt Center (SGC) and Preem refineries in Gothenburg Sweden.

The written background information is primary based on research literature within the field of ships airborne emission, interviews and technical information from engine manufacturers relevant to the topic.

## 4 Overview of marine fossil fuels

The majority of the existing and proposed marine fuels are of the same origin. The same fuel composition may be available from renewable sources (e.g. natural gas – bio gas, methane) but here only the most common are taken into consideration.

### 4.1 Marine fuel grades

There are at least four main grades of liquid marine fuels including marine gas oil (MGO), marine diesel oil (MDO or DO), marine fuel oil (MFO or FO) and heavy fuel oil (HFO).

MGO is marine gas oil – DMA and DMX grades.

DMA and DMX are the highest quality distillate normally supplied for marine use.

MDO is marine diesel oil – DMB and DMC grades.

DMB is a Distillate Diesel Oil, DMC is a Blended Diesel Oil.

MFO is a blend of MDO and HFO.

HFO is marine heavy fuel oil - Residual Marine (RM) grade.

Today HFO is the most common bunker fuel as it is the least expensive fuel option.



*Figure 4-1 An oil tanker taking on bunker fuel.*

*Source: <http://en.wikipedia.org/wiki/File:Bunkering-or-taking-fuel.jpg>*

## 4.2 Regulatory framework

The International Maritime Organization (IMO) is the specialized agency acting on behalf of the United Nations (UN). IMO has the responsibility for international improvement of maritime pollution and safety standards (IMO 2008b).

The original guidelines for regulations to limit airborne emissions from international shipping resulted from the entry into force of the Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) in May 2005.

MARPOL was adopted in its first state in 1973 by the IMO. The Annex VI to the convention regulates several pollutants, including NO<sub>x</sub> from newly built ships, and SO<sub>x</sub>.

Certain maritime regions are designated emission controlled areas (ECAs) where the regulated emission levels are lower than in the rest of the ocean.

Accordingly, regulations of air pollution from ships are only effective for certain aspects of the present shipping activities.

The regulations will become tighter in a stepwise manner and additionally, the number of emission control areas will potentially increase.



Figure 4-2 ECA's Emission Controlled Areas.

Source: (Greener Shipping in North America. DNV February 2011)

<http://viewer.zmags.com/publication/4ae38aec#/4ae38aec/1>

All waters surrounding Sweden are so called “Sulphur Emission Control Areas” (SECA).

There are two grades of marine fuel allowed in the SECA area:

Low Sulphur Heavy Fuel Oil (LSHF) with maximum allowed sulphur content of 1.0% by mass and Low Sulphur Marine Gas Oil (MGO DMA) with maximum sulphur content of 0.1% used in European inland waterways and in ports in the (SECA) area (The European Parliament and the Council of the European Union 2005).

### 4.3 Environmental impact of marine fuels

NO<sub>x</sub> particles, ozone, SO<sub>2</sub> and CO<sub>2</sub> are all products of combustion of fuel oil; they can be classified as either primary or secondary pollutants.

‘Primary pollutants’ is a term used for the pollutants that are formed during the actual combustion process, while ‘secondary pollutants’ are formed in the atmosphere as a consequence of chemical reactions moving the primary species.

The potential impact that categories influenced by air pollution from oil combustion pose are; health problems, acidification, eutrophication, photo-oxidant formation and climate change, to name the most important (Jackson and Jackson 1996).

An overview of these pollutants and their corresponding impact categories is presented in Table 4-1.

*Table 4-1 Primary pollutants from the combustion of oil and their major potential impacts.*

Impact categories	Pollutant					
	Particles	SO <sub>2</sub>	NO <sub>x</sub>	CO <sub>2</sub>	HC	CO
Health effects	X	X	X			X
Acidification		X	X			
Photo-oxidant formation			X		X	
Eutrophication			X			
Climate change				X	X (CH <sub>4</sub> )	

*Source: (Winnes 2010)*

#### **4.4 Particle formation**

Several chemical mechanisms are involved in the formation of soot from the hydrocarbon molecules in the fuel (Heywood 1988).

Soot consists mainly of hydrogen and carbon with a molar in freshly formed soot of H/C of 1 (Warnatz et al. 2006).

In the diesel cylinder, soot particles originate as a hydrocarbon chain or aromatic ring into which other hydrocarbon compounds attach. PAHs in particular have been identified as precursors of soot formation (Amann and Sieglä 1982; Warnatz et al. 2006).

The precursors of soot, the uncombusted hydrocarbons, result from the combustion of fuel air mixtures that are too lean or too rich.

Too lean mixtures will not ignite and too rich mixtures will not fully oxidize the hydrocarbons. Therefore, the local variations within the combustion chamber are central to the formation of particles (Warnatz et al. 2006).

The mechanisms involved in the formation of soot are still not completely understood.

##### **4.4.1 Particle composition**

Particulate matter is a collection of a very large number of complex solid and volatile particles which are suspended in the exhaust.

These particles can be divided into two main groups; soluble and solid particles. The soluble and solid particles can again be divided into soluble organic fraction and soluble inorganic fraction.

Soluble inorganic fraction consists mainly of sulfur originating from the fuel and water while the soluble organic fraction consists mainly of unburned hydrocarbon from the fuel or the lubricating oil.

The solid organic fraction mainly consist of solid carbonaceous particles originating from partly combusted fuel and lubricating oil, while the inorganic consists of metals and ash originating from the fuel and lubricating oil (Hellen, G. and J. Ristimäki 2007). The solid carbonaceous particles are called soot, elemental carbon (EC), black carbon (BC) etc.

#### 4.4.2 Particle definition

A particle is defined by Finlayson-Pitts and Pitts (2000) accordingly:

*‘Particles, or particulate matter, may be solid or liquid, with diameters between 0.002 and 100  $\mu\text{m}$ . The lower end of the size range is not sharply defined because there is no accepted criterion at which a cluster of molecules become a particle. The upper end corresponds to the size of drizzle or very fine sand; these particles are so large that they quickly fall out of the atmosphere and hence do not remain suspended for significant times’.*

#### 4.4.3 Effect of particles

Several epidemiological studies have been done that suggest elevated mortality risks are correlated to the concentrations of particles and some of them indicate that fine particles are more harmful than coarse particles and the ultrafine particles have been observed to primarily cause damage to other parts of the body than the lungs (Pope and Dockery 2006).

The global impact of shipping-related particle emission is estimated to be 64,000 premature deaths per year in 2002, and that number is predicted to increase to 91,000 by 2012 (Corbett et al. 2007).

The correlation between adverse health effects and particulate matter is well established, and ozone,  $\text{SO}_2$  and  $\text{NO}_2$  have been shown to alter lung function (World Health Organization 2006).

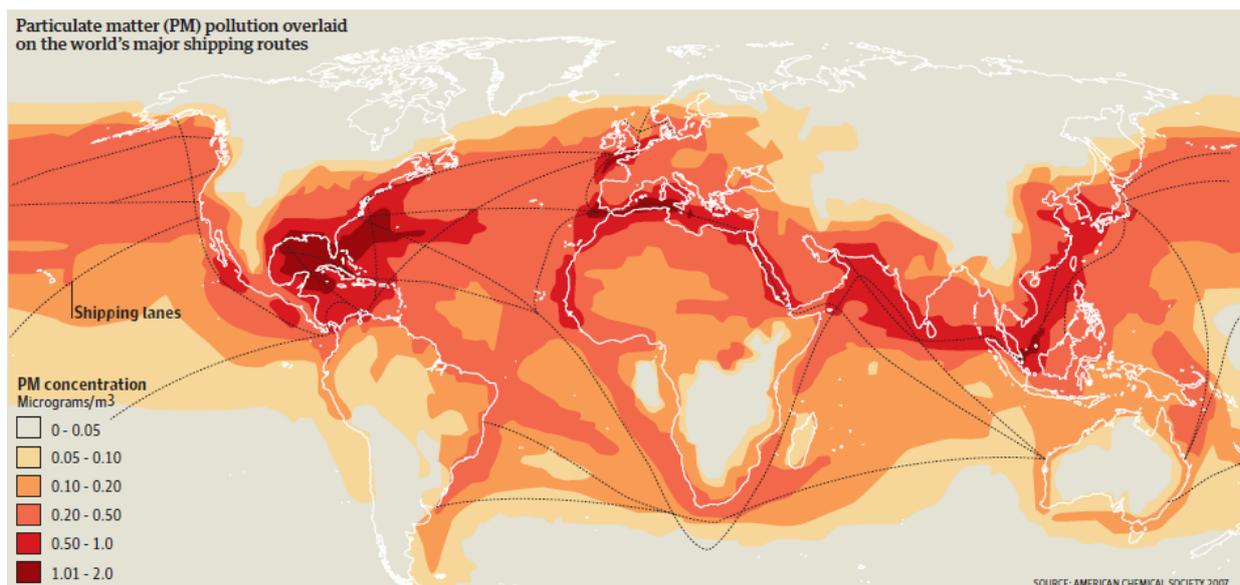


Figure 4-3 Particulate Matter pollution overlaid on the world's major shipping routes.

Source: (American Chemical Society 2007)

## **4.5 Sulphur (SO<sub>x</sub>)**

Sulphur dioxide (SO<sub>2</sub>) is a poisonous gaseous compound of sulphur and oxygen. Sulphur trioxide (SO<sub>3</sub>) is a significant pollutant, being the primary agent in acid rain. Sulfates (SO<sub>4</sub>) are fully oxidized ionic form of sulphur.

The directive 2005/33/EC of 0,1 % sulphur content are the strictest for marine fuel, however the technologies required to reduce sulfur to near-zero levels are in use in many areas of the world. European directive 2009/30/EC (EURO VI) regarding sulphur free Diesel 0,001 % is scheduled to be implemented 1 September 2015 for the transport models on land.

### **4.5.1 Sulphur formation**

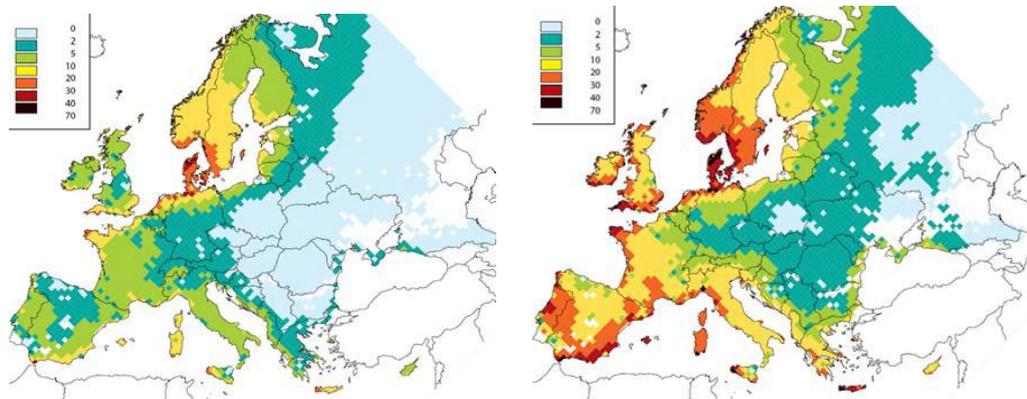
Sulphur is a naturally occurring component in crude oil. The emission of SO<sub>2</sub> and SO<sub>3</sub> is directly proportional to the amount of sulphur in the fuel as virtually all sulphur contained in the fuel is oxidized to SO<sub>2</sub> and SO<sub>3</sub> during and immediately after the combustion.

### **4.5.2 Sulphur composition**

The sulphur is chemically bounded to the hydrocarbons of the fuel and during the combustion, most sulphur is oxidized to SO<sub>2</sub>. SO<sub>3</sub> is typically 15:1 according to MAN B&W Diesel (1996). Sulphate particles in the exhaust system form during the cooling of the exhausts and a reaction between SO<sub>3</sub> and water, which forms H<sub>2</sub>SO<sub>4</sub>, which is very corrosive. Kasper et al. (2007) found that 1.4% of the sulphur in the fuel was in the form of sulphate in the exhaust gas particles.

### 4.5.3 Effects of Sulphur

The dominating fates for SO<sub>2</sub> in the atmosphere are oxidation or dry deposition. Enderesen et al. (2003) estimated that approximately half of the amount of emitted SO<sub>2</sub> from ships was deposited, mainly on the sea surface, by dry deposition. Two different pathways for H<sub>2</sub>SO<sub>4</sub> formation: either gaseous SO<sub>2</sub> reacts with hydroxyl radical molecules (HO), or it reacts heterogeneously in the liquid phase or on surfaces (Finlayson-Pitts and Pitts 2000). SO<sub>4</sub> increases the hygroscopicity of particles, which reduces the lifetime of the particles in the atmosphere due to cloud formation around the particles and the subsequent precipitation (Winners 2010).



*Figure 4-4 Percent of sulphur deposition originating from international shipping in 2000 (left panel) and projected for 2020 if no action was taken (right panel). Emission controls as result of the revisions to MARPOL Annex VI adopted in 2008 are expected to progressively reduce deposition. Source: (IIASA, 2007)*

### 4.5.4 Acidification

When sulphates or nitrates are abundant in aerosol particles, these particles become acidic and precipitate as acid rain. Acidification is tightly coupled to H<sub>2</sub>SO<sub>4</sub> and HNO<sub>3</sub>, which are formed by the oxidation of SO<sub>3</sub> and NO<sub>2</sub> (Finlayson-Pitt and Pitts 2000). The associated environmental impacts range from effects from wear on buildings and materials to the release of metal ions from lake sediments, altering the live of water living species and ultimately leading to fish death (see e.g. (Ottar 1986)).

## **4.6 Nitrogen Oxides (NO<sub>x</sub>)**

According to the International Maritime Organization (IMO), ocean-going ships released 25.8 million metric tons of nitrogen oxides in 2007. These emissions already equate to approximately 30 percent of global NO<sub>x</sub> emissions (Review of MARPOL Annex VI and the NO<sub>x</sub> Technical Code) and are projected to increase to 34.2 million metric tons by 2050 (Eyring *et al.*, 2007).

### **4.6.1 Nitrogen formation**

NO production is very efficient at temperatures above 2,000 K, resulting in a net production of NO during combustion and in the post-combustion gases (Bowman 1975). The peak temperature during combustion in large marine diesel engines is between 2,200 and 2,400 K (Lyyränen *et al.* 1999. Slow speed engines have higher specific emissions of NO<sub>x</sub> than engines of higher speeds (Cooper and Gustavsson 2004). The high rate of NO formation is related to high temperatures during combustion, the duration of these periods, as well as high oxygen concentrations (Heywood 1988).

Additional NO is formed from nitrogen in the fuel or via reactions between molecular nitrogen and the hydrocarbon species in the fuel.

Nitrogen in fuel has been shown to be an important source for NO, especially at high air to fuel ratios (lean to stoichiometric condition) during combustion (Bowman 1975). The lean combustion of diesel engines and a relatively high concentration of nitrogen in heavy fuel oils make fuel nitrogen a potential contributor to significant NO<sub>x</sub> concentrations in ship exhausts.

### **4.6.2 Nitrogen composition**

NO<sub>x</sub> is a collective name for NO and NO<sub>2</sub>, where NO is by far the most abundant in the exhaust gases. About 5-7% of NO is converted to NO<sub>2</sub> in the exhaust system or engine (Henningsen 1998). The share of NO<sub>2</sub> in NO<sub>x</sub> that leaves the combustion chamber is partly determined by local temperature conditions (Heywood 1988).

According to MAN B&W Diesel, approximately 1% of NO will form N<sub>2</sub>O (MAN B&W Diesel 1996).

### **4.6.3 Effects of Nitrogen Oxides**

Emission of NO<sub>x</sub> affects the climate in two ways. Firstly, together with hydrocarbons, NO<sub>x</sub> contribute to the formation of ozone. Ozone has a limited impact on global warming at the ground level. However, ozone can be transported higher where it has a significantly greater radiative forcing impact (Friedrich *et al*, 2007). Secondly, the emissions of NO<sub>x</sub> play a role in the reductions in the lifetime of methane. The reductions of methane have a cooling effect on the climate (Torvanger *et al*, 2007).

Understanding the effects of emissions from shipping is far from simple. Studies show e.g. that fuel consumption increases when NO<sub>x</sub> emissions are reduced by lowering the combustion temperature, which then generates higher levels of CO<sub>2</sub> and particles (Eyring *et al*, 2005).

Even though NO<sub>x</sub> emissions from shipping have both warming and cooling effects, the overall effect is believed to be warming and potentially equivalent to the effect of the CO<sub>2</sub> emissions (Friedrich *et al*, 2007).

### **4.7 Carbon Monoxide (CO)**

Carbon monoxide and NMVOC (Non-methane volatile organic compounds) are by-products of incomplete combustion. These emissions show a certain trade-off with NO<sub>x</sub>, as technologies aimed at reducing NO<sub>x</sub>, other than SCR, tend to increase these emissions. Typical levels of these emissions are very low, in the range of 0.1-0.3 g/kW·h, and little effort has been made to reduce them further.

### **4.8 Greenhouse gases (GHG)**

There are number of gases that contribute to global warming. Carbon dioxide (CO<sub>2</sub>) is the most abundant but methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are strong heat absorbent. They are all naturally occurring atmospheric gases that have increased significantly over the last century due to usage of fossil fuels.

#### **4.8.1 Carbon Dioxide (CO<sub>2</sub>)**

Carbon dioxide is an important greenhouse gas. To reduce CO<sub>2</sub> emission the key factor is to reduce the fuel consumption. Other option with potential benefit for reducing the production of CO<sub>2</sub> includes using LPG as fuel.

##### **4.8.1.1 Carbon Dioxide formation**

The amount of CO<sub>2</sub> emitted from ships depends on the type of fuel. For instance, certain fuels may contain more carbon per energy output than other fuels, and hence may produce more CO<sub>2</sub> emissions per unit of work done. The problem is that C is not containment but a critical part of the fuel.

##### **4.8.1.2 Carbon Dioxide composition**

The amount of CO<sub>2</sub> in the atmosphere is only 0.0360% Volume, what is concerning is the rate of change as the volume of this gas has increased by over 35% in the last three hundred years (Pidwirny 2006).

##### **4.8.1.3 Effects of Carbon Dioxide**

Carbon dioxide contributes to global warming by absorbing heat energy from the earth, trapping it and preventing its release into space. CO<sub>2</sub> does not, however, absorb the light energy from the sun. In short, carbon dioxide lets in the light energy emitted by the sun but traps the earth's heat energy.

##### **4.8.1.4 Carbon Dioxide reduction**

The operational aspects that have the largest impact on the CO<sub>2</sub> efficiency are, voyage performance (e.g. logistics, maintenance and speed), the ship design (e.g. type of engine, size, and shape of the ship) and the use of various energy-saving technologies.

Emissions of CO<sub>2</sub> can be cut by switching to fuels with lower total emissions through the full fuel cycle (i.e. production, refining, distribution and consumption). The switch from using residual fuels to distillate fuels that is implied by the sulphur regulation in revised MARPOL Annex IV has already been agreed, (residual fuel having higher CO<sub>2</sub> emission but distillate fuel having CO<sub>2</sub> emission during the refining process).

#### 4.8.2 Methane (HC<sub>4</sub>)

Methane slip from gas engines is a concern due to methane's properties as a greenhouse gas.

##### 4.8.2.1 Methane formation

Methane emissions are caused by unburned methane slipping through the combustion chamber of gas engines. As methane is the main component of natural gas, venting in oil production fields is also a source of methane emission into the atmosphere.

##### 4.8.2.2 Methane composition

The amount of Methane in the atmosphere is 0.00017% volume. Since 1750, methane concentrations in the atmosphere have increased by more than 150% (Pidwirny 2006).

##### 4.8.2.3 Effects of Methane

Methane is generally considered to be the second most important greenhouse gas contributing to global warming (Albritton, D.L., 2001), Methane itself is colorless, odorless and lighter than air, so it has little effect on local and regional air quality.

Methane is 62 times the near-term warming potential of CO<sub>2</sub>.

*Table 4-2 Global warming potential, time horizon. The amount removed from the atmosphere over a given number of years.*

Gas	Global Warming Potential		
	<u>Time Horizon</u>		
	20 Years	100 Years	500 Years
Carbon Dioxide	1	1	1
Methane	62	23	7
Nitrous Oxide	275	296	156

*Source (IPCC)*

## 5 Definition and characteristics of LPG

The term “liquefied petroleum gas” is applied to mixtures of light hydrocarbons which can be liquefied under moderate pressure at normal temperature but are gaseous under normal atmospheric conditions.

The main components of LPG are propane ( $C_3H_8$ ) and butane ( $C_4H_{10}$ ), mixed in any proportion or with air. LPG produced by separation of heavier or denser hydrocarbons from natural gas is mainly of the paraffinic (saturated) series.

LPG derived from oil-refinery gas may contain varying low amounts of olefinic (unsaturated) hydrocarbons. Propylene and butylenes are usually also present in small concentration. LPG has no smell, but a powerful odorant, ethyl mercaptan, is added so that leaks can be detected easily.

Main characteristics of Propane and Butane are as follows:

*Table 5-1 Properties of butane gas.*

Appearance	Color less, pressurized gas
Smell	Odorless, odorant “ethyl mercaptan is added”
Boiling point	-1 degree C
Flame point	-60 degree C
Flame range	1,9% to 8,5% in air
Thermal ignition point	360 degree C
Vapor pressure at 20 degree C	1,5 bar
Specific density (vapor)	2,09 (air = 1)

*Source (Preem 2010)*

*Table 5-2 Properties of propane gas.*

Appearance	Color less, pressurized gas
Smell	Odorless, odorant “ethyl mercaptan is added”
Boiling point	-42 degree C
Flame point	-104 degree C
Flame range	2,2% to 9,5% in air
Thermal ignition point	460 degree C
Vapor pressure at 20 degree C	7,2 bar
Specific density (vapor)	1,56 (air = 1)

*Source (Preem 2010)*

## **5.1 Application and advantages of LPG**

As an automotive fuel, LPG is the largest alternative fuel in Europe, distributed through a network of 31,000 filling stations to fuel more than 7 million vehicles (mainly passenger cars and buses) in 2007 (AEGPL 2011).

The clean burning properties and portability of LPG provide a substitute for traditional engine fuels such as petrol and diesel.

The main advantages of LPG are as follows:

- Because of its relatively fewer components, it is easy to achieve the correct fuel to air mix ratio that allows the complete combustion of the product. This gives LPG its clean burning characteristics.
- Both propane and butane are easily liquefied and stored in pressure containers. These properties make distribution both easy and safe.
- LPG is a good substitute for fuel oil in a modified internal combustion engines. Its clean burning properties, give reduced exhaust emissions, extended lubricant and engine life.

## **5.2 Production**

LPG comes from two sources. It can be obtained from the refining of crude oil. Simple refining in a crude distillation tower will yield about two percent LPG. When produced this way it is generally in pressurized form. LPG is also extracted from natural gas or crude oil streams that are formed naturally in oil and gas fields and is pumped out from the wells mixed in with other fuels, typically about 0.2 to 0.4 percent of the produced crude oil but much higher proportion is possible. LPG derived from oil refining. (40% of the world total; 75% of LPG in Europe) and natural gas processing (60% worldwide; 25% in Europe) (Statistical Review of Global LP Gas 2009).

### **5.3 Gas flaring and venting**

Gas flaring occurs when associated gas from an oil field is burnt releasing carbon dioxide into the environment. The process is frequently performed as it is too expensive and tricky to harness this gas and bring it to market. The oil companies until recently have only been interested in producing crude oil and therefore these gaseous fuels were considered to be by products.

### **5.4 Global environmental problem**

The World Bank in May 07 after a twelve year study estimated that the annual volume of associated gas being flared and vented is roughly 150-170 billion cubic meters (bcm), enough fuel to provide the combined annual natural gas consumption of Germany and France (A Twelve Year Record 2007).

Flaring in Africa alone reached 37 bcm in 2000, which could produce 200 Terawatt hours (TWh) of electricity, which is about 50 percent of the current power consumption of the African continent. It is widely acknowledged that flaring and venting of associated gas contributes significantly to greenhouse gas (GHG) emissions and has negative impacts on the environment.

The use of LPG avoids wasting a valuable energy source. Destroying the gas, through flaring or venting, not only generates air pollution and GHG emissions but also necessitates the consumption of equivalent quantities of other fuels.

## **6 LPG transportation**

The production of LPG derives from oil refining and by extraction from natural gas and crude oil streams. Due to the diverse sources of LPG, different modes for transport are needed for the distribution network.

### **6.1 Conditions for transport**

In order to successfully transport LPG it must be in liquid form. To achieve this, LPG requires to be exposed to appropriately moderate pressure and the correct cool temperature. Maintaining an ambient state during transportation is more expensive and considered to be more dangerous than the transportation of traditional marine fuels.

For comparison the cost of transporting LPG are roughly about 2 – 2.5 times the price of transporting Diesel. This is largely due to different densities and different safety standards each require. Thus LPG net back calculations are more sensitive to transport costs.

Within Sweden; no pipeline is currently available for LPG and the majority of onshore transport is conducted via rail and road. This method of transport requires tankers which must adhere to specific conditions to maintain the associated gases in liquid phase.

The proper tanker conditions must be maintained at all times during transportation since the ratio between the volumes of the vaporized gas versus liquefied gas are typically around 250:1.

LPG also burns very easily and as little as 1.5 – 11 % of LPG in air can create an explosive blend.

Strict guidelines for the transportation of associated gas are stated in the International Maritime Dangerous Goods (IMDG) regulations for flammable gases (Class 2.1 goods) wherein gas tank containers designed for transportation and storage of liquefied gases are governed by Code UN T50.44

## 6.2 ISO tank container

Tankers capacity is a function of length which comes in two sizes (20 and 40 feet long) 25 m<sup>3</sup> and 50 m<sup>3</sup> respectively.

Gas tank containers must meet all requirements for the transportation of dangerous goods in accordance to the Agreement on Dangerous Goods by Road (ADR), and the International Transport of Dangerous goods by Rail (RID) as well as to the - International Maritime Dangerous Goods Code (IMDG) for combined transports involving all kinds of shipments.



*Figure 6-1 40 feet ISO tank container.*

*Source: [http://expresslog.tradeindia.com/Exporters\\_Suppliers/Exporter17951.278870/40-ft-ISO-Tank-Container.html](http://expresslog.tradeindia.com/Exporters_Suppliers/Exporter17951.278870/40-ft-ISO-Tank-Container.html)*

### 6.3 Road Transport

This type of transport is normally used for the final delivery to the client and is sometimes used for up streaming the transportation of LPG to ports or railway depots. This method of transportation is flexible however very expensive over long distances in comparison to other modes of transport. The cargo capacity is typically ranging from 35 to 65 m<sup>3</sup>.

The construction and operation of specialized semi-trailers for propane and butane gases in general are subject to the European regulation - Accord européen relatif au transport international des marchandises Dangereuses par Route (ADR) for road transports.

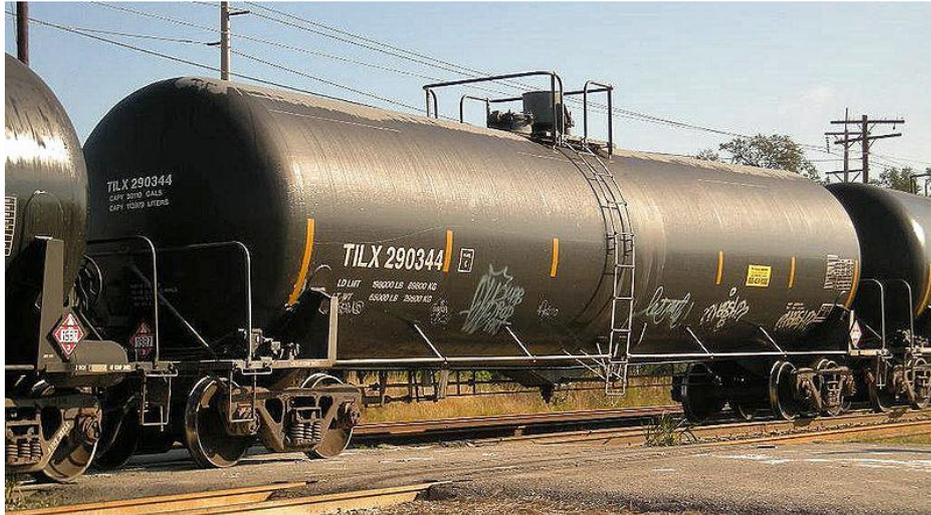


*Figure 6-2 LPG Semi trailer for road transport.*

*Source: [http://en.wikipedia.org/wiki/Tank\\_truck](http://en.wikipedia.org/wiki/Tank_truck)*

## 6.4 Trains

The construction and operation of Rail Tank Cars (RTCs) is also subject to the - International Transport of Dangerous goods by Rail (RID). They are available in Europe with capacities ranging from 85 - 120 m<sup>3</sup> (carrying 40 - 60 tone LPG).



*Figure 6-3 Rail tank wagon.*

*Source: [http://en.wikipedia.org/wiki/Tank\\_car](http://en.wikipedia.org/wiki/Tank_car)*

## 6.5 Shipping

LPG ships are suitable for carrying pressurized, semi-pressurized/refrigerated (able to trade from both pressure and refrigerated storages) or refrigerated.

The pressurized (ambient temperature, 18 bar for 100% propane), semi-pressurized / refrigerated (5 – 8 bar, -10 – 20 degree Celsius) the cargo capacity for those two types typically range up to 30.000 m<sup>3</sup> or refrigerated (ambient pressure, -43 degree Celsius for 100% propane) their cargo capacity typically range up to 100.000 m<sup>3</sup>.

The construction and operation of LPG Gas Tankers is subject to - International Maritime Dangerous Goods Code (IMDG).



*Figure 6-4 LPG Tanker.*

*Source: <http://www.ship-info.com/Vessels/9347516.jpg>*

## **6.6 Bunkering**

There are several available options regarding the bunkering of LPG. Tank capacities vary greatly and the most feasible solution will depend on vessel size and route. For instance; a ferry that travels a short distance from port to port can refuel often and in that case large tank capacity is not necessary. However a Ro-Pax vessel on a long distance route would need bunker capacity of a considerable size.

### **6.6.1 Rules and guidelines**

Bunkering of larger vessels in a harbor area is normally done by ship to ship transfer. This is likely to continue for LPG bunkering, for smaller ships bunkering from ISO containers, road or rail tankers is likely to be the most economic and convenient option. There are certain regulations to consider, individual local authorities and the responsible port authorities need to permit LPG bunkering at the chosen location.

The following national rules and guidelines have been used:

- Port Regulations
- Sea Regulations from the Swedish Transport Agency, Maritime department
- Land Regulations from the Swedish Civil Contingencies Agency (MSB)

For the two ships involved in the bunkering operation there are two set of rules:

- IMO IGC Code – (International Gas Code), Rules for the bunker ship
- IMO IGF Interim guidelines – (International Gas Fuel), Rules for the receiving ship

The IMO IGC Code is the international regulation for gas carriers and will therefore be valid for the bunker ship. For the receiving vessel, the ship using LPG as bunker fuel, the IGF interim guidelines are the regulations to be considered. The IGF guidelines are called “interim” since they are not yet finalized.

Ship to Ship bunkering of LPG is a form of LPG transfer and therefore SIGGTO, *Society of International Gas Tanker & terminal operators Ltd*, guidelines must be considered. Though the SIGTTO guidelines are focused on large scale LPG transfer from LPG carriers, many of the aspects could be applied to LPG bunkering.

If the bunker scenario includes transfer of both LPG and diesel (pilot fuel) from one ship to another, SIGGTO as well as the OCIMF, *Oil Companies International Maritime Forum*, guidelines need to be followed.

## 7 Marine gas engines

LPG is not currently considered to be a commercially viable alternative on the medium speed engine market due to historically higher price compared to fuel oil. As a result no engine manufacturer has yet offered a commercially available concept in that field.

On the low speed engine market MAN Diesel & Turbo has developed and certified a commercial available propulsion concept, though no ship-owner has placed an order for it yet.

LPG has been introduced on the private and leisure boat market through the Civitas project in Venice Italy (Case study 223). In that case outboard petrol engines were converted to using LPG as fuel through the same technology that is used in the car industry.



*Figure 7-1 The first boat of the demonstration fleet fitted with an LPG/petrol dual fuel engine.*

*Source: (Case study 223)*

## 7.1 MAN Diesel & Turbo (Low Speed Engine LPG)

MAN diesel & Turbo has introduced a new Liquid ME-GI (liquid gas injection) tow-stroke engine which is powered by LPG.

The Liquid ME-GI is a variant of the MAN Diesel & Turbo's ME-GI engine, which uses a control and safety system based on experience gained at working gas plants, including a 12K80MC-GI-s in Japan, and the development of a VOC (volatile organic compound) engine in the late 1990s.

The development follows the decision in the autumn 2010 to conduct full-scale type test during 2011 for the ME-GI concept at MAN's test center in Copenhagen.

### 7.1.1 Technical details

The special parts required to operate on LPG are: a ventilation system for venting the space between the inner and outer pipes of the double-wall piping, a sealing oil system, delivering sealing oil to the gas valves separating control oil and gas and an inert gas system to enable purging of the LPG system on the engine with inert gas.

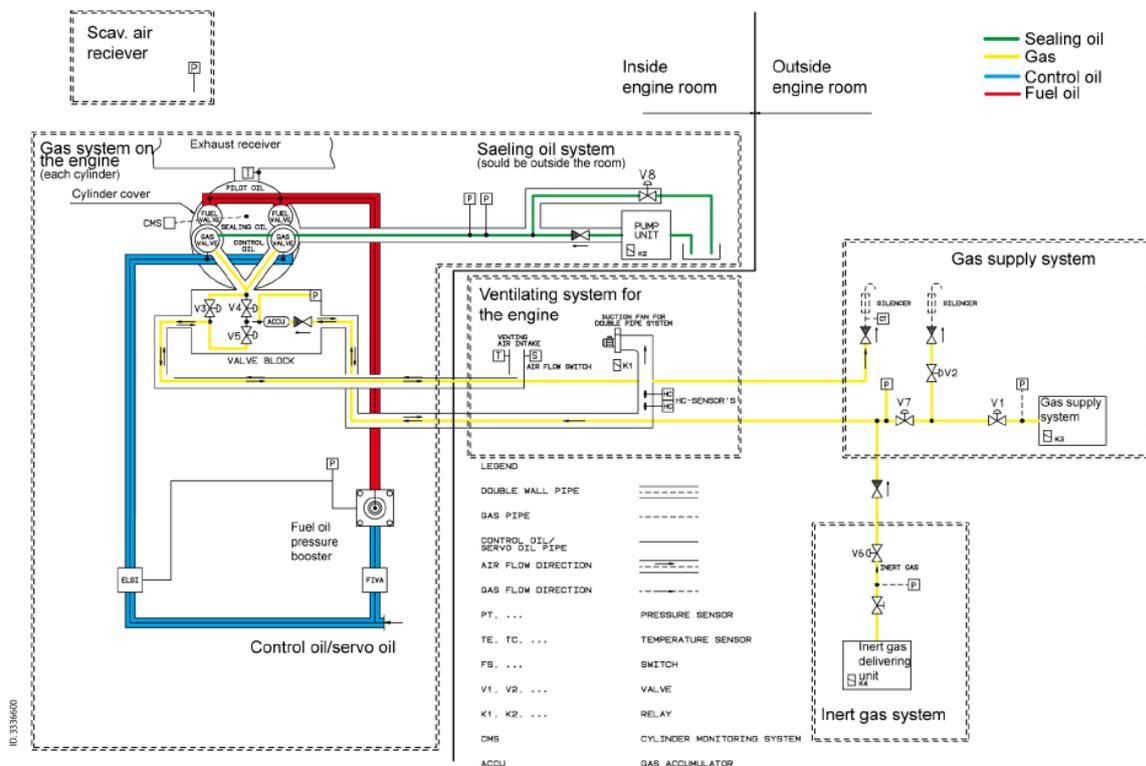


Figure 7-2 ME-GI system complete in schematic form.

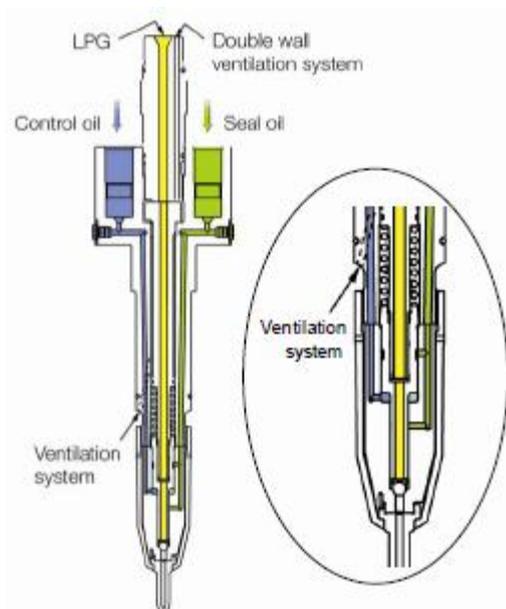
Source: (MAN Diesel & Turbo 2011)

Operation on dual fuel requires the injection of both pilot fuel and gas fuel into the combustion chamber via different types of valves arranged in the cylinder head. The ME-GI engine head is fitted with two valves for gas injection and two for pilot fuel. The pilot oil valve is a standard ME fuel oil valve without any changes, except for the nozzle. A common rail (constant pressure) gas supply system is fitted for high pressure gas distribution to each valve (CIMAC Congress 2010).

### 7.1.2 Fuel injection valves

Dual fuel operation requires valves for both the injection of pilot fuel and gas fuel. The valves are of separate types, and two are fitted for gas injection and two for pilot fuel. The media required for both fuel and gas operation are listed below:

- High-pressure LPG supply
- Fuel oil supply, also called pilot oil
- Control oil supply for actuation of gas injection valves
- Sealing oil supply to avoid any entry of gas into the control oil.



*Figure 7-3 Gas injection valve design for LPG operation.*

*Source: (MAN Diesel & Turbo 2011)*

### 7.1.3 Gas valve block

The valve block consists of a square steel block, bolted to the HCU side of the cylinder cover, see also Fig. 7-2. The valve block incorporates an accumulator volume filled with pressurized nitrogen, and a shutdown valve and two purge valves on the top of the block.

All connections in the block are sealed with special high-pressure gas sealing's. If a sealing breaks, the gas will be led into spaces that are connected to the double-wall pipe system, for leakage detection. The gas is supplied to the accumulator via a non-return valve placed in the accumulator inlet cover.

To ensure that the rate of gas flow does not drop too much during the injection period, the relative pressure drop in the accumulator is measured. The pressure drop should not exceed about 20-30 bar. Any larger pressure drop would indicate a severe leakage in the gas injection valve seats or a fractured gas pipe. The safety system will detect such events and shut down the gas injection.

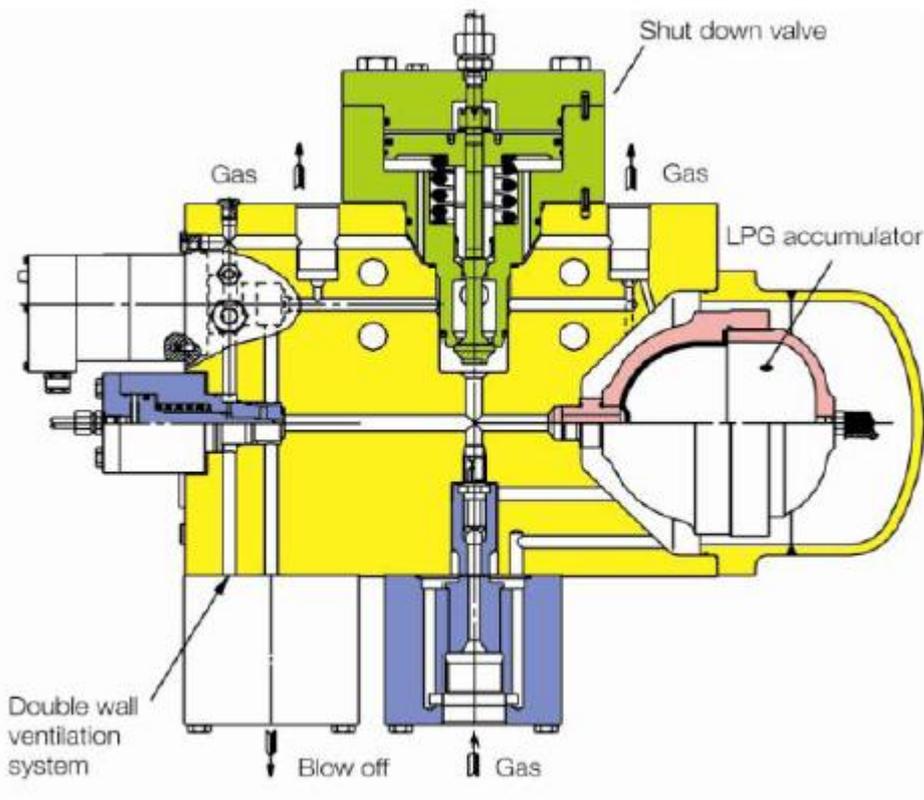


Figure 7-4 Valve block with shutdown valve and LPG accumulator.

Source: (MAN Diesel & Turbo 2011)

From the accumulator, the gas passes through a bore in the valve block to the shutdown valve, which in the gas mode is kept open by compressed air. From the shutdown valve (V4 in Figure 7-2), the gas is led to the gas injection valve via bores in the valve block and a high-pressure double wall pipe connecting the gas valve block to the injection valve. A blow-off valve (V3 in Figure 7-2), placed on top of the valve block, is designed to empty the gas bores when needed. A purge valve (V5 shown in Figure 7-2), which is also placed on the valve block, is designed to empty the gas valve block when the engine is no longer to operate in the gas mode. The accumulator in the gas valve block is filled with nitrogen, and the nitrogen is separated from the gas by a special membrane design capable of withstanding the different composition of LPG fuel types. Furthermore, the accumulator is separated from the engine room by a ventilated space around it.

#### **7.1.4 Gas pipes**

A common rail (constant pressure) system is to be fitted for high-pressure gas distribution to each valve block on each cylinder. Gas pipes are designed with double walls, with the outer shielding pipe designed as a measure to prevent gas outflow to the machinery spaces in the event of rupture of the inner gas pipe.

The ventilation inlet air must be taken from a gas safe area. Gas pipes are arranged in such a way, that air is sucked into the double-wall piping system from around the pipe inlet, from there into the branch pipes to the individual cylinder blocks, via the branch supply pipes to the main supply pipe, and via the suction blower to the atmosphere (see Fig. 7-2).

Ventilation air is to be exhausted to a safe place. The double-wall piping system is designed so that every part is ventilated. Any leakage of gas will be led to the ventilated part of the double-wall piping system and be detected by the HC sensors.

### 7.1.5 Emission level

Comparison of emission levels shows that there are benefits in the full range when using LPG as fuel: a 17 per cent reduction in CO<sub>2</sub>, 12 per cent reduction in NO<sub>x</sub>, a 92 per cent reduction in SO<sub>x</sub> and a 37 per cent reduction in particulates.

*Table 7-1 Emission comparison between HFO burning K50MC-C and LPG burning S50ME-GI.*

Estimated emissions HFO 3500 S. RW 1 <b>6K50MC-C</b>		Estimated emissions 8% pilot oil – 46% propane & 46% butane <b>6K50ME-GL</b>	
Load 100%	g/kwh	Load 100 %	g/kwh
CO <sub>2</sub>	556	CO	469
O <sub>2</sub> (%)	1223	O <sub>2</sub> (%)	1255
CO	0.71	CO	0.89
NO <sub>x</sub>	11.97	NO <sub>x</sub>	10.51
HC	0.28	HC	0.57
SO <sub>x</sub>	10.57	SO <sub>x</sub>	0.85
PM (mg/m <sup>3</sup> )	0.49	PM (mg/m <sup>3</sup> )	0,31

*Source: (MAN Diesel & Turbo 2011)*



*Figure 7-5 Graphical rendering of a MAN B&W 6S70ME-GI engine with gas components shown in blue. Image credit: MAN Diesel & Turbo SE*

*Source: (MAN Diesel & Turbo 2011)*

## **8 Feasibility of LPG-fueled vessels in Europe / Sweden**

The prerequisite for change of an industry fuel of chose for the marine market can be divided onto three fields:

Policy change like strengthen emission regulations, creating Emission Controlled Areas (ECA), Technology innovation, which is development of gas fueled engines, and price of fuel.

The policy change is already in place and is not just limited with Europe “Sulfur Emission Controlled Area” (SECA), the governments of USA and Canada are planning to create (ECA) zones along the coast line of North America and the Japanese government has expressed interest in creating (ECA) zone around their coastline.

Today all major manufacturers of marine engines are developing technology for utilizing gas as fuel. Currently one of the major engine manufacturers has commissioned a low speed engine that is certified for operation on LPG, it is likely that manufacturer on the medium speed engine market will develop the same option for their customers as soon as it is economically viable.

LPG is a byproduct of the oil refining process and the liquefying process of natural gas. The fuel change from HFO to MGO in the SECA area on the 1<sup>st</sup> January 2015 is likely to see an increase in demand and therefore increase the production of MGO and create an increase of the availability of LPG.

As natural gas is predicted to be the “next” fuel “competing with LS MGO as a non-diesel alternative” it is likely to have a strong presence on the marine market. This would lead to more availability of LPG on the market.

As LPG has been on the market since early 20<sup>th</sup> century the existing market is stable regarding supply and demand, with increased availability the price is likely to drop, making LPG more feasible as a fuel for new markets like as a marine fuel.

### **8.1 Availability of LPG**

LPG is already a well-established fuel that is widely available in Europe. All oil companies have distribution network for LPG coming from their oil refining process and smaller installations are at refueling stations for land-based LPG fueled vehicles.

## 8.2 Possible segments

The recreational boat market that is currently using diesel/petrol can also be recognized as potential customers of LPG marine fuel. There could be potentially a variation in the pricing structure as the distributional network they require is different than commercial shipping.

The Shipping segments that are potential for using LPG as fuel include ferry (both passenger and RoPax), harbor craft (including Coast Guard patrol vessels), and Short Sea Shipping.

### 8.2.1 Recreational boats

The Civitas project in Venice Italy (Case study 223) shows an interesting development for LPG as marine fuel for the petrol-driven private recreational boat markets. For that market to be viable it is necessary to open dedicated filling stations to serve that segment. The price incentive between petrol and LPG is the same as for the land transport



*Figure 8-1 An LPG-dedicated floating filling station.*

*Source: (Case study 223)*

### 8.2.2 Ferry

Ferries within the harbor area are currently propelled with low-emission diesel engines. Do to short round trips they can be re-fueled frequently. For ferries that do not carry any cargo below deck there should be adequate enough space for gas fuel tanks so bunker capacity for several days should be possible.

Ferries and RoPax vessel that operate in international service are all fueled with conventional diesel engines burning low sulfur fuel. There is a strong likelihood that this fleet could be converted to LPG operation on later stage.

### 8.2.3 Harbor craft

Internationally there is an increased interest in gas fueled Tugs and Towboats. Crowley Maritime Corporation, The Glosten Associates and Rolls-Royce have designed a LNG-fueled Tug. This design is attended for service in the port of Long Beach and in the Port of Los Angelis (Cavalier).

Wärtsilä with Ship Architects, Inc. are cooperating on a new concept LNG towboat design.

These vessels are intended for inland waterways and river service. Additionally there is an extensive market for inland waterways both for cargo and tourist service. Historically LNG has been a forerunner in gas applications but it is likely that LPG's price and availability will attract this market and that it will develop toward using LPG as fuel.

## 2011 GO CLEAN TOWBOAT

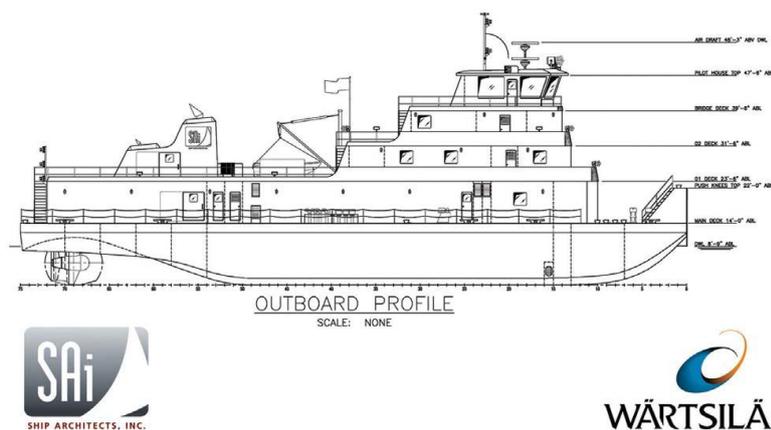


Figure 8-2 Outboard profile of Ship Architects, Inc.'s LNG-powered Towboat concept design. Image credit: Ship Architects. INC.

Source: <http://www.scribd.com/doc/48499291/Marine-News-February-2011>

### 8.2.4 Short sea shipping.

A considerable amount of cargo is shipped by feeders and coastal service vessels. The vessel designer Nordnorsk Skipskonsult AS has developed a LNG-fueled multi-purpose coastal vessel.



Figure 8-3 Coastal Vessel. Illustration: Nordnorsk Skipskonsult AS.

Source: (DNV 2011)

The ship will be delivered from TERSAN New Building Shipyard in Turkey in early 2012 and have Rolls Royce gas engines for propulsion (DNV 2011).

### 8.3 Prices

The price of LPG has historically been higher than the price of crude oil the trend has though been towards that LPG is now becoming the less expensive alternative.

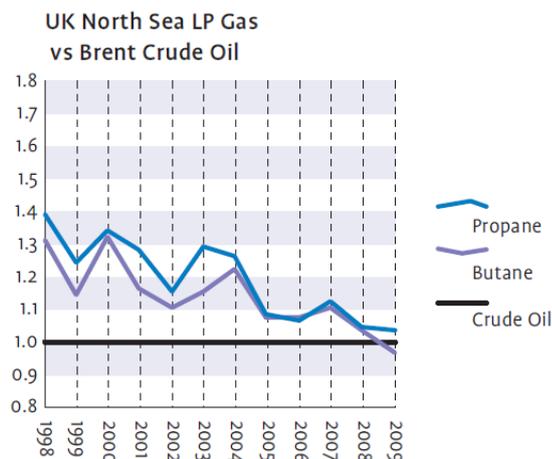


Figure 8-4 Average Annual LPG Price vs. Crude Oil.

Source: (Statistical Review of Global LP Gas 2009)

## LS MGO vs LPG

In this example Propane is used as a reference for LPG.

Variables:

Energy density of Diesel is 39600 MJ/m<sup>3</sup> and Propane is 25300 MJ/m<sup>3</sup> (Berkeley).

Price of LS MGO is 960 US \$/Metric Ton (Bunker world) and

Propane “North West Europe” is 800 \$/ Metric Ton (Argus International LPG)

Relative density of MGO DMA is 0.890 Metric Tonnes/m<sup>3</sup> (Shippedia) and Propane 0.582 Metric Tonnes/m<sup>3</sup> (Air Liquide).

Calculation for LS MGO.

$$\frac{396000 \text{ MJ/m}^3}{0,890 \text{ MT/m}^3} = 44494,38 \text{ MJ/MT an}$$

$$\frac{960 \text{ \$/MT}}{44494,38 \text{ MJ/MT}} = 0,0216 \text{ \$/MJ}$$

Calculation for Propane.

$$\frac{25300 \text{ MJ/m}^3}{0,582 \text{ MT/m}^3} = 43470,79 \text{ MJ/MT and}$$

$$\frac{800 \text{ \$/MT}}{43470,79 \text{ MJ/MT}} = 0,0184 \text{ \$/MJ}$$

This calculations shows that Propane is close to 15 % less expensive per energy unit than LS MGO DMA.

## Petrol vs LPG

### Variables:

Energy density of Petrol (automotive) is 34,2 MJ / liter and Propane is 25,3 MJ / liter (Berkeley).

Retail price of Petrol (automotive) EU average is 1,446 € / liter and retail price of LPG (automotive (GPL, Autogas)) EU average is 0,736 € / liter (Europe's Energy Portal).

Calculation for Petrol. 
$$\frac{1,466 \text{ €/liter}}{34,2 \text{ MJ/liter}} = 0,0429 \text{ € / MJ}$$

Calculation for LPG. 
$$\frac{0,736 \text{ €/liter}}{25,3 \text{ MJ/liter}} = 0,0290 \text{ € / MJ}$$

This calculation shows that LPG is close to 33 % less expensive per energy unit than Petrol.

It is estimated that the gas reserves available have the potential to long outlast our current oil reserves. Norway and Russia each have large resources of natural gas in their possession that is favorably close geographically to the European market.

Along with the current new emission rules ( MARPOL 73/78 Annex VI (SECA)) and (Directive 2005/33/EU) this close proximity encourages the potential opportunity for gas to become a main fuel in the maritime sector.

During the initial in phasing of LPG as a viable alternative; ferries and inland waterway transportation vessels, have the most to benefit. This makes them the most logical segment in the industry to start with.

The second stage of implementation would be ideal for RoRo ships and feeder traffic. These vessels operate mostly within the SECA area.

There is a great advantage, in particular for the early stages in implementation over to LPG, that there is already a highly developed distribution network ready to be tapped in to.

### **9.1 Reflection and further work**

When I originally set off to write this thesis, I was unclear how things would develop as it quickly became very apparent that not much has been published about LPG as marine fuel. This made writing this thesis both rewarding and very challenging for me.

My studies have given me great insight into different aspects of the fuel/gas markets. It has taught me to understand the potential consequences of failing to develop a viable safe fuel alternative and it has given me a clear understanding of the changes and challenges that the new restrictions of harmful substances in exhaust gas will bring.

In my opinion, these changes are nothing less than a revolution and can potentially offer the most important health improvement the shipping history would ever see.

The availability of higher quality fuel and cleaner exhaust gases are particularly important for the people that work in the ships engine rooms.

I set off with an ambitious agenda for writing this piece. In hindsight, given the lack of relevant sources available to me, I would have to concede I was rather over ambitious. It was not possible for me to delve as deep in to more specific details as I had intended. Originally I also intended to study more in depth the fuel economics but was not able to due to my own professional commitments and a genuine lack of available resources.

Future work based on this thesis result and given the above discussion would be an LPG market analysis with focus on supply, demand and distribution.

It would also be beneficial to acquire an environmental study with emphasis on working environment in ships engine rooms to further improve health condition for the crew.

## **10 Conclusion**

There are many potential benefits in utilizing the huge available gas reserves as marine fuel. In this thesis the focus has been on the environmental benefits associated with using LPG. Currently LPG is predominately used in the car and land transport sector. This means that to integrate LPG in to marine market should not be overly problematic nor should it prove to be overly costly to initiate.

The ability to easily liquefy the gas and its relative safe means of transport has created a highly dense distribution network. This makes LPG commercial available at any port in Europe.

The increasing environmental concerns and the advanced knowledge of the potential health risks associated to burning carbon fuels has driven policy makers to develop restrictions for limiting harmful emission that develop from burning these fuels.

The effects of exhaust emission from ships in relation to total emissions in coastal areas are now better understood. This new knowledge is driving improvements of emission regulations. These new regulations are forcing the marine industry to come up with modified or new technology. One option for meeting the demands for reduced emissions is to utilize LPG as a marine fuel.

The technology that has been developed for main propulsion systems designed to burn LPG and use marine diesel oil as pilot fuel is very promising for the low speed engine market.

Thou the medium speed engine market has not been considered economically viable there is no reason to doubt technical development if economics changes to be more favorable. The technology for using LPG in the petrol driven recreational boating market is already developed and that segment looks ready for marketing of LPG as alternative fuel option.

In the beginning a LPG marine fuel market would most likely comprises of small ferries, tug boats and coast guard vessels. The larger RoRo's and ocean going ships are likely to join on a later state.

There are clear benefits of using LPG as marine fuel; reduced emission of NO<sub>x</sub>, CO<sub>2</sub>, particulate matter and SO<sub>x</sub> is close to eliminated. For the shipping company there are numerous benefits in processing a green initiative and promoting a high environmental profile. There are operational benefits of LPG fuel systems as the engine life is typically longer compared to diesel engine with less maintenance and longer intervals between engine overhauls.

As Europeans are forerunners in this reduced emission development for marine transport there are many advantages to being first on the market.

It is likely that when the planned implementation ( MARPOL 73/78 Annex VI (SECA)) on 1<sup>st</sup> January 2015, there will be an acceleration of changes that happen very fast over a short period of time as shipping companies look for promote their own “Green Profile”. There is no reason to think that the marine transport market will be any different to supply and maintain then land transport is and consequently benefit from the mutual development towards sulphur free fuel.

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