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MÉMOIRE TECHNIQUE DE FIN D'ÉTUDES

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Diplôme d'Etudes Supérieures de la Marine Marchande

The Liquefied Natural Gas as marine fuel: feasibility, challenges to overcome and opportunities at stake

Author

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UASC SAJIR, first LNG ready ultra large container vessel (UASC, December 2015)

Dissertation written under the supervision of Valentin GREGORY, professor at Ecole Nationale Supérieure Maritime (ENSM) in Le Havre.

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Abstract :

Tougher environmental regulations set by the International Maritime Organization has led to new questions about the fuel of tomorrow. This dissertation examines this environmental trend and focuses on considering the liquefied natural gas as a marine fuel. The switch to LNG will raise many questions such as the availability of LNG, the technology and the capacity of the ship to be converted. This document will cover these questions and bring answers. It will also study the current LNG fuelled vessels, other than the LNG carriers.

Keywords :

Emissions

Fuel

IMO

LNG

Sulphur

Résumé :

L'adoption de normes environnementales plus strictes par l'Organisation Maritime Internationale a conduit à se poser la question du carburant maritime de demain. Ce mémoire étudie ces dispositions législatives sur l'environnement et examine le choix du gaz naturel liquide (GNL) comme carburant. Le passage au GNL soulève de nombreuses questions quant à la disponibilité du GNL, l'état de la technologie et la possibilité pour un navire considéré d'être converti. Le présent document va répondre à ces points et va aussi regarder l'état de la flotte mondiale déjà convertie au GNL.

Mots-clés :

Carburant
Emissions
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OMI
Soufre

Fiche synthétique

Titre : The Liquefied Natural Gas as marine fuel: feasibility, challenges to overcome and opportunities at stake (Le gaz naturel liquide comme carburant maritime, viabilité, défis à relever et enjeux à remporter)

M/T Bit Viking, premier navire converti au GNL (source Tarbit Shipping, 2014)

Mémoire pour l'obtention du Diplôme d'Etudes Supérieures de la Marine Marchande (DESMM) à l'Ecole Nationale Supérieure Maritime (ENSM) du Havre

Auteur : Alexandre POLGE

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Résumé :

La pollution atmosphérique fait l'objet depuis plusieurs années d'une attention accrue. Des politiques de réduction des émissions de gaz à effet de serre sont élaborées à différent niveaux. Les dispositions réglementaires d'envergure sont contenues dans l'Annexe VI de la Convention MARPOL. Par ailleurs, d’autres réglementations régionales ont vu le jour, telles que les zones SECA. Cette tendance de réduction des émissions amène la question des alternatives aux carburants fossiles. L’adoption par l’OMI, en novembre 2016, de la teneur maximum de soufre à 0.5% des combustibles pour 2020 accélère d’autant la réflexion sur le GNL.

Ce mémoire étudie ces dispositions législatives sur l’environnement et examine le choix du gaz naturel liquide (GNL) comme carburant. Le passage au GNL soulève de nombreuses zones d’ombre quant à la disponibilité du GNL, l’état de la technologie à embarquer et la possibilité pour un navire considéré d’être converti. Le principal frein pour les armateurs réside dans l’incertitude financière d’un tel investissement comparé à d’autres solutions, comme le passage au gasoil ou l’adoption de système de nettoyage des gaz d’échappement. Le mémoire s’efforce de répondre à ces points. De plus, il va aussi se pencher sur les navires déjà convertis au GNL afin de voir si l’adoption du GNL est un mouvement de fond ou non.

Plan du mémoire :

Après avoir étudié la législation environnementale en vigueur, et à venir (partie 1), le mémoire examine l’opportunité du GNL pour faire face à ces exigences environnementales (partie 2). Ensuite, l’adoption du GNL ouvre la porte à de nombreuses questions, telles que le réseau de distribution, le stockage ou encore la partie mécanique. Le présent document va s’attacher à étudier ces défis (partie 3). Enfin, le mémoire fera un tour d’horizon sur les navires ayant mis en application le GNL comme carburant (partie 4).

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ACRONYMS AND ABBREVIATIONS

BIMCO	Baltic and International Maritime Council
CH4	Methane
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
ECA	Emission Control Area
EEDI	Energy efficiency design index
EGR	Exhaust gas recirculation
EIAPP	Engine international air pollution prevention
EMSA	European Maritime Safety Agency
GHG	Greenhouse gases
GWP	Global warning potential
HFO	Heavy fuel oil
HHV	Higher heating value
IEEC	International energy efficiency certificate
IGC	International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code for the Construction of Gas-Fuelled Ships
IMO	International Maritime Organization
ISO	International Organization for Standardization
LNG	Liquefied natural gas
LHV	Lower heating value
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
N2O	Nitrous oxide
NECA	NOx Emission Control Area
NOx	Nitrogen oxides
PM	Particulate matter
SCR	Selective catalytic reduction
SECA	Sulphur Emission Control Area
SEEMP	Ship energy efficiency management plan
SOx	Sulphur oxides
ULSFO	Ultra low sulfur fuel oil
USCG	United States Coast Guard
WPCI	World Port Climate Initiative

INTRODUCTION

Shipping is the lifeblood of the world economy but the industry is facing tomorrow's big decisions because of climate change a scarcity of oil. Over the past decade, shipping has seen a surge of an increasing focus from the society, the International Maritime Organization and authorities, such as the European Union, to develop more stringent environmental regulations. Therefore, decisions about fuels and technology have to be taken in order to make the fleet future proof. While shipping is the lowest carbon mode of transport available, it has a crucial part to play in guiding the shift to a safe and sustainable economy.

In response to concerns about climate change, the international community, through the Kyoto Protocol in 1997, set binding targets to reduce greenhouse gas emissions. The Paris Agreement in 2015 reinforces this commitment. The shipping industry has a binding agreement in place with the MARPOL Annex VI which entered into force in January 2013. The new regulations set more stringent limits on NOx and SOx emissions from ships exhausts. The International Maritime Organization also created Emissions Control Areas (ECA). And new ECAs are about to be implemented. Chapter one details the drivers toward an alternative fuel.

The shipping industry has to undergo a transformation. To improve air quality, a different number of measures can be applied, such as burn low sulphur fuels, install scrubbers, switch to LNG, etc. The answers are not immediately evident. Considering the oil price is predicted to further increase, a change of energy source could be profitable. And so the alternative fuels debate has been dominated by the potential of the liquefied natural gas (LNG). The LNG is considered to be a promising fuel. Used as a marine fuel, the reduction of CO2 with 20%, NOx with up to 85% and SOx with almost 100%, compared to HFO, is indeed interesting. The second chapter will examine the feasibility of the LNG to answer these environmental regulations.

Yet, a broader uptake of the LNG as a fuel is hampered by the lack of infrastructure. Shipowners are also facing a number of questions regarding the available technology, the costs and the benefits. Switching to LNG will require a new fuel system design and the setting up of a reliable fuel supply network. The third chapter focus on the challenges to overcome for the LNG to be widely considered as an alternative to conventional fuels.

But even with all the cards in hands, shipowners will consider the financial and commercial feasibility to operate LNG fuelled ships. The last chapter will lay an overview of the different types of ships embracing the LNG propulsion. The aim of the present dissertation is to study the opportunity, the challenges and the feasibility of using LNG as a marine fuel.

1 – Drivers and trends in the search of an alternative marine fuel

Climate is undoubtedly changing. The Earth's rapidly warming temperatures over the past several decades cannot be explained by natural processes alone. Human activities are increasing the amount of heat-trapping gases in the atmosphere, the greenhouse gases (GHG). This observation is widely shared by both the international public opinion and international organizations. The shipping industry is a source of greenhouse gas emissions that contribute to climate change. In recognition of the importance of the climate change challenge, the International Maritime Organization (IMO) has introduced measures to limit the greenhouse gas emissions from shipping. These new regulations of shipping emissions are the main driver into finding new marine fuel. But not only. The conventional fuel availability and cost might decline over the years. This is another driver towards alternative marine fuel. But switching from a widely spread solution to a new one brings a lot of questions to shipowners. This chapter aims to study and expand this train of thought.

1.1 Air emissions from shipping

While the shipping industry is more fuel efficient than other transport sectors, it is a major contributor to climate change. The combustion of fossil fuel used by a vessel's engines produces greenhouse gases as well as non-GHG emissions.

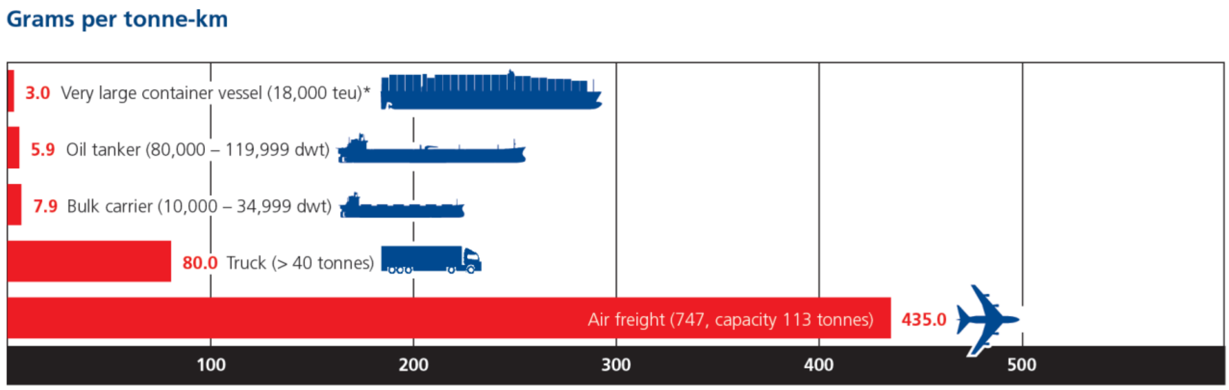

Figure 1: Comparison of typical CO2 emissions between modes of transport (ICS, 2104)

Greenhouse gas emissions

Gases that trap heat in the atmosphere are called greenhouse gases. The carbon dioxide (CO2) is the primary greenhouse gas emitted through human activities. Shipping, with just tens of thousands of vessels, is an important energy consumer and carbon emitter. According to the study on greenhouse gases conducted by the Maritime International Organization in 2014, the *"international shipping emissions for 2012 are estimated to be 796 million tonnes CO2 and 816 million tonnes CO2e for GHGs combining CO2, CH4 and N2O. International shipping accounts for approximately 2.2% and 2.1% of global CO2 and GHG emissions on a CO2 equivalent (CO2e) basis, respectively"* (1, page 32).

Third IMO GHG Study 2014 CO_2

Year	Global CO_2[1]	Total shipping	% of global	International shipping	% of global
2007	31,409	1,100	3.5%	885	2.8%
2008	32,204	1,135	3.5%	921	2.9%
2009	32,047	978	3.1%	855	2.7%
2010	33,612	915	2.7%	771	2.3%
2011	34,723	1,022	2.9%	850	2.4%
2012	35,640	938	2.6%	796	2.2%
Average	33,273	1,015	3.1%	846	2.6%

Third IMO GHG Study 2014 CO_2e

Year	Global CO_2e[2]	Total shipping	% of global	International shipping	% of global
2007	34,881	1,121	3.2%	903	2.6%
2008	35,677	1,157	3.2%	940	2.6%
2009	35,519	998	2.8%	873	2.5%
2010	37,085	935	2.5%	790	2.1%
2011	38,196	1,045	2.7%	871	2.3%
2012	39,113	961	2.5%	816	2.1%
Average	36,745	1,036	2.8%	866	2.4%

Figure 2: Shipping CO2 emissions compared with global CO2 (values in million tonnes CO2); and shipping GHGs (in CO2e) compared with global GHGs (values in million tonnes CO2e), (IMO, 2014)

To take into account the emission of other greenhouse gases when calculating the level of greenhouse gas emissions, the carbon dioxide equivalent (CO2e) is used. CO2e allows other greenhouse gas emissions to be expressed in terms of CO2 based on their relative global warming potential (GWP). CO2 has a GWP of 1, methane has a GWP of approximately 25 (on a 100 year time horizon). In other words, for every 1 tonne of methane (CH4) emitted, an equivalent of 25 tonnes of CO2 would be emitted.

Methane is the second most prevalent greenhouse gas emitted. Methane emissions result from combustion of heavy fuel oils and distillates (such as Marine Gas Oil) and from incomplete emissions of LNG. As said above, the methane is more efficient at trapping radiation than CO2.

Nitrous oxide (N_2O) results from the combustion of fuels. Nitrous oxide molecules stay in the atmosphere for an average of 114 years before being removed by a sink or destroyed through chemical reactions. The impact of nitrous oxide on warming the atmosphere is almost 300 times that of CO_2. The nitrous oxide is part of the family of nitrogen oxides (NO_x).

Non-GHG emissions

In addition to greenhouse gases, shipping produces other air emissions, most notably are the sulphur oxides (SO_x) and nitrogen oxides (NO_x). NO_x and SO_x play indirect roles in tropospheric ozone formation, which damages forests and crops and injures living tissue. They also contaminate water and cause acid rain. The same IMO study estimates that the international shipping is producing approximately 18.6 million tonnes of NO_x and 10.6 million tonnes of SO_x annually. "*Global NOx and SOx emissions from all shipping represent about 15% and 13% of global NOx and SOx from anthropogenic sources*" (1, page 33).

Both NO_x and SO_x are combustion products that are emitted in to the environment in the form of smoke. NO_x emissions are a function of the engine design while SO_x emissions are directly linked to the sulphur content of the fuel consumed.

Ships generate mainly emissions of carbon dioxide (CO_2), sulfur oxides (SO_x) and nitrogen oxides (NO_x). In recent years, many actions have been undertaken to significantly reduce air emissions from ships.

1.2 Environmental regulations

The shipping industry has become a key component of the world's economy. Over 90% of global trade is carried by sea. The propulsion of merchant shipping is dominated by diesel propulsion machinery. However, recent environmental regulations have been introduced by the IMO to mitigate the effects of climate change. The Annex VI (Regulations for the Prevention of Air Pollution from Ships) to the International Convention for the Prevention of Pollution from Ships (known as MARPOL) was adopted on 1997. This annex entered into force on 19th May 2005.

Greenhouse gas emissions

The Kyoto Protocol, adopted on 1997, is the first international treaty which aims to stabilize and reduce greenhouse gas emissions. Its article 2.2 states that "*the Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gas emissions not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO),* *respectively*" (3, page 2). On 2011, the IMO set two new policies to tackle the GHG emissions: the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) (4, pages 11-13).

Both EEDI and SEEMP are the first ever mandatory GHG regulations for the shipping industry. These policies, which came into effect on 1 January 2013, apply to all ships of 400 tonnes gross tonnage and above. The EEDI sets a minimum energy efficiency standard for new ships, while the SEEMP enables shipowners to measure the fuel efficiency of existing ships while operating at sea and in port.

The EEDI, which is probably the most important measure, will allow the development of new ships while taking into account the carbon dioxide production potential of the ship and its benefit in terms of cargo capacity and speed. The EEDI requires a minimum energy efficiency level (CO2 emissions) per capacity mile (tonne mile). The CO2 production potential includes three components:

• The amount of carbon dioxide directly attributable to the ship's propulsion machinery.
• The amount of carbon dioxide from the auxiliary power of the ship.
• The reduction of carbon dioxide due to energy efficiency technologies. For example, LNG fuelled ship.

The EEDI applies to the design of new ships above 400 gross tonnage and will include tankers, gas carriers, container ships and general cargo ships. These ships will require an International Energy Efficiency Certificate (IEEC) to show compliance with the EEDI. In the context of the EEDI, the use of LNG as a fuel would reduce the actual EEDI for a ship by 25% because of its associated CO2 savings. The EEDI is then one of the incentives for LNG fuelled ship development.

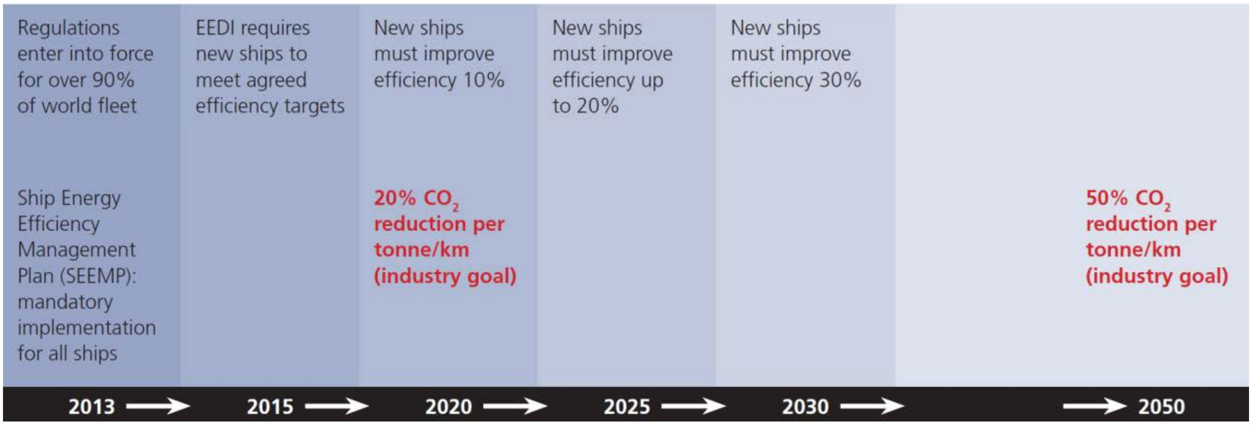

Figure 3: Technical regulations under MARPOL Annex VI, chapter 4 to reduce ship's CO2 (ICS, 2014)

Non-GHG emissions

Within the different exhaust emissions on a ship, the nitrogen oxides (NOx) and the sulphur oxides (SOx) are subject to regulation by the MARPOL Annex VI.

The formation of NOx in the combustion process is largely dependent on the peak temperatures encountered causing some of nitrogen in both in the combustion air and in the fuel itself to form oxides. Hence the control of NOx emissions is achieved through an initial survey leading to the issue of an Engine International Air Pollution Prevention (EIAPP) Certificate.

According to the regulation 13 of the MARPOL Annex VI, three levels (Tiers) of NOx emissions limits apply based on the ship construction date (5, pages 21-23).

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

Figure 4: NOx Emissions Limit and Tier Calculations (IMO)

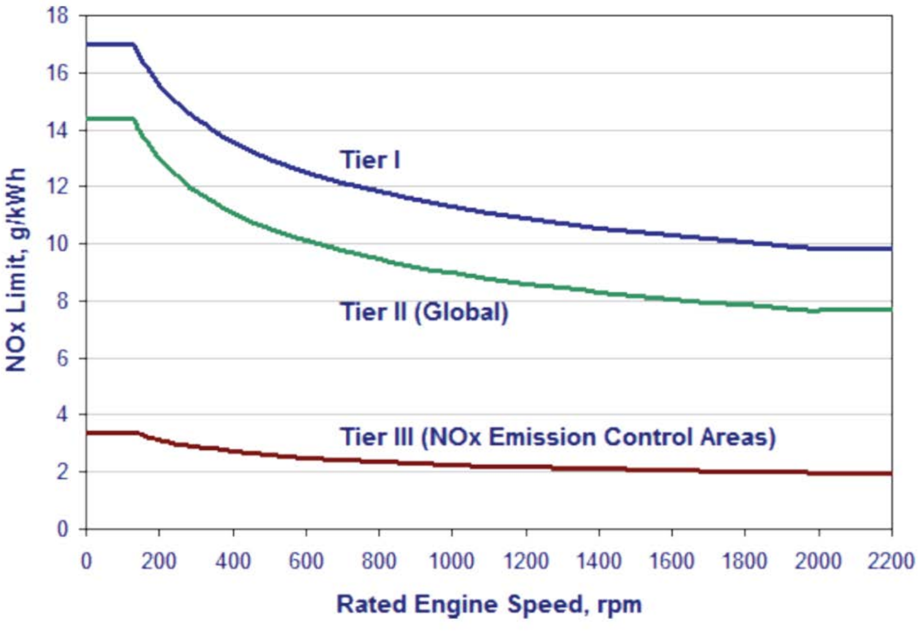

Figure 5: NOx emissions reduction under MARPOL Annex VI, regulation 13

NOx emission limits Tier I and Tier II are global requirements, whereas Tier III NOx emission limits only apply to ships whose keels are laid on or after January 1st 2016 if operating within NOx Emission Control Areas (NECA). And if new NOx ECAs are adopted (for instance the North Sea and Baltic Sea), the Tier III emission limits become applicable to vessels with keel-laying as of the date the new NOx ECAs goes into effect. The concept of Emission Control Area (ECA) will be explained in the following section (1.3).

The emissions of sulphur oxides (SOx) are regulated through a global limit on the sulphur content of bunker fuels. The Regulation 14 of the MARPOL Annex VI distinguishes whether the ship is sailing in a Sulphur Emission Control Area (SECA) or not.

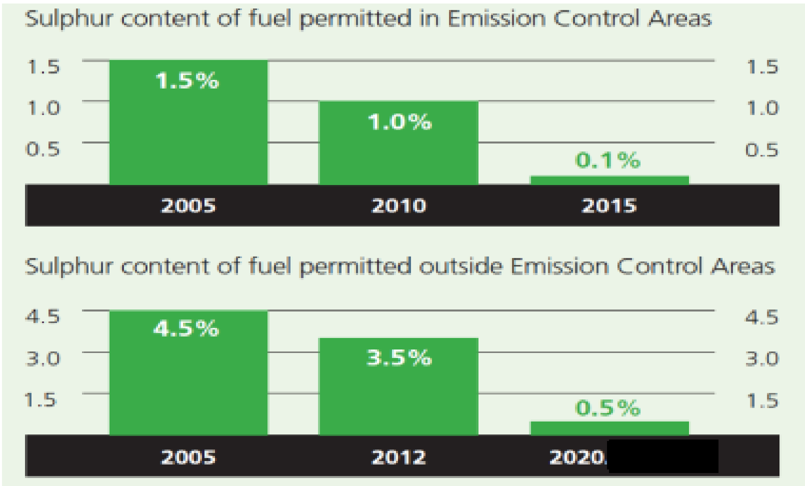

Figure 6: SOx emission cap set by MARPOL Annex VI, regulation 14

The last stage of the regulation 14 was the enforcement of the 0.1% sulphur cap in SECA in 2015. This regulation will be followed by a global sulphur cap elsewhere of 0.5% in 2020. The 70th session of the Marine Environment Protection Committee took place between 24 and 28 October 2016. The key outcome is *"the decision to implement a global sulphur cap of 0.50% in 2020 represents a significant cut from the 3.5% global limit currently in place and demonstrates a clear commitment by IMO to ensuring shipping meets its environmental obligations."* (6)

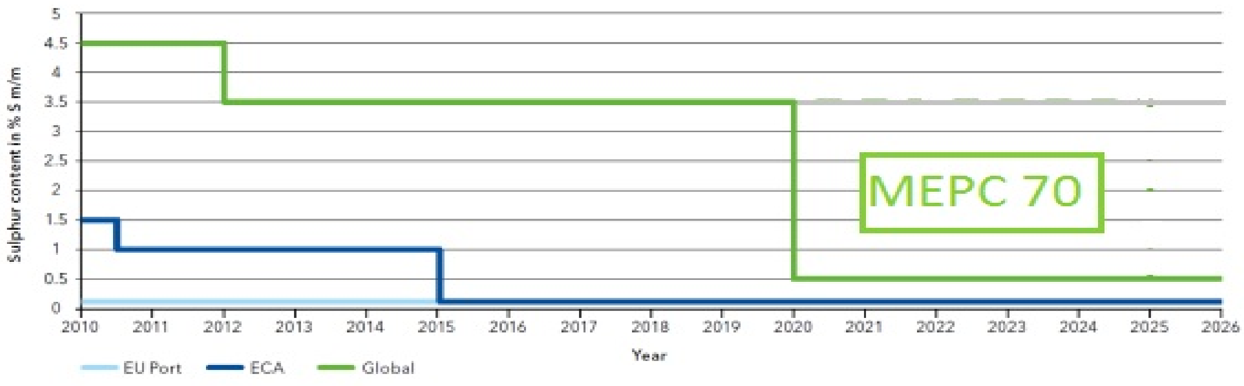

Figure 7: Applicable SOx limits (DNV GL)

1.3 Emission Control Area (ECA)

According to MARPOL Annex VI, an Emission Control Area (ECA) is defined as follows: "*An ECA is an area established by the IMO, where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from nitrogen oxides (NOx) or sulphur oxides (SOx) and particulate matter (PM) or all three types of emissions and their adverse impacts on human health and the environment*." (5, page 10). The following table shows the current ECA:

	Emissions	**In effect since**
Baltic Sea	SOx (and NOx)	19 May 2006
North Sea	SOx (and NOx)	22 November 2007
200 nautical miles from North America	SOx and NOx	1 August 2012
United States Caribbean Sea	SOx and NOx	1 January 2014

Regarding the Baltic Sea and the North Sea, the Marine Environment Protection Committee, during its 70th session, approved the designation of the aforementioned zones as NECA. The adoption of this amendment to the Regulation 13 of the Annex VI of MARPOL will be on the agenda for the MEPC 71th session (6).

Figure 8: The ECA in force now and the possible future ECA (DNV GL, 2016)

The trend is to have more and more ECA through the world. In China, ships berthing among the ports located in the three areas (Pearl River Delta, Yangtze River Delta and the Bohai Sea) will be obliged to use fuel containing less than 0.5% sulphur, starting January 1st, 2017 (7).

1.4 Conventional fuel availability and cost

Since 2015, the sulphur content of fuels used in the SECA dropped to 0.1%. Regarding the newly adopted regulation of a 0.5% sulphur limit in the marine fuel, BIMCO states *"it is not possible to determine that the global refining industry will have the capacity to produce enough marine fuel by 2020"* (8).

Figure 9: Bunker prices of IFO 380 (HFO) as of November 13th 2016

Figure 10: Bunker prices of MGO as of November 13th 2016

Figure 11: Bunker prices of ULSFO as of November 13th 2016

Marine Gas Oil (MGO) with 0.1% sulphur is already available. However, MGO price is higher than those of other heavy fuel oils (HFO and ULSFO) due to its production process. Indeed, being a distillated product, it involves an additional cost. This adds to the costs involved in the

desulphurization process for both MGO and ULSFO. Therefore, those two fuels are more expensive (around 50-60%) than heavy fuel oil.
This price gap will continue to widen further with the new IMO’s requirement to set up a global 0.5% sulphur cap for 2020. The consequence is foreseeable: there will be an increased fuel price for the MGO and ULSFO.

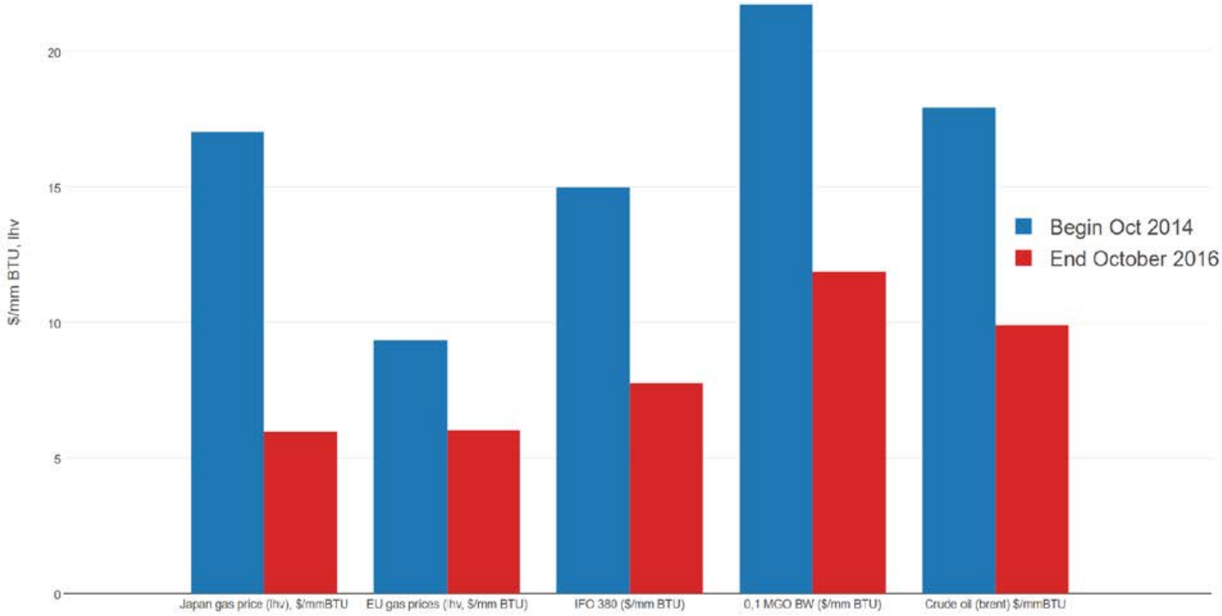

Figure 12: Gas and oil prices comparison between October 2014 and October 2016 (DNV GL 2016)

1.5 Trends and barriers

The environmental regulations and concerns are the main trends towards low carbon fuel. Environmental sustainability in the shipping industry has steadily improved over the years with new regulations in place. Those regulations aim to move the shipping industry away from fossil fuels. Regulators have increasingly introduced strict regulations on emissions: stringent SOx and NOx emission limits and mandatory efficiency standards (EEDI and SEEMP) to reduce CO2 emissions. This trend is likely to continue. In the future, we might even see shipping included in state-sponsored CO2 reduction agreements, such as a carbon tax or an emissions trading scheme.

The second trend is the fuel availability and cost. Even though estimates of future oil production vary and are controversial, there is still a growing scarcity of fossil fuels. *The world economy is projected to grow at around three per cent per year on average to 2050, doubling in size by 2030 and nearly doubling again by 2050. At the same time, the global population is expected to exceed nine billion in 2050* (9). It will have an effect on fossil energy reserves. Also the advent of the new regulations regarding the sulphur content of marine fuels, both in emission control areas and globally, will create an increased demand for low-sulphur fuels for shipping. There will be a steady rise in bunkering costs. Refinery capacity for producing distillates could even turn out to be insufficient for meeting the vastly increasing demand.

Dealing with the changes poses challenges to the shipowners. Which technology to adopt? When introducing a new fuel, existing ships may have to be retrofitted because of incompatible machinery. This makes changes a long term investment. For shipowners who take the risk to invest in new technologies solutions, there could be some unforeseen technical issues resulting in additional cost and delay.

Lack of infrastructure, such as bunkering facilities and supply chain, and uncertainty regarding long-term price are additional barriers for the introduction of any new fuel. New fuels will not start being used by shipowners if infrastructure is not available, and energy providers will not finance expensive infrastructure without first securing customers. Breaking this deadlock will require a coordinated effort and the political will to invest in the development of new infrastructure. However, the wheels of change are in motion. The juncture may therefore be a major driver for LNG as a ship fuel. This hold even truer with the newly implemented global cap of 0.5% sulphur content for marine fuel set for 2020.

2 – An attractive fuel solution for shipping with the LNG

One of the possible solutions for compliance with the more stringent air emission requirements for vessels in the sulphur emission control areas is the use of LNG as marine fuel, next to the use of low sulphur fuels and the installation of exhaust gas scrubbers. This second chapter will focus on the LNG, its characteristics, its price and availability, the legislation and its advantages and weaknesses against the fuel oil.

2.1 The fundamental principles of LNG

Physical properties

Natural gas is a gaseous mixture of hydrocarbons occurring in the earth’s crust. It is often found together with petroleum and coal deposits and as a hydrate on sea bed. Natural gas is also generated during decomposition of organic matter such as human and animal wastes and biomass. Liquefied natural gas, or LNG, is a natural gas that has been cooled sufficiently to condense into a liquid. At atmospheric pressure, the cryogenic temperature must be at -162°C. The cooling process shrinks the volume by about 600 times (10, page 2). This makes it commercially feasible to transport large volumes of gas in a ship. The liquefaction process requires the removal of the non-methane components like carbon dioxide and sulphur compounds to prevent the formation of solids.

LNG is not kept under pressure. LNG is flammable only if it comes into contact with an ignition source in its vapour state and the percentage of the gas in the air is between 5 and 15%. The vapour is colorless but can be seen as a white cloud. Indeed, the gas mixes with air because water vapour in the air is condensed by the coldness of the warming gas. LNG is not flammable in its liquid state.

Property	Unit	MGO	LNG
Mass Density	kg/m^3	860 – 900	442
Lower heating value	MJ/kg	40 – 43	52 - 55
Boiling point	°C	180 – 360	-162
Flash point	°C	>60	-187
Lower explosive limit	Volume % in air	0.5	4.4
Upper explosive limit	Volume % in air	7.5	15 - 17
Auto ignition temperature	°C	250 – 300	595

Figure 13: Properties of MGO and LNG (DNV GL, 2015)

The composition of the LNG varies slightly according to its source and processing, but it consists almost entirely of methane (CH4), which accounts for 85% up to 95%, along with a few percent of ethane, propane and butane, and a few trace of nitrogen (10, page 2).

Chemical	Formula	Percentage
Methane	CH_4	85-95%
Ethane	C_2H_6	5-15%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon dioxide	CO_2	0-5%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-3%
Hydrogen sulphide	H_2S	0-1%
Rare gases	A, He, Ne, Xe	trace

Figure 14: Composition of natural gas (API, 2015)

Energy value

The energy value (or heating value or calorific value) of a fuel is the amount of heat released during the combustion of a specified amount of fuel. The energy value is a characteristic for each

fuel. It is measured in units of energy per unit of the substance, usually mass, such as: kJ/kg. The heating value of a fuel is expressed by the higher and lower heating values (HHV and LHV).
The higher heating value (also known as gross calorific value or gross energy) of a fuel is defined as *the amount of heat released when the fuel is combusted and the products have returned to a temperature of 25°C* (11). The heat of condensation of the water is included in the total measured heat, it reduces the heat released. The lower heating value (also known as net calorific value) of a fuel is determined by *subtracting the heat of vaporization of water vapor (generated during combustion of a fuel) from the higher heating value* (11).

Fuel	**LHV [MJ/kg]**	**Fuel density [kg/m^3]**	**Energy density [MJ/m^3]**
MDO	42.7	900	38.430
LNG	54.7	442	24.177

Figure 15: Comparison between the energy characteristics of MDO and LNG

This table shows that the MDO/LNG energy density ratio is about 1.6. The lower heating value can be simplified as the energy concentration of the fuel. Together with density it will affect the required tank size to conserve the ship's range. Taking into account the characteristics of the LNG tanks, the tank capacity for a LNG fuelled ship ought to be 3 to 4 times more (12, page 389). This topic regarding the tanks will be further developed in the paragraph 3.2.

2.2 Pollutant emissions from LNG

Liquefied natural gas greatly reduces emissions to air. Due to the liquefaction process, LNG does not contain sulphur. These emissions are eliminated completely.
The NOx emissions can be reduced from 40% to 85% compared to HFO (13, page 22). The difference arises because there are two types of engine. LNG engines are either dual fuel or single fuel engines. Dual fuel engines are able to run either on liquid fuel oil or gaseous fuel and can be designed either as four-stroke engines or as two-stroke engines. The dual fuel engine has two modes. In gas mode, the engine runs on the Otto cycle and in fuel oil mode, it runs on the Diesel cycle. The paragraph 3.3 will explain the gas engine options.

Emission component	Emission reduction with LNG as fuel	Comments
SOx	100 %	Complies with ECA and 0.5% global sulphur cap
NOx low pressure engines (Otto cycle)	85 %	Complies with ECA 2016 Tier III regulations
NOx high pressure engines (Diesel cycle)	40 %	Need EGR/SCR to comply with ECA 2016 Tier III regulations
CO2	25 – 30 %	Benefit for the EEDI requirement, no other regulations yet
Particulate matter	95 – 100 %	No regulations yet

Figure 16: Air emissions reduction of LNG compared to HFO

	CO_2 equivalent [g/MJ] (Tab 3, DNV-2012-0719)			% CO_2 (HFO=100 %)	
Data from DNV No 2011-1449, rev 1 (Tab 16 mainly); DNV NO 2012-0719	Well To Tank CO_2 emissions (WTT)	Tank To Propeller CO_2 emissions (TTP)	Total CO_2 emissions	% Total	% Tank To Propeller (TTP)
Oil fuel (HFO)	9.80	77.70	87.50	100.00	100.00
Oil fuel (MGO)	12.70	74.40	87.10	99.54	95.75
LNG (from Qatar used in Europe)	10.70	69.50	80.20	91.66	89.45
LNG (from Qatar used in Qatar)	7.70	69.50	77.20	88.23	89.45

Figure 17: Comparison of CO2 emissions between HFO, MGO and LNG (DNV GL, 2015)

A study of DNV GL evaluated the greenhouse gas emissions from production to the tank of the ship and the emissions from production to the combustion of the fuel (14, page 33). Reduction of CO2 emission is possible due to the most favorable proportion of number of carbon and hydrogen atoms in methane particles (CH4) compared with other hydrocarbon fuels. The CO2 emissions are about 25% lower than conventional fuel oils.

However, the release of methane (called methane slip) is a challenge. As mentioned in part 1.1, methane, the prime constituent of natural gas, is 25 times more potent as a greenhouse gas than CO2. Therefore, methane slip during production, transportation, and use of natural gas can alter the benefits gained from switching to LNG. In the engine process, the methane slip is mainly caused by incomplete combustion. Most gas engines currently operate using the Otto cycle, a

principle of engine combustion that premixes combustion air with natural gas before entering the engine. The DNV GL study (13, page 23) has proven that this means of combustion often results in elevated methane concentrations in the exhaust, causing the so called methane slip. Depending on engine efficiency for four-stroke engine, the methane slip is in average 3%, *which is equivalent to a 25 % increase in GHG emissions* (13, page 23). As for the two-stroke engine, mainly developed by Wärtsilä, the methane slip is negligible.
According to the same DNV GL study, various technologies can be employed for tackling the problem of methane slip. *For Otto cycle engines, unburned methane can be reduced by using EGR, which improves combustion stability, or by exhaust gas after-treatment with methane oxidation catalysts using special catalytic materials. In diesel cycle engines, a high-pressure injection, dual-fuel concept can be used, which comes at the cost of a smaller reduction in NOx emissions. In this approach, the natural gas is not premixed with air before entering the engine. Instead, it is injected directly into the combustion chamber during the compression stroke following a diesel pilot injection* (13, page 23). These two solutions could practically eliminate the methane slip problem at the ship level.

In conclusion, the use of LNG has the potential to reduce CO2 emissions by up to 25 %, provided that methane slips can be eliminated in the production and combustion phases. Even though the fossil-based LNG cannot be classified as a sustainable fuel, it still has the advantage of reducing air pollution from shipping by removing totally SOx and reducing NOx up to 85 % and GHG by 25 % compared with conventional fuels.

2.3 Regulatory framework of LNG

IGC Code, 1983

Until recently, only LNG carriers used LNG as fuel with the boil-off gas from their cargo. The LNG carriers apply the international regulation laid down by the International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). The code was adopted in 1983. It provides an *international standard for safe transport by sea of liquefied gases in bulk and certain other substances* (15). But the relevance of the IGC Code to the wider use of LNG as a marine fuel is limited as the IMO did not explicitly allow LNG as fuel for other types of ship.

Resolution MSC 285(86), 2009

The first ship using LNG as bunker fuel was the Norwegian ferry GLUTRA which was built in 2000 in accordance with DNV classification society rules of 2001 (16). DNG GL was the first classification society to monitor the development of LNG as bunker fuel on board ships other than LNG carriers. These rules have been carried over by the IMO in 2009 with the adoption of the resolution MSC 285(86), *Interim Guidelines on Safety for Natural Gas-fuelled Engines* (17). The goal of these guidelines is *to provide criteria for the arrangement and installation of machinery for propulsion and auxiliary purposes, using natural gas as fuel, which will have an equivalent level of integrity in terms of safety, reliability and dependability as that which can be achieved with a new and comparable conventional oil fuelled main and auxiliary machinery* (17, page 4, preamble 2). This resolution applies only to new ships with the application to existing ships left to be determined by the individual states (17, page 6, section 1.1.3).

IGF Code, adopted on 2015, in force on January 1st, 2017

Considering that the use of gas as fuel, and in particularly the LNG, has increased in recent years, the IMO intended to set uniform standards for the conversion of existing ships. Therefore, during the 95th session of the MSC on June 2015, the IMO adopted the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). This code will entry into force on January 1st, 2017. The IGF Code replaces the guidelines set by the resolution MSC 285(86).

The IGF Code *contains mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuels, focusing initially on LNG. The Code addresses all areas that need special consideration for the usage of low-flashpoint fuels, taking 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* (18). The IGF Code applies to new ships and to existing ships converted to the use of gases or other low-flashpoint fuels on or after January 1st, 2017. This code is not mandatory to cargo ships of less than 500 GT.

The IMO took into account the fact that gas fuelled ships are quite new and technology will improve. So the section 2.3 of the IGF Code allows alternative fuels, appliances and arrangements design as long as *such fuels, appliances and arrangements can be used provided that these meet the intent of the goal and functional requirements concerned and provide an equivalent level of safety of the relevant chapters* (19, section 2.3).

Last but not the least, the IGF Code did not deal with the process of LNG bunkering. The absence of regulations is particularly unfortunate considering that the lack of bunkering infrastructure constitutes a barrier to the development of LNG as a marine fuel.

ISO (International Organization for Standardization)

The ISO, together with the IMO, has released two publications covering the use of LNG as marine fuel. The ISO 28460:2010 specifies *the requirements for ship, terminal and port service* *providers to ensure the safe transit of an LNG carrier through the port area and the safe and efficient transfer of its cargo* (20). While the ISO 18683:2015 (Guidelines for systems and installations for supply of LNG as fuel to ships) lays out *guidance on the requirements for the design and operation of the LNG bunkering facility and the interface between the supply facilities and the ships* (21). Although the ISO standards are voluntary, a lot of countries embed those standards into their own regulatory framework. Those guidelines will undoubtedly assure a smoother implementation of LNG as bunker fuel.

Classification Society Rules

As mentioned earlier, DNV GL (formerly DNV) was the first to introduce a set of rules for gas fuelled ships in 2001 and these rules were used as input for the IMO Interim Guidelines issued in 2009. DNV GL has since published recommended practices for LNG bunkering (22).

Classification society	Title of guideline
American Bureau of Shipping	Guide for propulsion and auxiliary systems for gas-fuelled ships
Bureau Veritas	Safety for gas-fuelled engine installations in ships
DNV GL	Guidelines for the use of gas as fuel for ship
Lloyds Register	Rules and regulations for the classification of natural gas fuelled ships

Figure 18: Classification society guidelines for LNG as marine fuel

United States of America

The United States Coast Guard (USCG) has issued a regulation (CG-521 No. 01-12) which provides a basis for the USA to accept the design of gas fuelled ships. These requirements are based on IMO resolution MSC.285 (86) with some minor modifications (23).

European Union

Regarding the European Union, there are two directives promoting LNG. First, the EU Directive on sulphur content in marine fuels (2012/33/EU) allows the use of LNG as an alternative fuel to comply with more stringent emission regulations (24). Then, the EU Directive on deployment of alternative fuels infrastructure (2014/94/EU) *aims at ensuring minimum coverage of LNG refueling points in main maritime and inland ports across Europe by 2025 and 2030 respectively* (25). Initiatives to align standards and regulations for the LNG bunkering are pushed through by the European Maritime Safety Agency (EMSA). On March 2013, a study on standards and rules for bunkering of gas-fuelled ships was published (26). The report leads to the adoption of the EU Directive 2014/94/EU.

With a regulatory framework for the use of LNG as marine fuel being set in motion, it is one less obstacle for the adoption of LNG.

2.4 LNG availability and price

Natural gas originates from oil fields and were often produced together. Therefore, the price of natural gas has been closed to the price of crude oil. However, since the last decade, there has been a sharp increase in natural gas availability. This was the result of new technical extractions that lead to the exploitation of the shale gas.

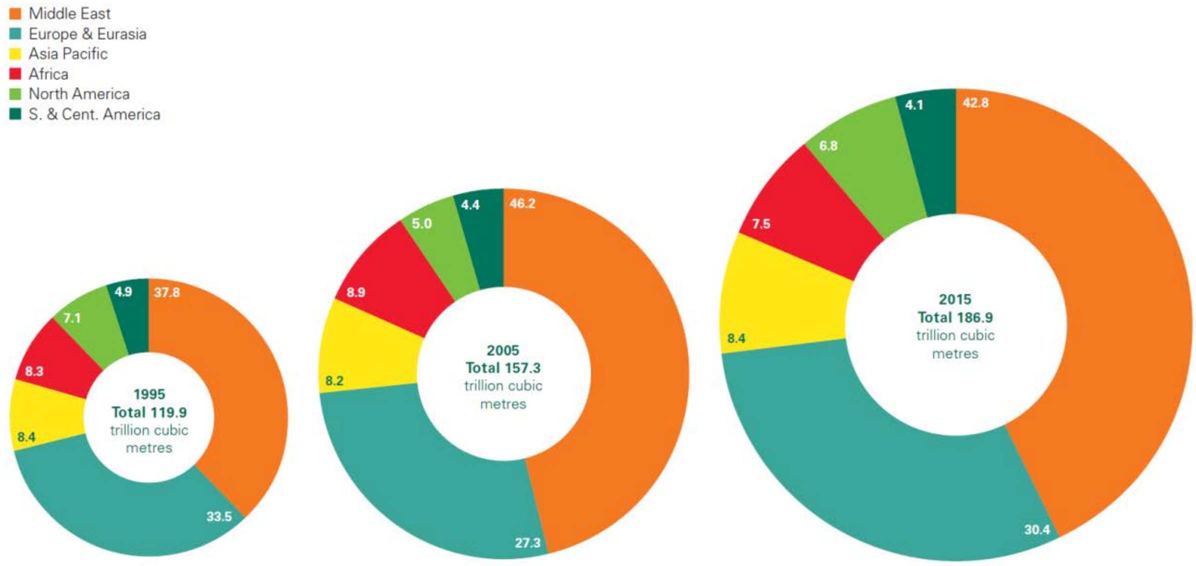

Figure 19: Distribution of proven reserves of natural gas in 1995, 2005 and 2015 (BP, 2016)

LNG becomes cheaper than crude oil. But there are significant regional price differences. In America, the standard gas wholesale price is the Henry Hub. This is the cheapest due to new sources of natural gas discovered continuously. On the opposite, the Japan gas price is the most expensive. This peek in demand for LNG in Japan is related to the Fukushima nuclear accident.

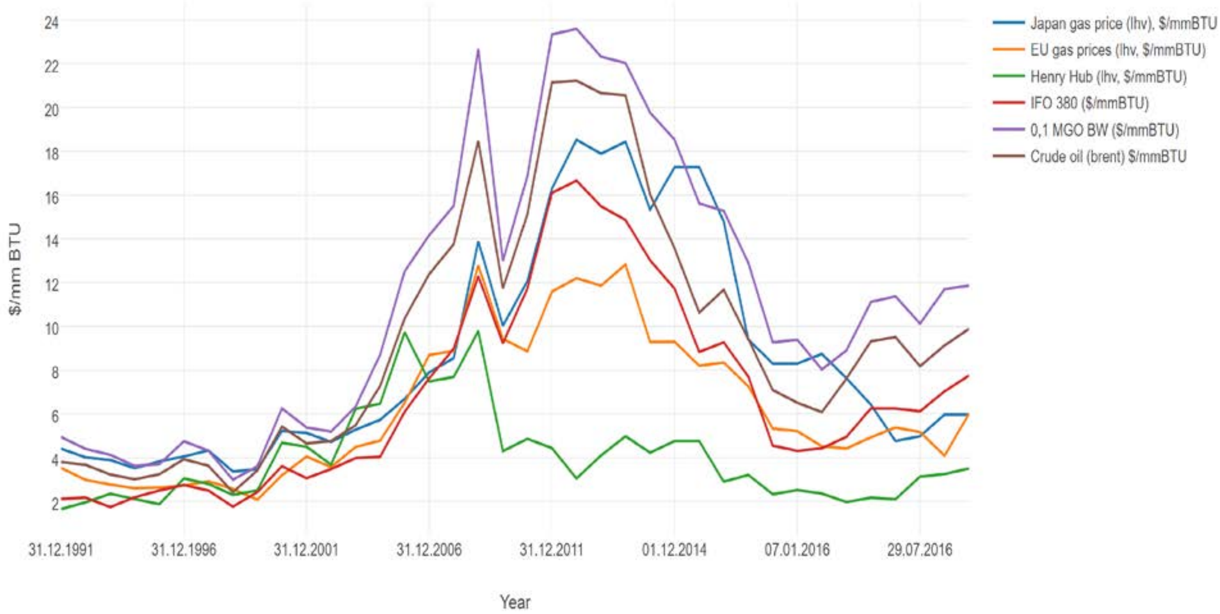

Figure 20: Price comparison of HFO, MGO and LNG (DNV GL, 2016)

In the long term, predictions are difficult but some basic assumptions can be made. From the shipping perspective, the key question is what is the comparative price of LNG versus the crude oil. On that point, it is clear that LNG pricing will be more appealing than the price of traditional ship fuel. Why? Mainly for two reasons. First, crude oil is used as raw material for many industrial processes other than energy and heat production. These processes are, in most cases, able to pay a premium price compared to energy production and it is usually not possible to substitute crude oil with natural gas. Then, the future national and international policies regarding climate change issues will keep this price advantage for the LNG. The market price of crude oil will probably be increased following any taxation and other legislation focusing on the reduction of greenhouse gas emissions.

2.5 Comparison of alternative solutions

Alternative fuels to oil has been used in the shipping sector in the past. Without going up to the days of sailing ships or steamships, there is a long list of alternative fuels that can be used in shipping. In the 1920s, a process to convert coal and natural gas into liquid fuels was invented by the Germans F. Fischer and H. Tropsch (27) and was heavily used during the World War II and in South Africa in the 1970s during the oil embargo. Today, the alternative fuels commonly considered, other than LNG, are electricity, biofuel (methanol and algae) and hydrogen.

The implementation of electricity energy for ship propulsion faces the problem of energy storage. Not to mention that the electricity should come from renewable power production.

Promoting the role of electricity seems to be best when the ship is at berth (cold ironing) rather than promoting battery driven ships.

Biofuels are attractive on paper since no changes in existing propulsion systems and infrastructures are needed. Indeed, biofuels can blend with any maritime diesels and heavy oil fuels. A problem will raise when their source come from an edible crops. However, the source can be from non-edible crops and algae, and therefore does not compete with food production. Also, in the event of a spill, biofuels reduce the risk to the marine environment since they biodegrade rapidly (28). The most promising biofuels today are the methanol and the algae-based biofuels. Algae seems to be the most efficient and the process has the benefit of consuming significant quantities of carbon dioxide. But this sector is in its early days. The US Navy is currently working on this option (29). As for the methanol, Stena Lines is already running a ferry using this fuel between Sweden and Germany (30). The advantages of methanol are that it can be created from natural gas and does not place the same demands on infrastructures than LNG.
However, the main limits on a global use of biofuels in the maritime industry are the cost and the availability. This could be a niche solution for some specific areas where the biofuel availability is guaranteed.

Hydrogen can act as an energy carrier. This energy will be delivered to fuel cells whom will convert it to electricity. This technology has been tested and proven on a supply ship since 2009 (31). However, hydrogen as a fuel is difficult and costly to produce and store. Same as LNG, hydrogen requires cryogenic storage. But, unlike LNG, significant research and developments have to be made to reduce the cost of this technology. Fuel cells are likely to become a part of the future power production but to fuel a ship, it definitely needs a lot more time.

In addition to these alternative fuels, there are two solutions beside LNG to meet with the new regulations: to continue using heavy fuel oil (HFO) but add a scrubber to decrease sulphur emissions or use marine gas oil as main fuel. It is possible to comply with the new sulphur cap of 0.5% by installing a scrubber to remove SOx in combination with either Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) for NOx cleaning. The advantage of the scrubber technology is that there is no change in fuel. Hence the availability of HFO is optimum and the shipowners do not need to retrofit or replace their engines. With scrubbers, the sulphur emissions are reduced to almost zero (32). The disadvantages are the required capital investments in scrubbers as well as the wastes produced by the scrubbers. Indeed, the infrastructures for scrubber waste deposition in ports are not yet in place. Other disadvantages with scrubbers are that the proportion of CO2 in the exhaust gases is not reduced. Scrubbers also occupy space and in some cases cargo capacity might be reduced.

3 – The challenges of LNG as marine fuel

On a technical level, the introduction of LNG will be accompanied by additional complexity, in the areas of fuel supply infrastructure, onboard storage, and new engine systems. On top of that, there is a need to assess the hazards of this new fuel as well as the need for a proper training.

3.1 The supply chain

The problem has often been described as a "chicken-and-egg" situation. To ensure a competitive fuel supply, LNG bunkering must be possible for each type of vessels and in multiple ports under the same conditions as HFO, for a broader use. So long as a sufficient demand for LNG fuel from the shipping sector is not perceived or forthcoming, bunker suppliers will be unwilling to shoulder the necessary infrastructure investments. On the other hand, as long as those necessary bunkering infrastructures are lacking, shipowners will not be willing to invest in LNG fuelled ships. Incentives appear to be required to overcome this dilemma. The key drivers for a change to LNG are the adoption of regulations, which is underway and an involvement of the local authorities.

As of today, there are almost two hundred terminals for LNG import-export in the world, covering about thirty countries (33, pages 61-69). These terminals are set up to transport LNG itself, not as bunkering facilities to supply ships. However, LNG bunkering facilities could be easily developed nearby these terminals. For the future, several governments have plans to ramp up LNG bunkering infrastructures. The first among them are Norway and Sweden. A small scale LNG production and storage supply ferries and supply ships around the Baltic countries. Then, the American shipping company TOTE already runs two container ships between Alaska, Washington State and Florida (34). In each of these states, there are bunkering facilities. In Europe, the port of Rotterdam and Antwerp announced that they have developed an LNG bunkering facilities too. The World Port Climate Initiative (WPCI) gathered the ports of Belgium (Antwerp and Zeebrugge), France (Le Havre), Germany (Bremerhaven, Brunsbüttel and Hamburg), Nederland (Rotterdam), Sweden (Gothenburg and Stockholm), and the United States (Long Beach). These ports are working together to promote the storage and bunkering of LNG (35). In addition to the private initiatives, the European Commission launched a plan to cover European ports with LNG bunkering facilities by 2025: *The Commission is proposing that LNG* *refuelling stations be installed in all 139 maritime and inland ports on the Trans European Core Network by 2020 and respectively 2025. These are not major gas terminals, but either fixed or mobile refuelling stations. This covers all major EU ports* (36).

Regarding the Asian continent, China and Singapore are on the track to equip themselves with such infrastructures. Singapore will begin to supply LNG to vessels by early 2017 (37) while China has *19 LNG bunkering pontoons, the main method of bunkering LNG-fuelled inland waterway vessels, as well as four LNG bunkering barges, and three small-scale LNG carriers* (38).

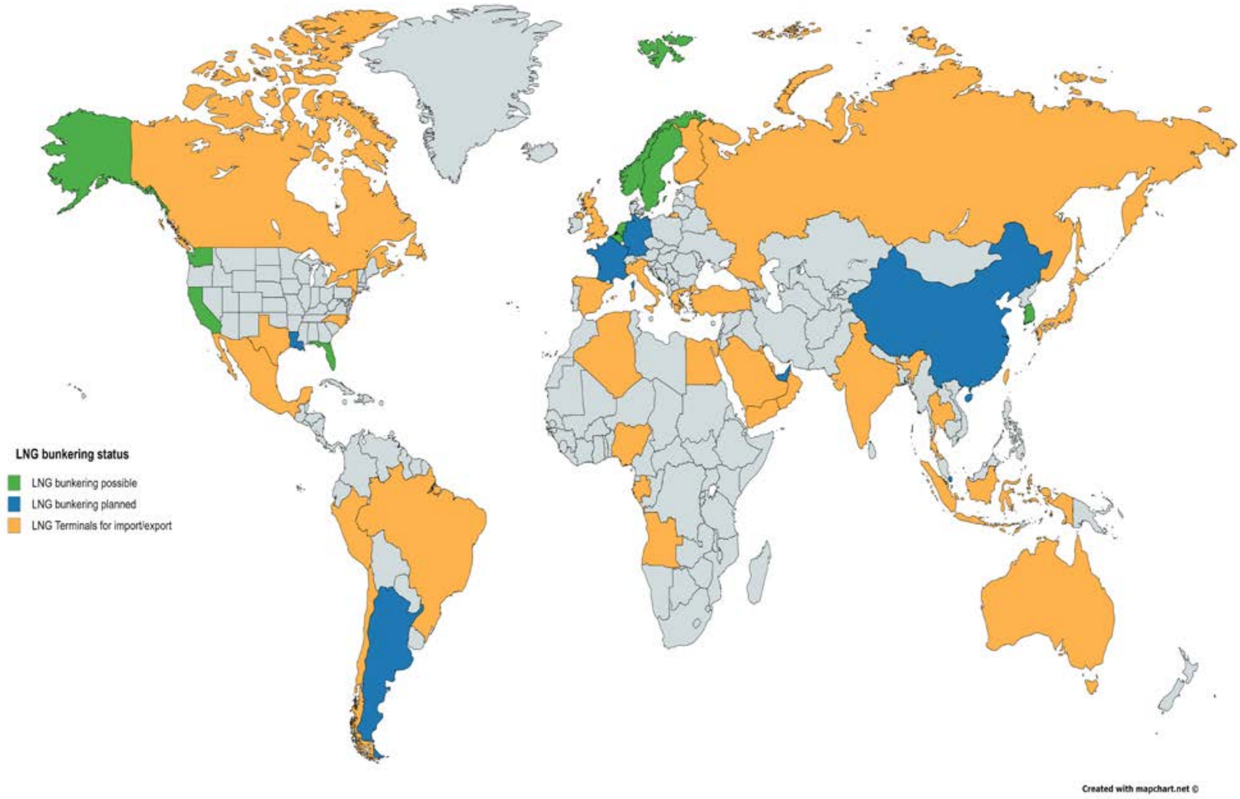

Figure 21: Status of LNG bunkering facilities worldwide

The “chicken-and-egg” problem for the LNG supply chain seems to be broken. But what does the supply chain consist of? Four LNG supply modes are possible: ship to ship transfer (STS), truck to ship (TTS), terminal to ship via pipeline (TPS) and the use of portable tanks (39, pages 8-10). STS bunkering is the standard transfer from a bunker vessel to another vessel. It offers a wide range of flexibility on quantity and transfer rate. It can be carried out at port while commercial activities are performed. Or at sea enabling the passing vessels to refuel without entering the port. The disadvantage of this method is the highest investment that has to be made.

TTS bunkering is done by the means of a truck’s storage tank to a vessel berthed. In practice, any jetty can be used to refuel small ships (tugs, ferries…). However, capacity can be limited. TTS bunkering option can be a temporary solution until the bunkering market makes a large investment in LNG bunker vessels.

With the TPS option, LNG is transferred from a land storage tank to a vessel via a cryogenic pipeline. Although it has a higher transfer rate, it is restricted by the location. Vessels have to be at the dedicated berth to bunker. This option is more suitable for all the existing LNG terminals. They could be converted to LNG bunkering facilities with a dedicated berth for bunkering to avoid interference with LNG carriers.

Lastly, the use of portable tanks is a flexible solution for bunkering and also for the ship. She does not need dedicated storage tank. But it can be a solution to only a few ships, due to the limited range.

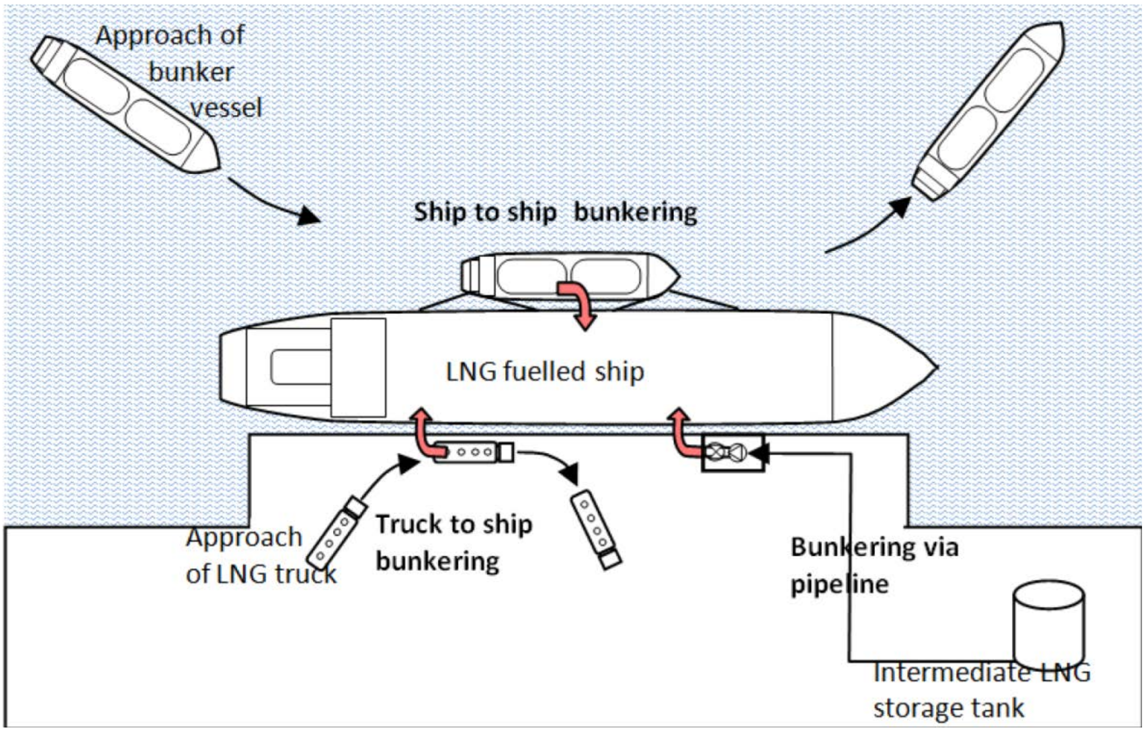

Figure 22: Overview of LNG bunkering operations (IMO, 2016)

The table below summarizes the pro et contra of the different bunker solutions.

	STS – Ship to ship	TTS – Truck to ship	TPS – Terminal to ship via pipeline
Advantages	Flexibility	Flexibility	Availability
	High loading rate	Low costs (investment and operation)	Large bunkering volumes are possible
	Large bunkering volumes are possible		
	Bunkering at sea possible		
Disadvantages	High costs (investments and operations	Low loading rate	Required a dedicated berth
		Small quantities	Occupy terminal space

3.2 The location of the LNG tanks onboard

When considering a LNG fuelled ship, there are three main criteria to take into account for the onboard storage of LNG: the tank design, size and location. The handling of boil-off gas is inevitable and has to be considered.

Tank design

The aim of this paragraph is to provide a brief overview of the available tank designs. The gas tanks have a containment system made up of four parts: primary barrier, secondary barrier, inter-barrier space and thermal insulation (12, pages 317-319). The primary barrier has to keep the liquid inside and prevent any leakage. The function of the secondary barrier is to contain the liquefied gas in case of a failure of the primary barrier. The space between the primary and secondary barriers is the inter-barrier space. The temperature of the liquefied gas is lower than the surroundings. Heat will flow from the higher temperature outside to the cold liquefied gas inside and cause the liquefied gas to evaporate (boil-off). The thermal insulation will minimized this boil-off. The tanks of the LNG carriers are defined in the IGC Code (15, chapter 4). The Code distinguishes the independent tanks (type A, B and C) from the membrane tanks.

The independent tanks are completely self-supporting and do not form a part of the ship's hull. Depending on pressure, there are three types of such tanks:

- Type A tanks: These tanks are prismatic tanks and are internally divided by a centerline bulkhead to reduce free surface effect.

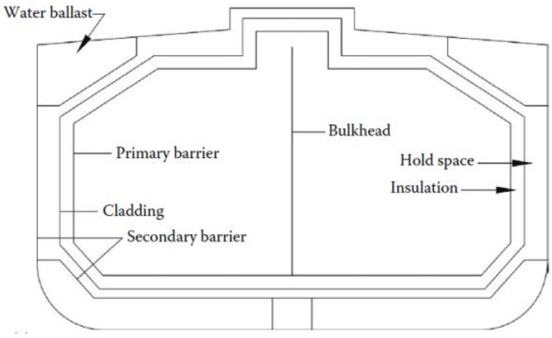

Figure 23: Cross section of a type A tank (Misra, 2016)

- Type B tanks: These tanks are normally spherical and welded to a vertical cylindrical skirt, which is the only connection to the ship's hull.

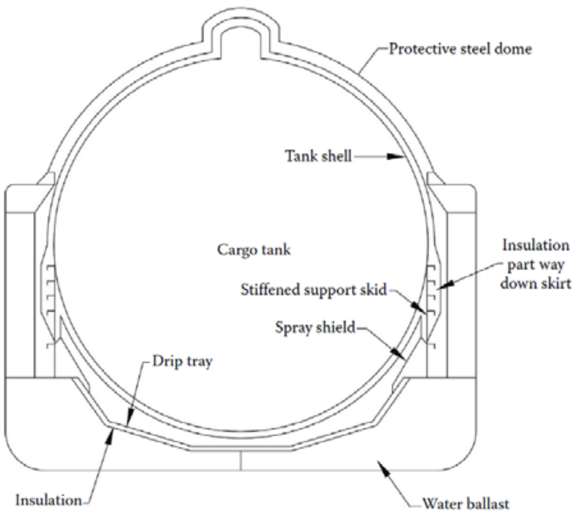

Figure 24: Cross section of a type B tank (Misra, 2016)

- Type C tanks: Theses tanks are cylindrical pressure tanks mounted horizontally on foundation. The tanks may be fitted on or below the deck. They are considered leak proof and no secondary barrier is required. According to the IMO study (40, pages 71-73), *most of the tank designs for the gas fuelled ships in operation, other than LNG carriers, are using vacuum insulated Type C tanks.*

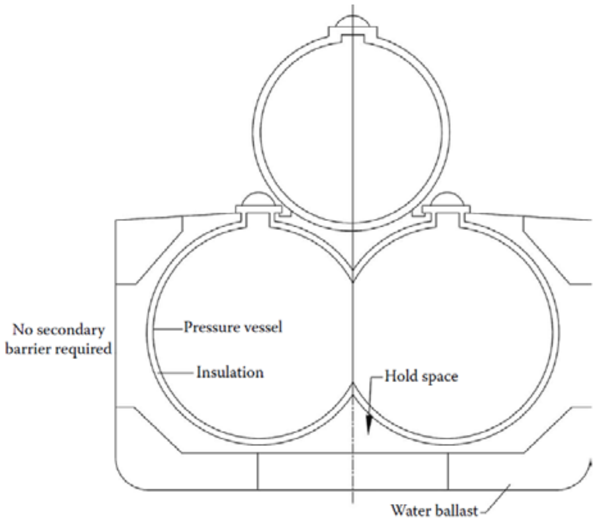

Figure 25: Cross section of a type C tank (Misra, 2016)

The membrane tanks are not self-supporting tanks. They consist of two independent and liquid tight barriers and two layers of insulation to protect the hull from the low temperatures and to limit the boil-off. These thanks are commonly used onboard LNG carriers.

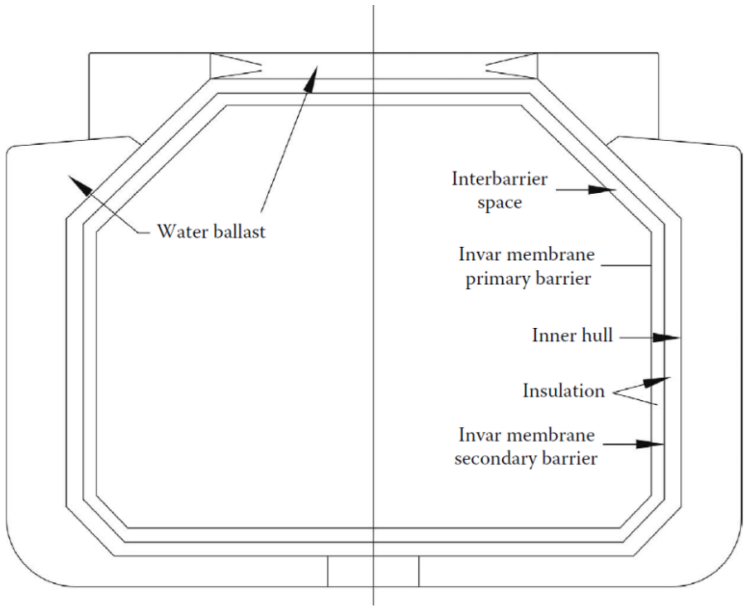

Figure 26: Cross section of a membrane tank (Misra, 2016)

The International Code for the Construction of Gas-Fuelled Ships (IGF Code) allows all of these types of tanks to be used in Article 6.4.15 (19).

Tank size

As shown in figure 15, the energy density ratio of HFO (or distillates) and LNG is 1.6. It means that to achieve the same autonomy, a LNG fuelled ship requires 1.6 time more fuel volume than a conventional ship. In addition, the LNG tanks require more space than fuel tanks.

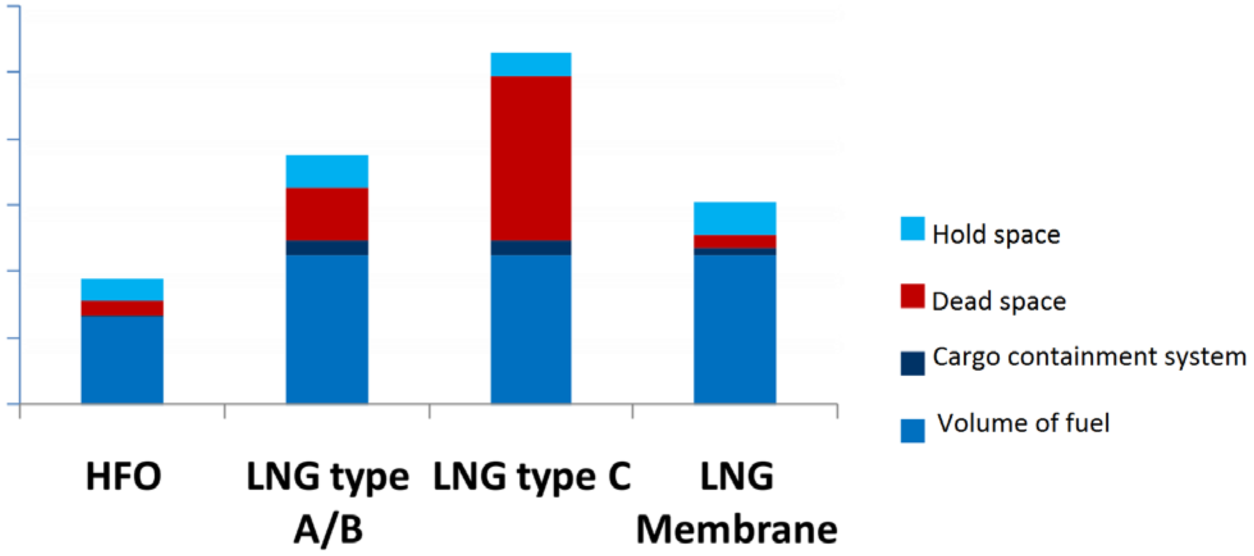

Figure 27: Comparison of the required volume onboard depending of the fuel (GTT, 2012)

The cargo containment system is the primary and secondary barrier, the associated insulation and any adjacent structure needed for the support of these elements. The hold space is the space enclosed by the ship's structure and the cargo containment system. Also, it is important to note that if the ship is running on dual fuel engine, some MDO capacities shall remain onboard and therefore restrict further the available cargo space.

Space requirements for LNG storage are about 2.5 to 3 times greater than for a conventional fuel, for similar autonomy. This may reduce the cargo capacity and be a major obstacle when considering to retrofit a ship.

Tank location

The location of LNG tanks is regulated. The IGF Code allows LNG tanks to be located both below and above deck. But the position of the tank is subject to restriction on the distance from the side and the bottom of the ship. The article 5.3 of the IGF Code (19) includes both deterministic and probabilistic tank location criteria. The former dictates that the tanks must be located within:

- *B/5 or 11.5 m, whichever is less, from the side shell;*
- *B/15 or 2.0 m, whichever is less, from of the bottom shell plating; and*
- *8% aft of the forward perpendicular for passenger ships*

The probabilistic rule allows the tank to be located closer to the side shell only if a proper analysis is carried out. Tanks located on deck will also need to be protected from mechanical damage. Also, if the ship is fitted with pure gas engines, two tanks are required to assure redundancy of fuel supply. For the dual fuel engine, the LNG tank cannot be close to the fuel oil tank.

Management of boil-off gas

Although LNG tanks are highly insulated, some heat will be unavoidable. The key issue is the management of the boil-off gas. To avoid any methane slip, the pressure increase inside the tank must be controlled without any release to the atmosphere. The IGF Code indicates some methods to maintain the pressure in the tank (19, article 6.9): reliquefaction of vapours, thermal oxidation of vapours, pressure accumulation, liquefied gas fuel cooling or energy consumption by the ship. Most commonly, the boil-off gas will be used to power the auxiliary engines and the boiler. The power demand should exceeds by far the natural boil-off from the tanks. However, when the ship is idle (at anchor for instance) and the power demand is very low, gas pressure will increase inside the tank. The excess boil-off gas will be directed to the boiler for incineration.

Inert gas system

According to the IGF Code (19, articles 6.13 and 6.14), the ship must be fitted with an inert gas equipment *capable of producing inert gas with oxygen content at no time greater than 5% by volume.*

3.3 Engine for gas-fuelled ships

Today, the two key engines for LNG fuelled ships are pure gas engine and dual fuel engine. Gas burning engines operate according to two different combustion cycles, the Otto or Diesel cycle. The main characteristics of these two cycles are shown in the table below:

Combustion cycle	Fuel injection	Ignition
Otto	The fuel is mixed with air and admitted to the cylinder before the compression starts.	The fuel is be ignited by an electric spark plug.
Diesel	The fuel is admitted to the cylinder at the end of the compression stroke.	Self-ignition of the fuel due to the compression.

The self-ignition temperature of LNG is too high to be reached by the compression cycle in the cylinder (14, pages 31-32). So the combustion has to be initiated by an ignition source. Engines running on gas only use a spark plug while the dual fuel engines use a pilot fuel (diesel). All major engine manufacturers offer different options for the engine, either pure gas engine or dual fuel engine.

Pure gas engine

The pure gas engines are also called lean burn engines and they run only on gas. Lean burn means that the air-fuel ratio is high which lead to lower combustion temperature and therefore lower NOx formation. The pure gas engine operates according to the Otto cycle, with an injection of gas at low pressure and a combustion triggered by a spark plug ignition. These engines are quite common in LNG fuelled ships operating in Norway and are favored for ferries and offshore vessels. The Rolls-Royce Bergen gas engines have a range of power between 1 500 and 9 000 kW. They are certified to meet IMO Tier 3 NOx limits. In comparison to new marine diesel engines, t*hese gas engines emit 86% less NOx, 98% less PM, and 30% less CO2. They also emit virtually no SO2 (41).*

These gas engines comply with the most stringent emission and fuel sulfur restrictions up to date. However, they do not have the flexibility to run on fuel oil, unlike the dual fuel engine.

Dual fuel engine

As the name implies, a dual fuel engine can either operate on gas or on diesel fuel, or with some combination of diesel and gas (gas-diesel engine). In gas mode, the engine works according to a lean burn Otto cycle, but the ignition is done by an injection of a pilot fuel in the cylinder. And in diesel mode, the engine operates according to the Diesel cycle. The switching between the fuels does not require any interruption in the operation of the engine (42, page 49). Dual fuel engines can be four-stroke or two-stroke. The two prominent manufacturers of engine, Man and Wärtsilä, offer four-stroke dual fuel engine, Otto cycle. The fuel gas pressure is around 5 to 6 bars, higher than the air pressure of the turbocharger.

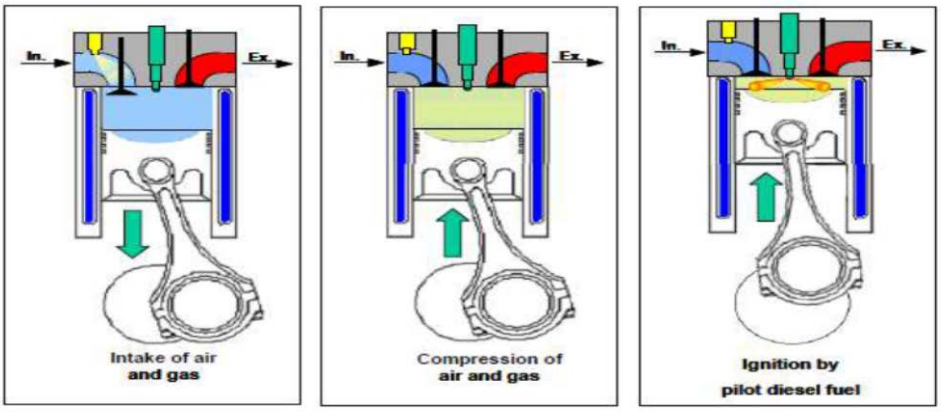

Figure 28: Otto cycle four-stroke dual fuel engine (W. Doug)

But the workhouse engine in the shipping industry is the two-stroke engine. Man and Wärtsilä have newly developed a two-stroke dual fuel engine. The Man engine ME-GI compresses first the air, then starts the combustion process by injecting fuel oil and inject the gas into the burning air-fuel oil mixture. The engine runs in Diesel cycle in gas mode and therefore the gas has to be injected at high pressure, about 300 bars (43, page 16). Man ME-GI two-stroke dual fuel engine has a power up to 82 440 kW and was released on 2014 (44, page 17).

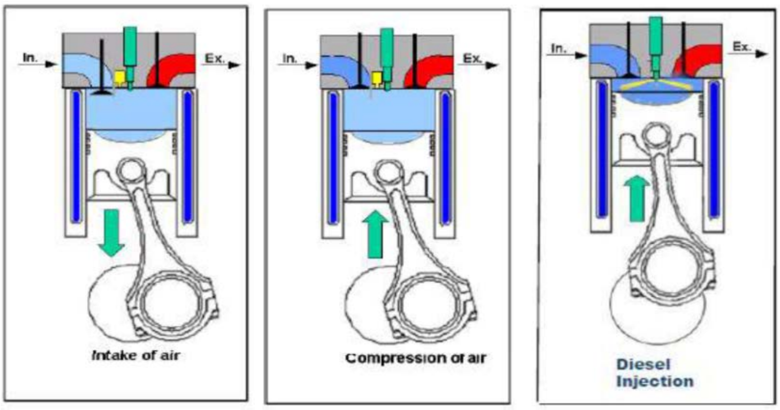

Figure 29: Diesel cycle two-stroke dual fuel engine (W. Doug)

As for Wärtsilä, its engine works on Otto cycle, injecting the gas at low pressure. The most powerful is the Wärtsilä X92DF, low speed two-stroke dual fuel engine, with a maximum power of 65 000 kW (45, page 7).

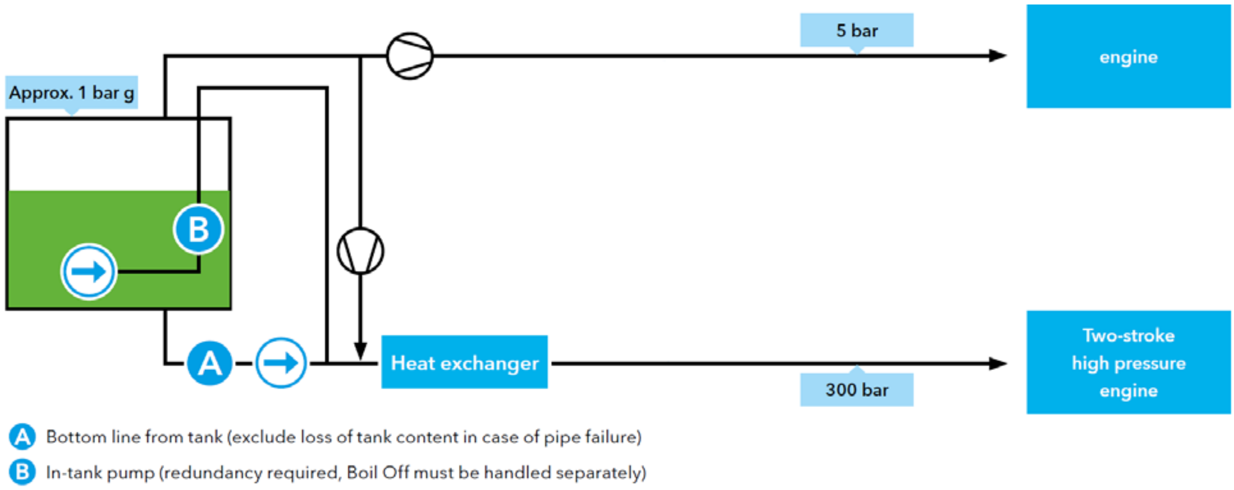

Figure 30: Layout of gas supply to the engine (DNV GL, 2015)

The main benefit of a dual fuel engine is its flexibility. Depending on the environmental regulations in force in the area or on the availability of LNG, the ship can run on LNG or on diesel.

3.4 Safety issues with LNG and training requirements

Being at an early stage of introduction, an accident involving the use of LNG as fuel would constitute a serious drawback for further development. Therefore, it is of utmost importance that the crew receives the adequate training. Excellent safety records from decades of LNG trading are a proof that the control of LNG hazards can be done.

LNG safety issues

In its liquid form, LNG cannot explode and is not flammable. In case of a spill, LNG will quickly become gas and evaporate easily because it is lighter than air. Hazards arise when LNG is in gaseous state, especially through uncontrolled release. The release could be caused by a tank rupture or a leak in the pipework. LNG evaporates quickly, leaving no residue. There is no environmental cleanup needed for LNG spills on water or land. Hazards can be divided into two categories: cryogenic effects and fire.

Carbon steel structures will brittle and fracture if exposed to cryogenic liquid. But stainless steel and aluminum do not suffer from cryogenic embrittlement (46, page 30). They should be applied to protect LNG sensitive areas, such as bunker station. For humans, frostbite is a serious injury and can have permanent damage.

Once the LNG has leaked, it will form a white cloud of gas, mainly composed of methane. The gas will mix with air and when it reaches a mix of 5-15% of gas, the cloud is ignitable. Outside this critical level, explosion or fire will not occur. With concentration less than 5%, the lower flammability limit (LFL), the LNG vapor would not burn because there is not enough methane. And with concentration higher than 15%, the upper flammability limit (UFL), there is insufficient oxygen to support the combustion.

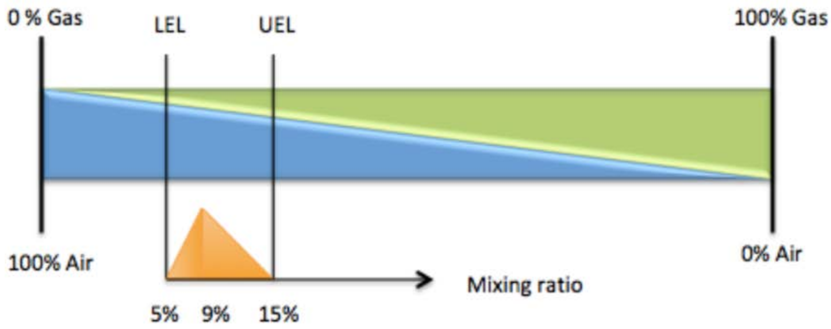

Figure 31: Explosion and flammability curve of methane (EMSA)

For an explosion to happen, the gas needs to be in a confined, reach the right mix with oxygen and have the presence of an ignition source. The IGF code, in its article 6.7, provides specific advice on tank and pipe design: *All fuel storage tanks shall be provided with a pressure relief system appropriate to the design of the fuel containment system and the fuel being carried. Pressure control systems specified in 6.9 shall be independent of the pressure relief systems.*

New training requirements

The resolution MSC 396(95), adopted on 11 June 2015, amends the STCW Convention. There are mandatory minimum requirements for the training and qualifications of masters, officers, ratings and other personnel on ships subject to the IGF Code (47).

4 – The outlook for a LNG fuelled fleet

As previously stated in this study, new environmental regulations are forcing shipowners to either change propulsion fuel or invest in costly exhaust gas cleaning systems. On top of that, the bunker price of distillate conventional fuels is expecting to rise. Thus, there will be a growing number of LNG fuelled vessels. This section aims to examine the research finding for different types of ships and shows the status of the LNG fuelled fleet with the current projects.

4.1 LNG for passenger ships

The first LNG fuelled ship (excluding LNG carriers) was built in Norway in 2000. The M/V Glutra is a 95 meter length ferry owned by Fjord1. Today, this company operates twelve LNG ferries along the Norwegian coast. The latest is the M/V Boknafjord, measuring 130 meters length and has capacity for 242 passenger cars and 600 passengers including crew (48).

Figure 32: M/V Boknafjord (Marine Traffic)

In 2013, the ferry company Viking Lines, operating in Baltic Sea, received the first large passenger vessel, the M/V Viking Grace. She measures 218 meters in length and has a capacity of 2 800 passengers and the length of the cargo lane is 1 200 meters. Gross tonnage is 57 600 tons. She is powered by 4 four-stroke dual fuel Wärtsilä engines, for a total power output of 30 600 kW. There are two fuel tanks, type C, 200 m3 each. The Viking Grace costs approximately 240 million euros (49, page 3) and was built in STX shipyard, Finland. She operates between Finland and Sweden. The bunker vessel Seagas has been specially built to supply the Viking Grace in Stockholm. According to the website LNG world news, Viking Line ordered on November 2016 another LNG fuelled ferry, slightly bigger than the Viking Grace. The contract is worth 190 million euros and the ship will be built in China (50). Another company, Fjord Line, also has LNG fuelled ferry. The M/V Stavangerfjord and the M/V Bergenfjord, delivered on 2014, have a capacity of 1 500 passengers and 600 cars. They operate between Norway and Denmark (51).

Figure 33: M/V Viking Grace and bunker vessel Seagas (Go LNG, 2014)

The technology for LNG fuelled ferry exists and could easily be developed in other geographical areas. On December 2016, Brittany Ferries has signed a letter of intent with a German shipyard to construct a new 42 000 GT LNG fuelled ferry, for the Portsmouth Caen line (52).

What about the cruise ship sector? To date, there is no LNG fuelled cruise ship sailing, yet. But Carnival ordered three LNG powered cruise ships, all made in Europe. These cruise ships are expected to be in service by 2019 (53). DNV GL has released in November 2015 a research study focusing on the retrofitting method and cost for cruise ships (54). As per this study, converting an existing ship to run on LNG can in principle be done by (54, page 19):

1 - Taking the ship out of operation and installing the LNG tanks and fuel handling systems in the existing hull. Such a retrofit will reduce the number of cabins and will involve technical complications as the LNG tanks require more space than HFO or MGO fuel tanks and such free space is not available on the ship. In addition, this is time-consuming and thus represents a loss of revenue due to the lengthy off-hire.

2 - Inserting a new "LNG Ready" prefabricated mid-body section containing all the LNG systems, additional cabins and public spaces into the ship. Such a retrofit can be done in a few weeks, the ship does not need to go on a lengthy off-hire and the passenger capacity will increase by approximately 10%. The investment is limited to approx. 10% to 12% of new building costs.

The DNV GL's study focus on the second choice, the elongation of the ship. The elongation technique has been done several times in the shipping industry. The last example was the cruise ship Enchantment of the Seas which received a 22 meters length elongation to increase the passenger capacity. The study shows that, *in a 23m compartment, the maximum possible volume of LNG is approximately 1 500m3 due to design and structural constraints* (cylindrical type C tanks). *The addition of new cabins will increase the total number of cabins by approximately 10%.* The study also highlighted that, with 1 500 m^3 of LNG, *approximately 70% - 80% of all existing cruise itineraries can be operated*. In order to cover the remaining 20% - 30%, the shipowner can either use the ship's dual-fuel capabilities and or perform a bunkering operation to fill up with LNG half way through the voyage. *A potential new mid-body section of 43m will be able to accommodate approximately 3,000m3 of LNG in total and this will enable the ship to carry out all the current itineraries.* Of course, the decision of elongation will involve the flag authorities and the class society. Several factors have to be taken into account, such as the hull's structure, the strengths, the bending moment, the firefighting arrangements… Regarding the mechanical factors, there is the possibility to convert the main engines into dual fuel engines. The ship power will have to be recalculated. And the HFO treatment systems and tanks can be removed, giving more space for LNG tanks. Lastly, the most important point is the financial assessment.

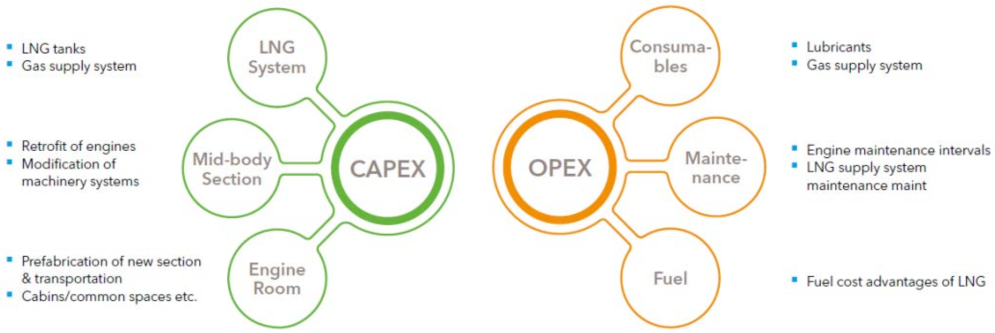

Figure 34: CAPEX and OPEX of retrofitting (DNV GL, 2015)

The scrubber and fuel switch case do not provide additional cabins and therefore no additional revenue from increased number of passengers. The DNV GL study developed four scenarios to calculate the payback time for the LNG option: *The difference in the scenarios is the percentage of profit on the yearly revenue generated from the new mid-body section. A spread of 0% - 50% profit on the revenue has been applied to represent the potential economic gains of the elongation. When calculating the financial attractiveness of the LNG option, the following assumptions were used:*

- LNG Price: $ 14/MMBtu (12.5% below HFO price)

- MGO Price: $ 25/MMBtu ($1,000/ton)

- HFO Price: $ 16/MMBtu ($614/ton)

- *No price increase over time is assumed*
- *100% gas mode operation when operating*
- *The thermal efficiencies of diesel and gas engines are assumed to be identical*
- *All engines running at the same load point (assumed average load of 50% MCR)*

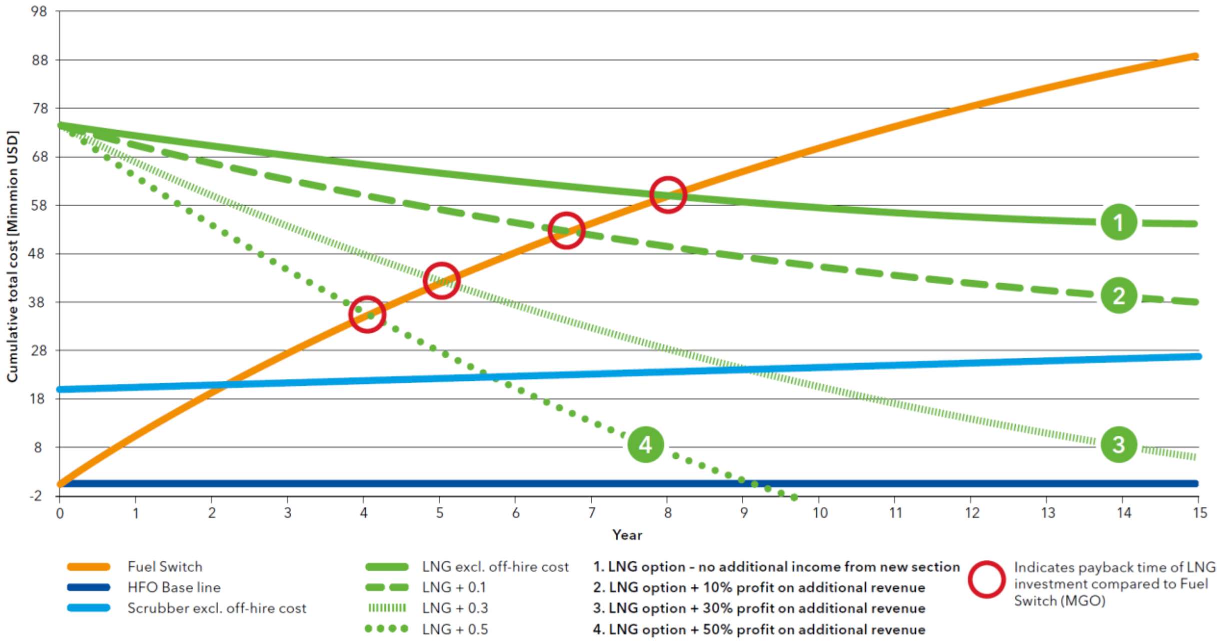

Figure 35: Net present value of cumulative cost to LNG retrofit (DNV GL, 2015)

The study concludes that *retrofitting cruise ships to run on LNG is not only technically but also financially feasible if an attractive LNG price can be achieved. The calculated payback time is 4-8 years compared to MGO.*

4.2 LNG for container ships

The American shipping company Tote was the first to introduce LNG powered container ships in the world on 2015. Tote currently has two new LNG container ships, dual fuel engine, both having a capacity of 3 100 TEU. Another American shipping company, Mason, ordered two dual fuel engine ConRo ships, 3 500 TEU and 800 vehicles capacity (55). For the retrofit, Tote is planning to convert two existing ConRo ships to LNG fuelled. And a German company converted the 1 036 TEU Wes Ameli to LNG with Man dual fuel engine and a 500 m^3 tank (56). Concerning the larger container ships, a step has been made by UASC towards LNG powered vessels. UASC is increasing its fleet capacity with eleven 15 000 TEU and six 18,800 TEU, all LNG ready (57). UASC decided that LNG would be a better option, rather than investing in scrubber technology. For the retrofit, t*he cargo hold directly in front of the engine room would be* *the most suitable location, with short piping routes to the LNG type B tank* (58, page 19). DNV GL, the class society for these ships, has endorsed this concept.

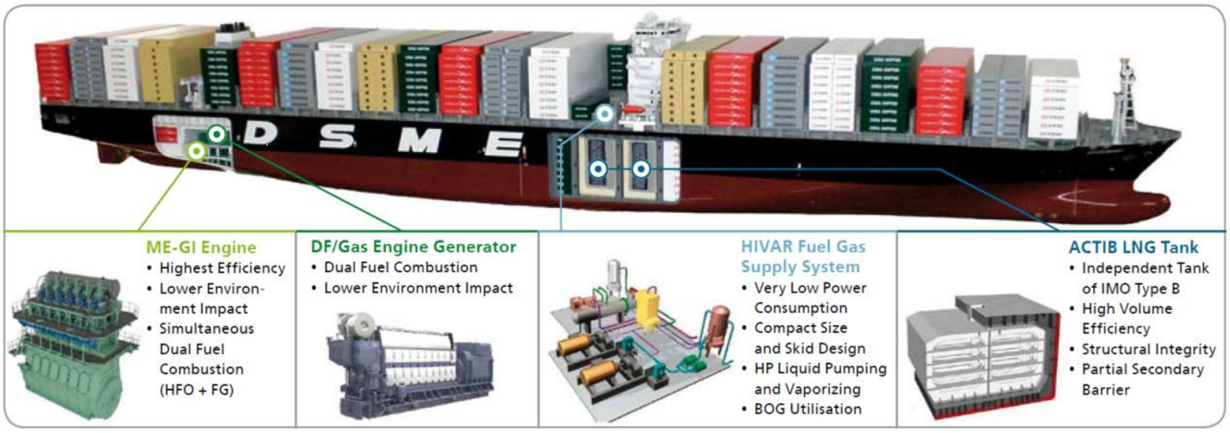

Figure 36: LNG ready container ship (DSME, 2015)

Same as the passenger vessels, container ships are moving toward LNG fuelled. But what could be the payback time compared to other solutions? A joint study with DNV GL and Man, on 2011, reviewed the costs and benefits of LNG for the container ships (59):

Five representative container vessel sizes were selected for the study. Round trips were selected for three trades: intra-European, Europe-Latin America and Europe-Asia. The ECA exposure was used as primary input parameter.

TEU	Speed (knots)	Main engine power (kW)	Round trip (nm)	default ECA share
2,500	20	14,500	5,300	65.1%
4,600	21	25,000	13,300	11.0%
8,500	23	47,500	23,000	6.3%
14,000	23	53,500	23,000	6.3%
18,000	23	65,000	23,000	6.3%

The LNG tank volume is selected to give the vessel half-round-trip endurance. Costs for LNG system include costs for the tanks, bunker station, gas preparation, gas line and main engine. LNG tanks are assumed to consume TEU slots, resulting in lost earnings, assumed only for every second voyage. The medium-sized container vessels (4,600 TEU and 8,500 TEU) have the largest losses with a maximum of about 3% of the total available TEU slots. Other operation costs such as crew, spare parts and maintenance are assumed to be 10% higher than the reference vessels (59, page 5).

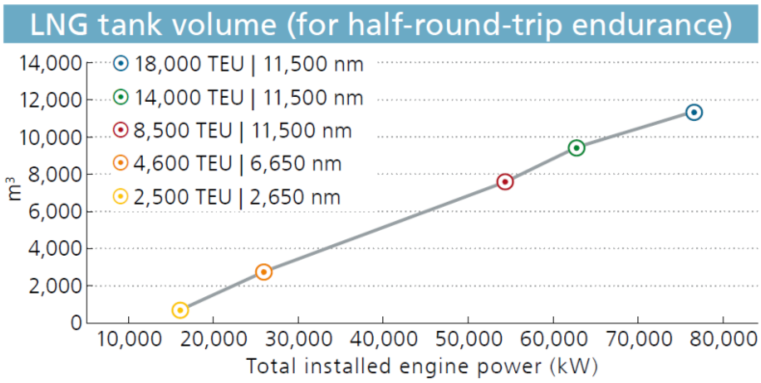

Figure 37: LNG tank volume used in the DNV GL – Man study

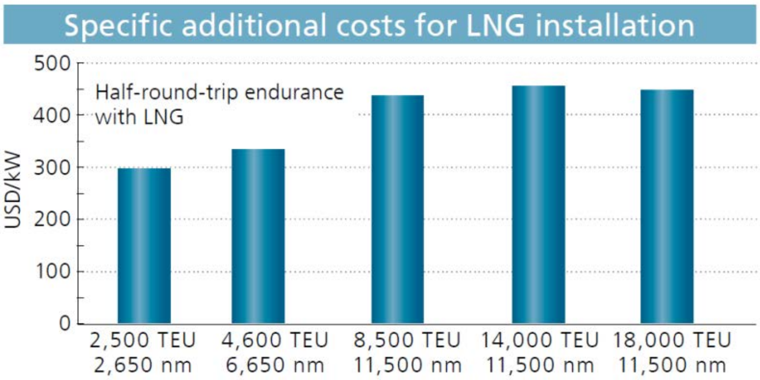

Figure 38: Cost of LNG installation

The assumption for the fuel price scenario is a faster price increase of MGO and LSHFO than HFO and LNG.

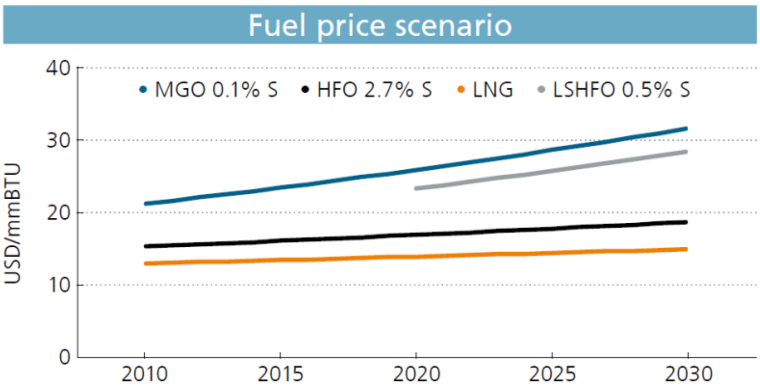

Figure 39: Fuel price scenario for this DNV GL – Man study

Cost advantages are the sum of fuel cost savings, additional operating costs and lost earnings. *For a 2,500 TEU regional vessel operating 65% inside European ECAs, significant cost advantages are predicted using LNG or scrubber by 2015 when strict fuel quality requirements enter into force. Payback time is shorter for solutions without WHR due to its relatively high* *investment costs* (59, page 7). A waste recovery system (WHR) consists of *an exhaust gas boiler supplying steam to a steam turbine to boost the electrical output. The system can be extended with a gas turbine utilizing the energy in the exhaust gas not used by the turbocharger. Waste heat recovery systems are modelled to reduce specific fuel consumption. Savings depend on engine load and ship size. Maximum benefit of 13% was assumed for the largest vessels at 75% MCR* (59, page 6).

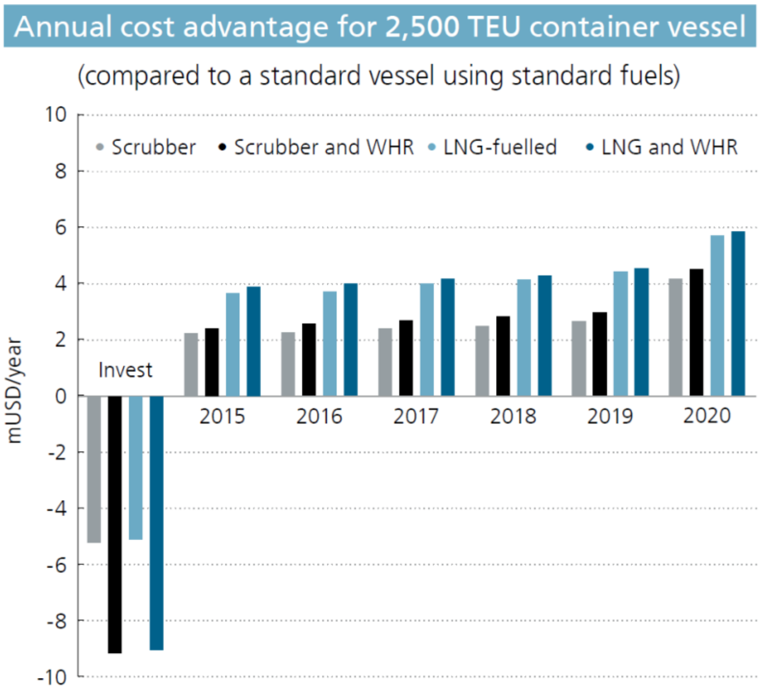

Figure 40: Annual cost advantage for a 2 500 TEU (DNV GL – Man)

According to this research study, the payback time is shorter for small container ships. The main reason is their relative smaller investment for the LNG system than larger vessels.

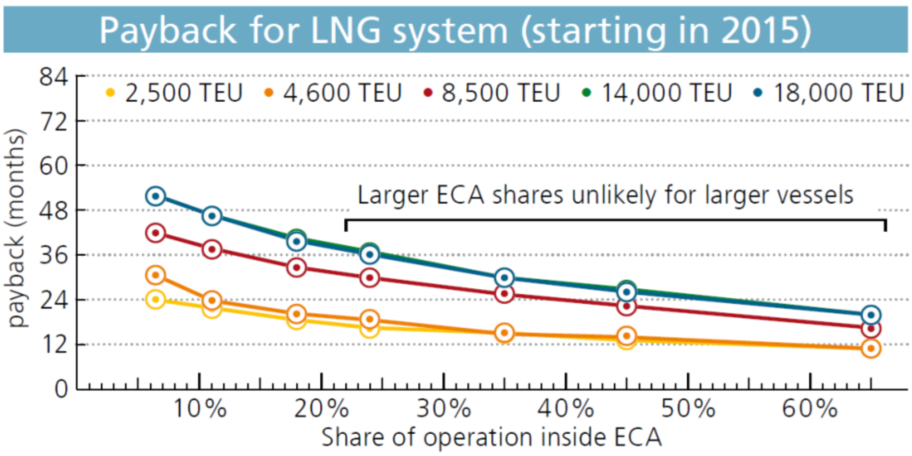

Figure 41: Payback for LNG system (DNV GL – Man)

Also, considering that the LNG is still not widely available, the distribution costs of LNG will reduce in the future, lowering the payback time.

4.3 LNG for bulk carriers

DNV GL performed a feasibility study in 2014 investigating the possibility for the bulk carrier vessels to be converted to LNG fuel (60). The study focus on a trade route between Europe and United States for two bulk carrier, Panamax and Kamsarmax. Kamsarmax refers to a new type of ships, larger than Panamax, that are suitable for berthing at the Port of Kamsar in Guinea, where the loading terminal of bauxite can accommodate vessels not more than 229 meter length. The main findings of the study indicated that (60, page 6):

- *500-700 m3 of LNG are sufficient to offer compliance for a roundtrip voyage with only one bunkering operation. A small LNG tank can be installed at the aft of the vessel.*
- *Approximately 2,000-2,500 m3 of LNG are needed to perform a roundtrip between US and Europe by only burning LNG.*
- *Approximately a gross volume of 3,000 m3 of LNG is the maximum volume that can be accommodated onboard a Kamsarmax vessel without compromising on the cargo capacity. This volume offers endurance flexibility to the vessel to trade on gas on all the identified Panamax/Kamsarmax trade routes.*
- *The final recommendation was to develop a design that could accommodate a minimum of 2,000 m3 LNG fuel tank capacity. This alternative gave the best balance between CAPEX and potential savings in future fuel costs and OPEX.*

On a bulk carrier, the available space is limited and therefore LNG tanks can be located only near the accommodations. The Japanese shipbuilder, Oshima, developed this design shown in the figure below.

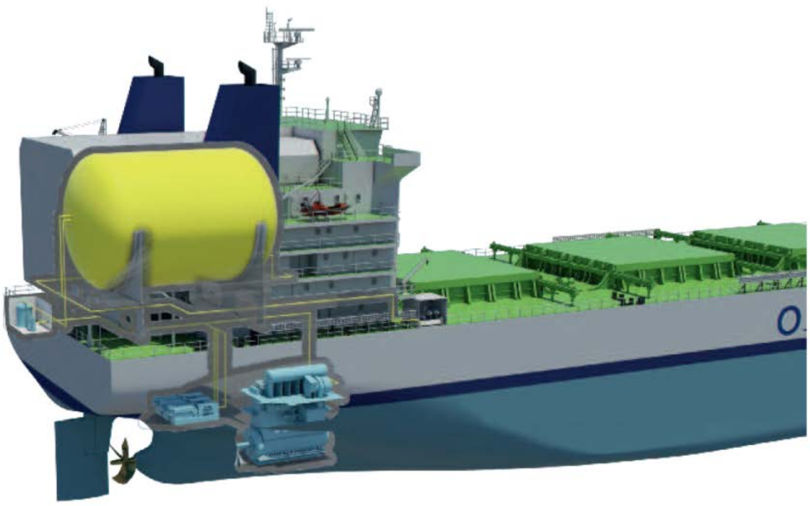

Figure 42: Location of LNG tank onboard a bulk carrier (Oshima)

The design is flexible to accommodate any tank size and type without any further design modifications. The dedicated tank space is suitable for one IMO type C tank with up to 2,500 m3 or one IMO type B tank with up to 3,000 m3 (60, page 8). Covering the tank with a steel cover provides additional safety and allows the accommodations to be completely separated from the LNG tank. A 50 000 dwt LNG fuelled bulk carrier is under construction by Hyundai and should be delivered at the end of 2017 (61). The concept is the same than the one explained.

4.4 LNG for tanker vessels

As for the tanker, is LNG an attractive option? The 25 000 dwt M/T Bit Viking was the first vessel ever to undergo a retrofit to LNG. She has a Wärtsilä dual fuel engine and two 500 m^3 LNG fuel tanks (62).

M/T tankers are usually engaged in spot trade, meaning that the ships have an unpredictable trading route. For shipowners, there could be a risk that LNG bunkering would not be possible. However, with dual fuel engine technology readily available, this concern fades away. DNV GL released a study in 2014, focusing on the commercial attractiveness of building a dual fuel 50 000 dwt oil tanker engaged on a voyage between Rotterdam and New Orleans (63). The study suggests that the vessel is fitted with a 3 000 m^3 tank, allowing the *vessel to bunker all of its fuel in the US, where LNG prices are considerably lower than in Europe* (63, page 6).

The study performed a financial comparison between LNG, MGO and HFO with scrubber.

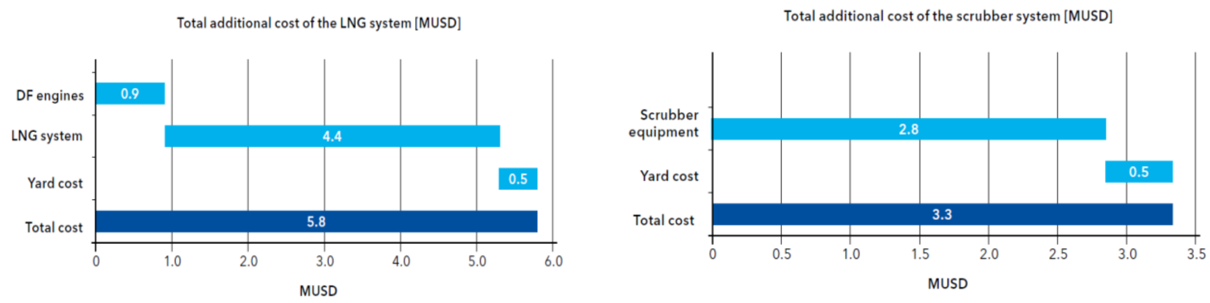

Figure 43: Cost of LNG system and HFO with scrubber (DNV GL, 2014)

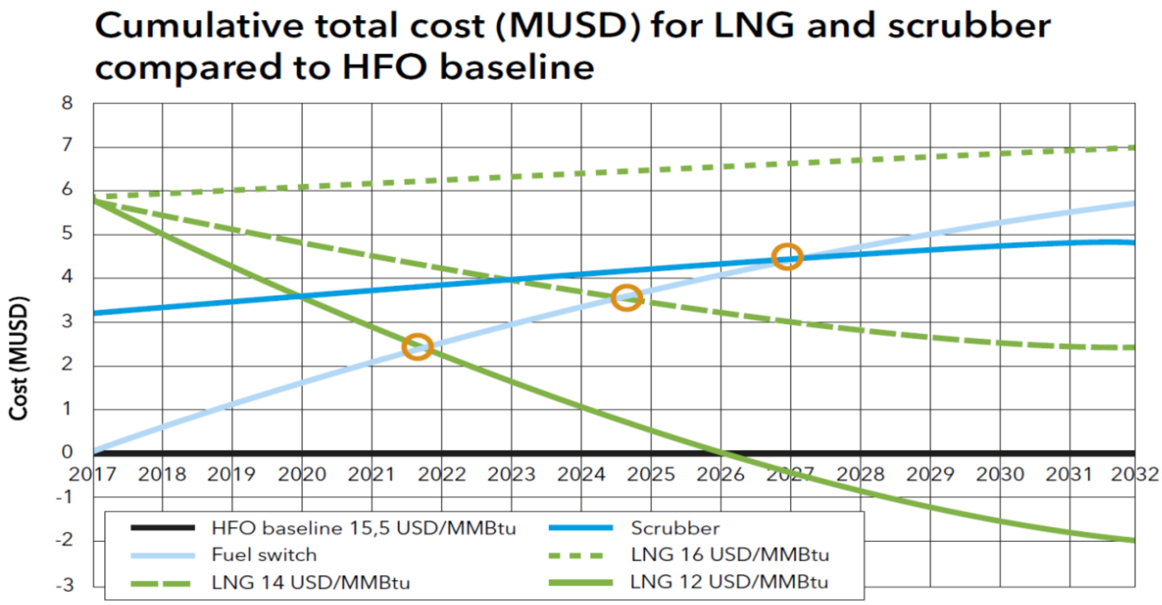

Figure 44: Payback time of the investment over fuel choice for a tanker (DNV GL, 2014)

The figure above presents the cumulative cost of the different fuel options for the tanker, compared to a HFO baseline. For an applied LNG price ranging from 12 USD/MMBtu (600 USD/ tonne) to 16 USD/MMBtu (900 USD/tonne), the study concludes that, *for LNG price of 12 USD/MMBtu, the payback time compared to HFO with a scrubber is 2.6 years, and 4.5 years compared to fuel switch to MGO* (63, page 7).

The same study completed today would certainly have a better payback time for LNG, considering the current price of 10 USD/MMBtu and the compulsory sulphur cap of 0.5% by 2020.

Conclusion

All the new environmental regulations urge the shipowners to investigate alternative solutions. Using liquefied natural gas as ship fuel promises less emissions and under circumstances, less fuel costs. LNG as a fuel, for non LNG carriers, started in Norway at the beginning of 2000. But since 2012, LNG has seen an increasing interest in the Baltic Sea and worldwide now. As of September 2016, there are 77 LNG fuelled ships in operations and 85 confirmed LNG new buildings (64). Will this trend continue? Upon completion of this dissertation, LNG is definitely here to stay.

However some uncertainties remain up to this date. The price of LNG delivered to the ship is difficult to predict. Base LNG prices vary from the USA to Japan by a factor of four. And the availability of LNG is scarce. Small scale LNG distribution is just starting to become available in Europe (outside Norway). And the retrofit of existing ships could be difficult to achieve mainly because of the dilemma between LNG tanks location and cargo space. The last barrier, perhaps the most important, is the financial uncertainty. Many reports prove that it is difficult to have a quick payback on the cost of converting to LNG. Moreover, there is also the risk of the costs being higher than expected due to the immaturity of the LNG fuelled vessels.

Nonetheless, the global actors of the shipping industry are working towards the adoption of LNG. An international LNG infrastructure is under development. A legislative framework is being adopted in many countries. LNG as fuel is now a proven and available solution, with gas engines covering a broad range of power outputs. Engine concepts include gas-only engines, and dual fuel four-stroke and two-stroke. Different designs allow many type of ships to be converted to LNG. Liquefied natural gas as a marine fuel has become a reality for international shipping.

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